NCHRP
REPORT 757

NATIONAL
COOPERATIVE
HIGHWAY
RESEARCH
PROGRAM

Long-Term Performance of
Epoxy Adhesive Anchor Systems

TRANSPORTATION RESEARCH BOARD

Long-Term Performance of Epoxy Adhesive Anchor Systems

DETAILS

268 pages | 8.5 x 11 | PAPERBACK
ISBN 978-0-309-28357-1 | DOI 10.17226/22470

AUTHORS

Cook, Ronald A.; Douglas, Elliot P.; Davis, Todd M.; and Liu, Changhua

NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

NCHRP REPORT 757

Long-Term Performance of Epoxy Adhesive Anchor Systems

Ronald A. Cook
Elliot P. Douglas
Todd M. Davis
Changhua Liu
UNIVERSITY OF FLORIDA
Gainesville, FL

Subscriber Categories
Bridges and Other Structures • Construction • Materials

Research sponsored by the American Association of State Highway and Transportation Officials
in cooperation with the Federal Highway Administration

TRANSPORTATION RESEARCH BOARD

WASHINGTON, D.C.
2013
www.TRB.org

NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

Systematic, well-designed research provides the most effective approach to the solution of many problems facing highway administrators and engineers. Often, highway problems are of local interest and can best be studied by highway departments individually or in cooperation with their state universities and others. However, the accelerating growth of highway transportation develops increasingly complex problems of wide interest to highway authorities. These problems are best studied through a coordinated program of cooperative research.

In recognition of these needs, the highway administrators of the American Association of State Highway and Transportation Officials initiated in 1962 an objective national highway research program employing modern scientific techniques. This program is supported on a continuing basis by funds from participating member states of the Association and it receives the full cooperation and support of the Federal Highway Administration, United States Department of Transportation.

The Transportation Research Board of the National Academies was requested by the Association to administer the research program because of the Board's recognized objectivity and understanding of modern research practices. The Board is uniquely suited for this purpose as it maintains an extensive committee structure from which authorities on any highway transportation subject may be drawn; it possesses avenues of communications and cooperation with federal, state and local governmental agencies, universities, and industry; its relationship to the National Research Council is an insurance of objectivity; it maintains a full-time research correlation staff of specialists in highway transportation matters to bring the findings of research directly to those who are in a position to use them.

The program is developed on the basis of research needs identified by chief administrators of the highway and transportation departments and by committees of AASHTO. Each year, specific areas of research needs to be included in the program are proposed to the National Research Council and the Board by the American Association of State Highway and Transportation Officials. Research projects to fulfill these needs are defined by the Board, and qualified research agencies are selected from those that have submitted proposals. Administration and surveillance of research contracts are the responsibilities of the National Research Council and the Transportation Research Board.

The needs for highway research are many, and the National Cooperative Highway Research Program can make significant contributions to the solution of highway transportation problems of mutual concern to many responsible groups. The program, however, is intended to complement rather than to substitute for or duplicate other highway research programs.

NCHRP REPORT 757

Project 04-37
ISSN 0077-5614
ISBN 978-0-309-28357-1
Library of Congress Control Number 2013950626

COPYRIGHT INFORMATION

NOTICE

The project that is the subject of this report was a part of the National Cooperative Highway Research Program, conducted by the Transportation Research Board with the approval of the Governing Board of the National Research Council.

The members of the technical panel selected to monitor this project and to review this report were chosen for their special competencies and with regard for appropriate balance. The report was reviewed by the technical panel and accepted for publication according to procedures established and overseen by the Transportation Research Board and approved by the Governing Board of the National Research Council.

The opinions and conclusions expressed or implied in this report are those of the researchers who performed the research and are not necessarily those of the Transportation Research Board, the National Research Council, or the program sponsors.

The Transportation Research Board of the National Academies, the National Research Council, and the sponsors of the National Cooperative Highway Research Program do not endorse products or manufacturers. Trade or manufacturers' names appear herein solely because they are considered essential to the object of the report.

Published reports of the

NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

are available from:

Transportation Research Board
Business Office
500 Fifth Street, NW
Washington, DC 20001

and can be ordered through the Internet at:

http://www.national-academies.org/trb/bookstore

Printed in the United States of America

THE NATIONAL ACADEMIES

Advisers to the Nation on Science, Engineering, and Medicine

The **National Academy of Sciences** is a private, nonprofit, self-perpetuating society of distinguished scholars engaged in scientific and engineering research, dedicated to the furtherance of science and technology and to their use for the general welfare. On the authority of the charter granted to it by the Congress in 1863, the Academy has a mandate that requires it to advise the federal government on scientific and technical matters. Dr. Ralph J. Cicerone is president of the National Academy of Sciences.

The **National Academy of Engineering** was established in 1964, under the charter of the National Academy of Sciences, as a parallel organization of outstanding engineers. It is autonomous in its administration and in the selection of its members, sharing with the National Academy of Sciences the responsibility for advising the federal government. The National Academy of Engineering also sponsors engineering programs aimed at meeting national needs, encourages education and research, and recognizes the superior achievements of engineers. Dr. C. D. Mote, Jr., is president of the National Academy of Engineering.

The **Institute of Medicine** was established in 1970 by the National Academy of Sciences to secure the services of eminent members of appropriate professions in the examination of policy matters pertaining to the health of the public. The Institute acts under the responsibility given to the National Academy of Sciences by its congressional charter to be an adviser to the federal government and, on its own initiative, to identify issues of medical care, research, and education. Dr. Harvey V. Fineberg is president of the Institute of Medicine.

The **National Research Council** was organized by the National Academy of Sciences in 1916 to associate the broad community of science and technology with the Academy's purposes of furthering knowledge and advising the federal government. Functioning in accordance with general policies determined by the Academy, the Council has become the principal operating agency of both the National Academy of Sciences and the National Academy of Engineering in providing services to the government, the public, and the scientific and engineering communities. The Council is administered jointly by both Academies and the Institute of Medicine. Dr. Ralph J. Cicerone and Dr. C. D. Mote, Jr., are chair and vice chair, respectively, of the National Research Council.

The **Transportation Research Board** is one of six major divisions of the National Research Council. The mission of the Transportation Research Board is to provide leadership in transportation innovation and progress through research and information exchange, conducted within a setting that is objective, interdisciplinary, and multimodal. The Board's varied activities annually engage about 7,000 engineers, scientists, and other transportation researchers and practitioners from the public and private sectors and academia, all of whom contribute their expertise in the public interest. The program is supported by state transportation departments, federal agencies including the component administrations of the U.S. Department of Transportation, and other organizations and individuals interested in the development of transportation. **www.TRB.org**

www.national-academies.org

COOPERATIVE RESEARCH PROGRAMS

CRP STAFF FOR NCHRP REPORT 757

Christopher W. Jenks, *Director, Cooperative Research Programs*
Crawford F. Jencks, *Deputy Director, Cooperative Research Programs*
Edward T. Harrigan, *Senior Program Officer*
Anthony Avery, *Senior Program Assistant*
Eileen P. Delaney, *Director of Publications*
Scott E. Hitchcock, *Editor*

NCHRP PROJECT 04-37 PANEL

Field of Materials and Construction—Area of General Materials

Christopher Hahin, *Illinois DOT, Springfield, IL* (Chair)
Mark A. Gaines, *Washington State DOT, Olympia, WA*
Craig J. Beissel, *AECOM, Mechanicsburg, PA*
Mark J. Bloschock, *Gibraltar Cable Barrier Systems, Marble Falls, TX*
Peter O. Jansson, *Michigan DOT, Lansing, MI*
Justin M. Ocel, *Federal Highway Administration, McLean, VA*
Madhwesh Raghavendrachar, *California DOT, Sacramento, CA*
Michael M. Sprinkel, *Virginia DOT, Charlottesville, VA*
Joey Hartmann, *FHWA Liaison*
Stephen F. Maher, *TRB Liaison*

AUTHOR ACKNOWLEDGMENTS

The research reported herein was performed under NCHRP Project 04-37 by the Department of Civil and Coastal Engineering at the University of Florida (UF).

Dr. Ronald A. Cook, P.E., Professor of Civil Engineering at UF, was the Project Director and Principal Investigator. The other authors of this report were Dr. Elliot P. Douglas, Associate Professor of Materials Science and Engineering at UF; Todd M. Davis, P.E., Research Assistant in Civil Engineering at UF; and Changhua Liu, Research Assistant in Materials Science and Engineering at UF. The work was done under the general supervision of Professors Cook and Douglas at UF.

Dr. Rolf Eligehausen, Dr. Jan Hofmann, and Ronald Blochwitz of the IWB laboratory at the University of Stuttgart in Stuttgart, Germany, were subcontracted for a portion of the experimental phase of the project.

The researchers are grateful to the Florida Department of Transportation State Materials Office for providing the use of their laboratories for concrete batching and dynamic shear rheometer (DSR) machine.

FOREWORD

By Edward T. Harrigan
Staff Officer
Transportation Research Board

This report presents proposed revisions to AASHTO materials, design, and construction specifications; design and quality assurance guidelines; and test methods for adhesive anchors in concrete. Thus, the report will be of immediate interest to materials, design, and construction engineers in state DOTs and the highway industry with responsibility for selection and use of adhesive anchors in concrete highway structures.

Adhesive anchor systems have widespread use throughout the world. They are used to anchor both threaded rods and reinforcing bars into hardened concrete. Common transportation structure applications for adhesive anchor systems include bridge widening, structure-mounted signs and appurtenances, luminaires and light poles, concrete repair and rehabilitation, barrier retrofitting, utility installation on existing structures, and tunneling finishing. The objective of NCHRP Project 4-37, "Long-Term Performance of Epoxy Adhesive Anchor Systems," was to develop proposed standard test methods, materials specifications, design specifications and guidelines, construction specifications and guidelines, and quality assurance guidelines for the use of adhesive anchor systems in transportation structure applications. Development of these standards was founded on the results of a comprehensive program of laboratory experiments to determine, predict, and verify the long-term performance of adhesive anchors under sustained load in their typical service applications and environments. The research was conducted by the University of Florida (Gainesville, Florida) with the participation of the University of Stuttgart (Stuttgart, Germany).

The research investigated the effects of various parameters on the long-term bond strength of adhesive anchors in hardened concrete. Testing was conducted on three adhesives of different chemistries that had passed current product evaluation criteria requiring sustained load testing at 110°F. A stress versus time-to-failure approach was used to evaluate the effects of various parameters on the sustained load performance of adhesive anchors. Within the range of parameters studied, only elevated service temperature (>120°F) and manufacturer's minimum cure time were shown to influence the sustained load performance beyond that predicted by short-term tests of fully cured adhesive.

Rheological analysis of the adhesives alone was conducted to investigate any correlation with anchor testing in concrete, but no consistent relationships were discovered that applied to all three adhesives investigated. Additionally the effect of early-age concrete on the bond strength of adhesive anchors was investigated.

This report fully documents the research and includes the following 13 appendixes:

APPENDIX A: ACI 355.4 Tables 3.1, 3.2, 3.3, 10.5, and 10.6
APPENDIX B: ACI–AASHTO Resistance Factor Investigation

APPENDIX C: Anchor Pullout Tests—University of Florida
APPENDIX D: Anchor Pullout Tests—University of Stuttgart
APPENDIX E: Adhesive-Alone Tests—University of Florida
APPENDIX F: Early-Age Concrete Evaluation—University of Stuttgart
APPENDIX N: AASHTO Standards and Specifications Flowchart
APPENDIX O: AASHTO Test Method
APPENDIX P: AASHTO Material Specification
APPENDIX Q: AASHTO Design Specification
APPENDIX R: AASHTO Design Guideline
APPENDIX S: AASHTO Quality Assurance Guideline
APPENDIX T: AASHTO Construction Specification

In addition, seven appendixes are available to download from the NCHRP Project 04-37 web page at http://apps.trb.org/cmsfeed/TRBNetProjectDisplay.asp?ProjectID=2495:

APPENDIX G: Concrete Mix Designs
APPENDIX H: Adhesive Anchor Post-Test Split-Core Investigations
APPENDIX I: Short-Term Test Results
APPENDIX J: Time to Rupture versus Time to Tertiary Creep Comparison
APPENDIX K: Sustained Load Creep Test Results
APPENDIX L: Stress versus Time-to-Failure Plots
APPENDIX M: Early-Age Concrete Investigation Short-Term Test Results

CONTENTS

Note: Many of the photographs, figures, and tables in this report have been converted from color to grayscale for printing. The electronic version of the report (posted on the Web at www.trb.org) retains the color versions.

SUMMARY

Long-Term Performance of Epoxy Adhesive Anchor Systems

The objective of this project was to develop recommended standard test methods and specifications, design guidelines and specifications, and quality assurance guidelines and construction specifications for the use of adhesive anchor systems in transportation structures. Development of these tests, specifications, and guidelines was founded on the results of a program of experiments to determine, predict, and verify the sustained-load performance of these systems under sustained load in their different applications and environments.

This project was divided into several phases; literature review, experimental program, and development of AASHTO standards and specifications. The following provides a summary of this report.

The literature review investigated the current state of art of adhesive anchors. Extensive discussion was devoted to the behavior of adhesive anchors in concrete as well as the many factors that can affect their short-term and sustained-load strength. Existing standards and specifications for the testing, design, construction, and inspection of adhesive anchors were covered.

A triage was conducted on many parameters identified as possibly affecting the sustained-load performance of adhesive anchors and the highest priority parameters were investigated in this project. A stress versus time-to-failure approach with tests performed at 110°F (43°C) was used to evaluate sensitivity of three adhesive anchor systems meeting the acceptance criteria of International Code Council Evaluation Service (ICC-ES) AC 308. The experimental stress versus time-to-failure relationship was compared to an expected relationship derived from the reduction in strength from short-term tests. Of all the various parameters investigated only elevated service temperature [>120°F (49°C)] and manufacturer's minimum cure time were shown to influence the sustained-load performance more than predicted by short-term tests of fully cured adhesive. It was recommended that anchors under sustained load exposed to temperatures of 120°F (49°C) or greater for significant portions of their service life should be tested and evaluated according to Temperature Category B in American Concrete Institute (ACI) 355.4 §8.5. Additionally, it was recommended that adhesive anchors for sustained-load applications be allowed to cure an additional 24 hours beyond manufacturer's minimum recommended cure time prior to loading or torquing.

Various tests were conducted on the adhesives alone (time-temperature superposition, time-stress superposition, and dogbone tensile tests) to investigate the existence of a correlation with long-term anchor pullout testing in concrete. No consistent correlations were detected for the adhesives in the study.

Tests were also conducted on the effect of early-age concrete strength on adhesive anchor bond strength. For the three adhesives investigated, one product (a vinyl ester) did not exhibit any significant increase in bond strength in concrete older than 14 days and the other two products (epoxies) did not exhibit any significant increase in bond strength in concrete older than 7 days.

The project also developed suggested recommended standards and specifications for AASHTO pertaining to adhesive anchors in concrete. The following standards and specifications were developed:

- Test methods and specifications and material specifications and commentary for inclusion in the *AASHTO Standard Specifications for Transportation Materials and Methods of Sampling and Testing,*
- Design guidelines,
- Design specifications and commentary for inclusion in the *AASHTO LRFD Bridge Design Specifications,*
- Quality assurance guidelines, and
- Construction specifications and commentary for inclusion in the *AASHTO LRFD Bridge Construction Specifications.*

The testing and material specifications made reference to the extensive and well-vetted testing program found within ACI 355.4 with a proposed exception for sustained-load testing. Design provisions for adhesive anchors in tensile loading were developed for AASHTO under given limitations. For cases that fall outside those restrictions, the designer was referred to ACI 318-11. Construction specifications were drafted for incorporation into the existing Section 29 “Embedment Anchors” of the *AASHTO LRFD Bridge Construction Specifications,* which previously addressed adhesive anchors. Quality assurance guidelines were drafted to orient construction and inspection personnel to adhesive anchor installation.

CHAPTER 1

Background

Introduction

The objectives of this research project were to:

- Investigate the influence of various parameters (e.g., type of adhesive, installation conditions, and in-service conditions) on the sustained-load performance of adhesive anchors and
- Develop recommended test methods, material specifications, design guidelines, design specifications, quality assurance guidelines, and construction specifications for AASHTO for the use of adhesive anchors in transportation structures.

This chapter begins with a brief overview of the background of the behavior and design of adhesive anchors in concrete. This chapter concludes with a review of the literature on adhesive anchors and is organized as follows:

- Parameters influencing bond strength,
- Test methods and material specifications related to adhesive anchor systems,
- Design guidelines and design specifications related to adhesive anchor systems, and
- Quality assurance guidelines and construction specifications related to adhesive anchor systems.

Background on Behavior/Design of Anchors

While various design standards and design methodology will be discussed in detail later, a general review of the current behavior/design for anchoring to concrete is provided for background.

This document adopts the definition of *adhesive* as found in ACI 355.4-11, which is as follows:

> *Adhesive – Any adhesive comprised of chemical components that cure when blended together. Adhesives are formulated from organic polymers, or a combination of organic polymers and inorganic materials. Organic polymers used in adhesives can include, but are not limited to, epoxies, polyurethanes, polyesters, methyl methacrylates and vinyl esters.*

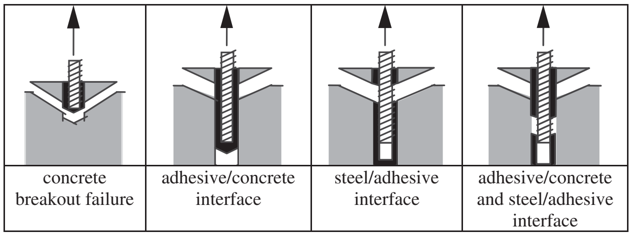
Behavioral Model

The behavioral model and resulting design procedures for adhesive anchors contained in most standards have been under development for the past 20 years. Detailed information on single adhesive anchor behavior is presented in Cook et al. (1998). Information on group and edge effects is presented in Eligehausen et al. (2006a). The following presents a general overview of the behavior/design model for single adhesive anchors.

Figure 1 shows typical failure modes exhibited by bonded anchors. Figure 2 shows the mechanism for load transfer in bonded anchors.

In the elastic range, adhesive anchors have been shown in Cook et al. (1993) to exhibit a hyperbolic tangent stress distribution along the bonded anchor as shown in Figure 3.

Research by McVay et al. (1996) used an elasto-plastic Sandler-DiMaggio constitutive model to show how the bond stress is distributed along the length of anchor under various stress levels (Figure 4 through Figure 7). Figure 4 through Figure 7 have been modified from their original in that the percent stress level has been identified for each curve. At low load levels, the stress distribution generally follows the elastic hyperbolic tangent stress distribution in which the adhesive close to the surface is higher stressed than the adhesive deeper in the hole. As the load level is increased above approximately 30% of the peak stress, the upper portions of the adhesive become plastic and redistribute the load further into the hole. As the load is further increased, deeper and deeper portions of the adhesive become plastic. As the stress level reaches approximately 70% of the peak stress, the stress distribution approaches a relatively uniform bond stress distribution along the entire length of the anchor. Any additional increase in load causes the adhesive to dilate providing for an increased capacity until failure.



Source: Cook et al. (1998)

Figure 1. Potential embedment failure modes of bonded anchors.

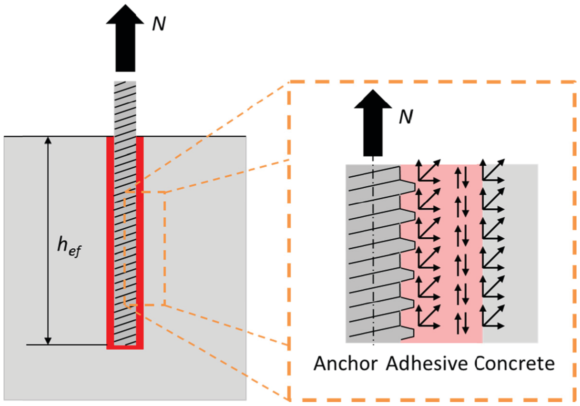


Figure 2. Mechanism of load transfer of a bonded anchor.

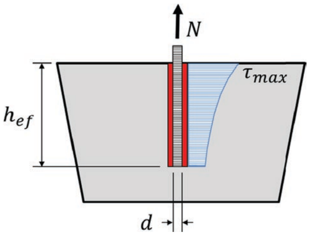
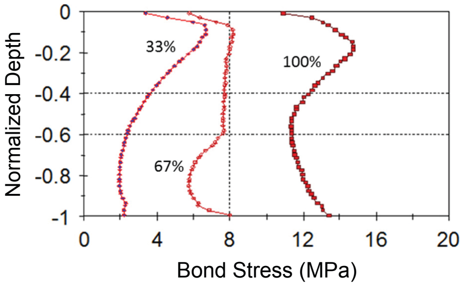
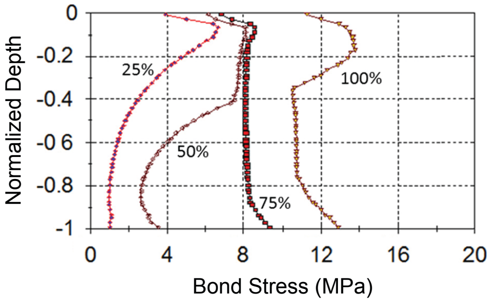


Figure 3. Hyperbolic tangent stress distribution (d = anchor diameter, τ_{max} = maximum bond stress).



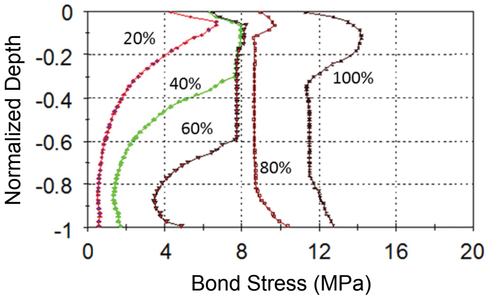
Source: McVay et al. (1996)

Figure 4. Stress distribution along length of adhesive anchor for h_{ef}/d_o = 4.00 (d_o = hole diameter).



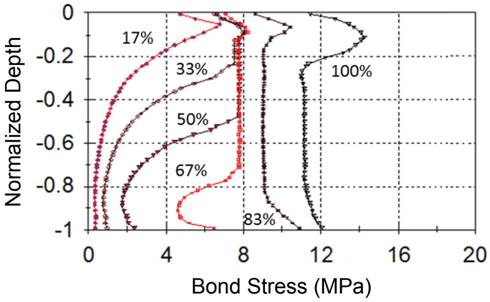
Source: McVay et al. (1996)

Figure 5. Stress distribution along length of adhesive anchor for h_{ef}/d_o = 5.33.



Source: McVay et al. (1996)

Figure 6. Stress distribution along length of adhesive anchor for h_{ef}/d_o = 6.67.



Source: McVay et al. (1996)

Figure 7. Stress distribution along length of adhesive anchor for h_{ef}/d_o = 8.00.

For adhesive-bonded anchors where the hole diameter does not exceed 1.5 times the anchor diameter and with an embedment depth to anchor diameter ratio not exceeding 20, the uniform bond stress model shown in Figure 8 and given by Equation 1 (Eq. 1) has been shown to be a valid behavioral model both experimentally and numerically [Cook et al. (1998)].

In Eq. 1, the mean failure load ($\bar{N}_\tau$) is a function of the product's mean bond strength ($\bar{\tau}$) multiplied by the bond area

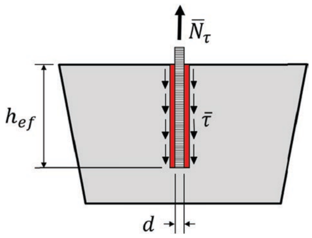


Figure 8. Uniform bond stress model for adhesive anchors.

calculated at the anchor diameter (d). As noted in Cook et al. (1998), test samples in a worldwide database indicated that the hole size is less than 1.5 times the anchor diameter for adhesive anchor applications. Anchors in holes larger than 1.5 times the anchor diameter typically use cementitious or polymer grout. For these typical adhesive anchor applications with hole sizes less than 1.5 times the anchor diameter, it is not practical to establish two separate interface bond strengths as shown in Figure 2 and, in fact, test data shows that the uniform bond stress model works quite well if the bond stress is determined from a series of product qualification tests by simply dividing the failure load by the bonded area calculated at the diameter of the anchor. Details of this are provided in Cook et al. (1998).

$$\bar{N}_\tau = \bar{\tau}\pi d h_{ef} \qquad \textit{Eq. 1}$$

where

$\bar{N}_\tau$ = mean failure load, lb,
$\bar{\tau}$ = mean bond strength, psi,
d = anchor diameter, in., and
h_{ef} = embedment depth, in.

For design, the nominal bond strength of adhesive-bonded anchors is dependent on the mean bond strength of anchors installed in accordance with manufacturer's printed installation instructions (MPII), adjusted for scatter of the product's test results, and for the product's sensitivity to installation and in-service conditions. As discussed in Cook and Konz (2001) the bond strength of properly installed bonded anchor products varies considerably. Based on tests of 20 adhesive anchor products, the mean bond strength at the adhesive/anchor interface for individual products ranged from 330 psi to 2,830 psi (2.3 MPa to 19.5 MPa).

Short-Term Sensitivity

The short-term load sensitivity of an adhesive to a specific variable can be determined from two series of short-term tests. A series of five baseline tests are conducted to determine the adhesive's short-term strength under standard conditions ($\bar{N}_{baseline}$). Another series of five tests are conducted with a specific variable introduced ($\bar{N}_{variable}$). The alpha-reduction factor (α) is determined by dividing the average load of the variable test by the average load of the baseline test. This is illustrated in Figure 9.

Eq. 2 provides the basic design relationship using load and resistance factor design (LRFD) for a single adhesive anchor. As shown by Eq. 2, the factored tension load (N_u) would need to be less than the design strength determined as a capacity reduction factor (ϕ) multiplied by the nominal bond capacity.

$$N_u \le \phi N_{bond} \qquad \textit{Eq. 2}$$

where

N_u = factored tension load, lb,
ϕ = capacity reduction factor,
$N_{bond} = \tau' \pi d h_{ef}$,
τ' = nominal bond stress, psi,
d = anchor diameter, in., and
h_{ef} = embedment depth, in.

The nominal bond strength (τ') is the 5% lower fractile of the mean bond strength (τ_k) adjusted by a series of reduction factors (α) for installation and in-service conditions as shown in Eq. 3.

$$\tau' = \tau_k \alpha_1 \alpha_2 \alpha_3 \qquad \textit{Eq. 3}$$

where

τ_k = 5% lower fractile of mean bond strength and
$\alpha_1, \alpha_2, \alpha_3$ = reduction factors determined from comparing the bond strength under different installation and in-service conditions to the baseline bond strength

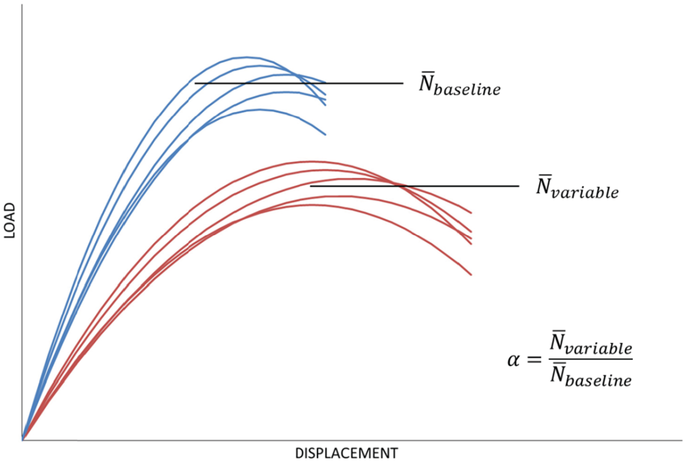


Figure 9. Calculation of reduction factor (α).

The 5% lower fractile, or characteristic value, (τ_k) is determined from Eq. 4:

$$\tau_k = \bar{\tau}(1 - K\nu) \qquad \textit{Eq. 4}$$

where

$\bar{\tau}$ = mean bond stress, psi;
K = tolerance factor corresponding to a 5% probability of non-exceedence with a 90% confidence using ACI 355.4. Note, other definitions of "characteristic value" exist. For example, ASTM D7729 uses an 80% confidence interval; and
ν = coefficient of variation.

Sustained-Load Sensitivity

The single anchor design model is provided for reference. Recommendations on how to incorporate the effects of sustained-load performance under various installation and in-service conditions are addressed in this project. For parameters that are shown to have a more aggravated effect under sustained load than under short-term load, a reduction factor (α) would be dependent on stress level and duration of load. This relationship is determined from the "stress versus time-to-failure" test series discussed later.

Parameters Influencing Bond Strength

As noted in Cook et al. (1994), Cook et al. (1996), and Cook and Konz (2001) there are many variables that affect the performance of adhesive anchors. Below is a list of many of the common factors with brief comments. A more in-depth discussion of each follows. Most of the items in the list are incorporated into ICC-ES AC308 (2008), ACI 355.4 (2011b), and EOTA ETAG 001 Part 5 (2002) discussed later in this chapter.

In-Service Factors:

- **Elevated Temperature:** temperature variations during the life of the structure, and effects of sustained elevated temperature.
- **Reduced Temperature:** brittleness associated with reduced temperature.
- **Moisture-in-Service:** adhesive anchor subjected to dry, damp, or immersed conditions during the life of the anchor.
- **Freeze–Thaw:** magnitude and frequency of freeze–thaw cycles.

Factors Related to the Adhesive:

- **Type of Adhesive:** for example: epoxy-mercaptan, epoxy-amine, vinylester, polyester, or hybrid.
- **Mixing Effort:** how well are the constituent parts mixed prior to installation.
- **Adhesive Curing Time When First Loaded:** 24 hours, 7 days, 28 days, or longer.
- **Bond Line Thickness:** how much space is there between the anchor and the sides of the hole.
- **Fiber Content of Adhesive:** type and proportion of fillers in the adhesive.
- **Chemical Resistance:** alkalinity, sulfur dioxide, and other compounds.

Installation Factors:

- **Hole Orientation:** downward, horizontal, upward.
- **Hole Drilling:** rotary hammer, core drill, or drilled in accordance with manufacturer's instructions.
- **Hole Cleaning:** uncleaned, partially cleaned, or cleaned in accordance with the manufacturer's instructions.
- **Moisture in Installation:** dry, damp, submerged, or installed in holes with moisture limitation conditions in accordance with manufacturer's instructions.
- **Installation Temperature:** concrete below freezing, adhesive below freezing, or preheated.
- **Depth of Hole (Embedment Depth):** the depth of the anchor can affect not only the bond strength but the type of failure.
- **Anchor Diameter:** anchor diameter can affect bond strength.
- **Type of Concrete:** Portland cement only, Portland cement with blast furnace slag, fly ash, or other additives.
- **Concrete Strength:** low compressive strength, high compressive strength.
- **Type of Coarse Aggregate:** mineralogy, absorption, and hardness (affects hole roughness).
- **Cracked or Uncracked Concrete:** the presence of cracks can reduce the bond strength significantly.
- **Concrete Age:** installed and/or loaded at early age.

In-Service Factors

Elevated Temperature. According to Messler (2004), "the greatest shortcoming of many structural adhesives is their limited tolerance of elevated temperature." However, adhesives with open-ring structures (polyimidazoles and substituted imidazoles) that close under high temperatures become stronger. He further adds that it is important to measure an adhesive's resistance to creep under sustained loading conditions especially if exposed to high temperature.

According to Adams and Wake (1984), an adhesive anchor system with sustained loads at a temperature 18°F (10°C) above its heat deflection temperature will exhibit significant creep. Experimental tests by CALTRANS in Dusel and Mir (1991) confirm this and explain that the adhesive will "soften and become rubbery" above its glass transition temperature (comparable to heat deflection temperature) and its bond strength will decrease.

Reduced Temperature. Reduced in-service temperatures can make adhesives more brittle as mentioned in Cognard (2005). Currently ICC-ES AC308 (2008) has a reduced temperature test only during installation. The commentary for ACI 355.4 (2011b) mentions that reduced temperature during installation increases viscosity and retards the cure time of adhesives.

Moisture-in-Service. While it has been widely known that the presence of moisture during the installation of the adhesive affects bond strength, a recent study [Chin et al. (2007)] indicates that the presence of moisture after curing can also affect the creep resistance of an anchor. Chin et al. (2007) of the National Institute of Standards and Technology (NIST) conducted thermo-viscoelastic analysis on ambient cure epoxy adhesives used in construction. This research showed that the presence of absorbed moisture after curing can create the same creep type behavior commonly seen in high temperature conditions.

Cognard (2005) mentions that water can degrade adhesives in three ways:

(1) Penetrate into the adhesive and soften it,
(2) Penetrate between the adhesive and the substrate thereby destroying the adhesion, and
(3) Penetrate into porous substrates causing swelling and detrimental movements.

Additionally, Cognard (2005) recommends that water resistance tests be performed if the adhesive will be subject to moisture during the life of the product.

Freeze–Thaw. The expansion and contraction of materials due to temperature changes and the expansion of water when it freezes tend to be detrimental to structural systems.

Factors Related to the Adhesive

Type of Adhesive. According to Cook and Konz (2001) adhesives can vary significantly between chemical groups and even within chemical groups. For example, on average, epoxy-based adhesives have higher bond strengths than ester-based adhesives.

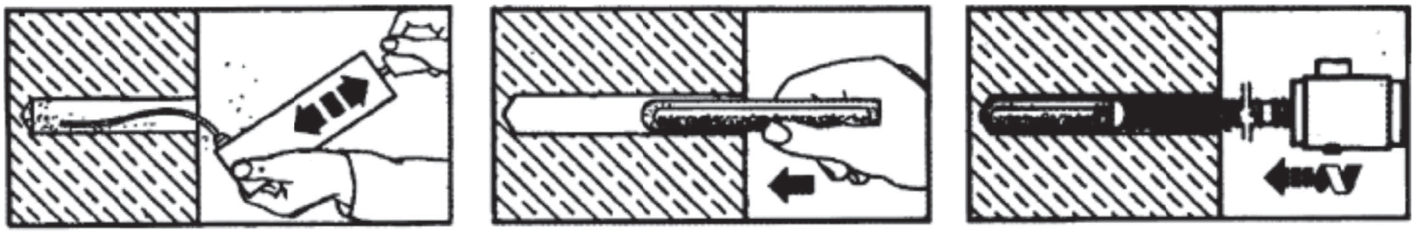
ASTM C881/C881M classifies seven types of epoxy-resin bonding systems, specifying Type IV as those that are for use in load-bearing applications for bonding hardened concrete to other materials, but Type IV is not specifically identified for epoxies used in adhesive anchor systems.

Fourier transform infrared spectroscopy (FTIR) is a test method to chemically characterize an adhesive as shown in the National Transportation Safety Board (NTSB) (2007b) report on the adhesives from the Boston Tunnel collapse. The results of an FTIR test can be used to investigate correlations in the chemical make-up of an adhesive and its bond strength.

ACI 355.4 includes several fingerprinting tests (discussed later) to identify the material and compare it against the manufacturer's standard.

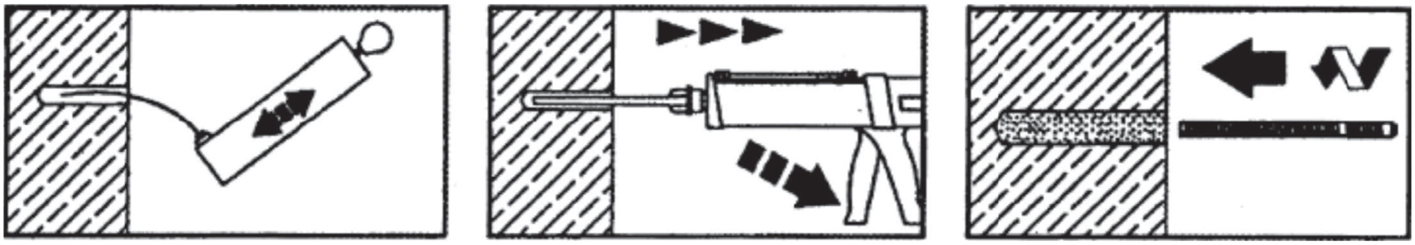
Mixing Effort. Bond strength is dependent on the proper composition of the adhesive. Adhesive anchor systems come in components that need to be mixed thoroughly and to the proper proportion prior to installation. Some systems are designed to guarantee proper proportions and thorough mixing, and some are solely dependent on the installer. Common systems include:

- **Glass and Foil Capsule Systems,** which contain specific amounts of polymer resin, accelerator, and a mineral aggregate. The capsules are placed in the hole and an anchor (with a chiseled end) is set with a hammer drill that bores through the capsule, thereby mixing the adhesive. See Figure 10 for a typical capsule anchor system.
- **Injection Systems** typically include plastic tubes of resin and hardener. The components are commonly mixed in a special nozzle as they are dispensed. The adhesive is injected into the hole and the anchor is installed afterwards. The anchor is usually rotated slowly during installation to prevent the formation of air bubbles which cause voids in the adhesive. See Figure 11 for a typical injection anchor system.
- **Other Systems** include pouches that contain the components, which are mixed manually and then dispensed into the hole. It is also possible to purchase the components separately and mix them manually.



Source: Cook et al. (1998)

Figure 10. Typical capsule anchor system.



Source: Cook et al. (1998)

Figure 11. Typical injection anchor system.

Whatever system is used, it is important that the components are mixed thoroughly and to the proper proportions. Manufacturers typically recommend mixing until a certain consistency and color is reached. The adhesive must completely fill voids between the anchor and the sides of the holes as any voids will reduce the effective area and subsequently the bond stress.

Adhesive Curing Time When First Loaded. According to Cook and Konz (2001), the duration of adhesive curing affects bond strength. Adhesives were tested at 24 hours and 7 days of cure time. Most anchors showed a decrease in bond strength over a shorter adhesive cure time; the average bond strength for a 24 hour cure was 88% of those with a seven day cure.

Bond Line Thickness. According to Çolak (2007), the smaller the dimension between the anchor and the side of the hole, the lower the potential for creep. Çolak (2007) conducted tests on anchors with a ratio of the hole diameter to the anchor diameter (d_o/d) range of 1.2 to 1.8. In these tests, it was noticed that creep resistance was increased when the bond line thickness of the adhesive was decreased. This relationship is supported by Section 2.3.7 of ACI 503.5R-92 (1997).

However, according to analytical studies by Krishnamurthy (1996), anchors with a much larger ratio of the hole diameter to the anchor diameter (d_o/d) range of 1.2 to 4.1, the bond line thickness does not significantly affect the capacity of the anchor. Therefore, current data is not conclusive.

Fiber Content of Adhesive. Section 2.3.7 of ACI 503.5R-92 (1997) and Çolak (2001) mention that creep resistance can be increased by increasing the fiber content of the adhesive.

Chemical Resistance. Cognard (2005) confirms that chemicals, oils, greases, and other compounds can penetrate the adhesive and degrade the adhesion with the anchor or the concrete causing a bond failure.

Installation Factors

Hole Orientation. The orientation of the hole has the potential to significantly affect the performance of adhesive anchors. Vertical or upwardly inclined holes prove difficult to fill with adhesive, as the adhesive will tend to run out of the hole. The subsequent voids reduce the bond area between the adhesive and the anchor and/or the concrete and a smaller bond area reduces bond strength.

Section 1.6 of the Florida Department of Transportation's (FDOT) (2009) *Structures Design Guidelines* and section 937 of the FDOT (2007) *Standard Specifications for Road and Bridge Construction* prohibit adhesive anchors to be installed in overhead or upwardly-inclined holes for the above mentioned reason. The New York and Pennsylvania departments of transportation have similar restrictions. From the Boston Tunnel collapse investigation report, NTSB (2007a), departments of transportation are prohibited from using adhesive anchors in sustained tensile-load overhead highway applications until the development of testing and protocols to ensure safety.

Due to the sensitivity of horizontal or vertically upward installed anchors to improper installation, ACI 355.4 requires that products be specifically approved for use in these conditions and be installed by certified personnel. The ACI-Concrete Reinforcing Steel Institute (CRSI) Adhesive Anchor Installation Certification Program entails both a written and performance evaluation that includes installation in vertically upward holes.

Hole Drilling. The two common methods of hole drilling involve diamond core drill bits, which produce a very smooth sided hole or carbide-tipped hammer-drill bits, which produce a rough sided hole. Since one of the ways the adhesive bonds with the concrete is by mechanical interlock, it was thought that a rough sided hole should provide better bond. This research project showed that for the three adhesives tested, an anchor installed in a core drilled hole had an average short-term strength of 74% that of an anchor installed in a rotary impact hammer drilled hole.

Hole Cleaning. According to Cook and Konz (2001) the cleanliness of the hole has a significant impact on bond strength, as dust created during the drilling operation can interfere with the adhesive/concrete bond surface. Tests were performed in which some holes were cleaned with compressed air and a non-metallic brush. In holes that were not cleaned, the average bond stress was 71% that of the cleaned holes (with a range from approximately 20% to 150%) and had an average coefficient of variation of 20%.

The type of brush is also significant. Section 416 of the FDOT (2007) *Standard Specifications for Road and Bridge*

Construction requires cleaning with a non-metallic brush, as metallic brushes tend to polish the sides of the holes, thereby reducing the ability of the adhesive to create a mechanical interlock with the sides of the hole.

Moisture in Installation. According to Cook and Konz (2001) the dampness of the hole significantly affects bond strength in two ways. It can restrict the entrance of adhesive into the pores of the concrete thereby reducing mechanical interlock, and moisture can interfere with the chemical reaction between the hardener and the resin.

It was demonstrated that anchors installed in damp holes (wet surface) produced an average bond strength for 20 products of 77% (with a range of approximately 20% to 150%) compared to a dry installation. Anchors installed in wet holes (standing water) produced an average bond strength of 43% (with a range of approximately 10% to 160%) compared to the dry installation.

Installation Temperature. For anchors installed at low temperatures, the final degree of hardening is smaller compared to installation at normal temperature. This might result in a reduction of the sustained-load bond strength.

Depth of Hole (Embedment Depth). Increasing the depth of the hole does have a slight impact on bond strength up to a point. According to tests by Krishnamurthy (1996), the load increases proportionally up to a limit of h_{ef}/d of 25 and then drops due to the bond stress not redistributing uniformly at depths over $25h_{ef}$.

Anchor Diameter. For most bonded anchor systems the bond strength measured in short-term tests decreases somewhat with increasing anchor diameter according to Eligehausen et al. (2006b). In general, it is assumed that bond strength is independent of the anchor diameter if within the manufacturer's recommendations for hole diameter.

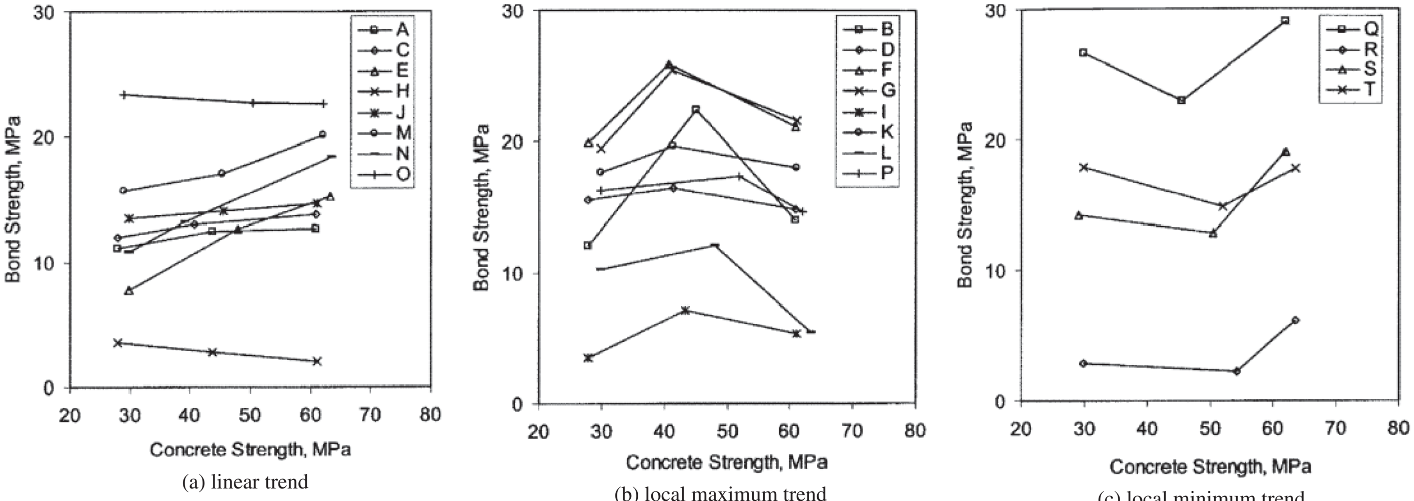
Type of Concrete. The concrete mix design can affect the bond strength of the adhesive anchor. This includes but is not limited to the type of cement, mix proportions, and the types of additives (air entrainment, plasticizers, fly ash, blast furnace slag). Tests conducted at the University of Florida by Anderson (1999) showed a reduction in bond stress in anchors installed in concrete with fly ash and blast furnace slag as compared to anchors installed in regular concrete without additives.

Concrete Strength. According to Cook and Konz (2001) there was no consistent correlation between bond strength and concrete strength among the adhesives tested (specimens A–T). As concrete strength was increased, some adhesives showed an increase in bond strength, and others displayed a local maximum or minimum at midrange strengths (Figure 12). This reveals that no broad rules can be applied, but must be determined for each adhesive. In the extreme cases, as the concrete strength was increased 100%, the largest increase in bond strength was 120% and the largest decrease was 35%.

Type of Coarse Aggregate. Cook and Konz (2001) determined through lab testing in concrete specimens with limestone and river gravel that the type of coarse aggregate plays a factor in bond strength.

Based on tests conducted by Caldwell (2001), the mineralogy of the aggregate also affects the bond strength. Of all the samples tested, concretes that used calcium-rich aggregates such as limestone failed at the lowest anchor loads. Additionally, concretes that used aggregates with high silicon content failed at relatively higher loads, although the findings were not conclusive.

Cook and Jain (2005) conducted tests on adhesive anchors in concrete with different coarse aggregate types. It was observed that adhesive anchors installed in concrete with harder coarse aggregates produced higher bond strengths. It



(a) linear trend

(b) local maximum trend

(c) local minimum trend

Source: Cook and Konz (2001)

Figure 12. Various relationships of bond strength as a function of concrete strength.

was concluded that the harder aggregates created rougher surfaces when the holes were drilled for the anchor. The rougher surface (as mentioned earlier) provided for more mechanical interlock and thus an increase in the bond strength.

Cracked or Uncracked Concrete. Based on research by Eligehausen and Balough (1995) cracked concrete can have a significant impact on adhesive bond strength. The researchers state that anchors in concrete, or the holes in the concrete created for adhesive anchors, will attract or even induce cracks at the anchor/hole location. Cracks in the concrete at an anchor will then tend to break down the bond between the concrete and the adhesive. Based on the research findings of Eligehausen and Balough (1995) and Fuchs et al. (1995), bond strengths in cracked concrete can vary from 33% to 70% of the bond strength in uncracked concrete. Similarly, Meszaros (1999) estimates from his research that bond strengths in cracked concrete are approximately 50% of the bond strength on uncracked concrete. See Figure 13 for a crack in a typical adhesive anchor application.

Concrete Age. Following casting, the concrete can remain damp for several days while it hydrates. ICC-ES AC308 requires that the anchors be installed in concrete after 21 days of curing. Part of the study for this project will be to determine if adhesive anchors installed in early-age concrete will have lower short-term bond strengths than those installed in concrete beyond 21 days. If lower in strength, this may be due to a synergistic effect of the very low concrete strengths and the high moisture content present in early-age concrete.

Synergistic Effects.

The above-mentioned factors are typically considered independently; however, their combinations can have amplified effects. According to Messler (2004), the combination of several climatic factors (heat, moisture, temperature cycling, moisture cycling, ultraviolet radiation, oxidation) can be particularly severe.

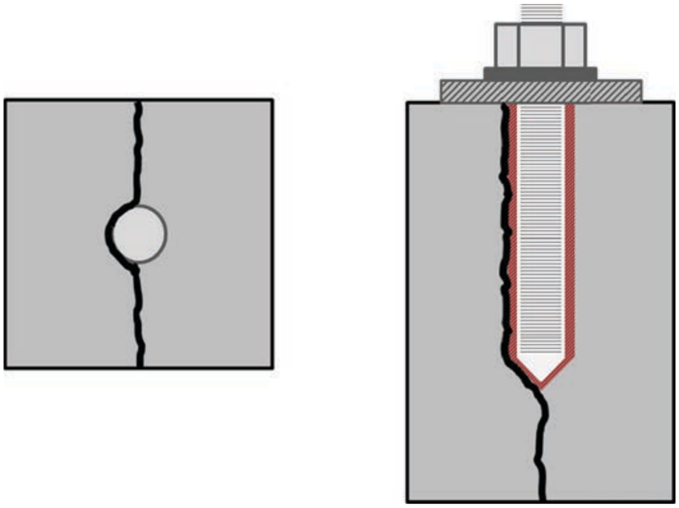


Figure 13. Typical crack location of bonded anchor.

Adhesive anchors historically have not been tested for moisture and temperature combinations. ASTM D1151-00 provides a standard for testing adhesives under different temperature and humidity exposures.

Test Methods and Material Specifications Related to Adhesive Anchor Systems

The review of test methods and material specifications related to adhesive anchors included national standards, state DOT standards, and international standards. Other test methods are also presented.

National Test Methods and Material Specifications

ASTM E488 Standard Test Methods for Strength of Anchors in Concrete and Masonry Elements

ASTM E488 provides the fundamental test procedures to determine the static, seismic, fatigue, and shock, tensile, and shear strengths of concrete and masonry anchors. These procedures serve as the basic building blocks for anchor testing and are either adopted in full or slightly modified by governing agencies. In all tests, the anchors are installed and conditioned at standard temperature [73°F (23°C)] and 50% relative humidity. The various tests methods contained within this test standard are briefly described below.

Static Tests. This standard discusses a series of tension and shear tests on five anchors for each variation of anchor size, type, embedment depth, and location. The tension test subjects an anchor to a tensile load and the shear test subjects the anchor to a shear load. In both tests the load is applied at a continuous load rate that will produce failure in 2 ± 1 minute. Load and displacement readings are monitored. The tension test can either have a confined or an unconfined test setup. The confined test setup isolates the failure to the adhesive bond surface in order to determine the bond strength. The unconfined test setup allows for bond failure with a shallow concrete cone or complete concrete breakout failure.

Seismic Tests. This standard discusses a series of seismic tests on five anchors for each variation of anchor size and type. Procedures are specified for both a seismic tension and shear test. In both tests the load is applied in cycles according to a specified program that simulates a seismic event. Load, displacement, and acceleration readings are monitored. The seismic shear test can either be conducted with a direct-loading or an indirect-loading procedure. The indirect-loading procedure attaches a weight to the structural member via the anchor and shakes the structural member thereby applying a seismic force to the anchor. At the end of the seismic shear tests, a static shear test is conducted to determine its residual strength.

Fatigue Tests. This standard discusses a series of tension and shear fatigue tests using any of the previously demonstrated test setups. In both tests the load is applied according to a fatigue program that specifies the loading method, load levels, frequency, and number of cycles. A static tension test is conducted at the conclusion of the fatigue loading program to determine the residual strength and failure mode.

Shock Tests. This standard discusses a series of tension and shear shock tests to determine either (1) if an anchor system will withstand a certain shock load or (2) the maximum shock load an anchor system can withstand without failure. The shock load is applied in a ramp loading rate over a 30 ms duration per shock. A static tension test is conducted at the conclusion of the shock test to determine the residual strength.

ASTM E1512 Standard Test Methods for Testing Bond Performance of Bonded Anchors

ASTM E1512 builds upon the test program established in ASTM E488 and while ASTM E488 is for all concrete anchor systems, ASTM E1512 is solely for bonded anchors. As with ASTM E488, ASTM E1512 is adopted by many governing agencies for the testing and evaluation of adhesive anchor systems. ASTM E1512 requires that static, fatigue, and seismic tests be conducted per the procedures set forth in ASTM E488, and specifies additional environmental test procedures.

The requirements for the environmental tests are as follows:

- Concrete of the same mix design in all series with the compressive strength between 2,500 psi and 3,500 psi at the time of testing,
- Concrete cured for 28 days,
- Anchors installed at 75°F ± 10°F (24°C ± 5°C),
- ½”-13 UNC threaded rods embedded 4½” in concrete, and
- Either confined or unconfined test, but all test series shall be the same.

The following environmental tests are briefly described below.

Test on Short-Term Effect of Fire. This test evaluates the performance of an anchor in a fire. This is an unconfined test on a minimum of three anchors in concrete. The slab is conditioned and the fire is applied as set forth in ASTM E119. A constant tension load is applied and temperature and displacement readings are recorded at 1 minute intervals until failure.

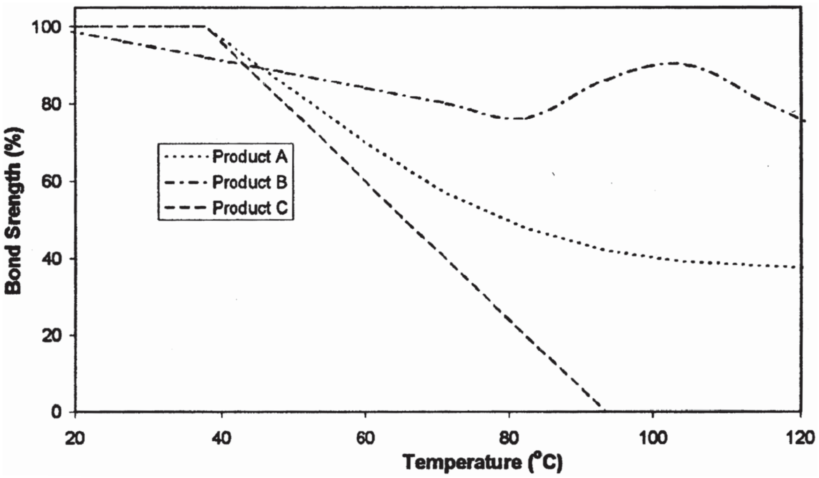
Radiation Test. This test evaluates the radiation resistance of an adhesive anchor system. The anchors are exposed to a minimum gamma radiation level of 2×10^7 rads. Static tension tests (confined or unconfined) are conducted and the irradiated samples are compared to baseline (confined or unconfined) samples.

Tests on Effect of Freezing and Thawing Conditions. This test evaluates the freeze–thaw resistance of an adhesive anchor system. A minimum of three confined or unconfined tests are conducted. Freeze-resistant concrete is used and the surface of the concrete is covered with ½” of water for a minimum of 3” around the anchor. A constant tension load is applied equal to 40% of the ultimate capacity. Fifty complete freeze–thaw cycles are conducted by lowering the temperature to −10°F (−23°C), holding for 3 hours, then raising to 104°F (40°C) and holding for 3 hours. Static tension tests are conducted following the fifty freeze–thaw cycles and the residual strength is compared to the baseline strength.

Test on Effects of Damp Environment. This test evaluates the sensitivity of an anchor system installed in damp or water-filled holes. A minimum of three confined or unconfined tests are conducted. Prior to anchor installation the holes are filled with tap water and kept full for seven days. The freestanding water is removed immediately before anchor installation. Following the required curing time, static tension tests are conducted to failure and the results compared to the baseline test. This test can also be conducted on water-filled holes in which the freestanding water is not removed prior to anchor installation.

Test on Effect of Elevated Temperature on Cured Samples. This test determines an adhesive anchor’s sensitivity to elevated temperature under short-term loads. A minimum of three confined or unconfined tests are conducted per temperature. Tests are conducted at 70°F (21°C) and at a minimum of four higher temperatures, one of which is at least 180°F (82°C). The anchors are installed and cured at 75°F ± 10°F (24°C ± 5°C) and following the cure time the specimens are heated to their test temperature. Following 24 hours at the stabilized test temperature, the specimens are removed and static tension tests are conducted. The static strengths for each test are normalized by the 70°F (21°C) test strength and presented in a chart showing the trend of normalized strength versus temperature. See Figure 14 for a sample bond strength versus temperature chart for three hypothetical adhesives.

Test on Effect of Reduced Temperature on Curing. This test determines an adhesive anchor’s sensitivity to curing at reduced temperature. A minimum of three confined or unconfined tests are conducted. The test member and anchor rod are conditioned at the test temperature for 24 hours prior to installation. The anchor is then installed and cured and once curing is completed, a static tension test is conducted and the result compared to a baseline test at 70°F (21°C).



Source: Cook et al. (1998)

Figure 14. Sample bond strength versus temperature curve for three hypothetical adhesives.

If the adhesive anchor is to be used below 50°F (10°C) an additional test is conducted. The conditioning and installation procedure is the same as described above. However, prior to removal of the specimen from the environmental chamber, a preload of 25% of the ultimate load is applied to the anchor. Once removed from the chamber, the specimen is heated uniformly to 75°F ± 10°F (24°C ± 5°C) over a period of 72 to 96 hours. Temperature and displacement readings are taken during this heating period. A static tension test is conducted to failure once the specimen has reached the desired temperature.

Creep Test. A minimum of three confined or unconfined tests are conducted per creep test series. The creep test is comprised of three separate individual tests as described below:

Static Tension Test Series at 75°F ± 10°F (24°C ± 5°C). This test series conducts a static tension test in order to determine the average ultimate tension load.

Static Tension Test Series at Elevated Temperature. This test series conducts a static tension test at a minimum concrete temperature of 110°F (43°C) to determine the average displacement at the ultimate tension load.

Creep Test Series at Elevated Temperature. Upon completion of the adhesive curing period, the concrete temperature is raised to a minimum temperature of 110°F ± 3°F (43°C ± 2°C) and stabilized for at least 24 hours. Next a preload of no more than 5% of the sustained creep load [40% of the ultimate tension load determined from the static tension test series at 75°F ± 10°F (24°C ± 5°C)] is applied to set the anchor and testing equipment before zeroing the test readings. Once the test equipment is zeroed, the remainder of the load is applied. The initial elastic displacement is recorded within the first 3 minutes of the test and subsequent displacement readings are taken every hour for the first 6 hours, and then daily for the remainder of the test.

Concrete temperature readings are conducted during the test and if the concrete temperature falls below the minimum temperature for more than 24 hours, the test duration is extended to account for the total time below the minimum temperature. The test is continued for 42 days (1,000 hours).

A logarithmic trendline of the displacement versus time is projected out to 600 days using a least squares fit through the data points using the equation:

$$\Delta = a \cdot \ln(t) + b$$

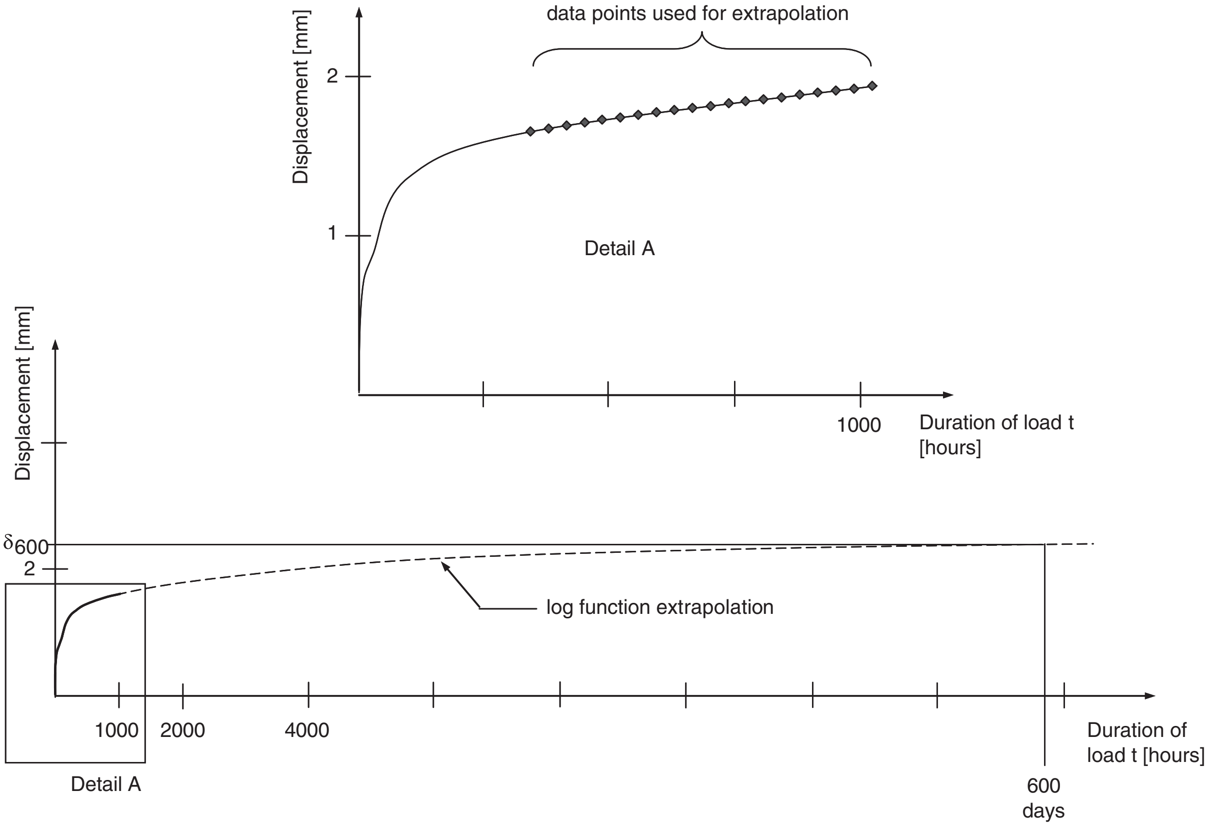
where

Δ = projected displacement,
t = time, and
a & b = constants evaluated by regression analysis.

This trendline is constructed from not less than the last 20 days (minimum of 20 data points). The projected displacement at 600 days is compared to the displacement from the static tension test series at elevated temperature. See Figure 15 for a graphical presentation of this projection.

ICC-ES AC58 Acceptance Criteria for Adhesive Anchors in Concrete and Masonry Elements

ICC-ES AC58 is an acceptance criteria based on allowable stress design (ASD) developed by the ICC-ES and first approved in January 1995. The purpose of these acceptance criteria was to provide a standard method and report for manufacturers to qualify their adhesive anchor products for use in concrete and masonry elements. Beginning in 2008, ICC-ES AC58 was no longer accepted by the International Building Code for anchorages in concrete and was replaced by ICC-ES AC308 (2008) (discussed later) and the current version of ICC-ES AC58 (2007) only addresses anchorages in masonry elements. A brief



Source: Eligehausen and Silva (2008)

Figure 15. Extrapolation of sustained load displacements per ASTM E1512.

discussion of ICC-ES AC58 (2005) is presented to provide a historical basis of adhesive anchor testing in concrete.

Twenty-one test series were identified by ICC-ES AC58 and many were based on ASTM E488 and ASTM E1512. There were 15 service-condition tests to determine design values. Of these 15 service-condition tests, 11 were tension tests, three were shear tests, and one was an oblique tension test. There were also six suitability requirement tests to evaluate the adhesive system's suitability for various conditions. It is important to note that of the 21 tests, only five were mandatory. If the anchor was not tested for the various optional tests, then it could not be qualified for that use.

Service-Condition Tests. Test series 1 through 3 were static tension tests on single anchors and reference the static tension test procedure set forth in ASTM E488. These three test series were conducted at three different concrete strengths.

Test series 4 through 7 evaluated the critical and minimum edge distances for tension loading. The different test series were all for single anchors and varied the concrete strength.

Test series 8 through 11 evaluated the critical and minimum spacings for anchor groups of two and four anchors.

Test series 12 was the static shear test of a single anchor and referenced the static shear test procedure set forth in ASTM E488.

Test series 13 through 14 evaluated the critical and minimum edge distances for shear loading.

Test series 15 was a combined tension and shear static test in which the direction of loading was at a 45° angle from the concrete.

Suitability Requirement Tests. Fire Resistance Test (optional). This test referenced the test on short-term effect of fire found in ASTM E1512-01. The test results were used to determine loads for hourly fire ratings.

Creep Test (optional). ICC-ES AC58 referred to ASTM E488 and ASTM E1512 for the general creep test procedure, with the following differences:

- Anchors were installed and cured at 70°F ± 5°F (21°C ± 3°C),
- The static tension test series was conducted at 70°F ± 5°F (21°C ± 3°C).
- Provided an allowable temperature tolerance of ± 3°F (± 1.7°C) during the static tension test series at elevated temperature and the creep test series at elevated temperature, and
- The average displacement at the mean static load must have satisfied the displacement limitations presented in tables in ICC-ES AC58.

The data was projected as discussed in the creep test procedure in ASTM E1512 (Figure 15). The anchor was accepted for creep if the average projected displacement at 600 days was less than (a) the average displacement at mean static load determined from static tension test series at elevated temperature (see Figure 16) and (b) 0.12 inches.

The rationale behind the acceptance criteria for the creep test procedure for adhesive anchors in ICC-ES AC58 is described in detail in *NCHRP Report 639* (NCHRP 2009) but is summarized below.

The test temperature was chosen as 110°F (43°C) as it was determined that this was an acceptable peak temperature for an anchor installed in a concrete bridge located in the California desert. The sustained load of 40% was based on a conversion from ASD with a factor of safety of 4 and a 1.6 multiplier for maximum anticipated sustained load. The test duration was determined from a database of tests in which tests that failed within a 120-day testing period did not pullout after 21 days. To be conservative, that duration was doubled to arrive at a 42-day testing period. The 600 day projection was chosen as it was determined that there would be approximately 600 days in which an anchor could be expected to be above 110°F (43°C) over a given lifetime of 50 years.

In-Service Temperature Test (required). This test referenced the test on the effect of service temperature found in ASTM E1512. The test results were used to establish adjustment factors for service loads.

Dampness Test (optional). This test referenced the test on the effects of damp environment found in ASTM E1512. Control specimens, which had all the same properties as the damp specimens except they were maintained dry, were also tested. The average tension load of the damp specimens must have been at least 80% of the average tension load of the control specimens. Each damp specimen result must not have varied from the average by 15% or all results must have been greater than 80% of the average tension load of the control specimens.

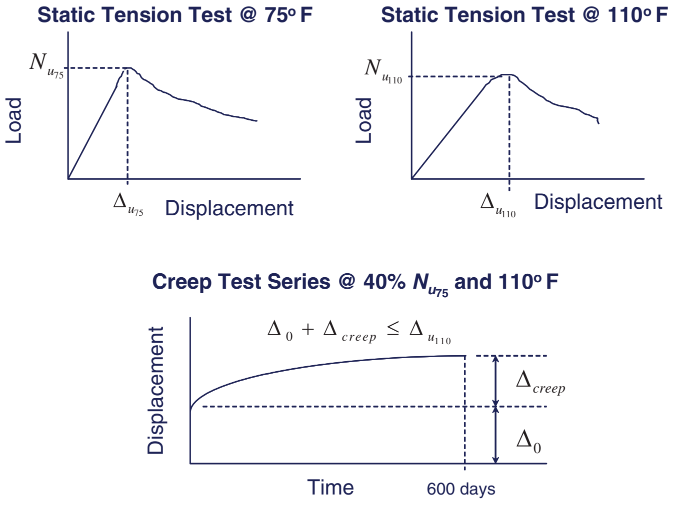


Figure 16. Basic pass/fail criteria per ICC-ES AC58.

Freezing and Thawing Test (optional). This test referenced the test on the effects of freezing and thawing conditions found in ASTM E1512.

Seismic Test (optional). ICC-ES AC58 provided two methods for seismic testing. Seismic Method 1 referred to the Structural Engineers Association of Southern California (SEAOSC) (1997) standard method for the test procedure and acceptance criteria. Seismic Method 2 subjected five ½" diameter anchors to a simulated alternating sinusoidal loading cycle in both tension and shear tests.

For the seismic tension tests, the maximum tension load (N_s) was 1.5 times the desired qualified tension load. The anchor was subjected to a series of sinusoidal loads of varying magnitudes and frequencies as listed below:

- 10 cycles at N_s,
- 30 cycles at $N_i = 0.625N_s$, and
- 100 cycles at $N_m = 0.25N_s$.

Following the cyclic loading, a static tension test was conducted to determine residual capacity.

The anchor was accepted if it withstood the cyclic loading, the residual capacity was at least 80% of the ultimate static tension load, and the maximum displacement satisfied the following equation:

$$\Delta_{ns} \le \frac{N_s}{T_{ref}} \Delta_{ult} \qquad \text{ICC-ES AC58 Eq. 3}$$

where

Δ_{ns} = maximum displacement during seismic test,
T_{ref} = average ultimate tension load, and
Δ_{ult} = displacement limitation for ultimate tension load.

For the seismic shear tests, the maximum shear load (V_s) was 1.5 times the desired qualified shear load. The anchor was subjected to a series of sinusoidal loads of varying magnitudes and frequencies as listed below:

- 10 cycles at V_s,
- 30 cycles at $V_i = 0.625V_s$, and
- 100 cycles at $V_m = 0.25V_s$.

Following the cyclic loading, a static shear test was conducted to determine residual capacity.

The anchor was accepted if it withstood the cyclic loading, the residual capacity was at least 80% of the ultimate static shear load, and the maximum displacement satisfied the following equation:

$$\Delta_{ns} \le \frac{2V_s}{V_{ref}} \Delta_{ult} \qquad \text{ICC-ES AC58 Eq. 4}$$

where

Δ_{ns} = maximum displacement during seismic test,
V_{ref} = average ultimate shear load, and
Δ_{ult} = displacement limitation for ultimate shear load.

Torque Tests. This test conducted five torque tests per anchor diameter. The manufacturer's specified torque moment was applied to the adhesive anchor and the resulting prestressing force was recorded. The 95% fractile of the prestressing force must have been less than 60% of the 5% fractile of the ultimate load of the confined reference tests.

ICC-ES AC308 Acceptance Criteria for Post-Installed Adhesive Anchors in Concrete Elements

ICC-ES AC308 (2008) was an acceptance criteria for adhesive anchors in concrete elements based on ultimate strength design—LRFD—developed by the International Code Council Evaluation Service (ICC-ES). The purpose of these acceptance criteria was to provide a standard method and report for manufacturers to qualify their post-installed adhesive anchor products. Beginning in 2008, ICC-ES AC308 replaced the previous acceptance criteria ICC-ES AC58 for installations in concrete.

ICC-ES AC308 was the source document for ACI 355.4 (2011b) *Qualification of Post-Installed Adhesive Anchors in Concrete.* Therefore the tests methods and specifications prescribed by ICC-ES AC308 are not discussed, rather a focus is made on the test procedures and specifications found in ACI 355.4.

ACI 355.4 Qualification of Post-Installed Adhesive Anchors in Concrete

ACI 355.4 (2011b) presents the testing and evaluation program of post-installed adhesive anchors in concrete. ICC-ES AC308 served as the basis for ACI 355.4 which was published by the American Concrete Institute (ACI) in 2011. Due to the tremendous research and development invested into ICC-ES AC308, and the consensus review process conducted by ACI, it is suggested that ACI 355.4 serve as the basis for the testing program and specifications for AASHTO.

The testing program specified by ACI 355.4 evaluates the following variables and installation and use conditions:

- **Hole cleaning procedures.** Typical manufacturer instructions can include vacuuming, blowing with compressed air, and brushing. Instructions indicate the number of brushes, duration, and cycles and can vary due to moisture condition of the concrete at installation. The default installation condition is dry concrete.
- **Permitted drilling methods.** Evaluates installations in holes created with rotary hammer drill with carbide tip, core drill, and rock drill. The default drilling method is rotary hammer drill with carbide tip.
- **Hole orientation.** Tests anchors oriented in the down, horizontal, and overhead orientation. The default orientation is down.
- **Installation temperature.** The default installation temperature range of the concrete is 50°F to 80°F (10°C to 27°C). Some test procedures allow installation at lower temperatures.
- **Embedment depth and anchor diameter.** The embedment depth and anchor diameters tested are specified by the manufacturer and within the ranges established by ACI 355.4.
- **Type of anchor.** Tests various materials (carbon, stainless); strengths; and geometries (threaded rod, deformed rebar, internally threaded inserts).
- **Environmental conditions of use.** Testing conditions are dry and wet environment with a service temperature range of 32°F to 104°F (0°C to 40°C). Optional conditions are elevated temperature and freezing-thawing conditions.
- **Chemical exposure.** Default condition is a high alkaline wet condition. The optional condition is sulfur dioxide.
- **Concrete condition.** Either uncracked or both cracked and uncracked.
- **Loading.** The default loading conditions are static and sustained loading. Seismic loading is optional.
- **Member thickness.** Determines the minimum thickness of a member to avoid spalling on the backside.

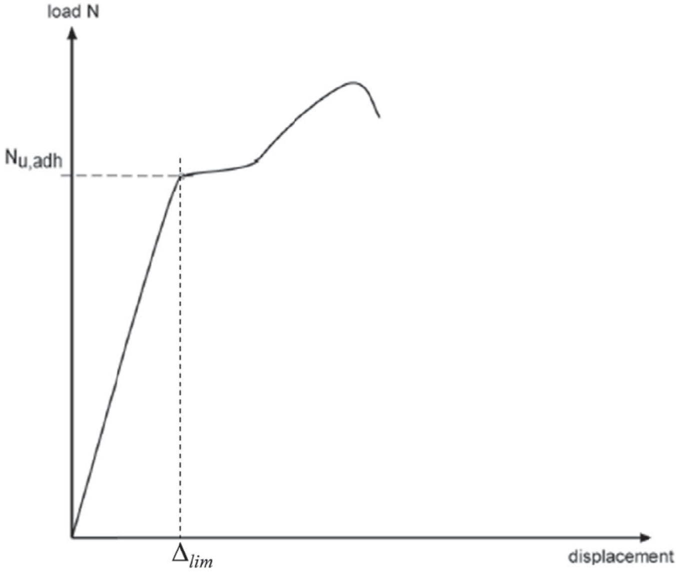
ACI 355.4 has four basic types of tests (identification tests, reference tests, reliability tests, and service-condition tests). Additional supplemental service-condition tests and assessment tests are also included. The testing schedule is presented in three tables divided between cracked and uncracked concrete applications. Optional tests are identified in the tables. The tables are listed below and are included in Appendix A:

- Table 3.1: Tests for adhesive anchors in uncracked concrete,
- Table 3.2: Tests for adhesive anchors in cracked and uncracked concrete, and
- Table 3.3: Reduced test program for adhesive anchors in cracked and uncracked concrete.

The reduced testing program mentioned by ACI 355.4 Table 3.3 uses predefined ratios of the characteristic limiting bond stress for use in cracked and in uncracked concrete. The characteristic bond stress is based on the 5% fractile as discussed earlier. All tests are referenced in ACI 355.4 Tables 3.1 through 3.3 by their ACI 355.4 section number. For conciseness, the test descriptions in this report are referred to by their ACI 355.4 section number.

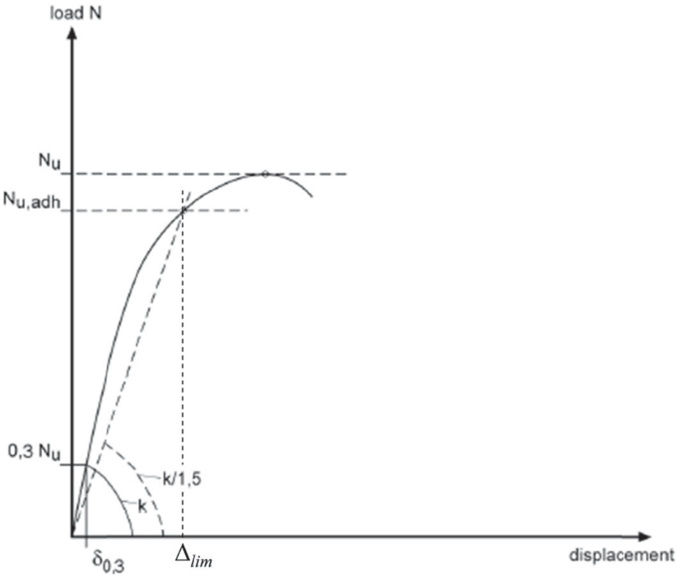
Assessment Approach. Section 10.4.4 addresses the requirements on load-displacement behavior. The purpose of the procedure presented is to locate the point on the load-displacement curve that represents an uncontrolled slip under tension. This point is identified as N_{adh}, or the loss of adhesion. Loss of adhesion occurs when the anchor and adhesive are extracted from the hole as a unit which is dependent primarily upon the roughness of the hole and is seen as a drastic loss in stiffness on a load-displacement curve (Figure 17). The ACI 355.4 procedure to locate N_{adh} is as follows:

- Determine a tangent stiffness at 30% of the peak static load (N_u), which is typically approximated as the secant stiffness from the origin to the point on the load-displacement curve at $0.30N_u$;
- Multiply the tangent stiffness by ⅔ and project this line until it intersects with the load-displacement curve;
- N_{adh} is taken at the point of a sudden change in stiffness (Figure 17);
- If there is not a very sudden change in stiffness, and the ⅔ secant line intersects the load-displacement curve before the peak, N_{adh} is taken at the intersection (Figure 18);
- If there is not a very sudden change in stiffness, and the ⅔ secant line intersects the load-displacement curve after the peak, N_{adh} is taken at the peak (Figure 19); and
- If the displacement at $0.30N_u$ is less than 0.002”, the origin is shifted to the point on the load-displacement curve at $0.30N_u$ and N_{adh} is taken at the ⅔-secant line and the load-displacement curve intersection (Figure 20).



Source: ACI 355.4 (2011b)

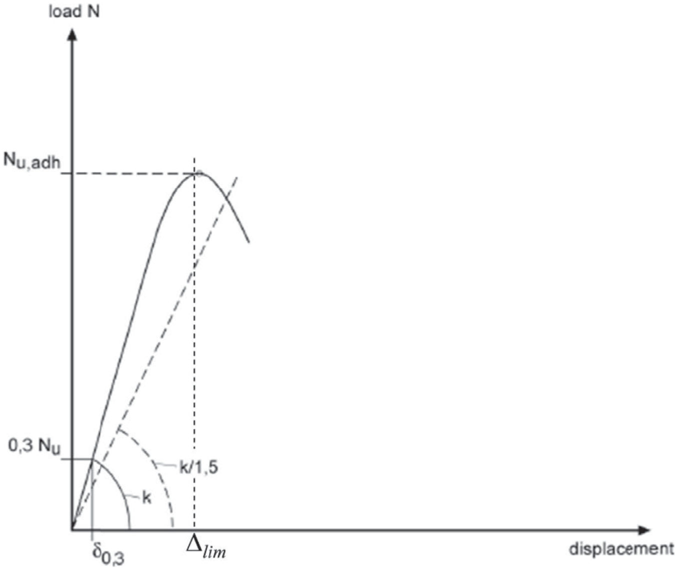
Figure 17. Evaluation of load at N_{adh} [Δ_{lim} = displacement corresponding to a loss of adhesion load (N_{adh})].



Source: ACI 355.4 (2011b)

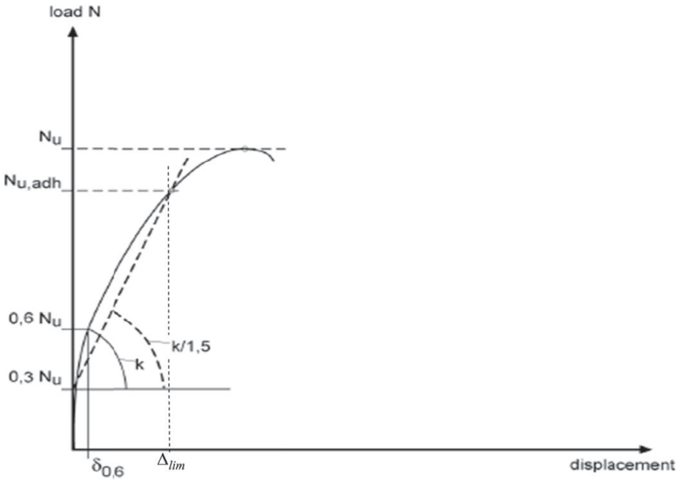
Figure 18. Evaluation of load at N_{adh} [k = tangent stiffness, $\delta_{0.3}$ = displacement at 30% of the peak tension load (N_u)].

Most of the tests discussed (except for the identification tests and test series: §6.0, §7.7, §7.8, §7.13, §7.19, §8.8, §8.9, §8.10, §8.11, §8.13, §9.1, §9.2) have a requirement on the coefficient of variation for load and displacement which is addressed in §10.4.2 and establishes a reduction factor if the coefficient of variation from the tests exceeds a certain threshold (30% for ultimate loads in reliability tests and 20% for other tests).



Source: ACI 355.4 (2011b)

Figure 19. Evaluation of load at N_{adh}.



Source: ACI 355.4 (2011b)

Figure 20. Evaluation of load at N_{adh}.

Identification Tests. In order to positively identify the adhesive being tested and compare it against the manufacturer's standard, ACI 355.4 §5.3 requires that at least three of the following tests be conducted.

- Infrared absorption spectroscopy per ASTM E1252;
- Bond strength per ASTM C882 or equivalent;
- Specific gravity per ASTM D1875;
- Gel time per ASTM C881;
- Viscosity per ASTM D2556, ASTM F1080, or equivalent; and
- Other appropriate tests to positively identify the material.

Reference Tests. For each batch of concrete, reference static tests are performed to establish baseline values to later calculate a ratio (α) to compare a specific test's results to the reference test results for the subsequent reliability and service-condition tests. These tests follow the ASTM E488 static test procedure and are conducted in dry concrete at standard temperature. These tests are referred to as 1a to 1d in ACI 355.4 Tables 3.1 to 3.3.

Reliability Tests. Reliability tests are conducted to determine an adhesive anchor's performance under adverse installation conditions and sustained load. ACI 355.4 Tables 3.1 to 3.3 refer to the tests by their section number. In the listing of the tests below, the ACI 355.4 section number is included for reference.

The baseline strength determined in the reference tests is used to evaluate the results from the reliability test. This evaluation creates a ratio, α, as calculated per ACI 355.4 Equation. 10-7, which is compared to a limit referred to as α_{req}.

$$\alpha = min\left[\frac{\overline{\tau}_{u,i}}{\overline{\tau}_{o,i}}; \frac{\tau_{k,i}}{\tau_{k,o,i}}\right] \leq \alpha_{req} \qquad \text{ACI 355.4 Eq.10-7}$$

where

$\overline{\tau}_{u,i}$ = mean bond stress from reliability test series in concrete batch or test member *i*,

$\overline{\tau}_{o,i}$ = mean bond stress from reference test series in concrete batch or test member *i*,

$\tau_{k,i}$ = characteristic bond stress from reliability test series in concrete batch or test member *i* calculated in accordance with §10.3,

$\tau_{k,o,i}$ = characteristic bond stress from reference test series in concrete batch or test member *i* calculated in accordance with §10.3, and

α_{req} = controlling value for reliability tests and service-condition tests where calculation of α is required.

The reference value (α_{req}) is specific to each test and is either given in Tables 3.1 to 3.3 or determined from §10.4.6 based on the anchor category.

Sensitivity to Hole Cleaning, Dry Concrete (ACI 355.4 §7.5). This test evaluates the sensitivity of an adhesive anchor to the degree of hole cleaning prior to installation in dry concrete. The hole is cleaned with 50% of the manufacturer's cleaning instructions. If the manufacturer does not specify the cleaning operation, no cleaning is conducted. A static tension test is conducted as specified in ASTM E488, continuously monitoring load and displacement to determine the ratio α per ACI 355.4 Eq. 10-7. This test is not required if the manufacturer requires that the holes be flushed with water.

Sensitivity to Hole Cleaning, Saturated Concrete (ACI 355.4 §7.6). This test evaluates the sensitivity of an adhesive anchor to the degree of hole cleaning prior to installation in saturated concrete. A pilot hole about one-half the diameter of the intended hole is drilled and kept filled with water for 8 days or until the concrete is saturated over a diameter of 1.5 times the hole diameter. Prior to installation, the water is removed with a vacuum and the hole is drilled to the required diameter. The hole is cleaned with the 50% cleaning effort as mentioned in §7.5 and the anchor is installed. Flushing the hole with water is allowed if specified by the manufacturer. A static tension test is conducted as specified in ASTM E488, continuously monitoring load and displacement to determine the ratio α per ACI 355.4 Eq. 10-7.

Sensitivity to Hole Cleaning, Water-Filled Hole (ACI 355.4 §7.7, optional). This test evaluates the sensitivity of an adhesive anchor to the degree of hole cleaning prior to installation in a water-filled hole. The test is identical to the test described in §7.6, except that the hole is filled with water after the reduced cleaning procedure. A static tension test is conducted as specified in ASTM E488, continuously monitoring load and displacement to determine the ratio α per ACI 355.4 Eq. 10-7.

Sensitivity to Hole Cleaning, Submerged Concrete (ACI 355.4 §7.8, optional). This test evaluates the sensitivity of an adhesive anchor to the degree of hole cleaning prior to installation in submerged concrete. The concrete member is covered with at least ½" of water during drilling, and is then subjected to the reduced cleaning effort (as described in §7.5), installation, and testing. A static tension test is conducted as specified in ASTM E488, continuously monitoring load and displacement to determine the ratio α per ACI 355.4 Eq. 10-7.

Sensitivity to Mixing Effort (ACI 355.4 §7.9). This test evaluates the sensitivity of the adhesive to a reduced mixing effort. This test is only for adhesive anchor systems in which the mixing of the adhesive components is controlled by the installer such as systems that require mixing until a color change occurs, or mixing for a specific duration or number of mixing repetitions. This test is not required for systems that use a cartridge system with static mixing nozzles or capsule anchor systems. A reduced mixing effort is defined as mixing the adhesive for only 75% of the required mixing time specified by the manufacturer. A static tension test is conducted as specified in ASTM E488, continuously monitoring load and displacement to determine the ratio α per ACI 355.4 Eq. 10-7.

Sensitivity to Installation in Water-Saturated Concrete (ACI 355.4 §7.10, optional). This test evaluates the sensitivity of an adhesive anchor to installation in saturated concrete. This test is similar to the test specified in §7.6 except that it requires a full cleaning effort as prescribed by the manufacturer. A static tension test is conducted as specified in ASTM E488, continuously monitoring load and displacement to determine the ratio α per ACI 355.4 Eq. 10-7.

Sensitivity to Installation in a Water-Filled Hole, Saturated Concrete (ACI 355.4 §7.11). This test evaluates the sensitivity of an adhesive anchor installation in a water-filled hole. This test is similar to the test specified in §7.7 except that it requires a full cleaning effort as prescribed by the manufacturer. A static tension test is conducted as specified in ASTM E488, continuously monitoring load and displacement to determine the ratio α per ACI 355.4 Eq. 10-7.

Sensitivity to Installation in Submerged Concrete (ACI 355.4 §7.12, optional). This test evaluates the sensitivity of an adhesive anchor installation in submerged concrete. This test is similar to the test specified in §7.8 except that it requires a full cleaning effort as prescribed by the manufacturer. A static tension test is conducted as specified in ASTM E488, continuously monitoring load and displacement to determine the ratio α per ACI 355.4 Eq. 10-7.

Sensitivity to Crack Width, Low-Strength Concrete (ACI 355.4 §7.13). This test evaluates the sensitivity of an adhesive anchor installed in low-strength concrete with a wide crack passing through the anchor location. Following anchor installation and adhesive curing, the crack is widened and a static tension test as specified in ASTM E488 is conducted, continuously monitoring load, displacement, and crack width to determine the ratio α per ACI 355.4 Eq. 10-7.

Sensitivity to Crack Width, High-Strength Concrete (ACI 355.4 §7.14). This test is similar to the test specified in §7.13 except that the concrete specimen is of high-strength concrete.

Sensitivity to Crack-Width Cycling (ACI 355.4 §7.15). This test evaluates an adhesive anchor's performance in cracked concrete whose crack width is cycled. An anchor is installed so that a crack runs through the middle of the hole and a tension load of about 30% of its characteristic resistance is applied. While the load is maintained on the anchor, the test member is cyclically loaded so that the crack width is cycled between two set limits at a frequency of 0.2 Hz for 1,000 cycles. Load and displacement are measured during the test and following the 1,000 cycles the anchor is unloaded and the resulting displacement and crack width is measured. A static tension test as specified in ASTM E488 is conducted, continuously monitoring load and displacement to determine the ratio α per ACI 355.4 Eq. 10-7. Additionally, the cumulative anchor displacement after 20 cycles must be less than 0.080" and the cumulative anchor displacement after the 1,000 cycles must be less than 0.120".

Sensitivity to Freezing and Thawing (ACI 355.4 §7.16). This test determines the performance of an adhesive anchor under freezing and thawing conditions. An anchor is installed in concrete and the top surface of the concrete is covered with ½" of water for a distance of 3" around the anchor. The anchor is loaded with a sustained load of about 55% of the average ultimate tension load of reference tests. Within two hours the temperature is lowered to −4°F ± 5°F (−20°C ± 2°C) and maintained for 14 hours. The temperature is then raised to +68°F ± 5°F (+20°C ± 2°C) within 1 hour and maintained for 14 hours. Fifty such cycles are conducted measuring load, displacement, and temperature. Following the 50 cycles, a static tension test as specified in ASTM E488 is conducted, continuously monitoring load and displacement to determine the ratio α per ACI 355.4 Eq. 10-7. Additionally, the rate of displacement increase shall decrease to zero as the number of freeze–thaw cycles increase.

Sensitivity to Sustained Loading at Standard and Maximum Long-Term Temperature (ACI 355.4 §7.17). The sustained loading test is similar to the procedure from ICC-ES AC58 (based on ASTM E1512) with the following changes:

- The sustained load is increased to about 55% of the average tension capacity of the reference tests;
- Sustained load tests are conducted at both standard temperature and the long-term elevated temperature; and
- Following the 42 day (1,000 hr) sustained load tests, the anchors are loaded until failure to determine the residual capacity.

The acceptance criteria as presented in ICC-ES AC58 were modified in the development of ICC-ES AC308 and are reflected in ACI 355.4. The displacement data is projected from the last 20 days (minimum of 20 data points) from the creep test using the Findley power law (instead of the logarithmic model) shown in ACI 355.4 Eq. 10-24.

$$\Delta(t) = \Delta_{t=0} + at^{b} \qquad \text{ACI 355.4 Eq. 10-24}$$

where

$\Delta(t)$ = total displacement at time t,
$\Delta_{t=0}$ = initial displacement under sustained load,
t = time corresponding to the recorded displacement, and
a, b = constants evaluated from a regression analysis.

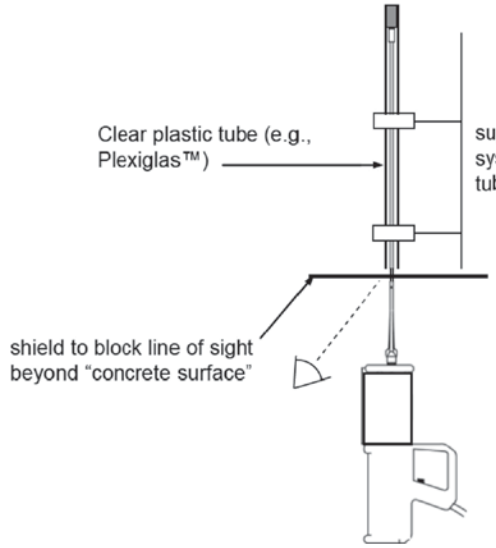
Using ACI 355.4 Eq. 10-24, the displacement is then estimated at the service lives of 10 years and 50 years. The adhesive anchor is accepted for sustained load if:

- The projected displacement at 10 years is less than the mean displacement at loss of adhesion for the reference test at elevated temperature,
- The projected displacement at 50 years is less than the mean displacement at loss of adhesion for the reference test at standard temperature, and
- The residual capacity is greater than 90% of the reference test's capacity.

Sensitivity to Installation Direction (ACI 355.4 §7.18, optional). This test evaluates the sensitivity of an adhesive anchor to hole orientation (horizontal or upward). This test installs anchors in holes that are oriented horizontally and vertically overhead. The anchors are installed with the most unfavorable installation temperature of the concrete and the adhesive. Static tension tests are conducted as specified in ASTM E488, continuously monitoring load and displacement to determine the ratio α per ACI 355.4 Eq. 10-7. Additionally, the anchor must not displace more than 0.05 times the anchor diameter during curing. There are additional subjective assessments on the adequacy of the manufacturer's procedures for overhead and horizontal installations. The effectiveness of the overhead installation procedure can be verified by the procedure shown in Figure 21.

Torque Tests (ACI 355.4 §7.19). This test evaluates the maximum torque that can be applied to an adhesive anchor without damaging the adhesive bond or yielding the anchor. Torque is applied to the anchor and measurements of torque and the resulting induced tension in the anchor are recorded. The torque reached in the test must be greater than 130% of the tightening torque specified by the manufacturer.

Service-Condition Tests. These tests are conducted to determine an adhesive anchor's performance under service conditions. In the listing of the tests below, the ACI 355.4 section number is included for reference.



Source: ACI 355.4 (2011b)

Figure 21. Procedure for verifying the effectiveness of overhead adhesive injection.

Tension Tests in Uncracked and Cracked Concrete (ACI 355.4 §8.4). These tests are conducted to determine the adhesive anchor's unconfined tension strength per ASTM E488 and are used as a baseline for unconfined tests. Tests are conducted in both low- and high-strength concrete for cracked and uncracked conditions.

Tension Tests at Elevated Temperature (ACI 355.4 §8.5). These tests are conducted to determine an adhesive anchor's sensitivity to elevated temperature. Static tension tests are conducted at various temperatures per Table 8.1 in ACI 355.4 (shown as Table 1). Anchors are installed and cured at standard temperature for both categories. For category A, tests are conducted at the long-term and the short-term temperature. For category B, tests are conducted at standard temperature, at the long-term temperature, at the short-term temperature, and at least two temperatures in between the long-term and the short-term temperature with a maximum increment of 35°F (20°C).

Following the cure time, the anchors are heated to the test temperature and tested per ASTM E488 with continuous measurements of load and displacement. Tests must be completed before the test member temperature falls below the test

Table 1. ACI 355.4 Table 8.1 - Minimum test temperatures.

Temperature Category	Long-Term Test Temperature[1], T_{lt}		Short-Term Test Temperature[1], T_{st}	
	°F	°C	°F	°C
A	110	43	176	80
B	≥110	≥43	$\geq T_{lt} + 20$	$\geq T_{lt} + 11$

[1] All test temperatures have a minus tolerance of 0°.

temperature. The ratios α_{lt} and α_{st} are calculated from the sustained load and short-term tests respectfully as shown in ACI 355.4 Eq. 10-26 and Eq. 10-27 below.

$$\alpha_{lt} = min\left[\frac{\overline{N}_{lt}}{\overline{N}_{o,i}}; \frac{N_{k,lt}}{N_{k,o,i}}\right] \leq 1.0 \qquad \text{ACI 355.4 Eq. 10-26}$$

$$\alpha_{st} = min\left[\frac{\overline{N}_{st}}{0.8\overline{N}_{lt}}; \frac{N_{k,st}}{0.8N_{k,lt}}\right] \leq 1.0 \qquad \text{ACI 355.4 Eq. 10-27}$$

where

$\overline{N}_{lt}$ = mean tension capacity at long-term elevated temperature,
$\overline{N}_{st}$ = mean tension capacity at short-term elevated temperature,
$\overline{N}_{o,i}$ = mean tension capacity of an anchor in reference test series *i*,
$N_{k,lt}$ = characteristic tension capacity at long-term elevated temperature,
$N_{k,st}$ = characteristic tension capacity at short-term elevated temperature, and
$N_{k,o,i}$ = characteristic tension capacity of an anchor in reference test series *i*.

Tension Tests with Decreased Installation Temperature (ACI 355.4 §8.6, optional). These tests determine an adhesive anchor's sensitivity to installation at reduced temperature. A minimum of five confined tests in uncracked concrete are conducted. The test member and anchor rod are conditioned at a test temperature below 50°F (10°C) for 24 hours prior to installation. The anchor is then installed and cured at the desired temperature. Once curing is completed, a static tension test is conducted.

If the test temperature is below 40°F (5°C) an additional test is conducted. The conditioning and installation procedure is the same as described above. However, prior to removal of the specimen from the environmental chamber, a preload of about 55% of the ultimate load is applied to the anchor. The specimen is then removed from the chamber and is heated uniformly to standard temperature over a period of 72 to 96 hours. Temperature and displacement readings are taken during this heating period. Once the specimen has reached the desired temperature, a static tension test is conducted to failure.

The mean and the 5% fractile of these tests shall be statistically equivalent to those of the reference tests. ACI 355.4 defines statistically equivalent as follows, if ". . . there are no significant differences between the means and between the standard deviations of the two groups. Such statistical equivalence shall be demonstrated using a one-sided Student's t-Test at a confidence level of 90%." Additionally, for anchors installed in concrete below 50°F (10°C), the displacement of the anchor under the sustained preload portion shall stabilize prior to static tension testing.

Establishment of Cure Time at Standard Temperature (ACI 355.4 §8.7). These tests are conducted to determine an adhesive anchor's sensitivity to reduced cure time. Comparison tests are conducted on anchors allowed to cure for the minimum curing time and on anchors that were cured for 24 hours longer than the minimum curing time. Confined static tension tests are conducted in uncracked concrete as specified in ASTM E488 while continuously monitoring load and displacement. The acceptance criterion for these tests is shown as ACI 355.4 Eq. 10-28:

$$min\left[\frac{\overline{N}_{cure}}{\overline{N}_{cure+24\text{h}}}; \frac{N_{k,cure}}{N_{k,cure+24\text{h}}}\right] \geq 0.9 \qquad \text{ACI 355.4 Eq. 10-28}$$

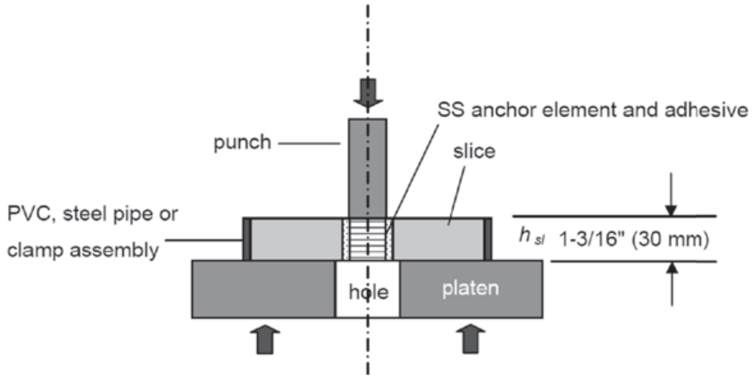
where

$\overline{N}_{cure}$ = mean tension capacity corresponding to the manufacturer's published minimum cure time,
$\overline{N}_{cure+24\text{h}}$ = mean tension capacity corresponding to the manufacturer's published minimum cure time + 24 hours,
$N_{k,cure}$ = characteristic tension capacity corresponding to the manufacturer's published minimum cure time, and
$N_{k,cure+24\text{h}}$ = characteristic tension capacity corresponding to the manufacturer's published minimum cure time + 24 hours.

Durability Assessment (ACI 355.4 §8.8, sulfur test is optional). These tests determine an adhesive anchor's sensitivity to harsh environments. Mandatory alkalinity tests are conducted and optional sulfur dioxide tests can be conducted. Specimens are made by installing adhesive anchors in 6" diameter concrete cylinders cast in PVC or steel pipe. After installation and curing, the cylinders are sliced into 1 3/16" ± 1/8" thick slices. A minimum of 10 slices are to be made for each environmental condition tested plus 10 for reference tests. The reference slices are stored at standard temperature and 50% relative humidity for 2,000 hours. The slices for the high alkalinity environment tests are stored for 2,000 hours in an alkaline solution with a pH = 13.2. The slices for the optional sulfur dioxide tests are tested according to EN ISO 6988 (Kesternich Test) with a concentration of 0.67% for at least 80 cycles.

Following storage, the anchors are punched out of the slices with the concrete restrained in a device similar to that shown in Figure 22. The bond stress for each slice is the peak load divided by the circumferential area of the anchor. A reduction factor α_{dur} is calculated for each durability test.

Verification of Full Concrete Capacity in a Corner (ACI 355.4 §8.9). These tests determine the critical edge distance (c_{ac})



Source: ACI 355.4 (2011b)

Figure 22. ACI 355.4 Punch test apparatus (h_{sl} = slice thickness as measured immediately prior to punch test).

in test members with the minimum thickness as specified by the manufacturer. Static tension tests per ASTM E488 are performed in low-strength uncracked concrete on anchors located in a corner with equal edge distances of c_{ac}. The tension capacity from these tests should be statistically equivalent to the tension capacity of reference tests performed away from a corner.

Determination of Minimum Spacing and Edge Distance to Preclude Splitting (ACI 355.4 §8.10, optional). The purpose of these tests is to evaluate the shear capacity of adhesive anchors. Static shear tests away from edges are performed per ASTM E488. The concrete should not crack during the test and the mean failure load must be greater than 90% of the expected failure load.

Test to Determine Shear Capacity of Anchor Elements with Non-Uniform Cross Section (ACI 355.4 §8.11). The purpose of these tests is to determine the shear capacity of anchors in which the shear capacity cannot be reliability calculated due to a non-uniform cross section. Static shear tests away from edges are performed per ASTM E488 with a few requirements on edge spacing and embedment depth.

Simulated Seismic Tension Tests (ACI 355.4 §8.12, optional). The purpose of these tests is to evaluate adhesive anchors subjected to a simulated seismic tension load in cracked concrete. Anchors are installed in a crack which is opened by 0.020″ prior to loading. A sinusoidal tension load is applied to the anchor with a frequency between 0.1 and 2 Hz. The peak tension load is initially at N_{eq} for 10 cycles, then reduced to N_i for 30 cycles, and finally to N_m for 100 cycles, where:

N_{eq} = about 50% of the mean tension capacity of reference tests,
$N_i = 75\%\ N_{eq}$, and
$N_m = 50\%\ N_{eq}$.

During the test, crack width, tension load, and displacement are recorded. Following the seismic loading, the crack is opened to the maximum crack width during the seismic test and a static tension test is conducted in accordance with ASTM E488 until failure.

For acceptance, the anchors must complete the seismic loading cycle without failure. Upon completion, the residual strength of the anchor must be at least 160% of N_{eq}. If the anchor does not complete the seismic loading cycle, a reduced value for N_{eq} ($N_{eq,reduced}$) is used until the anchors pass the criteria. If a reduced loading cycle is performed, a reduction factor $\alpha_{N,seis}$ is determined by dividing $N_{eq,reduced}$ by N_{eq}.

Simulated Seismic Shear Tests (ACI 355.4 §8.13, optional). The purpose of these tests is to evaluate adhesive anchors subjected to a simulated seismic shear load in cracked concrete. Anchors are installed in a crack which is opened by 0.020″ prior to loading. A sinusoidal shear load is applied to the anchor parallel to the crack with a frequency between 0.1 and 2 Hz. The peak shear load is initially at V_{eq} for 10 cycles, then reduced to V_i for 30 cycles, and finally to V_m for 100 cycles, where:

V_{eq} = about 50% of the mean shear capacity of reference tests,
$V_i = 75\%\ V_{eq}$, and
$V_m = 50\%\ V_{eq}$.

During the test, crack width, shear load, and displacement are recorded. Following the seismic loading, the crack is opened to the maximum crack width during the seismic test and a static shear test is conducted in accordance with ASTM E488 until failure.

For acceptance, the anchors must complete the seismic loading cycle without failure. Upon completion, the residual strength of the anchor must be at least 160% of V_{eq}. If the anchor does not complete the seismic loading cycle, a reduced value for V_{eq} ($V_{eq,reduced}$) is used until the anchors pass the criteria. If a reduced loading cycle is performed, a reduction factor $\alpha_{V,seis}$ is determined by dividing $V_{eq,reduced}$ by V_{eq}.

Additional Supplemental Tests. ACI 355.4 specifies a few additional supplemental tests:

Round Robin Tests (ACI 355.4 §9.1). These tests examine the effects of regional variations of concrete on the behavior of adhesive anchor systems. Tests are conducted at laboratories located in each time zone of the United States using aggregates representative of that region. Five confined and five unconfined static tension tests per ASTM E488 are conducted and compared with the original laboratory results to generate an adjustment factor α_{conc} for each laboratory and the minimum value is used.

Tests to Determine Minimum Member Thickness (ACI 355.4 §9.2). These tests verify the minimum member thickness as specified by the manufacturer. Ten anchors are installed at the maximum embedment depth in a concrete member and the member is checked for cracking or spalling.

Additional Assessment Tests. A few additional assessment tests are included if pertinent.

Multiple Anchor Type Supplementary Tests (ACI 355.4 §3.4). These tests investigate the effects of using anchors of different metal composition within an anchor group. The entire test program is conducted with one anchor type, and the other anchor types are subjected to a series of additional tests specified in ACI 355.4 Table 3.4.

Alternate Drilling Methods Supplementary Tests (ACI 355.4 §3.5). If the manufacturer permits drilling methods other than with rotary hammer drill and carbide bit, supplementary tests are conducted using the alternate drilling method.

ACI 355.4 Table 3.5 lists the tests to conduct on the alternate drilling method. If the results of these tests are not statistically equivalent to the results from their respective tests using the rotary hammer and carbide bit drilling method, all tests need to be conducted except for the shear capacity tests for an element having a non-uniform cross section (§8.11).

Resulting Design Values. The previously described testing program provides design values to be used by ACI 318-11 Appendix D. The bond stress for each service-condition test (τ_i) is calculated from ACI 355.4 Eq. 10-11:

$$\tau_i = \alpha_{setup}\frac{N_{u,i,fc}}{\pi d h_{ef}} \qquad \text{ACI 355.4 Eq. 10-11}$$

where

α_{setup} = 1.0 for unconfined test;
= 0.75 for confined test;
= 0.70 for confined test in cracked concrete;
$N_{u,i,fc}$ = peak tension load in test series i normalized to concrete strength of $f_c = 2{,}500$ psi, lbs;
d = anchor diameter, in.; and
h_{ef} = embedment depth, in.

The nominal characteristic bond stress for each service-condition test ($\tau_{k,nom(cr,uncr)}$) is calculated as per Eq. 3 shown earlier.

The limiting characteristic bond stress for each service-condition test ($\tau_{k(cr,uncr)}$) is adjusted for many reduction factors as shown in ACI 355.4 Eq. 10-12:

$$\tau_{k(cr,uncr)} = \tau_{k,nom(cr,uncr)}\,\beta\alpha_{lt}\alpha_{st}\alpha_{dur}\alpha_p\alpha_{conc}\alpha_{COV}\alpha_{cat3} \qquad \text{ACI 355.4 Eq. 10-12}$$

where:

$\beta = \min\left[\dfrac{\min\alpha}{\alpha_{req}};\min\alpha_{adh}\right]$ the reliability and service-condition tests listed in ACI 355.4 Table 10.2 and Table 10.3,
α = ratio of reliability test result to reference test result evaluated for all reliability tests listed in ACI 355.4 Table 10.2,
α_{lt} = reduction factor for maximum long-term temperature,
α_{st} = reduction factor for maximum short-term temperature,
α_{dur} = reduction factor for durability,
α_p = min. reduction factor for reduced sustained load in reliability tests,
α_{conc} = adjustment factor for regional concrete variation,
α_{COV} = reduction factor associated with the coefficient of variation of ultimate loads, and
α_{cat3} = reduction factor for anchor category 3.

Anchor Categories. Based on the alpha-reduction factor results of the reliability tests, anchors are classified into categories depending on the required level of inspection. Tables 10.5 and 10.6 in ACI 355.4 are used to compare the alpha-reduction factors from the different reliability tests against certain threshold values in order to assign a strength reduction (resistance) factor for design.

AASHTO Standard Specifications for Transportation Materials and Methods of Sampling and Testing

AASHTO (2008) *Standard Specifications for Transportation Materials and Methods of Sampling and Testing* was reviewed for a framework of specifications within which to incorporate specifications for adhesive anchors. The only test method dealing with adhesive systems was T 333-07 (2007c) *Linear Coefficient for Shrinkage on Cure of Adhesive Systems* which measures the change in length of a cured adhesive material. TP 84-10 (2010c) *Evaluation of Adhesive Anchors in Concrete under Sustained Loading Conditions* was recently created to evaluate adhesive anchors using the stress versus time-to-failure approach discussed in detail later in the chapter.

M 235M/M 235-03 (2007b) *Standard Specification for Epoxy Resin Adhesives* is the AASHTO version of ASTM C881-99 that provides specifications for seven types of adhesives and subsequent tests that refer to many ASTM tests. While Type IV adhesives are for bonding hardened concrete to other materials in load-bearing applications, it is not specifically for epoxy-adhesive anchor systems.

State DOT Test Methods and Material Specifications

A review was made of test methods and material specifications from various state departments of transportation (DOTs).

California Department of Transportation Acceptance Criteria for Adhesive Anchors in Concrete and Masonry Elements

Adhesive anchors for use in California Department of Transportation (CALTRANS) contracts must meet the requirements of International Conference of Building Officials (ICBO)-AC58 (ICC-ES AC58) as well as additional clarifications and amendments as found in CALTRANS (2010).

Four fingerprint tests are identified:

- Qualitative infrared analysis per ASTM E1252.
- Bond strength–slant shear per ASTM C882.
- Density per ASTM D1875.
- Gel time per ASTM C881.

Six additional tests not discussed in ICBO-AC58 are also required:

- Viscosity of adhesives per ASTM D2556.
- Deflection temperature per ASTM D648.
- Filler content per ASTM C881.
- Rheological properties per CALTRANS CTM438.
- Glass transition temperature per CALTRANS CTM438.
- Sag test to evaluate the tendency of the adhesive to flow out of overhead hole.

Four optional tests per ICBO-AC58 are required by CALTRANS:

- Creep test conducted per ASTM E1512.
- Dampness test.
- Freezing and thawing test.
- Seismic test.

A fire resistance test is required if there is a concern for a particular job or application.

Table 2. CTM681 sustained load values.

Stud Diameter (inches)	Sustained Tension Test Load (pounds)
1 ¼	31,000
1	17,900
⅞	14,400
¾	5,000
⅝	4,100
½	3,200
⅜	2,100
¼	1,000

CALTRANS Standard Specifications

Section 75 “Miscellaneous Metal” of the CALTRANS (2006b) *Standard Specifications* lists the requirements for resin capsule anchors tested under CALTRANS (2001) CTM681. A resin capsule anchor must withstand a sustained tensile load for at least 48 hours with a displacement less than 0.035”. The applied sustained load shall be in accordance with Table 2.

Anchors must be made of steel or stainless steel and hot-dip or mechanically galvanized.

CALTRANS has a test method for creep performance of adhesive anchor systems, but no comprehensive material specifications for adhesive anchors could be found in their standard specifications. While Section 95 of the CALTRANS (2006b) *Standard Specifications* deals with epoxy, there is no specific mention of an epoxy used for adhesive anchor applications. However, in Section 83 (Buildings and Barriers), there is a comment that anchor bolts that are set with epoxy shall use a two-component epoxy mixture as specified in Section 95-2.01 “Binder (Adhesive), Epoxy Resin Base.”

Texas Department of Transportation DMS-6100—Epoxies and Adhesives

Texas Department of Transportation (TxDOT) (2007a) DMS-6100 Epoxies and Adhesives classify epoxies and adhesives into nine types and specifies Type III to be used for dowel and tie bar adhesives. Type III adhesives are further classified into three classes (A–C). Class A is a bulk material for horizontal applications, Class B is for vertical applications, and Class C is either a bulk material or cartridge dispensed material for machine applications and can be applied horizontally or vertically.

Table 3 specifies the performance requirements for Type III adhesives tested according to TxDOT (2007b) Tex-614-J.

TxDOT (2007b) Tex-614-J requires that each component be distinctly colored and result in a third color when thoroughly mixed. Also the filler in the components must not damage the dispensing equipment and the extruder must meter the

Table 3. Performance requirements for Type III adhesives tested with Tex-614-J.

Physical Property	Requirements		
	Class A	Class B	Class C
Gel time, min.	25 min	25 min	6 min
Viscosity of mixed components, poise (Pa-s)	1,200 (120) max	20 (2) min 150 (50) max	-
Tensile bond @ 6 hr., psi (Mpa)	200 (1.40) min	200 (1.40) min	200 (1.40) min
Tensile bond @ 120°F (49°C), psi (Mpa)	400 (2.8) min	400 (2.8) min	400 (2.8) min
Thixotropy bond @ 120°F (49°C), mils (mm)	30 (0.75) min	-	30 (0.75) min
Wet pullout[1] strength, lbf. (kN)	4,500 (20) min	4,500 (20) min	4,500 (20) min

[1] The wet pullout test determines the strength of the adhesive bond between a steel anchor and the surface of a hole in concrete or masonry units.

proportioning and mixing of the components and handle the viscosity range of the components.

TxDOT Tex-641-J Testing Epoxy Materials

TxDOT (2007b) *Tex-641-J, Testing Epoxy Materials* is a collection of many material tests for adhesives. Five are required for Type III adhesives. Material specifications are covered in TxDOT (2007a) DMS-6100 Epoxies and Adhesives discussed later.

Gel Time. This test measures the gel time by mixing a sample at 77°F ± 2°F (25°C ± 1°C) and probing it with a toothpick until a ball of cured material forms at the center.

Viscosity. This test measures the viscosity of the adhesive using a Brookfield viscometer at 77°F ± 2°F (25°C ± 1°C).

Tensile Bond. This test measures the bond strength of the adhesive between two mortar briquettes. Two sets of three specimens are prepared for Type III adhesive. For each specimen, two mortar briquettes are joined with adhesive. One set of specimens is cured for 6 hours at 77°F ± 2°F (25°C ± 1°C) and the second set is cured for 48 hours at 120°F ± 2°F (49°C ± 1°C). Once cured, the specimens are placed into a tensile machine and loaded in tension until failure.

Thixotropy Bond @ 120°F (49°C). This test forms a 2" by 4" by 0.05" thick sample of adhesive on a metal plate conditioned at 120°F ± 2°F (49°C ± 1°C). The plates are then placed in an oven at 120°F ± 2°F (49°C ± 1°C) until the adhesive has hardened. The thickness retained is measured and the thixotropy bond is calculated as the average of eight thickness readings.

Wet Pullout Strength. In this test, a #3 (⅜") grade 60-ksi rebar is installed in a ⅝" diameter by 3.5" deep hole in a 6" diameter by 8" long concrete cylinder. The adhesive and anchor are installed and cured at 77°F ± 3°F (25°C ± 1°C). Following a 24-hour curing time, the block is submerged upright in a 77°F ± 3°F (25°C ± 1°C) water bath for 6 days. The anchor is then loaded in tension until failure.

New York State Department of Transportation Standard Specifications

New York State Department of Transportation (NYSDOT) (2008b) *Standard Specifications* Section 701-07 "Anchoring Materials—Chemically Curing" specifies the testing and material requirements for polymer anchoring materials for anchor bolts in concrete. The material must be non-metallic, non-shrink polymer resin in prepackaged or premeasured containers. It cannot contain corrosion promoting agents and must be insensitive to moisture. The material must last at least 6 months when stored between 40°F and 90°F (4°C and 32°C). The container must include the mixing instructions, setting time, and expiration date.

Section 701-07 specifies certain chemical resistances as tested per ASTM D471 at 70°F (21°C) for 24 hours as noted in Table 4.

Two series of tension pullout tests are specified for acceptance by the state. Test series 1 conducts three tests using 1" diameter threaded rods embedded 10" in concrete. The pullout load must be greater than the values found in Table 5. Test series 2 conducts two sets of three tests using ⅝" diameter threaded rods embedded 4" in concrete. The pullout load for each set must be greater than the values found in Table 5.

Section 654-3.03 "Anchorages" of NYSDOT (2008c) permits drilling by rotary impact drills only, and specifically does not permit core drills.

Table 4. NYSDOT chemical resistance requirements.

Chemical	Resistance
Gasoline	Slight swell
Hydraulic brake fluid	No effect
Motor Oil	No effect
Sodium chloride (5%)	No effect
Calcium chloride (5%)	No effect

Table 5. NYSDOT anchor tests minimum pullout loads.

Concrete Strength (psi)	Minimum Pullout Load (lbf)	
	Test series 1 1” dia. - 10” embedment	Test series 2 ⅝” dia. - 4” embedment
≤ 4,000	51,120	8,593
4,500	54,225	9,113
5,000	57,150	9,630
5,500	59,940	10,080

NYSDOT Engineering Instruction EI 08-012

NYSDOT (2008b) Engineering Instruction EI 08-012 was published in March of 2008 to limit the use of NYSDOT (2008c) Section 701-07 “Anchoring Materials – Chemical Curing.” This was due to recommendations from the National Transportation Safety Board (NTSB) to limit the use of adhesive anchors in overhead installations or in situations that could pose a risk to public safety. In such situations, NYSDOT recommends using alternative anchoring systems such as cementitious grout or mechanical anchor systems.

FDOT FM 5-568 Florida Method of Test for Anchor Systems for Adhesive-Bonded Anchors and Dowels.

FDOT (2000) FM 5-568 is FDOT’s test method for anchor systems with adhesive-bonded anchors and dowels. Its purpose is to determine the bond strength and performance characteristics of adhesive anchors in uncracked concrete. The material specifications for this test method are contained in Section 937 of FDOT (2007) *Standard Specifications for Road and Bridge Construction.* The tests contained in FDOT FM 5-568 reference the test procedures specified in ASTM E488 and ASTM E1512 with a few modifications/specifications as explained below.

Confined Tension. This test method specifies a confined test setup, an anchor diameter of ⅝” (16 mm), and an embedment of 4” (102 mm).

Damp-Hole Installation. This test method specifies a confined test setup, an anchor diameter of ⅝” (16 mm), and an embedment of 4” (102 mm).

Elevated Temperature. This test method specifies a confined test setup, an anchor diameter of ⅝” (16 mm), an embedment of 4” (102 mm), and a minimum temperature of 108°F (42°C).

Horizontal Orientation. This test is a static tension test on an anchor installed and cured in a horizontal orientation. This test method specifies a confined test setup, an anchor diameter of ⅝” (16 mm), and an embedment of 4” (102 mm).

Short-Term Cure. This test is a static tension test on an anchor installed and cured in a horizontal orientation. This test method specifies a confined test setup, an anchor diameter of ⅝” (16 mm), and an embedment of 4” (102 mm). The test load must be applied within 24 hours after installation.

Long-Term Load (Creep). This test conducts the creep test series listed in ASTM E1512 with the following specifications:

- References Table 2 of ASTM E488 for requirements on the distance between the reaction force and the anchor;
- The minimum sustained tension load of 40% of the average tension failure load is established by an unconfined tension test;
- The minimum testing temperature of the concrete and anchor specimens is 110°F (43°C);
- A load duration of 42 days; and
- Following the 42 day loading period, the temperature of the specimens is cooled to 70°F ± 5°F (21°C ± 3°C) and an unconfined tension test is performed.

Unconfined Static Tension Test. This test method specifies unconfined test setups with anchor diameters and embedments as follows:

- An anchor diameter of ⅝” (16 mm) and embedment of 4” (102 mm),
- An anchor diameter of ⅝” (16 mm) and embedment of 6” (152 mm), and
- An anchor diameter of ¾” (19 mm) and embedment of 6” (152 mm).

FDOT Standard Specifications for Road and Bridge Construction

The material specifications for adhesive anchor systems for FDOT are found in FDOT (2007) *Standard Specifications for Road and Bridge Construction,* Section 937 “Adhesive Bonding Material Systems for Structural Applications.”

Only systems that are specifically intended for bonding anchors and dowels into concrete in structural applications are allowed. FDOT restricts the use of adhesives that are manually combined from bulk supplies and only allows systems that are prepackaged in which the two components are in separate chambers and are automatically proportioned and mixed when discharged. Only undamaged full packages can be used (i.e., packages that were previously opened cannot be used). Adhesive anchors can only be installed in positions ranging from horizontal to vertically downward. Two types of adhesive systems (HV and HSHV) are defined as follows:

- **Type HV Adhesives:** Used in bonding materials for all horizontal installations and vertical installations other than constructing doweled pile splices, except when Type HSHV is required. Type HV adhesives may not be substituted for Type HSHV adhesives.

Table 6. FDOT Minimum performance requirements for adhesive systems.

Test or Property	Uniform Bond Stress Type HV Adhesive (psi)	Uniform Bond Stress Type HSHV Adhesive (psi)
Confined tension	2,290	3,060
Damp-hole installation	1,680	1,830
Elevated temperature	2,290	3,060
Horizontal orientation	2,060	2,060
Short-term cure	1,710	1,710
Specified bond strength	1,080	1,830

- **Type HSHV Adhesives:** Use higher strength Type HSHV adhesive bonding materials for installation of traffic railing barrier reinforcement and anchor bolts into existing concrete bridge decks.

HV and HSHV systems must be packaged to be automatically proportioned during installation.

Section 937 also specifies the minimum performance requirements for tests conducted under FM 5-568 as indicated in Table 6.

The coefficient of variation of the uniform bond stress is limited to 20%.

Three criteria are specified for the creep test and are listed as follows:

- The displacement rate shall decrease during the 42 day test period.
- The total displacement at 42 days (with load still applied) shall be less than 0.03” and the total displacement due to creep during the last 14 days must be less than 0.003”.
- After the 42 day test, the uniform bond stress from the confined tension test shall not be less than 1,800 psi.

Finally, a qualified products list (QPL) is maintained by FDOT in which manufacturers can apply for their products to be included once they have met the requirements of Section 937.

Illinois Department of Transportation Laboratory Test Procedure for Chemical Adhesives

Illinois Department of Transportation (IDOT) (2007a) *Laboratory Test Procedure for Chemical Adhesives* tests chemical adhesives for dowels and tie bars. The test procedure is for both gun grade adhesives and glass capsule adhesive systems. The glass capsule systems are installed using threaded rods in a ¾” diameter hole and embedded 5” into 4,000 psi dry concrete at 73°F ± 4°F (23°C ± 2°C). The gun grade adhesive systems use #5 epoxy coated 60 ksi rebar. The following tests are conducted:

Dry Conditioning. A static tension test per ASTM E488 is conducted within 1 hour of installation and stopped when the load reaches 16 kips or the displacement reaches 0.1”. The anchor system is accepted if it withstood a minimum load of 13.55 kips with less than 0.1” displacement.

Wet Conditioning. This test is similar to the “Dry Conditioning” test except the hole is filled with water for 12 hours and then removed prior to installation. A static tension test per ASTM E488 is conducted within 1 hour of installation and stopped when the load reaches 16 kips or the displacement reaches 0.1”. The anchor system is accepted if it withstood a minimum load of 13.55 kips with less than 0.1” displacement.

Cold Temperature Conditioning. This test is similar to the “dry conditioning” test except that the adhesive and threaded rod are conditioned to 32°F ± 4°F (0°C ± 2°C) prior to installation. The anchor is cured for 24 hours at the above temperature. A static tension test per ASTM E488 is conducted at the end of the 24 hour curing period and loaded until failure. The anchor system is accepted if the displacement at failure was less than 0.1”.

Compressive Strength. This test is not for glass capsule systems. This test tests two 1” diameter by 2” cylinder specimens at 73°F ± 4°F (23°C ± 2°C). One specimen is tested at 1 hour and the other at 24 hours after casting. The adhesive is accepted if the 1 hour compressive strength is greater than 3,000 psi and the 24 hour compressive strength is greater than 4,000 psi.

Horizontal Installation Stability. This test is not for glass capsule systems. This test installs a 1¼” diameter by 14” long smooth steel dowel bar into a horizontal 9” long by 1⅜” diameter clear plastic tube at 73°F ± 4°F (23°C ± 2°C). The anchor system is accepted if the anchor could be installed by hand without “appreciable drain down” from the top of the tube.

Infrared Spectrophotometer “Fingerprint.” A fingerprint record is made of the cured adhesive for future reference.

IDOT Standard Specifications for Road and Bridge Construction

Section 1027.01 “Chemical Adhesive” of IDOT (2007b) *Standard Specifications for Road and Bridge Construction* references IDOT (2007a) *Laboratory Test Procedure for Chemical Adhesives* for the testing and acceptance of chemical adhesives. Section 1027.01 states that the adhesive must consist of a two-part fast-setting resin and filler/hardener.

Washington State Department of Transportation Standard Specifications

Section 9-26 “Epoxy Resins” of Washington State Department of Transportation (WSDOT) (2008b) *Standard*

Specifications lists the various types of epoxy bonding agents per the classification found in ASTM C881. Section 6-02.3(18) "Placing Anchor Bolts" discusses the requirements for placing grouted anchor bolts and does not specifically mention adhesive anchors.

Michigan Department of Transportation Material Source Guide

Specification 712.03J "Adhesive Systems for Structural Anchor & Lane Ties" of the Qualified Products List (QPL) in the Michigan Department of Transportation (MDOT) (2009) *Material Source Guide* states that anchors should be installed per the manufacturer's instructions with a minimum embedment depth of 9 diameters for threaded rod.

Virginia Department of Transportation Road and Bridge Specifications

Section 214 "Epoxy-Resin Systems" of Virginia Department of Transportation (VDOT) (2007a) *Road and Bridge Specifications* lists various types of epoxy-resin systems for various uses, but does not include adhesive anchors. Section 519 "Sound Barrier Walls" specifically prohibits the use of epoxy or adhesive anchors.

International Test Methods and Material Specifications

The following summarizes the review of international test standards and material specifications.

EOTA ETAG 001 Part 5 – Bonded Anchors

Part 5 of EOTA (2002) ETAG 001 *Guideline for European Technical Approval of Metal Anchors for Use in Concrete* addresses bonded anchors. This technical approval document was created in 2002 and has undergone several amendments. EOTA (2002) ETAG 001 Part 5 served as the basis for ICC-ES AC308 which subsequently served as the basis for ACI 355.4 discussed above. A review of EOTA (2002) ETAG 001 Part 5 did not provide any new information than what was already discussed with ACI 355.4.

Federation Internationale du Beton Design of Anchorages in Concrete

The Federation Internationale du Beton (fib) (2011) *Design of Anchorages in Concrete* does not provide adhesive anchor qualification and quality control requirements, rather Section 1.3 references other previously discussed standards such as:

- EOTA ETAG 001,
- ICC-ES AC308, and
- ACI 355.2.

Other Test Methods

The following section presents various alternate test methods that can potentially evaluate sustained load performance of adhesive anchor systems.

Short-Term Incremental Loading Test for Adhesive Anchors

ASTM E488 provides for two load rates in the static tension test: a continuous load rate that will produce failure at around 2 minutes and an incremental load rate that loads at 15% intervals and holds each step for 2 minutes. Several static tension tests were conducted at the University of Florida under NCHRP 20-07/Task 255 using a modified incremental load rate. Figure 23 shows a sample anchor test loaded with the incremental load rate.

Under the incremental load rate, it was noticed that at the lower stress levels the anchor would initially displace when the load was held constant but would eventually stabilize over the 2 minute interval. However, at the higher stress levels, some anchors would continue to displace over the 2 minute interval.

Stress versus Time-to-Failure Test

NCHRP (2009) Project 20-07/Task 255 investigated sustained load testing for adhesive anchors and recommended a "stress versus time-to-failure" test method for AASHTO that has been adopted as AASHTO TP 84-10. The following is a summary of that test method; more detailed information is presented in NCHRP Report 639 (2009).

The test method begins by placing five specimens under confined static tension tests to determine the *mean static load* at an elevated temperature of 110°F (43°C). Subsequent sustained load test series are conducted on five specimens at two lower stress levels at an elevated temperature of 110°F (43°C). It was recommended that these lower stress levels be within the specified ranges of 70% to 80% and 60% to 70% of the *mean static load.* Ideally, the stress levels chosen would create data points in separate log cycles. The sustained load tests are conducted until failure, which is defined as the initiation of tertiary creep.

The data is plotted on a stress versus time-to-failure graph (semi-log plot). A least squares trendline is drawn through each data point and projected linearly (on the log scale).

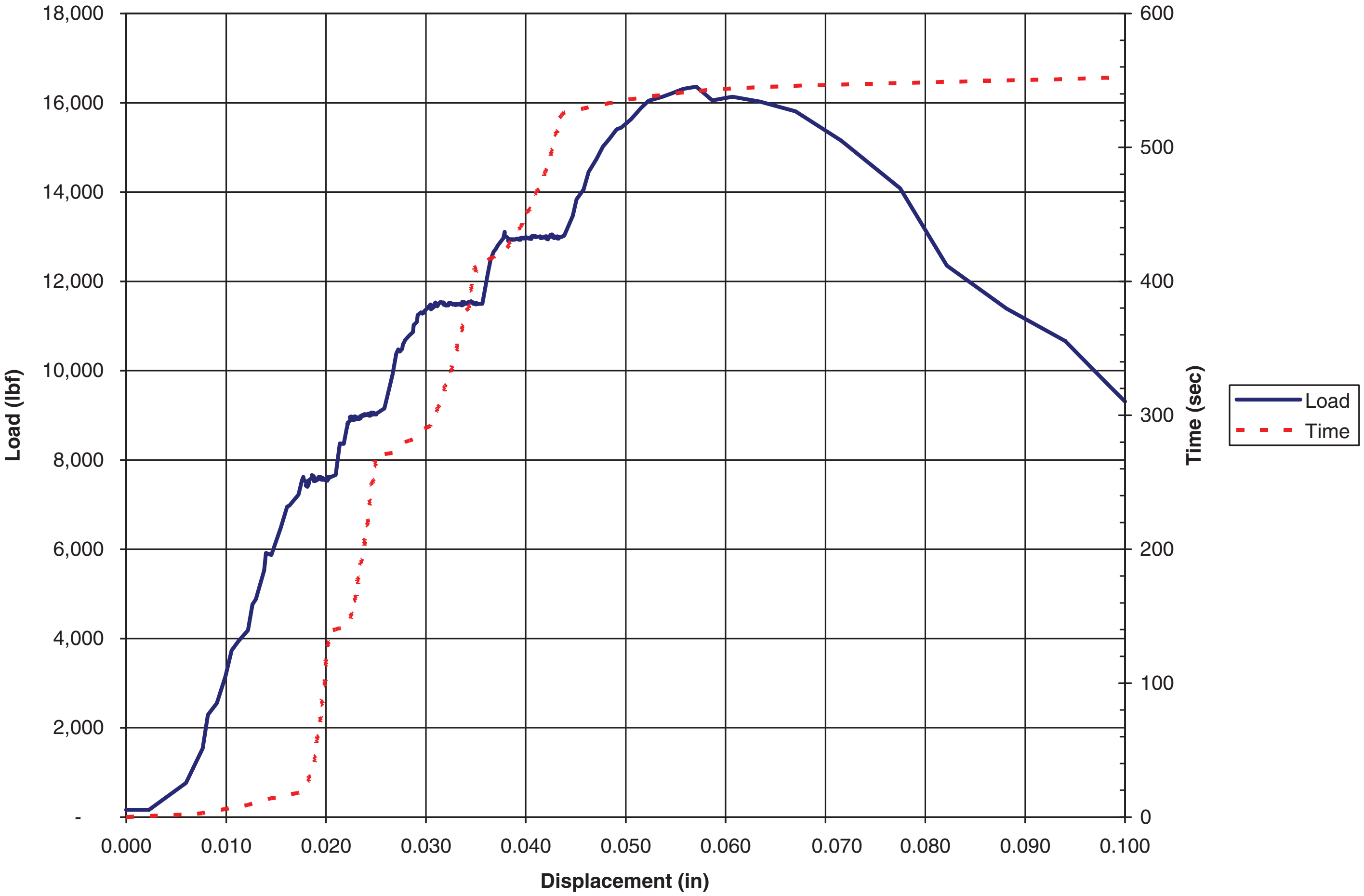


Figure 23. Load versus displacement and time versus displacement graph for a sample anchor with incremental loading showing time versus displacement response.

According to Klompen et al. (2005), most polymers show a linear relationship between the logarithm of increasing time to failure and decreasing stress; however, some polymers do exhibit a lower bound stress level.

While a linear projection would be sufficient and possibly conservative, a manufacturer can perform longer term tests at lower stress levels in order to better define the curve. See Figure 24 for a sample stress versus time-to-failure graph. The test data can also be summarized in a table of estimated failure loads at specified structure lifetimes.

NCHRP Report 639 (2009) indicates that the "stress versus time-to-failure" test method provided a viable means for evaluating the sustained load performance of adhesive anchors. This method was adopted as the primary method of assessing a parameter's influence on sustained load performance for this project. A detailed discussion of how this method was implemented is described later.

Adhesive-Alone Tests

Adhesive-alone tests involve testing the adhesive without the concrete and anchor. This approach could be simpler, cheaper, and quicker than tests that involve the entire adhesive anchor system installed in concrete.

It is understood that the interaction of the adhesive with the concrete is an important variable to creep resistance and is essential to be included in the testing. Therefore, it was not reasonable to only test the adhesive alone for the evaluation of short-term and sustained load performance of adhesive anchors in concrete, but such tests were included in the project since they could possibly serve as:

- qualifying or prescreening tests prior to further more expensive/timely testing,
- fingerprinting tests to confirm the identity of an adhesive on site, and
- comparison tests between adhesives.

Time–Temperature Superposition and Master Curves. Time–temperature superposition is the idea that a change in temperature produces the same effect as a change in measurement time for a viscoelastic material. This proposal allows the researcher to conduct tests on a sample over a range of temperatures and shift the results along the time axis until

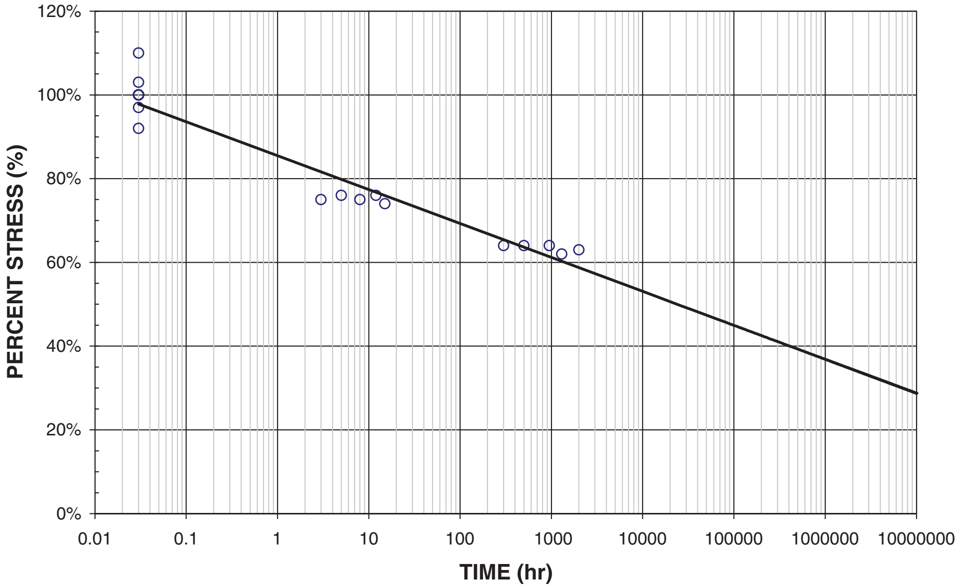


Figure 24. Sample stress versus time-to-failure graph.

they superimpose, creating what is called a master curve, thereby providing predictions of the material's behavior over a broader range of time.

Crawford (1998) explains that the glass transition temperature (T_g) is usually taken as the reference temperature. If the properties of an adhesive are known at T_g, then the properties at any temperature can be determined. Per Hunston et al. (1980) this relationship is valid for materials with more simple chemistries, but may not be valid for more complex materials.

Various ASTM test methods exist for determining the glass transition temperature. ASTM E1356 uses differential scanning calorimetry (DSC) to monitor the heat flow of a specimen as it is heated or cooled through the glass transition region. ASTM E1545 uses thermomechanical analysis to measure the movement of a probe in contact with a specimen as it changes from a vitreous solid to an amorphous liquid while it is heated through its glass transition temperature. ASTM E1640 uses dynamic mechanical analysis to oscillate a specimen at a fixed or resonant frequency and monitors the change in the viscoelastic response as it is heated. The glass transition region is marked by a decrease in storage modulus and an increase in the loss modulus and tan-δ.

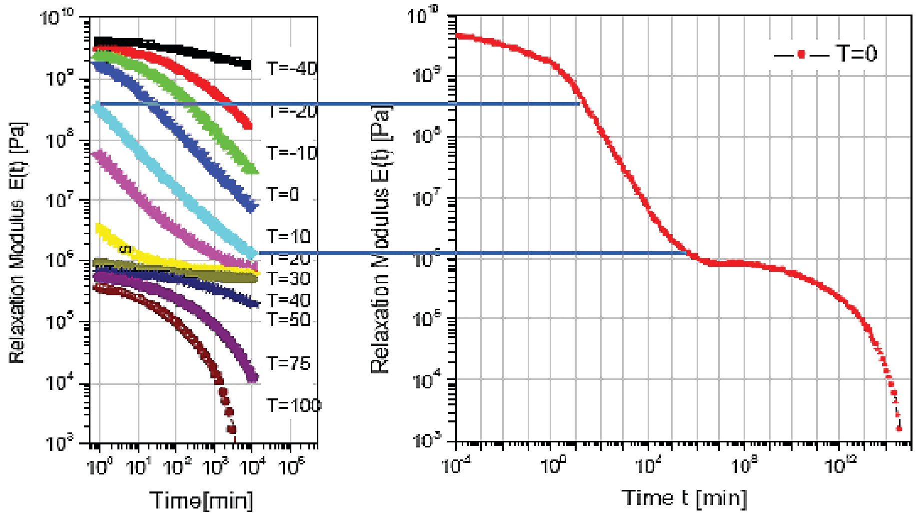
Master curves are a common method of simplifying and presenting data dealing with time-temperature equivalence and can be used to extend the data beyond the testing range. Vuoristo and Kuokkala (2002) conducted creep tests at different temperatures and used master curves to predict the behavior of an epoxy used on rolls in the paper making industry by expanding the data by two orders of magnitude. Master curves are also used in ASTM D2990 as an accepted method to predict sustained load properties of plastics.

Time–temperature superposition works well for polymers within the linear viscoelastic region where compliance is independent of stress. For materials whose compliance increases as stress increases, time–temperature superposition is not appropriate.

Figure 25 is a sample master curve created from stress relaxation data. The left side of the figure shows the stress relaxation data for various temperatures. These curves were then shifted until they lined up and formed the master curve as shown on the right side of the figure.

Time–Stress Superposition. Time–stress superposition is another method to create a master curve from several short-term tests at a constant temperature at various stress levels. This approach is more practical for materials not within the linear viscoelastic region where the compliance changes as stress changes. Tests are conducted on a sample at a constant temperature over a range of stress levels. Similar to time–temperature superposition, the curves can be shifted along the time axis to create a master curve at a particular stress level (Figure 26 and Figure 27).

For strains in the linear viscoelastic range, the time–temperature superposition principle works well. However, the time–temperature superposition principle only relates the temperature to time and if the strain or stress is large enough to change the speed of the underlying molecular motion mechanism or even alter the mechanism, the predicted time response from only using the time–temperature superposition principle will not be accurate. A few theories tried to address this issue by assuming that there were no changes in the underlying mechanism and only the stress or strain altered the speed. Using such an



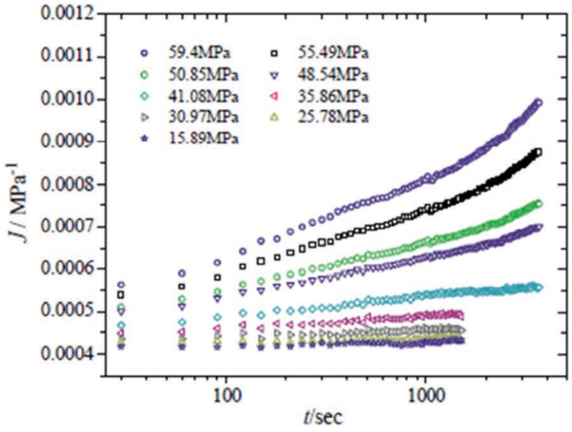
Source: Hunston and Chin (2008)

Figure 25. Sample master curve using time-temperature superposition.

approach, a stress or strain shift factor can also be introduced. The time–stress superposition shows satisfactory results for a few polymer systems but its validity needs to be verified for each material.

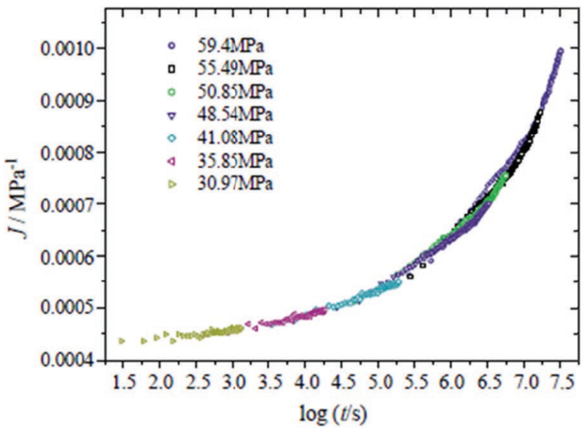
Dynamic Mechanical Thermal Analysis Tests. Dynamic mechanical thermal analysis (DMTA) tests take thin samples of an adhesive and subject them to many cycles of a tensile load. Chin et al. (2007) conducted DMTA tests on two adhesives in which tensile strain sweeps were conducted at different temperatures and the test data was used to perform a time–temperature superposition. The storage modulus (*E*′), loss modulus (*E*″), and tan delta (*E*″/*E*′) were calculated and master curves were generated for both adhesives. Figure 28 and Figure 29 present the *E*′, *E*″, and tan delta curves (respectively) generated by the researchers.

Creep Compliance Curves. Creep compliance is defined as the strain due to creep divided by stress. Creep compliance curves are plotted versus time and since the strain is normalized by stress, these curves provide an indication of displacement versus time and can be used to show a material's creep deformation properties over time. In the National Institute of Standards and Technology (NIST) study by Chin et al. (2007), creep compliance curves were generated that displayed the predicted creep behavior of two adhesives over time. Figure 30 clearly illustrates that the two adhesives tested are predicted to have different creep properties. Chin et al. (2007) warn that these estimated creep compliance curves are "not



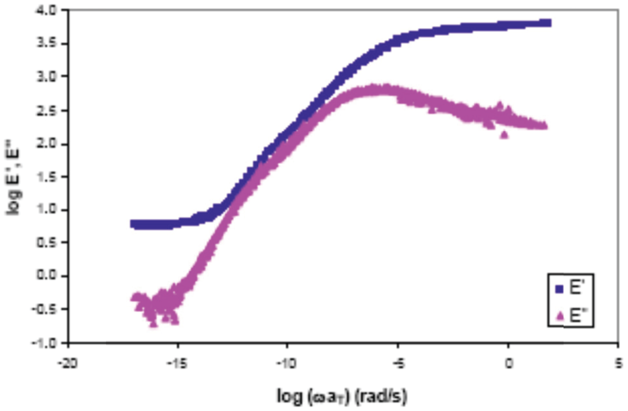
Source: Jazouli et al. (2005)

Figure 26. Individual compliance curves used in time–stress superposition.



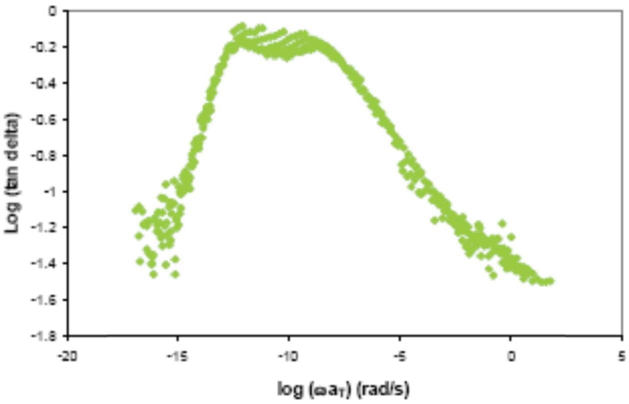
Source: Jazouli et al. (2005)

Figure 27. Sample master curve using time–stress superposition.



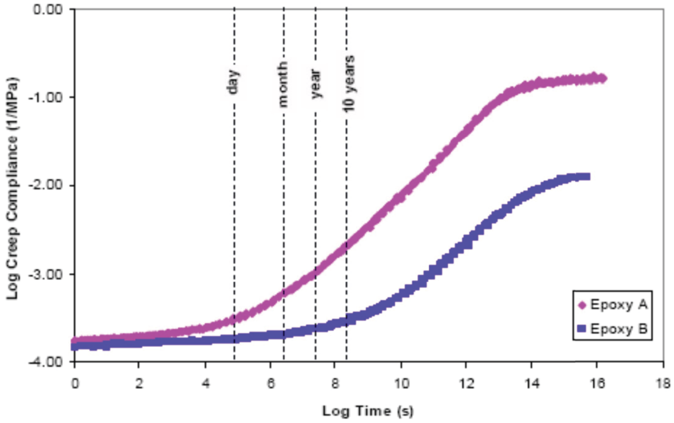
Source: Chin et al. (2007)

Figure 28. E' and E" master curves for an epoxy.



Source: Chin et al. (2007)

Figure 29. Tan delta master curve for an epoxy.



Source: Chin et al. (2007)

Figure 30. Creep compliance curve for two epoxies.

a substitute for the direct measurement of creep behavior" because they are limited to the linear viscoelastic region and adhesive anchors under sustained loading may function in the nonlinear region, especially as failure is approached. However, they can be valuable as fingerprinting tests or prescreening tests by which to indicate which adhesives warrant further/more exact testing by manufacturers.

CALTRANS Test Method 438. CALTRANS (2006a) Test Method 438 determines rheological properties of adhesives using a dynamic shear rheometer (DSR). This test method, also confined to the linear viscoelastic range as discussed above, cannot be used as a direct measurement of creep performance, but might be able to be used as a prescreening test.

Tensile Creep Tests. ASTM D2990 (2001) provides the testing procedure for a tensile creep test. Tensile creep tests load small "dogbone" specimens of adhesive using the dimensions for Type I or Type II dogbones as specified in ASTM D638 (Figure 31). Two specimens are required for each stress level tested or three specimens if fewer than four stress levels are used. A minimum of three stress levels is recommended for materials that show linear viscoelasticity and at least five stress levels for materials that are significantly affected by stress.

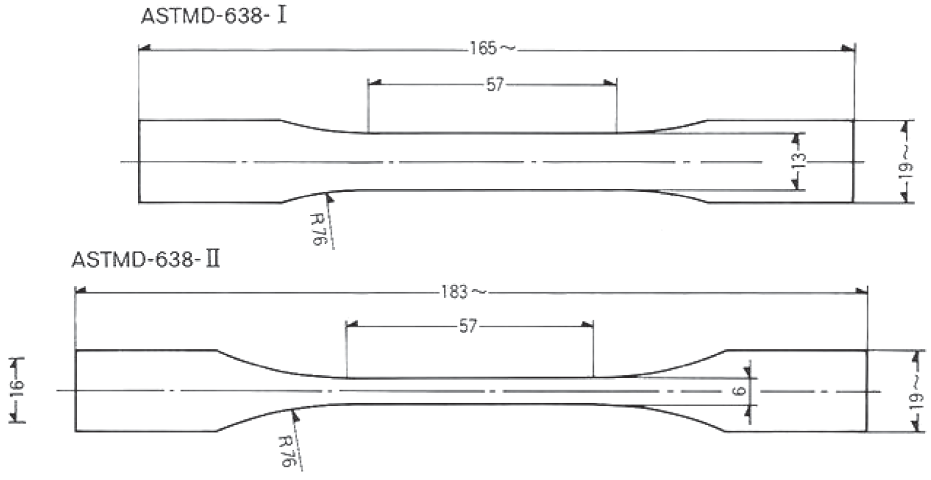
ASTM D2990 specifies that the tensile creep specimens are loaded to the given stress level within 5 seconds. Measurements of extension, temperature, and humidity are recorded at progressively longer time intervals. ASTM D2990 suggests the following approximate time schedule: 1, 6, 12, and 30 min; 1, 2, 5, 20, 50, 100, 200, 500, 700, and 1,000 hours; and monthly beyond 1,000 hours. The tests are continued until failure. Test series can be conducted under different testing conditions (temperature, humidity, cure time) to evaluate the effect of a parameter on the adhesive's creep performance.

To determine the 100% stress level (mean static strength), static load tests on five specimens are conducted per the procedure specified in ASTM D638. ASTM D638 specifies a constant strain loading rate that produces failure between 30 seconds and 5 minutes.

NCHRP Report 639 (2009) recommends that both the static load tests and the sustained load tests must be loaded with the same load transfer duration. It is recommended that the load transfer duration of both the ASTM D638 static load tests and the ASTM D2990 tensile creep tests be set at 2 ± 1 minutes, as specified for the static load tests and sustained load tests for anchor pullout tests.

Design Guidelines and Specifications Related to Adhesive Anchor Systems

The review of design guidelines and specifications related to adhesive anchors included national standards, state DOT standards, and international standards. The test methods



Source: ASTM D638

Figure 31. ASTM D638 Type I and Type II specimens.

and specifications described above generate design values (e.g., bond stress) that are used in the design calculations described below.

National Design Guidelines and Specifications

ICC-ES AC308 Acceptance Criteria for Post-Installed Adhesive Anchors in Concrete Elements

ICC-ES AC308 provides both ASD and LRFD design provisions. Only the LRFD method will be addressed in this report. The ICC-ES AC308 LRFD (strength design) method presented in Section 3.3 provided the basis for development of the adhesive anchor provisions in ACI 318-11 Appendix D. ACI 355.4 will not include design provisions. The design methodology provided in ICC-ES AC308 will be discussed under ACI 318-11.

ACI 318-11 Building Code Requirements for Structural Concrete

ACI 318-11 Appendix D addresses anchorage to concrete and recently incorporated the design provisions for adhesive anchors developed by ICC-ES AC308. A general overview of adhesive anchor provisions is presented below.

ACI 318-11 Appendix D specifies various strength reduction factors (ϕ) depending on type of failure, steel element (brittle or ductile), presence of supplementary reinforcement, and category as defined by ACI 355.2. The strength reduction factors range from 0.45 to 0.75.

Tension. ACI 318 Appendix D considers the following design strengths (failure modes) for anchors in tension that are illustrated in Figure 32:

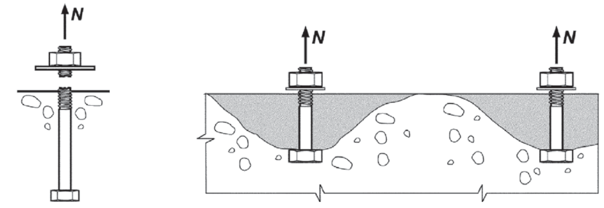
(a) Steel strength of anchor in tension;
(b) Concrete breakout strength of anchor in tension;
(c) Pullout strength of cast-in, post-installed expansion or undercut anchor in tension;
(d) Concrete side-face blowout strength of a headed anchor in tension; and
(e) Bond strength of adhesive anchor in tension.

Steel strength of anchor in tension. The nominal strength of the anchor in tension as governed by the steel (N_{sa}) is determined as:

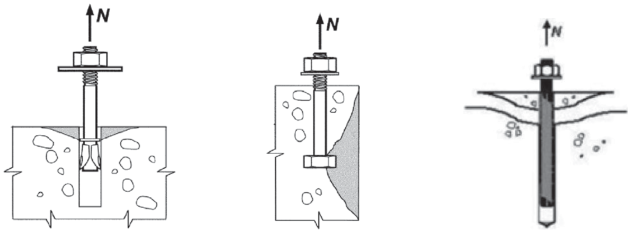
$$N_{sa} = A_{se,N} f_{uta} \qquad \text{ACI 318 Eq. D-2}$$

where

$A_{se,N}$ = effective cross section of a single anchor, in.^{2} and
f_{uta} = specified tensile strength of anchor steel, psi.



(a) Steel strength failure (b) Concrete breakout failure



(c) Pullout failure (d) Concrete side-face blowout failure (e) Adhesive bond strength failure

Source: ACI 318-11 (2011a)

Figure 32. ACI 318-11 tension failure modes.

The value (f_{uta}) used in Eq. D-2 must not exceed $1.9f_{ya}$ or 125,000 psi where f_{ya} is the specified yield strength of the anchor steel in psi. The $1.9f_{ya}$ limit is to ensure that yielding does not occur under service loads.

Concrete breakout strength of anchor in tension. The nominal concrete breakout strength of a single anchor (N_{cb}) or a group of anchors (N_{cbg}) shall not exceed:

Single anchor:

$$N_{cb} = \frac{A_{Nc}}{A_{Nco}} \psi_{ed,N}\ \psi_{c,N}\ \psi_{cp,N} N_b \qquad \text{ACI 318 Eq. D-3}$$

Group of anchors:

$$N_{cbg} = \frac{A_{Nc}}{A_{Nco}} \psi_{ec,N}\ \psi_{ed,N}\ \psi_{c,N} \psi_{cp,N} N_b \qquad \text{ACI 318 Eq. D-4}$$

where

A_{Nc} = projected concrete failure area of a single anchor or a group of anchors that can be approximated as the base of a rectangle that is resulted by projecting the failure surface out $1.5h_{ef}$ from the centerlines of the anchor or from the centerlines of the anchors in a group of adhesive anchors, in.^{2};

A_{Nco} = projected concrete failure area of a single anchor with edge distance equal or greater than $1.5h_{ef}$, in.^{2};

$$A_{Nco} = 9h_{ef}2 \qquad \text{ACI 318 Eq. D-5}$$

h_{ef} = effective embedment depth of anchor, in.;

$\psi_{ec,N}$ = modification factor for eccentricity of applied loads;

$\psi_{ed,N}$ = modification factor for edge effects;

$\psi_{c,N}$ = modification factor based on presence or absence of cracking;

$\psi_{cp,N}$ = modification factor for anchor in uncracked concrete without supplementary reinforcement;

N_b = the basic concrete breakout strength of a single anchor in tension in cracked concrete;

$$N_b = k_c \lambda_a \sqrt{f'_c}\, h_{ef}^{1.5} \qquad \text{ACI 318 Eq. D-6}$$

k_c = 17 for post-installed anchors;

= 24 for cast-in-place anchors;

λ_a = modification factor for lightweight concrete; and

f'_c = specified compressive strength, psi.

Pullout strength of cast-in, post-installed expansion or undercut anchor in tension. This failure mode does not apply to adhesive anchors.

Concrete side-face blowout strength of a headed anchor in tension. This failure mode does not apply to adhesive anchors.

Bond strength of adhesive anchor in tension. The nominal bond strength of a single adhesive anchor (N_a) or a group of adhesive anchors (N_{ag}) shall not exceed:

Single anchor:

$$N_a = \frac{A_{Na}}{A_{Nao}} \psi_{ed,Na} \psi_{cp,Na} N_{ba} \qquad \text{ACI 318 Eq. D-18}$$

Group of anchors:

$$N_{ag} = \frac{A_{Na}}{A_{Nao}} \psi_{ec,Na} \psi_{ed,Na} \psi_{cp,Na} N_{ba} \qquad \text{ACI 318 Eq. D-19}$$

where

A_{Na} = projected influence area of a single adhesive anchor or a group of adhesive anchors that can be approximated as the base of a rectangle that is resulted by projecting the failure surface out c_{Na} from the centerlines of the anchors in a group of adhesive anchors, in.^{2};

A_{Nao} = projected influence area of a single anchor with edge distance equal or greater than c_{Na}, in.^{2};

$$A_{Nao} = (2c_{Na})^2 \qquad \text{ACI 318 Eq. D-20}$$

c_{Na} = edge distance required to develop the full bond strength of a single adhesive anchor, in.;

$$C_{Na} = 10d_a \sqrt{\frac{\tau_{uncr}}{1{,}100}} \qquad \text{ACI 318 Eq. D-21}$$

d_a = nominal diameter of adhesive anchor, in.;

τ_{uncr} = characteristic limiting bond stress of adhesive anchor in uncracked concrete, psi;

$\psi_{ec,Na}$ = modification factor for eccentricity of applied loads;

$\psi_{ed,Na}$ = modification factor for edge effects;

$\psi_{cp,Na}$ = modification factor for anchor in uncracked concrete without supplementary reinforcement;

N_{ba} = the basic bond strength of a single adhesive anchor in tension in cracked concrete;

$$N_{ba} = \lambda_a \tau_{cr} \pi d_a h_{ef} \qquad \text{ACI 318 Eq. D-22}$$

λ_a = modification factor for lightweight concrete;

τ_{cr} = characteristic limiting bond stress of adhesive anchor in cracked concrete, psi; and

h_{ef} = effective embedment depth of anchor, in.

If test results for τ_{cr} from ACI 355.4 are not available, then the values in Table 7 for τ_{cr} and τ_{uncr} can be used. Note that the values in Table 7 are multiplied by 0.4 if the anchor is subject to sustained tension loading.

Table 7. Characteristic bond stress to use in absence of test results.

Installation and Service Conditions	Moisture Content of Concrete at Time of Anchor Installation	Peak In-Service Temperature of Concrete (°F)	τ_{cr} (psi)	τ_{uncr} (psi)
Outdoor	Dry to fully saturated	175	200	650
Indoor	Dry	110	300	1,000

Notes:

Where anchor design includes sustained tension loading, multiply values of τ_{cr} and τ_{uncr} by 0.4.

Where anchor design includes earthquake loads for structures assigned to seismic design category C, D, E, or F, multiply values of τ_{cr} by 0.8 and τ_{uncr} by 0.4.

The nominal tension strength (N_n) is then the lesser of N_{sa}, N_{cb}, and N_a for single adhesive anchors or N_{sa}, N_{cbg}, and N_{ag} for a group of adhesive anchors. In addition, per ACI 318-11 D.4.1.2, a 55% limitation is placed on the anchor in a connection that resists the highest sustained load.

Shear. ACI 318 Appendix D considers the following design strengths (failure modes) for anchors in shear that are illustrated in Figure 33:

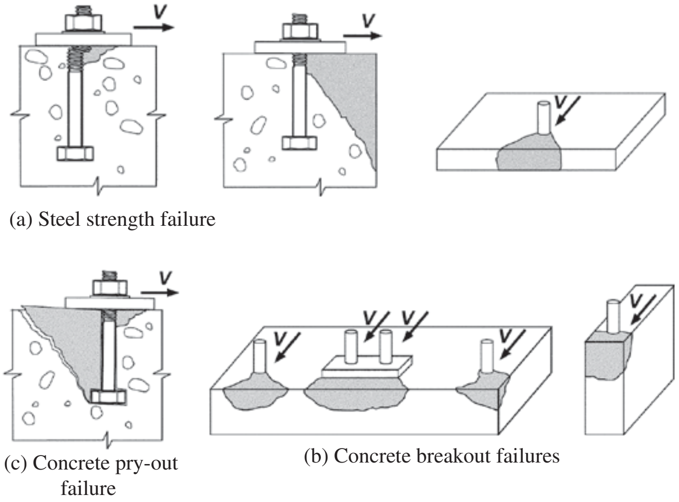
(a) Steel strength of anchor in shear,
(b) Concrete breakout strength of anchor in shear, and
(c) Concrete pry-out strength anchor in shear.

Steel strength of anchor in shear. The nominal strength of an anchor in shear as governed by the steel (V_{sa}) is determined as:

$$V_{sa} = 0.60 A_{se,V} f_{uta} \qquad \text{ACI 318 Eq. D-29}$$

where

$A_{se,V}$ = effective cross section of a single anchor in shear, in.^{2} and
f_{uta} = specified tensile strength of anchor steel, psi.



(a) Steel strength failure

(c) Concrete pry-out failure

(b) Concrete breakout failures

Source: ACI 318-11 (2011a)

Figure 33. ACI 318-11 shear failure modes.

The value (f_{uta}) used in Eq. D-29 must not exceed 1.9f_{ya} or 125,000 psi where f_{ya} is the specified yield strength of the anchor steel in psi. The 1.9f_{ya} limit is to ensure that yielding does not occur under service loads.

Concrete breakout strength of anchor in shear. The nominal concrete breakout strength of a single anchor (V_{cb}) or a group of anchors (V_{cbg}) in shear shall not exceed:

Single anchor:

$$V_{cb} = \frac{A_{Vc}}{A_{Vco}} \psi_{ed,V} \psi_{c,V} \psi_{h,V} V_b \qquad \text{ACI 318 Eq. D-30}$$

Group of anchors:

$$V_{cbg} = \frac{A_{Vc}}{A_{Vco}} \psi_{ec,V} \psi_{ed,V} \psi_{c,V} \psi_{h,V} V_b \qquad \text{ACI 318 Eq. D-31}$$

where

A_{Vc} = projected area of the failure surface on the side of the concrete member at its edge for a single anchor or group of anchors, in.^{2};
A_{Vco} = projected area for a single anchor in a deep member with a distance from the edge greater than 1.5c_{a1} in the direction of the shear force, in.^{2};

$$A_{Vco} = 4.5(c_{a1})^2 \qquad \text{ACI 318 Eq. D-32}$$

c_{a1} = distance from the center of the anchor to edge of the member in the direction of the shear load, in.;
$\psi_{ec,V}$ = modification factor for eccentricity of applied loads;
$\psi_{ed,V}$ = modification factor for edge effects;
$\psi_{c,V}$ = modification factor based on presence or absence of cracking;
$\psi_{h,V}$ = modification factor for anchor in concrete where the member thickness is less than 1.5c_{a1};
V_b = the basic concrete breakout strength of a single anchor in shear in cracked concrete is the lesser of Eq. D-33 and D-34;

$$V_b = \left(7\left(\frac{l_e}{d_a}\right)^{0.2} \sqrt{d_a}\right) \lambda_a \sqrt{f_c'}\,(c_{a1})^{1.5} \qquad \text{ACI 318 Eq. D-33}$$

$$V_b = 9\lambda_a\sqrt{f_c'}(c_{a1})^{1.5} \qquad \text{ACI 318 Eq. D-34}$$

l_e = load-bearing length of anchor, in.;
d_a = nominal diameter of adhesive anchor, in.;
λ_a = modification factor for lightweight concrete; and
f_c' = specified compressive strength, psi.

Concrete pry-out strength of anchor in shear. The nominal pry-out strength of a single anchor (V_{cp}) or a group of anchors (V_{cpg}) in shear shall not exceed:

Single anchor:

$$V_{cp} = k_{cp}N_{cp} \qquad \text{ACI 318 Eq. D-40}$$

Group of anchors:

$$V_{cpg} = k_{cp}N_{cpg} \qquad \text{ACI 318 Eq. D-41}$$

where

k_{cp} = 1.0 for $h_{ef} < 2.5$ in.;
k_{cp} = 2.0 for $h_{ef} \geq 2.5$ in.;
N_{cp} = basic concrete pry-out strength of a single anchor, lbs; and
N_{cpg} = basic concrete pry-out strength of a group of anchors, lbs.

The nominal shear strength (V_n) is then the lesser of V_{sa}, V_{cb}, V_{cp} for single adhesive anchors or V_{sa}, V_{cbg}, V_{cpg} for a group of adhesive anchors.

Tension and Shear Interaction. ACI 318-11 Appendix D uses a tri-linear approach to tension–shear interaction expressed in the following equation with two conditions:

$$\frac{N_{ua}}{\varphi N_n} + \frac{V_{ua}}{\varphi V_n} \leq 1.2 \qquad \text{ACI 318 Eq. D-32}$$

but

if $V_{ua} \leq 0.2\varphi V_n$, then full strength in tension can be used;
if $N_{ua} \leq 0.2\varphi N_n$, then full strength in shear can be used;

where

N_{ua} = factored tension force, lbs;
N_n = nominal strength in tension, lbs;
V_{ua} = factored shear force, lbs;
V_n = nominal strength in shear, lbs; and
φ = strength reduction factor.

AASHTO LRFD Bridge Design Specifications

The AASHTO (2010b) *LRFD Bridge Design Specifications* was reviewed for a framework of design specifications related to general anchor bolt design within which the epoxy adhesive design standards could be incorporated. Article 14.8.3 "Anchorages and Anchor Bolts" presents the design requirements for anchor bolts. It refers to article 6.13.2.10.2 for the tensile resistance, article 6.13.2.12 for the shear resistance, and article 6.13.2.11 for combined tension–shear resistance. The commentary in C14.8.3.1 refers the designer to ACI 318 Appendix D for global design of anchorages. These three references to Section 6 only evaluate the resistance of the bolt and do not consider concrete failure. Article 5.7.5 addresses the bearing resistance of the concrete, but there is no provision for concrete breakout and side-face blowout in tension and concrete breakout and pry-out failure in shear.

Comparison Between ACI 318-11 and AASHTO LRFD Bridge Design Specifications

As AASHTO does not currently have design provisions for adhesive anchors, one possible solution is to reference ACI 318-11 Appendix D. A comparison of the nominal and factored resistances for similar design situations found in ACI 318-11 and AASHTO (2010b) *LRFD Bridge Design Specifications* was conducted to determine if any changes to the resistance and/or load factors in ACI for reference by AASHTO. The results are summarized below and more detail can be found in Appendix B.

Resistance Factors. For concrete sections, Table 8 lists the resistance factors found in the AASHTO (2010b) *LRFD Bridge Design Specifications* and ACI 318-11.

Table 8. Comparison of ACI strength reduction factors and AASHTO resistance factors.

Factor	ACI 318-11		AASHTO	
Tension-controlled section	0.90	9.3.2.1	0.90	5.5.4.2.1
Compression-controlled sections (Spiral reinforcement)	0.75	9.3.2.2	0.75	5.5.4.2.1
Compression-controlled sections (Tie reinforcement)	0.65	9.3.2.2	0.75	5.5.4.2.1
Shear (normal weight)	0.75	9.3.2.3	0.90	5.5.4.2.1
Shear (lightweight)	0.60[1]	9.3.2.3	0.70	5.5.4.2.1
Bearing	0.65	9.3.2.4	0.70	5.5.4.2.1

Note: Assuming an average value of $\lambda = 0.80$ from ACI 8.6.1, and for comparison with AASHTO, the ACI phi factor reported in this table is $\varphi' = \varphi\lambda = (0.75)(0.80) = 0.60$.

Table 9. Ratio of factored resistance determined by ACI (2011a) to AASHTO (2010b).

Factored Resistance	ACI/AASHTO
Tension controlled section	1.00
Compression-controlled sections (spiral reinforcement)	1.00
Compression-controlled sections (tie reinforcement)	0.87
Shear (normal weight)	0.83
Shear (lightweight)	0.86
Bearing	0.93

The design provisions per ACI 318-11 and AASHTO (2010b) *LRFD Bridge Design Specifications* produce identical nominal resistances for flexure, shear, axial compression, and bearing of concrete. As the nominal resistances are identical, the factored resistances (design strengths) will only vary by their resistance factors (strength reduction factors). Table 9 presents the ratio (ACI/AASHTO) of the above factored resistances. For all the cases evaluated, ACI is either identical to or more conservative than AASHTO in determining the nominal and factored resistances.

ACI 318-11 determines the factored resistance for anchor bolt steel failure in Appendix H and Table 10 lists the ratio (ACI/AASHTO) of the factored resistance for anchor bolt steel failure in tension. In all cases, ACI is more conservative than AASHTO.

The factored resistances for adhesive anchor design cannot be compared between ACI and AASHTO as no design provisions for adhesive anchors exist in AASHTO. Therefore, it is the researchers' opinion that if ACI is conservative for the cases examined, then it should be conservative for AASHTO to use ACI design provisions for adhesive anchor design.

Table 10. Ratio of factored resistance for steel strength in tension as computed by ACI (2011a) and AASHTO (2010b) for ductile steel elements.

Bolt Diameter (in.)	$\varphi N_{sa(\mathrm{ACI})}/\varphi T_{n(\mathrm{AASHTO})}$
⅝	0.91
¾	0.93
⅞	0.95
1	0.95
1 ⅛	0.95
1 ¼	0.97
1 ⅜	0.96
1 ½	0.98
1 ¾	0.97
2	0.98

Notes:
The resistance factors used are $\varphi = 0.75$ for ACI design equation and $\varphi = 0.80$ for AASHTO design equation.
T_n = nominal resistance of a bolt in tension.
F_{ub} = specified minimum tensile strength of a bolt.
$F_{ub} = f_{uta}$.

Load Factors. Load factors found in AASHTO (2010b) of 1.25 for dead loads and 1.75 for live loads are higher than the load factors used in ACI Equation 9.2 of 1.2 for dead loads and 1.6 for live loads. The difference is associated with the design life and importance of the structures.

Summary. In every comparable case of factored resistance as determined by ACI and AASHTO, ACI is either the same or more conservative than AASHTO. Additionally, for the load cases considered, AASHTO's factored loads are higher. Therefore, it seems reasonable that using factored resistances for anchor design from ACI 318-11 with AASHTO load combinations will result in a conservative design.

As a result, it is both appropriate and conservative for AASHTO to use the factored resistances (design strengths) in ACI 318-11 Appendix D in conjunction with the load factors in AASHTO for adhesive anchor design. There does not appear to be any justification for AASHTO using higher factored resistances than ACI for adhesive anchors. Perhaps a future reliability study could be performed to determine if higher factored resistances could be permitted for adhesive anchors.

AASHTO Standard Specifications for Structural Supports for Highway Signs, Luminaires, and Traffic Signals

Article 5.17 of AASHTO (2009) *Standard Specifications for Structural Supports for Highway Signs, Luminaires, and Traffic Signals* was also investigated for a possible anchor bolt design framework in which to incorporate adhesive anchors. AASHTO (2009) provides ASD design guidelines for cast-in-place anchor bolts. No provision is made for adhesive anchors. To ensure a ductile failure, anchor bolts must be designed so that they reach their minimum tensile strength prior to concrete failure. It specifies that the following failure modes be addressed:

- Bolt failure,
- Load transfer from anchor to concrete,
- Concrete tensile strength,
- Lateral bursting of concrete, and
- Base plate failure.

The ASD design provisions in Article 5.17 were adapted from *NCHRP Report 469* (2002). AASHTO (2009) mainly addresses the design of the anchor bolt itself and provides ASD equations for allowable tension, compression, and shear stresses on the bolt as well as interaction equations for combined tension and shear and combined compression and shear. Bending stresses are considered for double-nut anchor bolt connections if the clearance between the bottom of the leveling nuts and the top of the concrete exceeds one bolt diameter.

While outside of the scope of AASHTO (2009), it recommends other design considerations such as:

- Block shear rupture,
- Shear lag,
- Prying action, and
- Base plate stiffness.

NCHRP Report 469: Fatigue-Resistant Design of Cantilevered Signal, Sign, and Light Supports

NCHRP Report 469: Fatigue-Resistant Design of Cantilevered Signal, Sign, and Light Supports (2002) includes a "Recommended Anchor Rod Specification and Commentary" as Appendix A of the report. The specification is for the design, installation, and inspection of cast-in-place anchor rods and does not cover post-installed anchors, but allows them as "alternative design anchors."

NCHRP (2002) uses an LRFD approach and designs anchor bolts for tensile strength, compressive strength, shear strength, combined tension and shear, bearing at anchor rod shear holes, and tensile fatigue.

The American Concrete Institute (ACI) is referred to for concrete design.

State DOT Design Guidelines and Specifications

A review was made of design guidelines and specifications from the various state departments of transportation listed earlier.

NYSDOT Bridge Design Manual

NYSDOT (2008a) *Bridge Manual* refers to Section 14.8.3 of AASHTO (2010b) *LRFD Bridge Design Specifications* for the design of anchor bolts. Section 6.8.5.4 of NYSDOT (2008a) allows for post-installed grouted anchors that are allowed for rehabilitation projects and recommends that proof-load tests be conducted. It further recommends an embedment depth of 12″ for 1″ diameter bolts.

FDOT Structures Manual

Section 1.6 of volume 1 of the FDOT (2009) *Structures Design Guidelines* provides FDOT's design guidelines for adhesive anchors. FDOT does not allow adhesive anchors for overhead or upwardly inclined holes. Furthermore, adhesive anchors are not allowed for loading conditions with a predominately sustained load. A predominately sustained load is defined as a load where the permanent portion of the factored tension load exceeds 30%.

The reduction factors (ϕ) specified by FDOT are as follows:

$\phi_c = 0.85$ for adhesive anchors controlled by concrete embedment,
$\phi_c = 1.00$ for extreme events, and
$\phi_s = 0.90$ for adhesive anchors controlled by anchor steel.

The following design requirements are specified by FDOT:

Tension. FDOT considers the following design strengths for anchors in tension:

Tensile strength controlled by anchor steel. The design tension strength controlled by anchor steel (φN_s) is defined as:

$$\varphi N_s = \varphi_s A_e f_y \qquad \text{FDOT Eq. 1-2}$$

where

φ_s = strength reduction factor;
A_e = effective tensile stress area of steel anchor (may be 75% of gross area for threaded anchors), in.^{2}; and
f_y = minimum specified yield strength of steel, ksi.

Tensile strength controlled by adhesive bond. The design tension strength controlled by adhesive bond (φN_c) is defined as:

$$\varphi N_c = \varphi_c \Psi_e \Psi_{gn} N_o \qquad \text{FDOT Eq. 1-3}$$

where

φ_c = strength reduction factor;
Ψ_e = modification factor to account for edge distances;
Ψ_{gn} = modification factor for groups;
N_o = nominal tensile strength of adhesive bond, kips;

$$N_o = T' \pi d h_e \qquad \text{FDOT Eq. 1-4}$$

T' = nominal bond strength of adhesive product, ksi:
T' = 1.08 ksi for type V and HV adhesive product on FDOT QPL;
T' = 1.83 ksi for type HSHV adhesive product on FDOT QPL;
d = nominal diameter of adhesive anchor, in.; and
h_e = anchor embedment depth, in.

The design tension strength (φN_n) is the smaller of φN_s and φN_c.

Shear. FDOT considers the following design strengths for anchors in shear:

Shear strength controlled by anchor steel. The design shear strength controlled by anchor steel (φV_s) is defined as:

$$\varphi V_s = \varphi_s 0.7 A_e f_y \qquad \text{FDOT Eq. 1-7}$$

where

φ_s = strength reduction factor;
A_e = effective tensile stress area of steel anchor (may be 75% of gross area for threaded anchors), in.^{2}; and
f_y = minimum specified yield strength of steel, ksi.

Shear strength controlled by concrete breakout. The design shear strength controlled by concrete breakout (φV_C) is defined as:

$$\varphi V_c = \varphi_c \Psi_{gv} 0.4534 c^{1.5} \sqrt{f_c'} \qquad \text{FDOT Eq. 1-8}$$

where

φ_c = strength reduction factor;
Ψ_{gv} = modification factor for groups;
c = anchor edge distance from center of anchor to free edge, in.; and
f_c' = minimum specified compressive strength of concrete, ksi.

The design shear strength (φV_n) is the smaller of φV_S and φV_C.

Tension and Shear Interaction. FDOT uses a linear approach to tension–shear interaction expressed in the following equation:

$$\frac{N_u}{\varphi N_n} + \frac{V_u}{\varphi V_n} \le 1.0 \qquad \text{FDOT Eq. 1-10}$$

where:

N_u = factored tension load, kips;
N_n = design tension strength, kips;
V_u = factored shear load, kips;
V_n = design shear strength, kips; and
φ = strength reduction factor.

IDOT Bridge Manual

The only reference to anchor bolt design in IDOT (2008) *Bridge Manual* was found in Section 3.7.3, which addresses seismic design of bridge bearings. The design approach taken by IDOT for bridge bearing during seismic events is to prevent the loss of span. Loss of span is prevented by adequately detailing seat widths and span lengths. Connection elements or anchor bolts are designed to fail at a certain level of acceleration. When the connection elements fail, the bearing seat width or span length must be large enough to prevent loss of span.

In this design approach, the anchor bolts are only designed for shear. The number of anchor bolts is determined by dividing the base shear at the bearing by the allowable shear force per anchor.

When soil conditions are poor or it is not possible to enlarge seat lengths, the anchor bolts must be designed to remain elastic during the seismic event. In this situation, the anchor bolts must be designed for combined shear and tension.

The only specific reference to epoxy anchor bolts is made in Section 3.7.4, which address the conversion of an existing abutment into a semi-integral abutment.

Pennsylvania Department of Transportation Design Manual Part 4—Structures. Pennsylvania Department of Transportation (PENNDOT) (2007) *Design Manual Part 4—Structures* Section 3.6.4.9 refers to sections 5.17 and 5.12 of AASHTO (2009) *Standard Specifications for Structural Supports for Highway Signs, Luminaries, and Traffic Signals* for the design of anchor bolts.

PENNDOT (2007) has restrictions on the use of adhesive anchors. Section 3.6.8 addresses adhesive anchor design in general and states that adhesive anchors are not allowed in tension applications for permanent installations. Section 3.6.4.9 addresses the anchor bolt design for sound barrier walls and specifically does not permit adhesive anchors. Section 5.5 pertains to bridge rehabilitation strategies and provides a detail in Section 5.5.2.4 (Figure 5.5.2.4-4) for a repair of expansion dams using adhesive anchors for cases in which the bolts were sheared off.

WSDOT Bridge Design Manual

Section 10.1.2 "Bridge Mounted Signs" of WSDOT (2008a) *Bridge Design Manual* specifically mentions using resin bonded anchors in new and existing structures. The anchors must be installed per the manufacturer's specifications in dry concrete and the nuts must be torqued to the proof load.

MDOT Bridge Design Manual

Section 7.06.02 of the MDOT (2005) *Bridge Design Manual* provides design guidelines for bonded anchors. The embedment depth for A307 bolts is nine times the nominal anchor diameter. Bonded anchors are designed for tension and shear, but only steel failure is addressed. The allowable tension and shear loads are defined as follows:

$$\text{Allowable tensile load} = \frac{1.25 f_y A_T}{FS}$$

$$\text{Allowable shear load} = 0.30 f_y A_T$$

where:

A_T = tensile stress area (net section through threads),
f_y = yield strength, and
FS = factor of safety = 4.

Adhesive anchors are specifically prohibited in overhead applications with a sustained tension load.

MDOT Moratorium on the Use of Adhesive Anchors in Sustained Tensile-Load-Only Overhead Applications

MDOT (2008) Bureau of Highway Instructional Memorandum 2008-07 "Moratorium on the Use of Adhesive Anchors in Sustained Tensile-Load-Only Overhead Applications" imposed a moratorium on overhead sustained tension loading applications.

VDOT IIM-S&B-40.2 Sound Barrier Wall Attachments

VDOT (2007b) memorandum IIM-S&B-40.2 "Sound Barrier Wall Attachments" prohibits using adhesive anchors in attaching structure mounted walls.

VDOT IIM-S&B-76.2 Adhesive Anchors for Structural Applications

VDOT (2008a) memorandum IIM-S&B-76.2 "Adhesive Anchors for Structural Applications" limits the use of adhesive anchors to shear loading only. It specifically prohibits using adhesive anchors in applications of sustained, cyclical, and fatigue tension loadings.

International Design Guidelines and Specifications

Two international design guidelines were reviewed for anchor design provisions.

EOTA ETAG 001 Annex C – Design Methods for Anchorages

Annex C of EOTA (1997b) ETAG 001 *Guideline for European Technical Approval of Metal Anchors for Use in Concrete* presents a design methodology for bonded anchors. This technical approval document was created in 1997 and has undergone several amendments. EOTA (1997b) ETAG 001 Annex C served as the basis for the adhesive anchor provisions in ACI 318-11 Appendix D. A review of EOTA (1997b) ETAG 001 Annex C did not produce any new information than what was already discussed with ACI 318-11 Appendix D.

fib Design of Anchorages in Concrete

The fib (2011) *Design of Anchorages in Concrete* has design methodology for adhesive anchors subject to tension and shear loading. The design methodology is only applicable for anchors with a predominate static load. Part 3 presents both an elastic and a plastic design procedure summarized in two flowcharts. Most of the calculations are similar to those presented by ACI 318-11.

Tension. The design procedure for tensile resistance evaluates the following resistances.

Steel resistance. The equation to calculate steel resistance is similar to ACI 318 Eq. D-3.

Concrete pullout resistance. The characteristic resistance of a combined pullout and cone failure ($N_{Rk,p}$) is as follows:

$$N_{Rk,p} = N^0_{Rk,p}\Psi_{A,Np}\Psi_{s,Np}\Psi_{g,Np}\Psi_{ec,Np}\Psi_{re,Np} \qquad \text{fib Eq. 16.2-1}$$

where:

$N^0_{Rk,p}$ = characteristic bond resistance similar to ACI 318-11 Eq. D-22;

$\Psi_{A,Np}$ = modification factor due to geometric effects, comparable to the $\frac{A_{Na}}{A_{Nao}}$ factor in ACI 318-11 Appendix D;

$\Psi_{s,Np}$ = modification factor due to edge effects, comparable to $\Psi_{ed,N}$ in ACI 318-11 Appendix D;

$\Psi_{g,Np}$ = modification factor accounting for the failure surface of groups: Often this is neglected for simplification;

$\Psi_{ec,Np}$ = modification factor due to eccentricity effects in groups, comparable to $\Psi_{ec,Na}$ in ACI 318-11 Appendix D; and

$\Psi_{re,Np}$ = modification factor due to shell spalling in cases of low embedment depth and closely spaced reinforcement.

Concrete cone resistance. The characteristic resistance of an anchor or group of anchors due to cone failure ($N_{Rk,c}$) is as follows:

$$N_{Rk,c} = N^0_{Rk,c}\Psi_{A,N}\Psi_{s,N}\Psi_{ec,N}\Psi_{re,N} \qquad \text{fib Eq. 10.1-2}$$

where:

$N^0_{Rk,c}$ = characteristic resistance similar to ACI 318-11 Eq. D-6;

$\Psi_{A,N}$ = modification factor due to geometric effects, comparable to the $\frac{A_{Nc}}{A_{Nco}}$ factor in ACI 318-11 Appendix D;

$\Psi_{s,N}$ = modification factor due to edge effects, comparable to $\Psi_{ed,N}$ in ACI 318-11 Appendix D;

$\Psi_{ec,N}$ = modification factor due to eccentricity effects in groups, comparable to $\Psi_{ec,N}$ in ACI 318-11 Appendix D; and

$\Psi_{re,N}$ = modification factor due to shell spalling in cases of low embedment depth and closely spaced reinforcement.

Concrete splitting. The characteristic resistance of an anchor or group of anchors due to splitting failure is calculated using fib Eq. 10.1-2 with an additional modification factor ($\Psi_{h,sp}$) to account for the influence of member thickness.

Shear. The design procedure for shear resistance evaluates the following resistances:

Steel resistance. The equation to calculate steel resistance is similar to ACI 318 Eq. D-29 except it specifies a constant of 0.5 instead of 0.6.

Concrete pry-out resistance. The equation to calculate concrete pry-out resistance is similar to ACI 318 Eq. D-40 and Eq. D-41.

Concrete edge resistance. The characteristic resistance of an anchor or group of anchors close to an edge ($V_{Rk,c}$) is as follows:

$$V_{Rk,c} = V^0_{Rk,c}\Psi_{A,V}\Psi_{h,V}\Psi_{s,V}\Psi_{ec,V}\Psi_{\alpha,V}\Psi_{re,V} \qquad \text{fib Eq. 10.2-5}$$

where

$V^0_{Rk,c}$ = characteristic resistance similar to ACI 318-11 Eq. D-33;
$\Psi_{A,V}$ = modification factor due to geometric effects, comparable to the $\frac{A_{Vc}}{A_{Vco}}$ factor in ACI 318-11 Appendix D;
$\Psi_{h,V}$ = modification factor due to edge effects, comparable to $\Psi_{h,V}$ in ACI 318-11 Appendix D;
$\Psi_{s,V}$ = modification factor due to edge effects, comparable to $\Psi_{ed,V}$ in ACI 318-11 Appendix D;
$\Psi_{ec,V}$ = modification factor due to eccentricity effects in groups, comparable to $\Psi_{ec,V}$ in ACI 318-11 Appendix D;
$\Psi_{\alpha,V}$ = modification factor to take into account the angle of the applied load; and
$\Psi_{re,V}$ = modification factor due to type of edge reinforcement used.

Tension and Shear Interaction. The fib (2011) *Design of Anchorages in Concrete* uses a tri-linear approach to tension–shear interaction similar to that found in ACI 318-11 Appendix D.

Quality Assurance Guidelines and Construction Specifications Related to Adhesive Anchor Systems

The review of quality assurance guidelines and construction specifications related to adhesive anchors included national standards, state DOT standards, and international standards. Manufacturer's printed installation instructions (MPII) were also reviewed for an understanding of what is typically required in adhesive anchor installations.

National Quality Assurance and Construction Specifications

ICC-ES AC308 Acceptance Criteria for Post-Installed Adhesive Anchors in Concrete Elements

Section 14 of ICC-ES AC308 includes quality assurance guidelines for the inspector of adhesive anchor installations. Since ACI 355.4 was developed from ICC-ES AC308, the provisions set forth in ICC-ES AC308 will not be discussed, but will be addressed under the discussion of ACI 355.4.

ACI 355.4 Qualification of Post-Installed Adhesive Anchors in Concrete

ACI 355.4 presents a quality assurance program for the inspector of post-installed adhesive anchors. Section 13 of ACI 355.4 specifies the quality assurance requirements. Manufacturers must have an approved quality assurance program with a quality control manual for each product. Manufacturers must undergo unannounced inspections according to the requirements of ISO/IEC 17011 by an inspection agency under ISO/IEC 17020. Manufacturers must supply inspection manuals for each product and anchors must be installed with special inspection in accordance with the building code and ACI 355.4.

When required, continuous special inspection shall be conducted in which all aspects of the installation must be inspected by an inspector. However, holes can be drilled without an inspector present as long as the inspector inspects the drill bit and verifies the hole sizes. The following must be verified:

- Hole drilling method in accordance with the manufacturer's specifications;
- Hole location, diameter, and depth;
- Hole cleaning per the manufacturer's specifications;
- Anchor type, material, diameter, and length;
- Adhesive identification and expiration date; and
- Installation in accordance with the manufacturer's specifications.

When required, periodic special inspections shall be conducted in which the inspector inspects all aspects listed above for each anchor type for the same construction personnel. Only the initial installation needs to be inspected and the rest can be installed without the inspector as long as the same product is installed by the same personnel. For long construction projects, the inspector should regularly verify that the adhesive product is being installed correctly.

When required, a proof loading program should be conducted which includes the following:

- frequency of proof loading based on anchor type, diameter, and embedment depth;
- proof loads by anchor type, diameter, and location;
- acceptable displacement at proof load; and
- action taken to remediate a case of excessive displacement or the failure to achieve the proof load.

Proof-load tests should be confined tension tests with the proof load not exceeding 50% of the expected ultimate load based on adhesive bond strength nor 80% of the anchor yield strength.

AASHTO LRFD Bridge Construction Specifications

Section 18.9 of AASHTO (2010a) *LRFD Bridge Construction Specifications* addresses anchor bolts for bearing devices and only references cast-in or grouted anchor bolts.

Section 29 specifically mentions adhesive anchors and requires that they be prequalified by universal test standards. The user is encouraged to follow the MPII for drilling and only allows core drilling if it is specified by manufacturer or anchors have been tested in core drilled holes. Core drills are allowed to cut rebar. The user is referred to the MPII for proper cleaning procedures. This section provides for sacrificial and proof-load testing and guidance on torquing of the anchor bolts.

AASHTO Standard Specifications for Structural Supports for Highway Signs, Luminaires, and Traffic Signals

Section 5.17.5 of AASHTO (2009) *Standard Specifications for Structural Supports for Highway Signs, Luminaires, and Traffic Signals* specifies that anchor bolts must be installed with sufficient length, cover, and anchorage in concrete to ensure a ductile failure. Additionally, AASHTO (2009) places a limit on misalignment of 1:40 from vertical for anchor bolt installation.

NCHRP Report 469 Fatigue-Resistant Design of Cantilevered Signal, Sign, and Light Supports

NCHRP Report 469: Fatigue-Resistant Design of Cantilevered Signal, Sign, and Light Supports (2002) includes a "Recommended Anchor Rod Specification and Commentary" as Appendix A of the report. The specification provides guidance for installation and construction inspection. While this report only addresses cast-in-place anchors and not adhesive anchors, most of the information covers the casting of anchor bolts in concrete and tightening of the anchor bolt following concrete curing.

The specification provides guidance for straightening a misaligned bolt. The maximum misalignment allowed is 1:40 from vertical. If an anchor bolt does not exceed a misalignment of 1:20 from vertical it can be straightened by hitting it with a hammer or bending it with a jack or pipe.

State DOT Quality Assurance and Construction Specifications

A review was made of quality assurance and construction specifications from various state departments of transportation.

CALTRANS Standard Specifications

Section 75 of CALTRANS (2006b) *Standard Specifications* refers to the manufacturer's specifications for installation requirements. Anchors must be installed such that the equipment attached to it will bear firmly against the concrete. If there is no mention in the manufacturer's instructions regarding the installation torque, the anchors should be torqued to the values listed in Table 11. It should be noted that using the torque values proposed by CALTRANS generates different stress levels in the resin adhesive, and therefore the commensurate loads associated with these thread stresses vary substantially and do not reflect uniform conditions in the fastener or adhesive.

TxDOT Standard Specifications for Construction and Maintenance of Highways, Streets, and Bridges

TxDOT addresses the installation of anchor bolts in Section 420.4 of TxDOT (2004) *Standard Specifications*

Table 11. CALTRANS installation torque values.

Stud Diameter (inches)	Resin Capsule Anchors (foot-pounds)
1 ¼	400
1	230
⅞	175
¾	150
⅝	75
½	30
⅜	18
¼	-

for Construction and Maintenance of Highways, Streets, and Bridges. For epoxy installations it specifies a hole diameter of 1/16" to 1/4" greater than the anchor diameter. For prepackaged systems, it requires that the manufacturer's cleaning instructions be followed exactly. A procedure must be established for the cleaning and preparation of the holes, which includes cleaning the holes of loose material, grease, oil, and other substances. The holes should be blown with filtered compressed air and be in a dry condition prior to installation. The space between the anchor and the sides of the hole must be completely filled with adhesive.

Section 420.4 specifies a Type III adhesive per TxDOT (2007a) DMS-6100 for neat epoxies and Type VIII for epoxy grout.

NYSDOT Standard Specifications

Section 586-2.01 "Drilling and Grouting Bolts" of NYSDOT (2008c) *Standard Specifications* restricts the use of adhesive anchors in overhead installations or for applications with a sustained tensile load.

Section 586-3.01 "Drilling and Grouting Bolts" of NYSDOT (2008c) specifies the installation requirements for adhesive anchors. A rotary impact drill should be used but if reinforcement is encountered during drilling, a core drill can be used only to cut the rebar, and the rotary impact drill used for the remainder of the drilling. Lubricants cannot be used during drilling and drilling should not cause damage to concrete. Prior to installation, the holes must be dry and clean of loose material. The bolts should be inserted the full depth of the hole and jiggled to ensure complete coverage by the adhesive. Excess adhesive should be struck-off flush with the surface. Horizontal installations are allowed and care should be taken to ensure that the adhesive does not run out of the hole.

Section 586-3.02 "Pullout Testing" of NYSDOT (2008c) specifies the requirements for pullout testing. A table is provided in the specification to determine the number of anchors to test depending on lot size. The load applied should not exceed 90% of the ASTM proof load (ASTM A568 for anchor bolts and ASTM A615 for reinforcing bars) or 90% of the anchor yield strength if the ASTM proof load is not given. Once the test load is reached, the test is stopped. Anchors pass the test if they can attain the load without permanently displacing.

Section 586 of NYSDOT (2008c) includes the changes addressed by NYSDOT (2008b) Engineering Instruction EI 08-012 discussed earlier.

FDOT Standard Specifications for Road and Bridge Construction

FDOT specifies in Section 416 "Installing Adhesive-Bonded Anchors and Dowels for Structural Applications" of FDOT (2007) *Standard Specifications for Road and Bridge Construction* that the installation of adhesive anchors and the equipment used for the installation must be in accordance with the manufacturer's specifications. FDOT only allows an adhesive anchor product that meets Section 937 of FDOT (2007) *Standard Specifications for Road and Bridge Construction* and is included in the qualified products list (QPL) maintained by the state. The following requirements pertain to the installation of adhesive anchors:

- Install in structurally sound concrete member free of cracks in the area of the anchor;
- Use a rotary hammer drill and carbide bit unless otherwise specified by the manufacturer;
- The hole diameter must be greater than 105% and less than 150% of the anchor diameter;
- Clean the hole according to the manufacturer's requirements, but at a minimum blow with compressed air, then brush, and blow again with compressed air;
- Use only a non-metallic brush to prevent polishing the hole;
- Follow the manufacturer's requirements regarding limits on anchor position, dampness, ambient temperature, and curing time; and
- Fill the hole with the adhesive such that it is within ¼″ of concrete surface after placement of anchor.

IDOT Standard Specifications for Road and Bridge Construction

Section 509.06 "Setting Anchor Rods" of IDOT (2007b) *Standard Specifications for Road and Bridge Construction* requires that the holes be drilled to the diameter and depth specified by the manufacturer. The rods should be set with capsule or cartridge systems previously approved by the state and installed per the manufacturer's instructions.

Section 521.06 "Anchor Bolts, Rods, and Side Retainers" of IDOT (2007b) *Standard Specifications for Road and Bridge Construction* requires verification of the holes for depth and diameter prior to installation. Holes are required to be kept dry and to be blown clean prior to installation. Following installation, the top of the bolt shall be measured in order to determine proper embedment. The anchor bolts should allow for ½″ to 2″ above the top of the nut.

WSDOT Construction Manual

Section 6-3.2C "Use of Epoxy Resins" of the WSDOT (2009) *Construction Manual* warns the user against viewing epoxy resins as a cure-all for bonding applications due to their inherent limitations. Specific caution is mentioned regarding using epoxy resins below 50°F (10°C). Several guidelines are provided for the inspector of epoxy-resin systems:

- Epoxy resin must be completely mixed,
- Verify the temperature and/or moisture limitations of the epoxy resin,
- Area should be cleaned and prepared according to the manufacturer's specifications prior to installation, and
- The epoxy should completely fill the space around the anchor.

The material portion of WSDOT (2009) includes Section 9-4.60, which addresses "Epoxy Systems" and Section 9-4.61 for "Resin Bonded Anchors." Section 9-4.61 refers to a qualified products list (QPL) maintained by the state for material approval. If a resin bonded anchor system is not on the QPL, test results from ASTM E488 and manufacturer's certificate of compliance can be submitted for approval.

MDOT Standard Specifications for Construction

Section 712 "Bridge Rehabilitation—Concrete" of MDOT (2003) *Standard Specifications for Construction* allows the installation of adhesive anchoring of bars in vertical and horizontal applications.

International Quality Assurance and Construction Specifications

The following summarizes the review of international standards related to quality assurance guidelines and construction specifications.

EOTA ETAG 001

Part 1 of EOTA (1997a) ETAG 001 does not provide much information regarding quality assurance or construction specifications. Reference is made to the manufacturer's installation requirements, but limits the installation to a temperature range of 23°F to 104°F (−5°C to 40°C).

Part 5 of EOTA (2002) ETAG 001 allows for installation in dry, wet, and flooded holes. It also specifies that the holes are to be drilled as specified by the manufacturer.

Manufacturer's Installation Recommendations

Due to the fact that many specifications refer to the manufacturer's printed installation instructions (MPII), the installation requirements from three different products (names withheld) have been included to serve as a reference for what is typically specified by manufacturers. The manufacturers and the products chosen were not necessarily what were used in the testing program of this research project.

Manufacturer's specifications contain information regarding storage conditions (temperature and humidity ranges) and warnings to check that the expiration date has not passed prior to installation.

There are many similarities amongst manufacturer's installation instructions. Most include instructions on cleaning the hole which can include blowing with compressed air and brushing. There is a procedure to confirm that the adhesive is thoroughly mixed, by number of squeezes of the applicator or by visually inspecting the color of the adhesive. Additionally, there is a process for injecting the adhesive in the hole to avoid air voids. And finally there are instructions for inserting the anchor.

Manufacturer X

This product is an epoxy resin with quartz and titanium dioxide.

The hole is prepared by drilling to the proper depth with a drill bit 1/8" larger than the anchor diameter. The hole is then blown out using a nozzle and 80 psi (minimum) oil-free compressed air for four seconds. The hole is then brushed up and down four times with a nylon brush. And finally the hole is blown for another four seconds with compressed air.

The adhesive is discharged using a cartridge and self-mixing nozzle. Initially the adhesive is discharged to the side until the discharge has a uniform color signifying complete mixing. The hole is filled by inserting the nozzle to the bottom and discharging the adhesive. The nozzle is extracted as the hole fills in order to avoid the formation of air voids. The hole is filled to ½ to 2/3 full in dry and damp holes and completely full in water-filled holes in order to remove all the water. The clean oil-free anchor is installed in the hole while slowly turning it until it contacts the bottom of the hole. The anchor should not be disturbed until the adhesive has fully cured.

Horizontal and overhead installations are allowed and the installation is the same, except that a retaining cap is placed over the hole to keep the adhesive within the hole.

Manufacturer Y

This product is an epoxy resin with an amine hardener.

The hole is drilled with a rotary hammer drill and a drill bit confirming to American National Standards Institute (ANSI) B212.15.1994. The drill bit diameter is equal to the rod diameter plus 1/16" for anchor diameters of 3/8" and ½" or the rod diameter plus 1/8" for anchor diameters of 5/8" and above. The manufacturer limits anchors of 5/8" and above to horizontal and downward installations only.

The hole is cleaned with 50 psi to 100 psi compressed air starting at the bottom using a nozzle and oscillating the nozzle in and out of the hole four times for a total of four seconds. If the hole is filled with water or sludge, the hole can be cleaned with pressurized water.

The hole is then cleaned with a brush by inserting the brush into the hole in a clockwise fashion. The brush is turned one complete revolution for each ½" of depth. Once the brush has reached the bottom, the brush is turned four complete times. The brush is then removed from the hole by rotating it one complete revolution for every ½" of depth. Alternatively, the brush can be attached to a drill. The hole is then blown with compressed air or flushed with pressurized water as before.

The adhesive is discharged and discarded from the cartridge tool until the adhesive is of a uniform color. The nozzle is inserted to the bottom of the hole and slowly pulled out while discharging in a circular motion maintaining the tip of the nozzle under the level of the adhesive. The hole is filled to 60% full. For holes underwater, the hole is filled entirely with adhesive thereby displacing all the water. The concrete must be between 50°F (10°C) and 110°F (43°C) during installation.

The anchor is inserted in a counterclockwise motion and jiggled to remove air pockets. The anchor must not be disturbed during working time until the cure time has elapsed.

Manufacturer Z

This product is a hybrid with methacrylate hardener, cementitious material, and quartz filler.

The hole is drilled with a carbide bit to the proper depth and diameter. The hole is then cleaned with 80 psi compressed air using a nozzle inserted to the bottom of the hole. The hole is cleaned three times with a wire brush that is twisted while inserting. The hole is then blown with compressed air again. For holes with standing water, the hole must be flushed with water, brushed, and then flushed with water again. The standing water must be removed prior to inserting the adhesive.

Depending on the size of the cartridge, the adhesive from the first two or three trigger pulls are discarded [four trigger pulls are discarded if the temperature is below 41°F (5°C)]. The adhesive is inserted in the hole without forming air pockets to ½ to ⅔ full.

The anchor rod is inserted while twisting and can be adjusted during the specified gel time. The anchor should not be disturbed between the gel time and the cure time.

Summary

This chapter summarized the findings from the literature review, which investigated the behavior of adhesive anchor systems as well as test methods and material specifications, design guidelines and specifications, and quality assurance guidelines and construction specifications related to adhesive anchors in concrete. Extensive investigation and research was involved in the development of the documents reviewed in this chapter, which provided a solid base upon which to develop specifications for AASHTO. One of the significant limitations of the state-of-the-art in adhesive anchors is the effect of various installation and in-service parameters on the sustained load performance of adhesive anchors. Most state DOTs rely on tests that emphasize short-term tests that consider conditions (wetness, time of cure, application of lubricating oils and salt water, etc.); placement and pullout to failure; or a specified acceptable deformation. However, creep rates are not specifically addressed in state DOT tests, although they are very important with respect to temperature, longevity, and the ability to carry loads.

The next chapter presents the test program developed to investigate those effects for inclusion of adhesive anchors into the AASHTO specifications.

CHAPTER 2

Research Approach

This chapter summarizes the laboratory testing program used to investigate the effect of various parameters on the sustained load performance of adhesive anchors in concrete, the potential for using adhesive-alone testing to evaluate the sustained load performance of adhesive anchors, and the effect of early-age concrete on the short-term bond strength of adhesive anchors. The parameters considered, as well as the triage approach used to prioritize the parameters, are presented. Finally, a detailed discussion on the testing program is presented in four sections:

- Anchor pullout testing at the University of Florida,
- Anchor pullout testing at the University of Stuttgart,
- Adhesive-alone testing at the University of Florida, and
- Early-age concrete evaluation at the University of Stuttgart.

Research Plan

The experimental program was implemented as follows.

Baseline Tests

Short-term (2-minute) pullout tests were performed on three adhesive anchor systems (A, B, and C) installed in concrete to establish their baseline short-term strength. Additional long-term tests were performed until failure on each adhesive anchor system at various percentages of the mean short-term strength. The resulting data were used to generate a stress versus time to failure for each adhesive anchor system under the baseline "control" conditions.

Parameter Tests

Short-term tests were conducted on each anchor system under a variety of installation and in-service conditions. An alpha-reduction factor for the short-term strength was determined, which represents the effect that the parameter had on the bond strength at 2 minutes (duration of the short-term tests).

Subsequent long-term tests were conducted on the adhesive anchor under the same variety of parameters and the resulting stress versus time-to-failure relationship was evaluated.

Influence Ratio

If a given parameter has the same effect on the bond strength in the long term as it does in the short term, then the alpha-reduction factor at a given time to failure should be the same as the alpha-reduction factor evaluated at 2 minutes.

Figure 34 shows the basic concept behind the use of the "stress versus time-to-failure" test method to evaluate the effect of a particular parameter on the sustained load performance of an adhesive anchor. The baseline "stress versus time-to-failure" relationship is shown as the solid line in Figure 34. (Note that sample data points are not included in Figure 34 for clarity.)

For analysis purposes, an α_{ST}-baseline curve can be created on the stress versus time-to-failure plot (Figure 34) in which the alpha-reduction factor at any given time to failure is identical to the alpha-reduction factor evaluated at 2 minutes. The stress versus time-to-failure relationship for a given parameter established from experimental data can be used to determine a long-term alpha-reduction factor (α_{LT}) which is the stress to cause failure at a given time to failure divided by the baseline stress level at that particular time to failure. This α_{LT} can therefore be compared to the α_{ST}-baseline curve. If at any given point in time, the stress level to cause failure predicted by the α_{ST}-baseline is greater than the determination from the trend of experimental data, then the parameter has an adverse effect on the sustained load performance of an adhesive anchor.

This can also be visualized by normalizing the short-term alpha-reduction factor (α_{ST}) by the alpha-reduction factor determined from long-term testing (α_{LT}) in what can be referred to as the influence ratio, as illustrated in Figure 35.

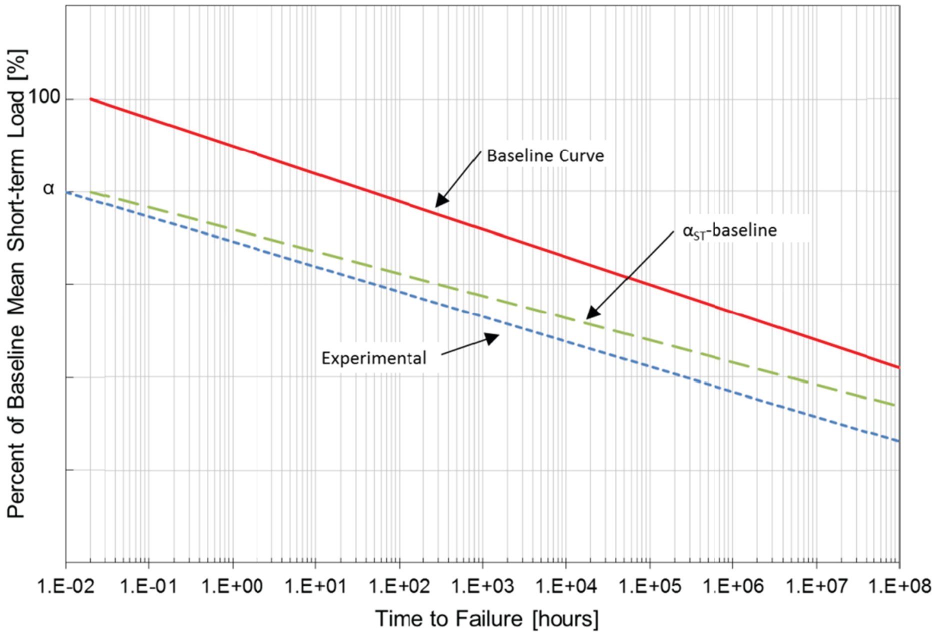


Figure 34. "Stress versus time-to-failure" comparison of experimental, baseline, and α_{ST}-baseline trends.

$$\text{Influence Ratio} = \frac{\alpha_{ST}}{\alpha_{LT}}$$

If the influence ratio is greater than one, then the parameter has an influence on sustained load. Conversely, influence ratios less than one indicate that the given parameter does not have an influence on the sustained load performance.

Dogbone Tests

A similar testing program (baseline tests, parameter tests, influence ratios) was conducted on dogbone specimens of the adhesive alone to determine if stress versus time-to-failure relationships determined from adhesive-alone dogbone tensile tests could be indicators of the long-term performance of adhesive anchors in concrete.

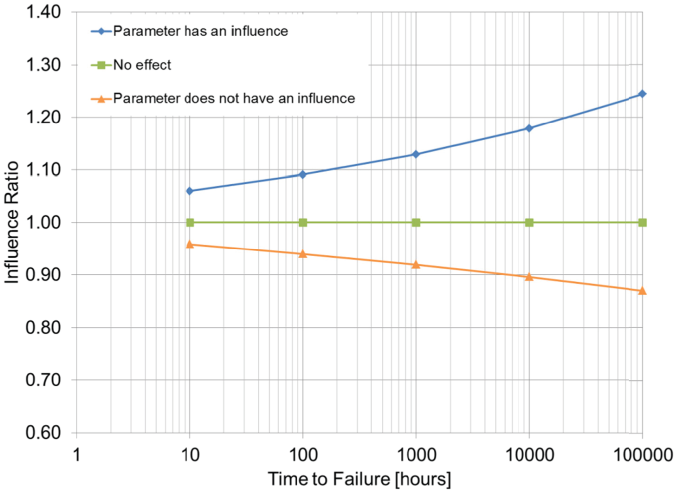


Figure 35. Influence ratio of a parameter versus time.

Adhesive-Alone Tests

Additional adhesive-alone (DMTA and creep) tests were conducted on a DSR machine to generate strain versus time (and compliance versus time) curves. These curves were compared to similar curves created from the dogbone tests and anchor pull-out tests to investigate if these simple and short-duration tests could be used to predict the long-term performance of adhesive anchor systems in concrete.

Early-Age Investigation

Finally, short-term tests were conducted on each of the three adhesive anchor systems at various days beyond concrete casting to determine the effect of concrete age on adhesive anchor short-term bond strength.

Parameters Identified for Testing

The previous chapter identified many parameters that have the possibility of affecting the performance of adhesive anchor systems. Because of the project budget and timeline, not all parameters could be tested; therefore, a triage was conducted based on literature and the experience of the research team to determine which parameters were believed to have the potential for the most significant impact on sustained load performance and to develop a test program to investigate those parameters. This triage approach established three categories:

- **High priority parameters.** Parameters thought to have the potential for a significant impact on sustained load performance and definitely should be tested.
- **Medium priority parameters.** Parameters thought to have some potential for impact on sustained load performance and should be tested if budget and time permit.
- **Low priority parameters.** Parameters thought to have a minimal potential for impact on sustained load performance and are not recommended to be tested under this project.

Table 12 lists the parameters identified earlier with their rated priority and test series identification as listed in the test matrices shown in Table 14 and Table 15. As noted in Table 12, all high- and medium-priority parameters were included in the planned test program.

Explanation of Triage Results

The following describes the rationale for the prioritization of the parameters listed in Table 12 and how the influence of each parameter would be evaluated if chosen for testing.

High Priority Parameters

These parameters were identified as having a strong possibility for affecting the sustained load performance of adhesive anchors.

Elevated In-Service Temperature. In-service temperature has a significant effect on the sustained load performance of adhesive anchor systems especially for adhesives with different glass transition temperatures. Test series 3 and 4 were tested at above 120°F (49°C) and at 70°F (21°C) respectively in order to investigate the effect of in-service temperature. Sustained load tests were performed with the bonded anchor system that showed the lowest glass transition temperature. These test series were intended to investigate if the relationship between long-term bond strength and short-term bond strength was influenced by the in-service temperatures of 70°F (21°C), 110°F (43°C) (baseline), and >120°F (>49°C).

Moisture-in-Service. Test series 8 consisted of sustained load tests on an adhesive installed dry but maintained wet during the sustained load test. It was thought that the mechanisms that could potentially reduce the sustained load capacity due to in-service moisture were (1) plasticization of the

Table 12. Prioritization of identified parameters.

Parameter	High Priority	Medium Priority	Low Priority	Test Series*
In-service factors				
Elevated temperature	X			3,4
Reduced temperature			X	
Moisture-in- service	X			8
Freeze–thaw			X	
Factors related to the adhesive				
Type of adhesive	X			1,2,21
Mixing effort			X	
Adhesive curing time when first loaded	X			22
Bond line thickness			X	
Fiber content of adhesive			X	
Chemical resistance			X	
Installation factors				
Hole orientation	X			5,6
Hole drilling	X			13
Hole cleaning	X			9
Moisture in installation	X			7
Installation Temperature		X		10,11
Depth of hole (embedment depth)			X	
Anchor diameter			X	
Type of concrete	X			12,14,15
Concrete strength			X	
Type of coarse aggregate			X	
Cracked or uncracked concrete			X	
Confined or unconfined test setup		X		16
Early-age concrete		X		17

* See Table 14 for description of test series 1–17 and Table 15 for description of test series 21–22.

adhesive, (2) reduction in the adhesive bond strength due to moisture, and (3) degradation of the adhesive due to a high alkaline environment found in moist concrete. It was thought that exposure to a high alkaline environment was the controlling mechanism, and therefore sustained load tests were conducted on the adhesive that showed the highest sensitivity to alkalinity as determined by the resistance to alkalinity test results provided in the ICC-ES AC308 evaluation service report (ESR) for each adhesive.

Type of Adhesive. It is well known that adhesives performance differs significantly for given parameters and duration of loading. Three adhesives from different manufacturers and of different adhesive types were tested in this project. It was recommended to include at least an epoxy and a vinyl ester. Baseline short-term and sustained load tests were conducted on all adhesives (series 1, 2, and 21). Due to project budget and timeline, sustained load tests were not conducted on all adhesives for every identified parameter, but rather the adhesive that was the most sensitive to the given parameter in short-term tests.

The three adhesive anchor systems chosen all met the assessment criteria of ICC-ES AC308, indicating that they are viable for structural applications. In addition, the test results of the extensive ICC-ES AC308 testing program could provide useful information in this research project.

Adhesive Curing Time When First Loaded. If a sustained load is applied before the adhesive is completely cured, the initial displacement and strain rate might be higher than that of a specimen with a completely cured adhesive. In order to investigate the sensitivity to cure time, tensile creep adhesive-alone tests (test series 22) were conducted on adhesive dogbone coupons at varying degrees of cure time. Baseline short-term tensile creep tests were conducted at the manufacturer's specified cure time and at 7 days. Sustained load tensile creep tests were conducted on all adhesives at 7 days cure time and at the manufacturer's specified cure time on the adhesive that showed the most sensitivity to cure time from the short-term tests.

Adhesive anchor pullout tests were not conducted on specimens at varying cure times due to the logistical difficulties and the time duration required to condition a specimen of concrete from the installation temperature to the testing temperature.

Hole Orientation. The presence of voids has a significant effect on the bond stress of an adhesive anchor. It is well known that voids in the adhesive will occur more often with anchors improperly installed horizontally or overhead. Anchors were installed horizontally and vertically in test series 5 and 6 respectively. Sustained load tests were performed with two bonded anchor systems.

Hole Drilling. Hole drilling has been shown to influence bond strength due to the resulting roughness of the sides of the holes from different hole drilling methods. Most manufacturers recommend rotary hammer drills with carbide bits. While in general, holes were drilled by rotary hammer drills with carbide drill bits, test series 13 used a diamond core drill. The sustained load tests were performed with the product approved for core drilling that was shown to be the most sensitive to the type of drilling with respect to bond strength established by short-term tests.

Hole Cleaning. It is well known that the degree of hole cleaning can significantly influence the short-term bond strength. Test series 9 used a reduced cleaning effort (50% of the manufacturer's recommended cleaning procedure as specified by ACI 355.4-11 test series 7.5) on anchors installed in dry holes. The sustained load tests were performed with the product that was shown to be the most sensitive to a reduced cleaning effort with respect to bond strength established by short-term tests.

Moisture in Installation. Due to the significant decrease in short-term bond strength for anchors installed in damp and submerged holes, it was highly recommended that the influence of moisture during installation be tested in this project. Test series 7 installed anchors in a wet/damp hole and conducted sustained load tests in a dry condition. The sustained load tests were performed with the product that was shown to be the most sensitive to a wet installation with respect to bond strength established by short-term tests.

Type of Concrete. Anchor pullout tests at the University of Florida have shown that the short-term bond strength might be influenced by the composition of the concrete (e.g., amount of fly ash or blast furnace slag). The reasons for this might be due to the different porosity of the concrete compared to concrete without additives or perhaps due to the general surface condition of the drilled/cleaned hole. Test series 12 (standard DOT mix), 14 (20% fly ash), and 15 (50% blast furnace slag) were introduced in an attempt to address this question. The sustained load tests were performed with the product that was shown to be the most sensitive to the different concrete mixes.

Medium Priority Parameters

These parameters were identified as having a possibility for affecting the sustained load performance of adhesive anchors and/or they were recommended by the NCHRP panel for investigation during the proposal review.

Installation Temperature. If anchors are installed at low temperatures, the final degree of curing is lower compared to installation at normal temperature. This might result in a reduction of the long-term bond strength. Therefore test series 10 and 11 were performed with anchors installed in concrete at the manufacturer's lowest permissible installation temperature with the adhesive preheated to the manufacturer's lowest permissible adhesive temperature to ease adhesive injection. The adhesive with the lowest degree of cross-linking was chosen for testing. As any additional heating after installation causes additional curing of the adhesive, test series 10 was conducted at the manufacturer's minimum temperature and test series 11 was conducted at 110°F (43°C).

Unconfined Test Setup. Confined tests are used to ensure a bond failure. The bond failure may occur at the interface between the anchor and the adhesive and/or the adhesive and concrete and/or in the adhesive itself. In contrast, in unconfined tests, failure is often characterized with a concrete cone for shallow embedments and/or adhesives with high bond strengths. In order to ensure that both the short-term tests and sustained load tests in this program resulted in failures associated with bond strength, the confined testing method was used. Final design standards are based on unconfined bond strength established from short-term confined tests modified by a factor of 0.75 per ACI 355.4.

In general, it is assumed that the ratio of long-term bond strength to short-term bond strength is independent of the type of support (confined, unconfined) provided bond failure is the controlling factor of the unconfined condition and not concrete breakout. To check the validity of this assumption unconfined tests were performed (test series 16).

Early-Age Concrete. It was suggested by the NCHRP project panel to investigate the effects of concrete age on the short-term bond strength. It is assumed that the synergistic effects of the low concrete strength and the high moisture content found in early-age concrete can affect the short-term bond strength of an anchor installed in early-age concrete. Test series 17 investigated the effects of concrete age by installing anchors in concrete at various ages (3, 6, 13, 20, and 27 days) and conducting short-term anchor pullout tests after 24 hours of adhesive cure time. Sustained load performance due to installation in early-age concrete was not to be investigated in this project.

Low Priority Parameters

As the products used in this project had all met the assessment criteria of ICC-ES AC308, these parameters were identified as possibly having a minimal effect (or none at all) on the sustained load performance of adhesive anchors used in this project. It was decided by the researchers and the NCHRP project panel that they not be tested during this project.

Reduced In-Service Temperature. During approval tests of bonded anchors, according to ICC-ES AC308 or EOTA ETAG 001 Part 5, freeze/thaw tests are performed with anchors installed at normal ambient temperature in wet concrete. The anchors are loaded in tension with 55% the mean short-term pullout failure load. After 50 freeze/thaw cycles the residual bond strength is measured, which must be statistically equivalent with the short-term bond strength. It was recommended that the influence of long-term below-freezing temperatures on the long-term bond strength be considered low priority and not be investigated during the present research project.

Freeze–Thaw. See discussion above regarding reduced in-service temperature. It was recommended that influence of freeze–thaw cycling be considered a low priority and not be investigated in this research project.

Mixing Effort. The test program used bonded anchors with the adhesive delivered in cartridges. The anchors were installed according to the MPII. When using cartridges with their corresponding mixing nozzle and the correct injection gun and following the manufacturer's instructions (typically discarding the first inches of the mixed mortar) it may be assumed that the adhesive is thoroughly mixed. Incorrect mixing of the adhesive may only occur with these systems if the mixing nozzle is manipulated (e.g. shortened) or an inappropriate mixing gun is used. These are gross installation errors outside of the MPII and were not recommended to be evaluated in this research project.

Incomplete mixing might occur with bonded anchors if the adhesive is delivered in bulk and mixed on site in an open container without controlled metering with a hand or machine mixer. These types of bonded injection anchors are not currently addressed in this research project since they are outside of the scope of ICC-ES AC308 (§1.2.4.2) and ACI 355.4 (§1.2.3).

Bond Line Thickness. In general, all tests were performed with the gap thickness according to the MPII. A test series was proposed for consideration where the diameter of the hole was enlarged to check if the ratio of long-term bond strength to short-term bond strength was influenced by the hole diameter. The researchers and the NCHRP project panel chose not to test this parameter as it was deemed a gross installation error and to allow for testing of other higher priority parameters.

Fiber Content of Adhesive. Since bulk mixing products were not considered by this project, the influence on sustained load performance of fiber content as modified by the installer was not addressed either. The influence of fiber content on sustained load performance could have coincidentally been examined if two of the three adhesives chosen were identical except for the amount of fiber content. However, this was not the case and the influence of fiber content was not a criterion when choosing the three adhesives to test in the project.

Chemical Resistance. Chemical resistance is currently tested by ACI 355.4 §8.8 by two durability tests, a test for alkalinity and an optional sulfur dioxide test. As discussed earlier, both of these tests subject 1³⁄₁₆" slices to very harsh environments for long durations (2,000 hours). Test series 8, which tests for sensitivity to in-service moisture, will subject the adhesive anchor to an alkaline environment since damp concrete is a naturally alkaline material. Since adhesive anchors installed in concrete are embedded much deeper than the 1³⁄₁₆" slices used in ACI 355.4 durability tests, the exposure to sulfur dioxide of a normal adhesive anchor will not be as extreme as the condition found in the tests.

Sustained load adhesive anchor chemical resistance tests were not conducted since the durability tests of ACI 355.4 are long-term tests and the reduction factor obtained from these tests, α_{dur}, was considered sufficient to account for chemical effects for both short-term and long-term loading conditions.

Depth of Hole (Embedment Depth). Extensive short-term testing and analytical work has shown that the bond strength is not significantly influenced by the embedment depth in the ranges typically specified of about four to 20 anchor diameters. The authors feel that it can be safely assumed that the long-term bond strength is also not significantly influenced by the embedment depth. Therefore, all tests were performed with one embedment depth per anchor diameter.

Anchor Diameter. For most bonded anchor systems the bond strength measured in short-term tests decreases somewhat with increasing anchor diameter (Eligehausen et al., 2006b). The NCHRP project panel initially requested that anchor diameter be investigated, but later agreed to forgo this test parameter in order to evaluate a standard DOT concrete mix (test series 12).

Concrete Strength. As discussed earlier, there is no direct correlation between concrete strength and bond strength. Since confined tests isolate the failure mode to the adhesive bond (eliminating the concrete cone failure mode) the effect of the concrete strength was not considered to be significant. As a result, influence of concrete strength on sustained load performance of adhesive anchors was not included in this test program.

Type of Coarse Aggregate. This was not directly tested in this test program. Test series 12 (TS12) used granite aggregate but the concrete mix was different from the control in many ways. The effects of aggregates are accounted for in the ACI 355.4 test program via a series of round robin tests that evaluate the impact of regional differences on concrete mixtures.

Cracked or Uncracked Concrete. Cracked concrete was not tested in this test program, but the ACI 355.4 test program contains test procedures for anchors to be qualified for use in both cracked and uncracked concrete.

Testing Program

Table 13 provides a summary of the testing program. Table 14 and Table 15 provide more detailed information on the anchor pullout testing program and the adhesive-alone testing program respectively. The equipment and tools used in the testing program are what was available at the laboratories and their use does not necessarily reflect an endorsement by the researchers.

Anchor Pullout Testing Program

Based on the triage approach discussed earlier, Table 14 presents the test matrix for anchor pullout testing program of threaded rods embedded in concrete for test series 1 through 17. Table 14 shows the test series, testing conditions with the tested parameter, explanations in notes at the bottom, number of tests per series, and location of testing. Tests were conducted at the University of Florida (UF) and the University of Stuttgart (US).

Test series 1 through 16 began with short-term static load tests per the static tension test procedure per ASTM E-488. Five repetitions were conducted on each adhesive and their values averaged to determine the mean short-term load strength.

Test series 1 through 16 concluded with a series of sustained load tests per the test procedure per AASHTO TP 84-10 with a few modifications. Three anchors were loaded until failure at four stress levels for test series 1 and 2 and three stress levels for test series 3–16. The time to failure was evaluated at the time of rupture and as the time to tertiary creep per AASHTO TP 84-10.

For laboratory logistics and in order to remove the effects of continued curing beyond the manufacturer's stated cure time, all anchors were allowed to cure 7 days, and then were conditioned to the testing temperature for 24 hours prior to testing.

Test series 17 only evaluated the effect of early-age concrete on the short-term bond strength. Its influence on the sustained load performance was not evaluated in this research project and therefore no sustained load testing was conducted for test series 17.

Table 13. Summary test program.

Test	Specification	Test Series	Description	Data
Short-term static load	ASTM E488	1–16, 17	Anchor pullout from concrete	Mean short-term load strength
Sustained load	AASHTO TP 84-10 (modified)	1–16	Anchor pullout from concrete at 3 or 4 stress levels	Time to rupture (as measure of time to failure)
Static load strength (dogbone specimen)	ASTM D638 (modified)	21–22	Adhesive only	Mean short-term load strength
Sustained load (creep) (dogbone specimen)	ASTM D2990 (modified)	21–22	Adhesive only	Time to failure and time to tertiary creep
Dynamic mechanical thermal analysis			Adhesive only	Stress, strain, and creep compliance

Table 14. Proposed test matrix for anchor pullout testing.

Test Series	Test Description (Influencing parameter)	Installation Temperature	Orientation during installation	Moisture of concrete during installation/ service	Cleaning	Anchor Size x h_{ef}	Concrete Composition	Product Type A	Product Type B	Product Type C	Test Temperature	Type of support	Number of sustained load steps	Number of sustained load tests	Number of reference tests	Test Location
								(0)	(0)	(0)			(1)			(10)
1	Baseline tests UF	75°F	downward	dry/dry	full	5/8x3	Standard	X	X	X	110°F	confined	4	36	15	UF
2	Baseline tests US					M12x80		X	X	X			4	36	15	US
3	Service temperature	75°F	downward	dry/dry	full	M12/80	Standard		X (2)		>120°F	confined	3	9	5 (11)	US
4									X (2)		70°F		3	9	5 (11)	US
5	Installation direction	75°F	horizontal	dry/dry	full	M12/80	Standard	X (3)		X (3)	110°F	confined	3	18	10 (11)	US
6			overhead					X (3)		X (3)			3	18	10 (11)	US
7	Moisture during installation or service	75°F	downward	damp/dry	full	5/8x3	Standard	X (4)			110°F	confined	3	9	5 (11)	UF
8				dry/damp		M12/80			X (4a)		70°F		3	9	5 (11)	US
9	Hole cleaning	75°F	downward	dry/dry	reduced	5/8x3	Standard			X (5)	110°F	confined	3	9	5 (11)	UF
10	Installation temperature	MFR min (6) & (6a)	downward	dry/dry	full	M12x80	Standard	X (7)			MFR min (6)	confined	3	9	5 (11)	US
11								X (7)			110°F		3	9	5 (11)	US
12	DOT Concrete mix	75°F	downward	dry/dry	full	5/8x3	DOT	X			110°F	confined	3	9	5 (11)	UF
13	Type of drilling	75°F	downward	dry/dry	full	5/8x3	Standard		X		110°F	confined	3	9	5 (11)	UF
14	Concrete composition	75°F	downward	dry/dry	full	5/8x3	with FA		X (8)		110°F	confined	3	9	5 (11)	UF
15							with BFS	X (9)					3	9	5 (11)	UF
16	Test setup (wide support)	75°F	downward	dry/dry	full	5/8x3	Standard			X	110°F	un-confined	3	9	5 (11)	UF
17	Concrete Age (tested at 3 days)	75°F	downward	dry/dry	full	M12x80	Standard	X	X	X	75°F	confined	0	0	15 (11)	US
	Concrete Age (tested at 7 days)							X	X	X			0	0	15 (11)	US
	Concrete Age (tested at 14 days)							X	X	X			0	0	15 (11)	US
	Concrete Age (tested at 21 days)							X	X	X			0	0	15 (11)	US
	Concrete Age (tested at 28 days)							X	X	X			0	0	15 (11)	US
													Sum	216	185	

Notes:

(0) Type A = vinyl ester system, type B = epoxy system, type C = epoxy system.

(1) 4 sustained loads N_p / $N_{u,m}$(reference) 0.75/0.65/0.55/0.45. Creep tests with N_p = 0.55 $N_{u,m}$ will be used to compare with current approach of AC308
3 sustained loads N_p / $N_{u,m}$(reference) 0.70/0.55/0.40.

(2) Only the product that is most sensitive to increased temperature (high ratio glass transition temperature to service temperature) will be tested.

(3) Only the top two products that are most sensitive to installation direction (occurrence of voids) in static tests will be tested.

(4) Only the product that is most sensitive to wet concrete in static tests will be tested.

(4a) Product that is sensitive to high alkalinity will be tested. The tests are performed at normal ambient temperature because under increased temperature the concrete will dry out.

(5) Only the product that is most sensitive to hole cleaning (no brushing) will be tested.

(6) Concrete at manufacturer's lowest permissible concrete temeprature.

(6a) Mortar at manufacturer's lowest permissible mortar preheating temperature.

(7) Only the product that is most sensitive to low installation temperature (low degree of cross linking) will be tested.

(8) Only the product that is most sensitive to fly ash concrete will be tested.

(9) Only the product that is most sensitive to blast furnace slag concrete will be tested.

(10) UF = University of Florida, US = University of Stuttgart.

(11) It is assumed that the influence of the investigated parameter on the short-term bond strength is known from previous tests. If not, all products will be tested and the number of reference tests will increase.

Table 15. Proposed test matrix for tensile creep testing.

Test Series	Test Description	Cure Time	Test Temperature	Short-Term Tests: Product Type A (0)	Short-Term Tests: Product Type B (0)	Short-Term Tests: Product Type C (0)	Sustained Load Tests (1): Product Type A	Sustained Load Tests (1): Product Type B	Sustained Load Tests (1): Product Type C
21	Baseline	7 days	110°F (43°C)	5	5	5	12	12	12
22	Cure time	mfr spec	110°F (43°C)	5	5	5	12 (2)		
			Sum	10	10	10	24	12	12

Notes:

(0) Type A = vinyl ester system, type B = epoxy system, type C = epoxy system

(1) Four stress levels times three repetitions for baseline

(2) Only the product that is most sensitive to load at reduced cure time will be tested

mfr = manufacturer.

Adhesive-Alone Testing Program

Based on the triage approach discussed above, Table 15 presents the test matrix for the tensile creep testing program of dogbone specimens of the adhesives for series 21 and 22.

Test series 21 and 22 began with short-term load tests per the tensile testing procedure presented in ASTM D638. Five repetitions were conducted on each adhesive and their values averaged to determine the mean short-term load strength.

Test series 21 and 22 concluded with a series of sustained load tests per the tensile creep test procedure from ASTM D2990 (2001). Three adhesive dogbone specimens were loaded until failure at four stress levels for test series 21 and 22. The time to failure was determined as time to rupture as discussed above.

Adhesive-alone tests were conducted on a dynamic shear rheometer (DSR) to develop master curves using time–temperature and time–stress superposition to compare with creep compliance curves from dogbone and anchor pullout tests.

Anchor Pullout Tests—University of Florida

Overview

The following test series (Table 16) were conducted at the University of Florida; see Table 14 for a detailed test matrix.

The short-term and sustained load (creep) tests generally followed the test procedure found in AASHTO TP 84-10 with the following modifications:

Table 16. Test descriptions.

Test Series	Test Description
1	Baseline
7	Moisture during installation
9	Reduced hole cleaning
12	Standard DOT mix
13	Type of drilling
14	Concrete composition— fly ash
15	Concrete composition—blast furnace Slag
16	Test setup—unconfined

Concrete

- AASHTO TP 84-10 specifies that the concrete mix should be plain concrete without any admixtures. For all tests except for test series 12, 14, and 15 the concrete mix did not have any admixtures or additives. Test series 12 had granite aggregate, water reducer, and fly ash. Test series 14 and 15 used the baseline concrete mix but replaced the cement with 20% fly ash and 50% blast furnace slag respectfully.
- AASHTO TP 84-10 specifies that the concrete mix should have a compressive strength between 2,500 to 4,000 psi at time of testing. For this project, the NCHRP panel chose to specify concrete with a compressive strength between 4,000 and 6,000 psi at time of testing to better conform to typical DOT concrete mixes.

Adhesive

- Adhesives of different chemistries from three manufacturers were chosen to investigate their sensitivity to sustained load.
- Only adhesive anchor systems that met the assessment criteria of ICC-ES AC308 were used. The adhesive chemistries are briefly described below:
  - Adhesive A: This product is a vinyl ester with acrylic monomers with a peroxide hardener and quartz filler.
  - Adhesive B: This product is an epoxy resin with amine hardeners and quartz filler.
  - Adhesive C: This product is an epoxy resin with an amine blend.

Anchor

- As allowed in AASHTO TP 84-10, a ⅝” diameter threaded rod was used to avoid a steel failure mode.
- As allowed in AASHTO TP 84-10, to further reduce the possibility of steel failure, ASTM A354 grade BD steel with 130 ksi yield strength and 150 ksi ultimate strength was used, which is greater than the minimum specified strength of ASTM A193 grade B-7 steel.

- A 3⅛" embedment depth for the ⅝" diameter bars was chosen based on minimum recommendations from AASHTO TP 84-10 to ensure adhesive failure.

Test Procedure

- All tests were confined tests except for test series 16, which evaluated the effect of the test setup and were unconfined tests.
- The stress levels set for the sustained load (creep) test were initially at 85%, 75%, and 65% mean static load for all test series and an additional stress level of 55% mean static load for the baseline tests. After testing began, it was decided to adjust the stress levels due to early failure times at 85% and 75% mean static load.
- As allowed in AASHTO TP 84-10 the frequency of data readings for the long-term (creep) tests was reduced over time according to the following schedule:
  - Every 0.5 seconds during loading,
  - Every 5 seconds for 10 minutes (120 readings),
  - Every 30 seconds for 1 hour (120 readings),
  - Every 5 minutes for 10 hours (120 readings), and
  - Every hour thereafter until failure.

Details on the anchor pullout testing program at the University of Florida can be found in Appendix C.

Anchor Pullout Tests—University of Stuttgart

This section presents the test program conducted at the University of Stuttgart Institut für Werkstoffe im Bauwesen (IWB) to investigate the effect of various parameters on the sustained load performance of three adhesive anchor systems.

Overview

The following test series (Table 17) were conducted at the University of Stuttgart; see Table 14 for a detailed test matrix.

Table 17. Test descriptions.

Test Series	Test Description
2	Baseline
3	Service temperature: +120°F (+49°C)
4	Service temperature: +70°F (21°C)
5	Installation direction: horizontal
6	Installation direction: overhead
8	Moisture during installation
10	Installation temperature: mfr min Service temperature: mfr min
11	Installation temperature: mfr min Service temperature : 110°F (43°C)

The short-term and sustained load (creep) tests were performed in accordance with the test procedures described in AASHTO TP 84-10 with the following modifications:

Concrete

- The concrete mix design for all test series followed the requirements of Deutsches Institut für Normung (DIN) EN 206-1 (Part 1: Specification, performance, production and conformity). For this research project, the NCHRP panel chose to specify concrete with a compressive strength between 4,000 and 6,000 psi at time of testing to conform to typical DOT concrete mixes. This corresponds to a concrete C25/30 according to DIN EN 206-1.

Adhesive

- Only adhesives that met the assessment criteria of ICC-ES AC308 were used.
- Adhesives of different chemistries from three manufacturers were chosen to investigate their sensitivity to sustained load.
- These were the same three adhesives used in the University of Florida tests.

Anchor

- Due to a limitation of the test rigs for the creep tests, the anchor was limited to M12 metric threaded rods with approximately ½" diameter (12 mm).
- To avoid steel failure in short-term tests, steel grade 12.9 was used, corresponding to a 174-ksi ultimate strength and a 157-ksi yield strength.
- The embedment depth was h_{ef} = 3.15" (80 mm). This depth was chosen in order to compare the results with the numerous creep tests that were previously performed at the IWB using the same embedment depth.
- Generally the anchors were centered at the bottom of the borehole with the use of a centering guide except for tests that were specifically performed to examine the behavior under special installation conditions (horizontal and overhead installation direction). The special centering guide used was not part of any of the tested anchoring systems. The 0.6" (15-mm) high centering guide was placed in the bottom of a 3.75" (95-mm) deep hole providing a 3.15" (80-mm) embedment depth. The centering guide had a conical indention that guided the anchors during the installation procedure.

Test Procedure

- All tests were confined tests.
- The stress levels set for the sustained load (creep) test were initially at 85%, 75%, and 65% mean static load for all test series and an additional stress level of 55% mean static load

for the baseline tests. After testing began, it was decided to adjust the stress levels due to early failure times at 85% and 75% mean static load.
- Due to a limitation of the measuring system, the frequency of data readings for the sustained load (creep) tests was not able to be varied and set to 10 minutes. Generally the first reading for a test occurred 120 seconds after the end of initial loading.

Details on the anchor pullout testing program at the University of Stuttgart can be found in Appendix D.

Adhesive-Alone Tests—University of Florida

This section presents the test program conducted at the University of Florida to investigate the isolated sustained load and short-term creep behavior of the adhesive alone.

Overview

The following test series (Table 18) were conducted at the University of Florida; see Table 14 for a detailed test matrix.

The short-term tests generally followed the test procedure found in ASTM D638 with the following modifications:

- Tested at 110°F (43°C) with an attached oven chamber and
- Crosshead speeds were 0.1”, 0.4”, and 0.2” (2.5, 10, and 5 mm)/minute respectively for adhesive A, B, and C depending on the brittleness of the sample.

The sustained load (creep) tests generally followed the test procedure found in ASTM D2990 (2001) with the following modifications:

- The weight for tensile creep was not directly applied to the specimen but through a lever arm system;
- The strain was continuously measured by strain gauges;
- Samples were conditioned as described in the following section; and
- Stress levels were selected to be 35%, 45%, 55% and 75% of the adhesive’s maximum tensile stress obtained from short-term tests.

Details on the adhesive-alone testing program at the University of Florida can be found in Appendix E.

Table 18. Test descriptions.

Test Series	Test Description
21	Baseline
22	Manufacturer cure time

Early-Age Concrete Evaluation—University of Stuttgart

This section presents the test program conducted at the IWB laboratory of the University of Stuttgart to investigate the effect of early-age concrete on the short-term performance of three adhesive anchor systems.

Overview

The early-age concrete investigation is identified as test series 17. Refer to Table 14 for a complete description of the test program. The short-term confined tests generally followed the test procedure found in ASTM E488. Anchors were installed in concrete slabs of various ages (3, 6, 13, 20, and 27 days) and tested 24 hours later. Their short-term bond strength as well as other parameters (compressive strength, split tensile strength, initial surface absorption, hardness, and internal concrete temperature and relative humidity) were measured. Modulus of elasticity of the concrete was not considered.

Details on the early-age concrete testing program at the University of Stuttgart can be found in Appendix F.

Short-Term Anchor Pullout Data Reduction

The following provides information related to data reduction.

Displacement Adjustments

As the anchors were initially loaded, the system took up slack (from the coupler, nuts, lading frame, etc.) producing large initial displacement readings. These large initial displacement readings at the beginning of the test were not due to interface slip between the adhesive and anchor or adhesive and concrete. Instead of adjusting the displacement readings for the initial slack in the system during testing, all data was recorded and adjustments were made after testing. The data acquisition system did however zero out the first position reading from the linear potentiometers (linear-pots) and all displacements readings were calculated from that initial position reading.

The initial displacement readings were later adjusted to account for the slack in the system by extending a secant line through the load-displacement curve to the x-axis to determine the x-intercept (Figure 36). The secant line intersected the load-displacement curve at approximately 10% and 30% of the peak load. The x-intercept was then used to adjust the load-displacement curve to intersect the origin.

The displacement readings were also adjusted for the strain in the anchor between the concrete surface and the coupler. This was accomplished by adjusting the displacement reading by subtracting a strain correction factor (δ_{cor}) multiplied by the load reading.

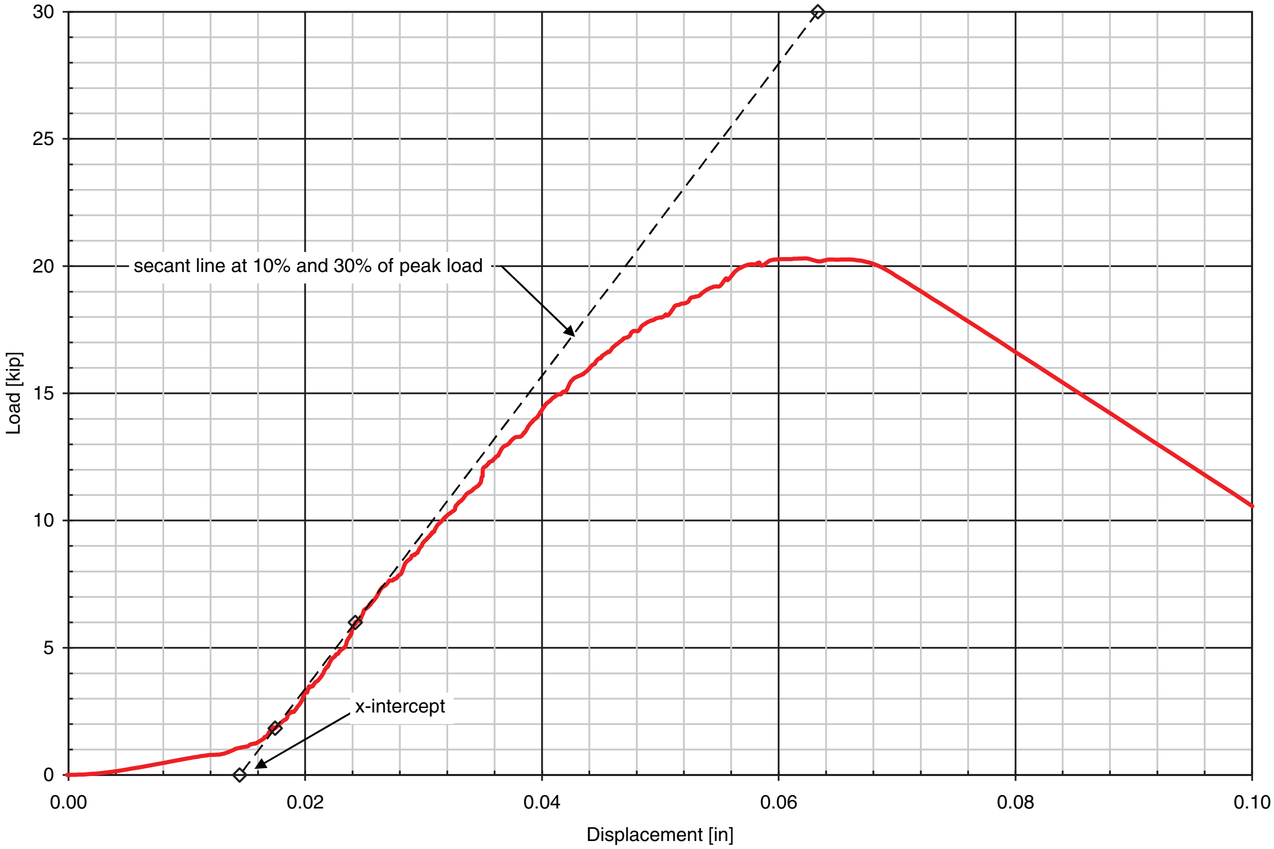


Figure 36. Removing the effect of slack in the load-displacement graph.

$$disp_{adj} = disp - N \cdot \delta_{cor}$$

where

$disp_{adj}$ = displacement adjusted for strain in anchor,
$disp$ = unadjusted displacement, and
N = load.

$$\delta_{cor} = \frac{l}{A_e E}$$

where

l = distance between top of concrete and coupler,
A_e = effective area of anchor, and
E = modulus of elasticity of anchor steel.

For the ⅝" diameter anchor pullout tests at the University of Florida:

$l = 2$ in.,
$A_e = 0.226$ in.^{2},
$E = 29{,}000$ ksi, and
$\delta_{cor} = 0.000305$ in./kip.

For the 12 mm diameter anchor pullout tests at the University of Stuttgart:

$l = 3.54$" (90 mm),
$A_e = 0.131$ in.^{2} (84.8 mm^2),
$E = 29{,}000$ ksi (200 GPa), and
$\delta_{cor} = 0.000929$ in./kip (0.0053 mm/kN).

Determining Static Load Strength

The static load strength is the strength of an adhesive determined from the short-term load test. Due to various possible failure modes, this might not be the maximum static load. The mean static load (MSL) is the average of the static adhesive strength values for an adhesive determined from a series of short-term load tests. This value is used to determine the percent load values in the sustained load (creep) test.

There are several methods available to analyze the load-displacement behavior of a short-term load test in determining the static load strength which is referred to as N_{adh} by ACI 355.4. Section 10.4.4 of ACI 355.4 presents the following procedure:

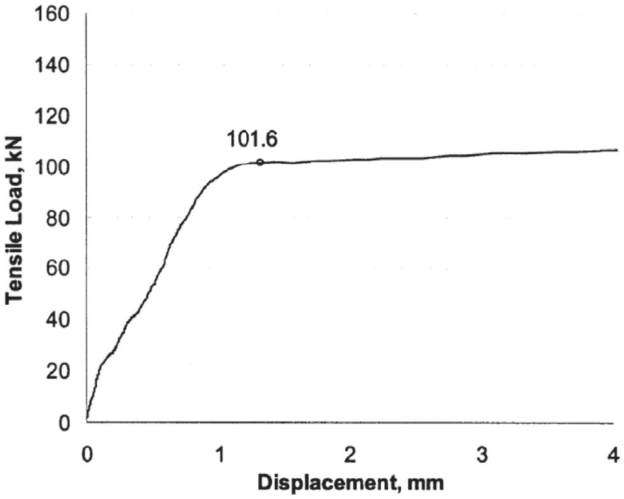
- Determine a tangent stiffness at 30% of the maximum static load (N_u), which is typically approximated as the secant stiffness from the origin to the point on the load-displacement curve at $0.30N_u$.
- If the displacement at $0.30N_u$ is less than 0.002 in., the origin is shifted to the point on the load-displacement curve at $0.30N_u$.

- Multiply the tangent stiffness by ⅔ and project this line until it intersects with the load-displacement curve.
- N_{adh} is taken at the intersection if the load at the intersection is less than N_u.
- N_{adh} is taken as N_u if the load at the intersection is greater than N_u.

This method was analyzed and was not recommended, as it tended to drastically underestimate the static load strength in a few cases as can be seen in Figure 40.

Another procedure was presented by Cook and Konz (2001), in which they classified three types of load-displacement response (strength controlled, stiffness controlled, and displacement controlled) and described methods to determine the static load strength for each type of situation. The responses and methods of analysis are summarized below:

- **Strength controlled.** This failure mode is defined by a very sharp peak in the load-displacement curve with a drastic reduction in the stiffness of the adhesive anchor beyond the peak. The static load strength is determined to be at the peak on the load-displacement graph. Figure 37 shows a typical curve of a strength-controlled failure.
- **Stiffness controlled.** This failure mode is defined by a large initial stiffness and a drastic change in stiffness, which does not decrease but rather continues to increase at a lower slope. Due to the absence of a "peak" in the curve, the static load strength is determined by finding the point at a tangent stiffness of 30 kips/in (5 kN/mm). The tangent stiffness (slope) at a given data point can be approximated by calculating the slope between a point five data points after and five data points before a given point. Figure 38 shows a typical curve of a stiffness-controlled failure.

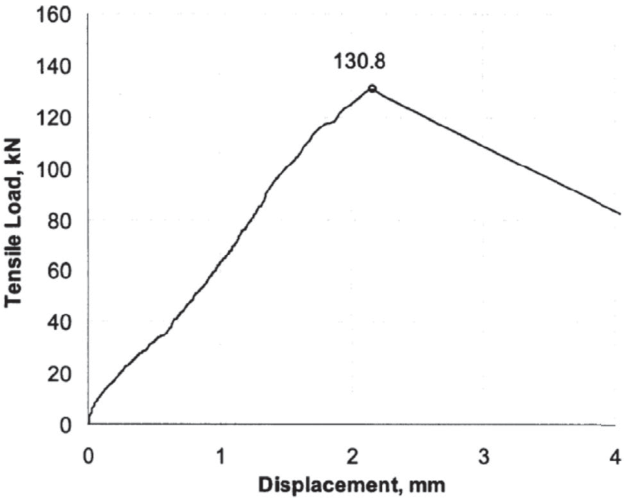


Source: Cook and Konz (2001)

Figure 38. Typical stiffness-controlled failure.

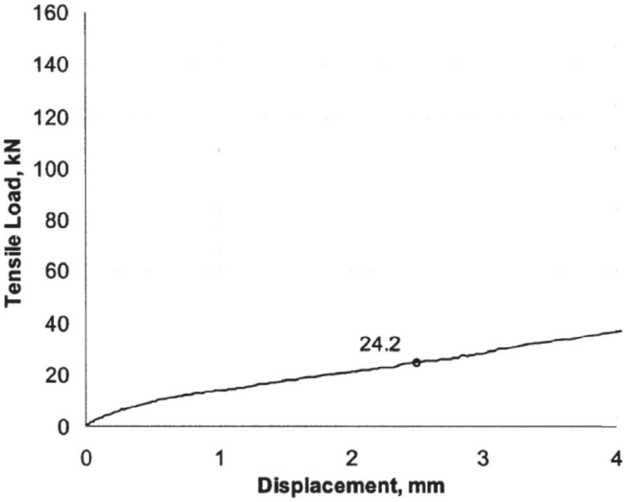
- **Displacement controlled.** This failure mode has a load-displacement curve with a relatively constant stiffness above the stiffness-controlled threshold of 30 kips/in. (5 kN/mm). The maximum static load occurs at very high, and impractical displacements. In this case, the static load strength is set at a point with a displacement of 0.1 in. (2.5 mm). While the 0.1 in displacement seems arbitrary, this failure mode usually only occurs in inferior products. Since this research was limited to products that met the assessment criteria of ICC-ES AC308 (ACI 355.4), this failure mode was not expected and was not observed. Figure 39 shows a typical curve of a displacement-controlled failure.

The method presented by Cook and Konz (2001) exhibited better results than the ACI 355.4 approach and was the approach chosen for the project. Figure 40 is a load-displacement



Source: Cook and Konz (2001)

Figure 37. Typical strength-controlled failure.



Source: Cook and Konz (2001)

Figure 39. Typical displacement-controlled failure.

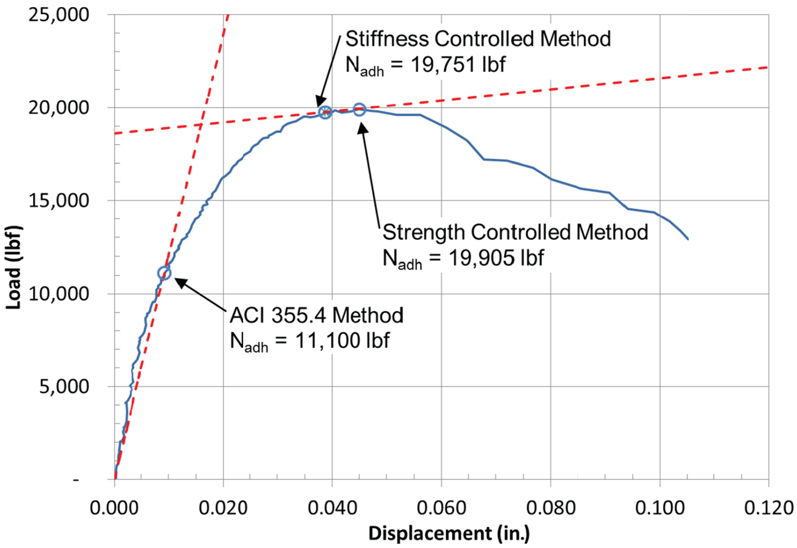


Figure 40. Example of calculating static load strength from various methods.

graph for a short-term load test conducted showing the static load strength calculated by three different methods.

- The ACI 355.4 procedure estimated N_{adh} as 11,100 lbf.
- The strength-controlled method estimated N_{adh} as 19,905 lbf.
- The stiffness-controlled method estimated N_{adh} as 19,751 lbf.

For each test, the static load strength was recorded and the mean static load for each adhesive was determined from the average of the tests.

Static Bond Stress

The static bond stress (τ_{adh}) was calculated as the static load strength (N_{adh}) divided by the adhesive bond area at the interface with the anchor A_{adh}, or:

$$\tau_{adh} = N_{adh} / A_{adh}$$

where

$A_{adh} = \pi \, d \, h_{ef}$,
d = diameter of anchor (0.625” at UF and 0.472” at US), and
h_{ef} = embedment depth of hole (3.125” at UF and 3.150” at US).

The static bond stress was calculated to compare the results between the laboratories at the University of Florida and the University of Stuttgart as different diameters and embedment depths were used.

Sustained Load Anchor Pullout Data Reduction

The following provides information related to data reduction.

Determination of Time to Failure

Time to failure was initially evaluated as both the onset of tertiary creep and as the time to rupture.

Based on recommendations from NCHRP (2009) the change in slope method was used to determine the onset of tertiary creep. This method calculated the slope at a given point as the slope between it and the prior data point. The change in slopes between the given point and the following data point was plotted and examined over the region just prior to rupture. It was suggested that this examination be conducted on a normal graph (not log time). The rupture point was easily identified on the displacement vs. time graph by its near vertical slope. A suggested range for examining the change in slope was from 80% to 100% of time to rupture. Due to minor fluctuations in the displacement readings, the slope might change from positive to negative several times over this range. Tertiary creep was defined as the time the change in slope became positive for the last time prior to rupture. This method produced favorable results and a sample graph is shown as Figure 41.

The time to rupture was identified as the point when the anchor pulled out of the hole, which is indicated by a vertical line on the displacement versus time graph. This proved to be a very easy and reproducible analysis and did not vary significantly from the initiation of tertiary creep. Both times were determined for each test and the values for the UF and US baseline series are listed in Appendix J. Apart from a few exceptions, there was an average 3% difference between the two values. In three cases there was a larger difference, but this was for three tests at US and was due to the very short failure time (20 minutes) in relation to the sampling resolution of 10 minutes. As the time to rupture and onset of

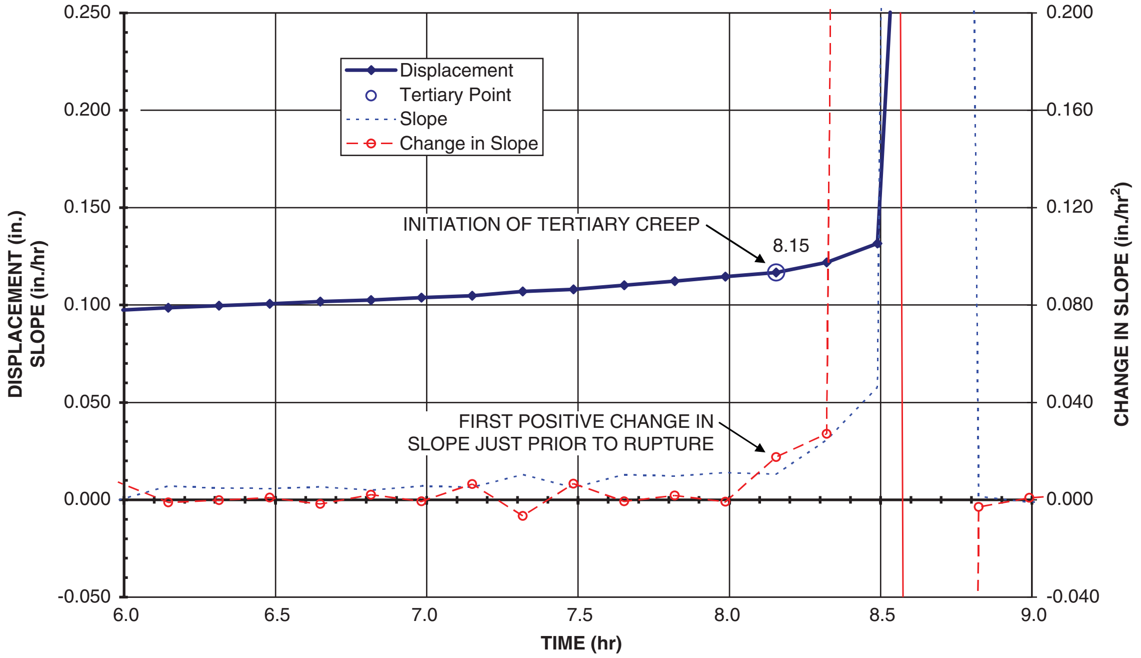


Figure 41. Example of the change in slope method.

tertiary creep analysis produced essentially the same time to failures, it was decided to use the time to rupture as the determination of time to failure as it was a much simpler method.

Assessment of a Parameter's Impact on Sustained Load Performance

Test series 1 through 16 and 21 through 22 evaluated a parameter's influence on sustained load performance using the "stress versus time-to-failure" test method (either by anchor pullout tests or "dogbone" tensile creep tests) to evaluate the performance of adhesive anchors under sustained load. Unlike the "displacement projection" test method found in ASTM E1512-01, ICC-ES AC58, ICC-ES AC308 and ACI 355.4, the "stress versus time-to-failure" method does not rely upon projections of measured displacements but simply records the time to failure of the anchor. The only disadvantage of this method is that it takes an unknown time to complete the tests since they are all conducted to failure.

Suggested Improvements

A few possible changes were identified to improve the sustained load anchor pullout test procedure performed at the University of Florida.

- In case of an eccentricity with the loading rod, one of the two linear potentiometers could produce a negative displacement reading that would generate an error in the averaged displacement. It is suggested that either one linear potentiometer be placed concentric with the anchor axis or a coupler with three linear potentiometers be used.

A few possible changes were identified to improve the dogbone testing procedure.

- Thinner samples would allow for lower loads during both the creep test and the static test.
- Sustained load creep test frames could have better isolation from each other so that the falling weight of a failed sample will not disturb other adjacent running tests.

Summary

This chapter summarized the parameters that could possibly affect sustained load performance of adhesive anchor systems. Due to project budget and timeline, a triage was conducted to prioritize the parameters in order to test those thought to have the most impact. A general overview of the test program and analysis procedures was presented. The following chapter discusses the findings and applications.

CHAPTER 3

Findings and Applications

The purpose of this chapter is to describe the procedures used to reduce the experimental data into usable results. The tests were labeled with a series of letters and numbers. The short-term load tests are identified as TS-A-ST-R, where:

TS:	Test Series (01–16, 21, 22);
A:	Signifies the adhesive type (A, B, or C);
ST:	Signifies short-term test; and
R:	Test repetition number (1–13).

The sustained load tests are identified as TS-A-PP-R, where:

TS:	Test Series (01–16, 21, 22);
A:	Signifies the adhesive type (A, B, or C);
PP:	Signifies stress level percentage (85, 75, 65, etc.); and
R:	Test repetition number (1–15).

The tests on the effects of early-age concrete (TS17) are identified as DDD-A-ST-R, where:

DDD:	Day of testing (D04, D07, D14, D21, D28);
A:	Signifies the adhesive type (A, B, or C);
ST:	Signifies short-term test; and
R:	Test repetition number (1–5).

Short-Term Anchor Pullout Load Testing

The short-term load tests were conducted as described in Chapter 2. The following provides the test results.

Short-term Load Test Results

The load-displacement graphs along with the peak load and displacement values for the short-term load tests conducted at the University of Florida and the University of Stuttgart are included in Appendix I.

Rejection of Outliers

The modified Thompson tau technique was used to test for outliers. In this method, the absolute value of the deviation (δ_i) of a data point from the mean is compared against the standard deviation (s_x) times Thompson's tau value (τ), which is tabulated by number of data points and can be found in most statistics textbooks. The modified Thompson's tau value is 1.572 for five data points and 1.798 for ten data points (Wheeler and Ganji, 2004). A data point is rejected if $\delta_i > s_x\tau$. If a data point is rejected, the mean and standard deviation are recalculated from the remaining values.

The following data points (Table 19) were determined to be outliers by the Thompson tau technique and chosen for rejection.

These are assumed to have failed at lower bonds stresses due to incomplete curing issues with adhesive C.

During installation of the above two series of five anchors (series 7 and 16) there were times at which the installer stopped the continuous injection and set the cartridge gun down for a few minutes. During this set-down period it appears that some unequal mixing of components occurred in the mixing nozzle. Adhesive C was significantly more difficult to dispense by hand during installation, compared to the other adhesives. The difficulty in dispensing indicated that at least one of the components was very viscous. If one component was significantly more viscous than the other, it is possible that during the set-down period there could have been an abundance of the other component (which flowed more easily) in the mixing nozzle. When the cartridge gun was picked back up and the installation resumed, the adhesive in the nozzle had an improper ratio of adhesive components. This resulted in the following repetition being poorly mixed and at low strength. Any subsequent repetitions seemed to be at full strength as the poorly mixed adhesive in the nozzle had been replaced.

A qualification test for evaluating this effect is presented in the proposed AASHTO Standard Method of Test in Appendix O.

Statistical Analysis

The results of a statistical analysis for each test are presented in Table 20 through Table 25 for the tests conducted

Table 19. Results of modified Thompson tau technique.

	Test Series	Adhesive	Repetition	Value (kips)	Mean (kips)	δ_i (kips)	$s_x\tau$ (kips)	Result
7	Moisture (installation)	C	4	8.5	21.1	12.6	11.1	REJECT
16	Test setup (unconfined)	C	5	5.87	9.03	3.16	3.04	REJECT

Table 20. Statistical analysis for short-term tests on adhesive A at University of Florida.

	Test Series	Mean (kips)	Std. Dev. (kips)	COV	Alpha-Reduct. Factor	t-test[1] p value	Significantly Different?
1	Baseline	19.8	1.1	0.06			
7	Moisture (installation)	16.2	0.9	0.06	0.82	0.00	YES
9	Hole cleaning (reduced)	18.4	0.8	0.04	0.93	0.01	YES
12	Concrete mix (DOT)	16.6	2.6	0.15	0.84	0.02	YES
13	Type of drilling (cored)	11.9	1.5	0.12	0.60	0.00	YES
14	Concrete Mix (FA)	18.5	1.2	0.07	0.93	0.04	YES
15	Concrete Mix (BFS)	17.4	0.7	0.04	0.88	0.00	YES
16	Test setup (unconfined)	10.4	0.3	0.03	0.53	0.00	YES

[1] Student's t-test is one-sided at a confidence level of 90%.

Table 21. Statistical analysis for short-term tests on adhesive B at University of Florida.

	Test Series	Mean (kips)	Std. Dev. (kips)	COV	Alpha-Reduct. Factor	t-test[1] p value	Significantly Different?
1	Baseline	25.7	1.3	0.05			
7	Moisture (installation)	24.1	1.4	0.06	0.94	0.03	YES
9	Hole Cleaning (reduced)	23.8	1.4	0.06	0.93	0.02	YES
12	Concrete Mix (DOT)	22.4	2.0	0.09	0.87	0.01	YES
13	Type of Drilling (cored)	18.7	1.7	0.09	0.73	0.00	YES
14	Concrete Mix (FA)	23.4	2.9	0.12	0.91	0.08	YES
15	Concrete Mix (BFS)	25.5	0.5	0.02	0.99	0.39	NO
16	Test setup (unconfined)	11.0	1.0	0.09	0.43	0.00	YES

[1] Student's t-test is one-sided at a confidence level of 90%.

Table 22. Statistical analysis for short-term tests on adhesive C at University of Florida.

Test Series		Mean (kips)	Sd. Dev. (kips)	COV	Alpha-Reduct. Factor	t-test[1] p value	Significantly Different?
1	Baseline	26.3	1.7	0.06			
7[2]	Moisture (installation)	24.2	0.9	0.04	0.92	0.01	YES
9	Hole Cleaning (reduced)	21.3	1.4	0.06	0.81	0.00	YES
12	Concrete Mix (DOT)	25.1	1.0	0.04	0.95	0.05	YES
13	Type of Drilling (cored)	23.2	0.2	0.01	0.88	0.00	YES
14	Concrete Mix (FA)	26.5	0.6	0.02	1.01	0.37	NO
15	Concrete Mix (BFS)	24.8	0.8	0.03	0.94	0.02	YES
16[3]	Test setup (unconfined)	9.8	0.9	0.09	0.37	0.00	YES

[1] Student's t-test is one-sided at a confidence level of 90%.

[2] Repetition 4 of test series 7 is considered an outlier and is not included in statistical calculations.

[3] Repetition 5 of test series 16 is considered an outlier and is not included in statistical calculations.

Table 23. Statistical analysis for short-term tests on adhesive A at University of Stuttgart.

Test Series[1]		Mean (kips)	Std. Dev. (kips)	COV	Alpha-Reduct. Factor	t-test[2] p value	Significantly Different?
2	Baseline	14.7	0.6	0.04			
5	Installation direction (horizontal)	15.8	0.5	0.03	1.07	0.01	YES
6	Installation direction (overhead)	16.1	0.6	0.04	1.09	0.00	YES

[1] Test series 3, 4, and 8 were determined from other criteria as discussed later.

[2] Student's t-test is one-sided at a confidence level of 90%.

on adhesives A through C at the University of Florida and the University of Stuttgart, respectively, to compare the baseline short-term test results to the short-term test results for each parameter. The statistical analysis includes the mean, standard deviation, and coefficient of variation for each data set. An alpha-reduction factor is also calculated as the mean of a particular test series divided by the mean of its respective baseline test series.

Table 24. Statistical analysis for short-term tests on adhesive B at University of Stuttgart.

Test Series		Mean (kips)	Std. Dev. (kips)	COV
2	Baseline	19.3	0.7	0.04

A one-sided student t-test with a confidence interval of 90% was conducted on each test series against its respective baseline test series to determine if the results of a particular test series were significantly different from its respective baseline test series. A one-sided t-test was chosen with the null hypothesis so that the mean of a test series was not less than the mean of

Table 25. Statistical analysis for short-term tests on adhesive C at University of Stuttgart.

Test Series		Mean (kips)	Std. Dev. (kips)	COV
2	Baseline	18.5	1.0	0.05

Note:
Adhesive C was not used for sustained load investigation.

the baseline. A 90% confidence interval was chosen as it is the common practice in ACI 355.4 and indicates a 10% significance level ($\alpha = 0.10$ in t-test table). Therefore, if the p value from the t-test was less than the significance level, then the null hypothesis was rejected and the parameter test data sets were significantly different than the baseline test data sets.

As the short-term tests for TS 3, 4, 8, 10, and 11 were conducted later in the testing program, a few baseline short-term tests were conducted near the end of the project to investigate if the bond strength changed over time. Two repetitions of adhesive A and three repetitions of adhesive B were conducted at the University of Florida and at the University of Stuttgart. The results are presented in Appendix I and Table 26. Due to the 20% increase in baseline strengths for the specimens at the University of Stuttgart, the alpha factors and sustained load tests for TS 3, 4, 8, 10, and 11 were referenced to the later short-term tests. The short-term results and resulting alpha factors for these tests are presented in Table 27 and Table 28.

The 20% increase in bond strengths at the University of Stuttgart is most likely due to the increase in concrete strength between the two testing dates. While the concrete strengths for the specimens at University of Florida stayed consistent within

Table 26. Comparison of late baseline tests to initial baseline tests.

Lab – Adhesive[1]	Date of Testing	Mean (kips)	Standard Deviation (kips)	COV	Ratio of Final/Initial
UF – A (initial)	8/2010	19.8	1.1	0.06	0.93
UF – A (final)	4/2012	18.3	0.4	0.02	
UF – B (initial)	8/2010	25.7	1.3	0.05	0.94
UF – B (final)	4/2012	24.1	3.4	0.14	
US – A (initial)	8/2010	14.7	0.6	0.04	1.17
US – A (final)	4/2012	17.2	0.8	0.05	
US – B (initial)	8/2010	19.3	0.7	0.04	1.19
US – B (final)	4/2012	22.9	0.4	0.02	

[1] UF = University of Florida, US = University of Stuttgart.

Table 27. Statistical analysis for late short-term tests on adhesive A at University of Stuttgart.

Test Series		Mean (kips)	Std. Dev. (kips)	COV	Alpha-Reduct. Factor	t-test[1] p value	Significantly Different?
2	Baseline	17.2	0.8	0.05			
10	Installation temperature (mfr min/mfr min)	18.9	0.8	0.04	1.10	0.06	YES
11	Installation temperature [mfr min/110°F (43°C)]	14.8	0.6	0.04	0.86	0.05	YES

[1] Student's t-test is one-sided at a confidence level of 90%.

Table 28. Statistical analysis for late short-term tests on adhesive B at University of Stuttgart.

Test Series		Mean (kips)	Std. Dev. (kips)	COV	Alpha-Reduct. Factor	t-test[1] p value	Significantly Different?
2	Baseline	22.9	0.4	0.02			
3	Service temperature [>120°F (49°C)]	23.1	0.4	0.02	1.01	0.29	NO
4	Service temperature [70°F (21°C)]	27.2	0.6	0.02	1.19	0.00	YES
8	Moisture (service)	24.4	0.7	0.03	1.07	0.00	YES

[1] Student's t-test is one-sided at a confidence level of 90%.

Table 29. Bond stress analysis.

Lab – Adhesive	Mean (psi)	Standard Deviation (psi)	COV	Ratio Of Means US/UF
UF – A	3,226	180	0.06	0.98
US – A	3,153	129	0.04	
UF – B	4,182	218	0.05	0.99
US – B	4,125	156	0.04	
UF – C	4,293	277	0.06	0.92
US – C	3,949	204	0.05	

UF = University of Florida, US = University of Stuttgart.

the testing period, the concrete strengths at the University of Stuttgart increased approximately 50% over the course of the project. This is most likely due to the CEM I 32.5R cement used in Stuttgart which was a blended cement with pozzolans.

Bond Stress Analysis

As the tests at the University of Florida and the University of Stuttgart were conducted with different anchor diameters and embedment depths, the static bond stress was calculated for the baseline tests series 1 and 2 for comparison (Table 29). For adhesives A and B the means of the bond stresses determined by the University of Stuttgart (US) and the University of Florida (UF) were very close, 98% and 99%, respectively. The ratio of the means for Adhesive C was 92%.

Figure 42 compares the bond stress results from both laboratories. The means are plotted with an error bar indicating one standard deviation spread above and below the mean. This shows that the bond stress results between the two laboratories are statistically equivalent.

The stress–displacement graphs along with the peak stress and displacement values for the short-term load tests conducted at the University of Florida and the University of Stuttgart are included in Appendix I.

Selection of Adhesive for Sustained Load Investigation

The determination of which adhesive to test for sustained load performance for test series 5 through 7, 9, and 12 through 16 was based on the lowest alpha-reduction factor. A summary of the alpha-reduction factors is presented in Table 30 and accompanying Figure 43. The adhesives chosen for sustained load evaluation are highlighted in Table 30.

The NCHRP project panel recommended testing two adhesives for sensitivity to installation direction, therefore two adhesives were chosen for test series 5 and 6. Adhesive A was chosen as it exhibited the lowest alpha-reduction factor. Near

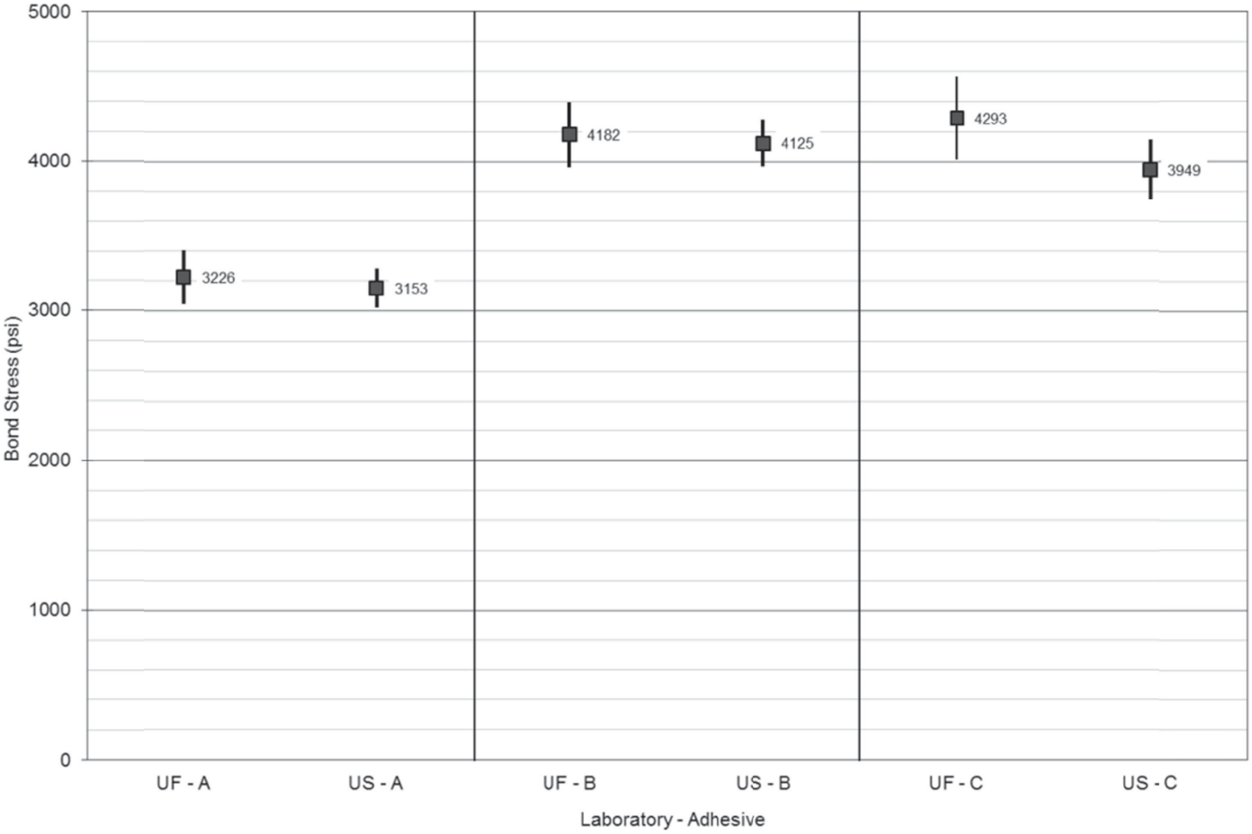


Figure 42. Bond stress analysis.

Table 30. Summary of alpha-reduction factors.[1]

Test Series		Adhesive A	Adhesive B	Adhesive C	UF[2]	US[2]
3	Service temperature (>120°F (49°C))[3]		1.01			X
4	Service temperature (70°F (21°C))[3]		1.19			X
5	Installation direction (horizontal)[4]	1.07				X
6	Installation direction (overhead)[4]	1.09				X
7	Moisture (installation)	0.82	0.94	0.92	X	
8	Moisture (service)[3]		1.07			X
9	Hole Cleaning (reduced)	0.93	0.93	0.81	X	
10	Installation temperature (mfr min/mfr min)[3]	1.10				X
11	Installation temperature (mfr min/110°F (43°C))[3]	0.86				X
12	Concrete Mix (DOT)	0.84	0.87	0.95	X	
13	Type of Drilling (cored)	0.60	0.73	0.88	X	
14	Concrete Mix (FA)	0.93	0.91	1.01	X	
15	Concrete Mix (BFS)	0.88	0.99	0.94	X	
16	Test setup (unconfined)	0.53	0.43	0.37	X	

[1] Adhesives chosen for investigation of sensitivity to sustained loading are highlighted.

[2] UF = University of Florida, US = University of Stuttgart.

[3] Test series 3, 4, 8, 10, & 11 used other criteria besides the lowest alpha-reduction factor to select the product for sustained load investigation as discussed below. Therefore only the alpha-reduction for the product selected was determined.

[4] Adhesive A was chosen for test series 5 & 6 based on separate preliminary short-term tests.

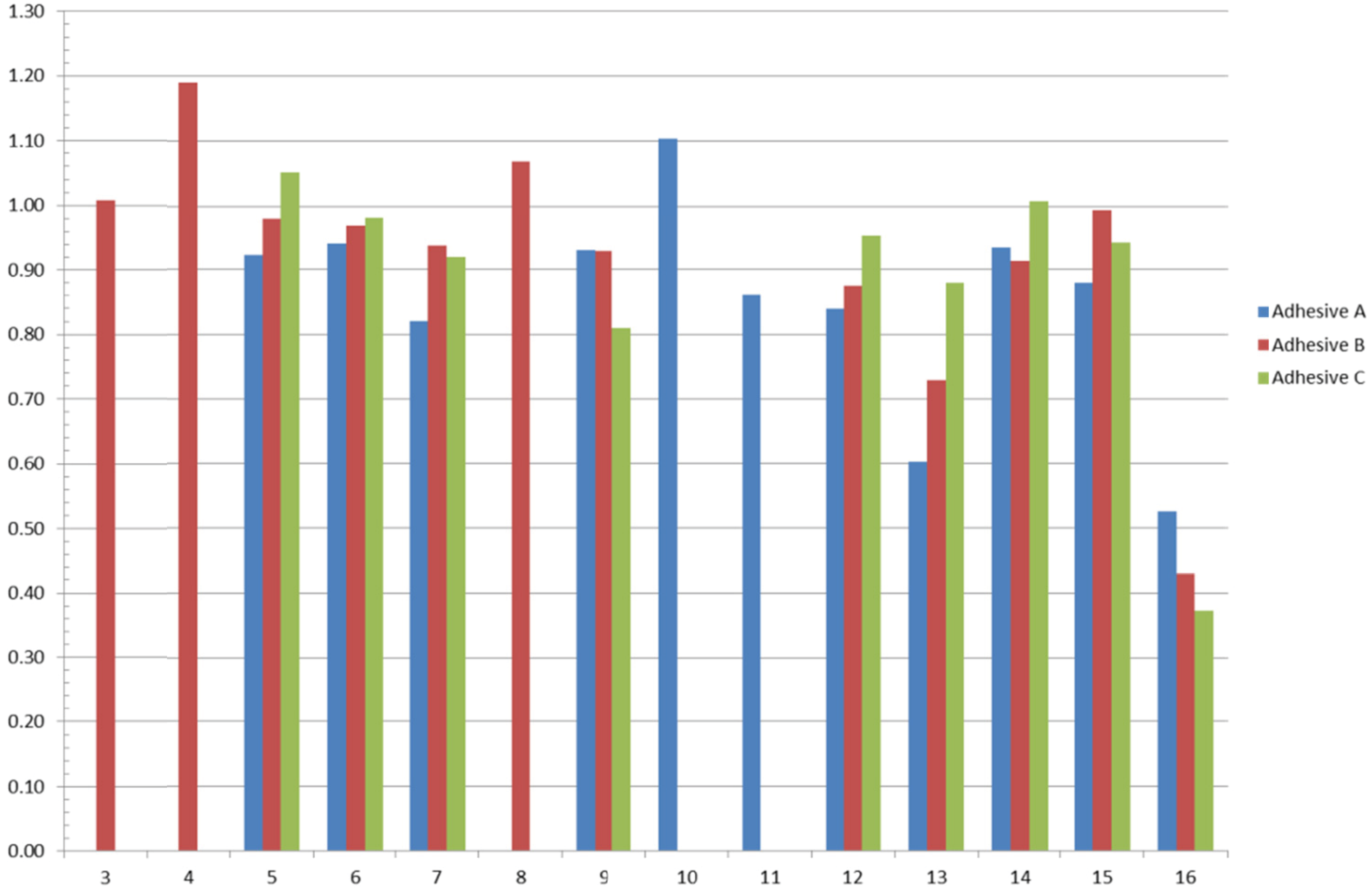


Figure 43. Summary of alpha-reduction factors per test series.

Table 31. Glass transition temperatures.

Parameter	Adhesive A (°C)	Adhesive B (°C)	Adhesive C (°C)
Week cure	52	51	55

Notes:
Values obtained from DSC tests performed at the University of Florida.

Table 32. Alkalinity sensitivity reduction factor.

Parameter	Adhesive A	Adhesive B	Adhesive C
Alkalinity sensitivity	0.95	0.86	1.00

Notes:
Values provided by the manufacturers.

the end of the project, it was decided not to test a second adhesive for test series 5 and 6 as (1) the results from the sustained load results for adhesive A did not show a significant difference from the baseline and (2) it took longer to complete the testing program due to the longer than anticipated test durations.

The adhesives chosen for sustained load investigation for test series 3 and 4 were based on the lowest glass transition temperature (T_g). The glass transition temperatures for each adhesive based on DSC analysis conducted at the University of Florida are presented in Table 31. Adhesive B was chosen for investigation for sustained load sensitivity for test series 3 and 4.

The adhesive chosen for sustained load investigation for test series 8 was based on the adhesive that was most sensitive to alkalinity. The manufacturers provided the results from the alkalinity sensitivity slice tests found in ICC-ES AC308 Section 9.8. The results are summarized in Table 32. Adhesive B was chosen for investigation for sustained load sensitivity for test series 8.

It was initially decided to choose the adhesive for sustained load investigation for test series 10 and 11 based on the lowest degree of cross-linking. The values for the degree of cross-linking for each adhesive based on DSC analysis conducted at the University of Florida are presented in Table 33. However, the adhesive with the lowest degree of cross-linking had a relatively high temperature for the lowest permissible installation temperature. Table 34 summarizes the lowest permissible installation temperatures. Adhesive A was chosen for investigation for sustained load sensitivity for test series 10 and 11 as it had the second lowest degree of cross-linking and the lowest permissible installation temperature.

Table 33. Degree of cross-linking.

Parameter	Adhesive A (%)	Adhesive B (%)	Adhesive C (%)
Week cure	95.4	96.3	87.8

Notes:
Values obtained from DSC tests performed at the University of Florida.

Table 34. Lowest manufacturer specified installation temperature.

Parameter	Adhesive A (°C)	Adhesive B (°C)	Adhesive C (°C)
Installation Temperature	0	5	10

Discussion on Unconfined Results

At the time of installation and testing for test series 16 (unconfined setup) the concrete compressive strength was 4,360 psi. The confined bond strengths as determined from the short-term baseline tests were as follows:

- $\tau_{confined,adhesive\ A} = 3{,}225\ psi$
- $\tau_{confined,adhesive\ B} = 4{,}180\ psi$
- $\tau_{confined,adhesive\ C} = 4{,}290\ psi$

Due to the high confined bond strength of these adhesives it was anticipated that concrete breakout failure would occur for the standard ⅝” × 3.125” anchor used in the unconfined short-term tests.

Taking a coefficient for mean concrete breakout strength of $k = 35$ from Fuchs et al. (1995), the predicted concrete breakout strength (N_{cb}) was:

$$N_{cb} = k\sqrt{f_c'}\,h_{ef}^{1.5}$$

$$N_{cb} = 35\sqrt{4{,}360\ psi}\,(3.125\ in)^{1.5}$$

$$N_{cb} = 12{,}800\ lbf$$

$$N_{cb} = 12.8\ kips$$

Assuming a 0.75 ratio (ACI 355.4-11 §10.4.5.1) of unconfined bond strength to confined bond strength to determine the unconfined bond strength (N_a) from a series of confined tests for each adhesive was:

$$N_a = \tau_{unconfined}\ \pi\ d\ h_{ef}$$

$$N_a = 0.75\tau_{unconfined}\ \pi\ d\ h_{ef}$$

$$N_{a,\ adhesive\ A} = 0.75(3{,}225\ psi)\pi(0.625\ in^2)(3.125\ in)$$

$$N_{a,\ adhesive\ A} = 14{,}800\ lbf$$

$$N_{a,\ adhesive\ A} = 14.8\ kips$$

$$N_{a,\ adhesive\ B} = 0.75(4{,}180\ psi)\pi(0.625\ in^2)(3.125\ in)$$

$$N_{a,\ adhesive\ B} = 19{,}200\ lbf$$

$$N_{a,\ adhesive\ B} = 19.2\ kips$$

Table 35. Test series 16 (unconfined setup) short-term verification tests results with adhesive C in higher strength concrete at 110°F (43°C).

Test Setup	Test Repetition (kips) 1	2	3	Mean	STD	COV	Alpha-Setup
Confined	22.7	24.8	1.5 *	23.8	1.4	0.06	
Unconfined	10.3	8.9	10.1	9.7	0.7	0.08	0.41

Notes:

* Test repetition 3 for the unconfined tests was considered an outlier and was not used in the calculation of the mean. Prior to testing, the adhesive was still tacky after a week of curing. After testing, the anchor was removed from the hole and the adhesive was still tacky, indicating that it was not fully cured.

$$N_{a,\,adhesive\,C} = 0.75(4{,}290\ psi)\pi(0.625\ in^2)(3.125\ in)$$

$$N_{a,\,adhesive\,C} = 19{,}700\ lbf$$

$$N_{a,\,adhesive\,C} = 19.7\ kips$$

For the tests, high-strength steel was used to prevent yielding during testing (ASTM A354 grade BD) with a tensile strength f_u = 150 ksi and a yield strength f_{ya} = 130 ksi. The steel yield strength of a ⅝" diameter ($A_{se} = 0.226$ in^2) threaded rod (N_{sa}) is:

$$N_{sa} = A_{se} f_{ya}$$

$$N_{sa} = (0.226\ in^2)(130\ ksi)$$

$$N_{sa} = 29.4\ kips$$

As a result, the unconfined short-term tests were expected to exhibit concrete breakout at around 13 kips.

The short-term tests results for test series 16 (unconfined setup) are presented in Table 20, Table 21, and Table 22. The anchors were installed in test slabs with a minimum edge distance of $2.56h_{ef}$ and spacing from the anchor to the test frame of $2h_{ef}$ which is greater than or equal to the $2h_{ef}$ requirement in ASTM E488-10. As indicated in Table 20, Table 21, and Table 22, the failure loads were less than the expected 13 kips from concrete breakout for all products.

The anchors had an apparent bond failure mode characterized by a shallow cone at the top and a bond failure along the lower portions of the anchor. As the alpha-setup ratios (0.53, 0.43, and 0.37) were much less than the accepted ratio of 0.75, a series of verification tests was conducted as described below.

A series of short-term tests with adhesive C was conducted in higher strength (6,550 psi) concrete to verify the short-term results for test series 16. For the new concrete blocks, the predicted concrete breakout strength (N_{cb}) was:

$$N_{cb} = k\sqrt{f'_c}\,h_{ef}^{1.5}$$

$$N_{cb} = 35\sqrt{6{,}550\ psi}\,(3.125\ in)^{1.5}$$

$$N_{cb} = 15{,}600\ lbf$$

$$N_{cb} = 15.6\ kips$$

The short-term tests results for test series 16 verification tests at 110°F (43°C) are presented in Table 35 and Figure 44. The short-term tests results for test series 16 verification tests at 80°F (27°C) are presented in Table 36 and Figure 45. The anchors were installed in test slabs with a minimum edge distance of $4h_{ef}$ and spacing from the anchor to the test frame of $2h_{ef}$ which is greater than or equal to the $2h_{ef}$ requirement in ASTM E488-10.

The mean of the unconfined tests results of the verification tests was 9.7 kips at 110°F (43°C) and 11.1 kips at 80°F (27°C), which are similar to the previous test results of 9.8 kips and well below the expected concrete breakout strength of 15.6 kips and the expected unconfined bond strength using a 0.75 ratio of unconfined to confined of 19.7 kips. The alpha-reduction factor for the verification tests was 0.41 at 110°F (43°C) and 0.40 at 80°F (27°C). This indicates that for unconfined tests, temperature does not have an effect and the alpha-setup factor is well below the assumed 0.75, and lies within the range of 0.35 to 0.55 for these products.

Sustained Load Anchor Pullout Testing

The sustained load (creep) tests were conducted as described in Chapter 2. The following provides the test results of the sustained load tests.

Modification to Testing Program

It was initially decided to test the baseline series at 85%, 75%, 65%, and 55%. However due to very early failures in the 85% and 75% stress levels, it was decided to test adhesives A, B, and C at 45% and adhesive A at 35%. Near the end of the project, several more tests were conducted at the higher stress levels ~65% to 85% to reexamine the early failures.

Additionally, test series 3 to 16 were initially scheduled to be tested at three different stress levels. Based on the above

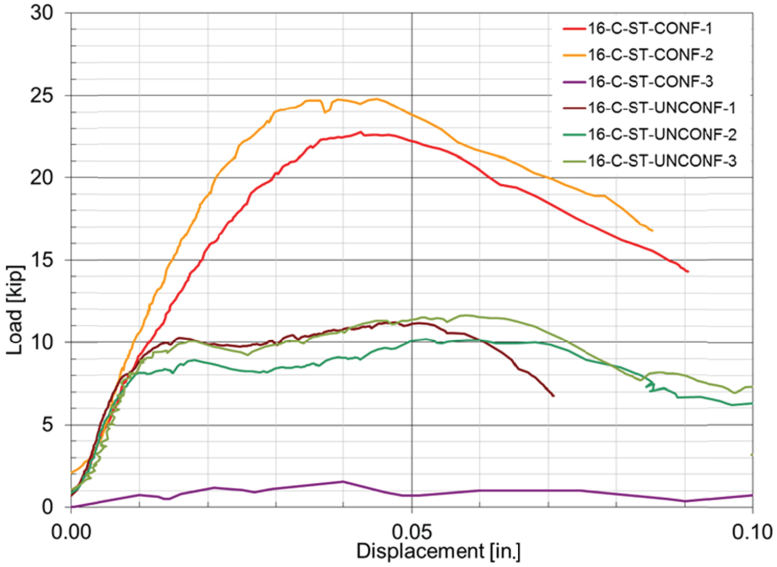


Figure 44. Test series 16 (unconfined setup) short-term verification tests results with adhesive C in higher strength concrete at 110°F (43°C).

Table 36. Test series 16 (unconfined setup) short-term verification tests results with adhesive C in higher strength concrete at 80°F (27°C).

Test Setup	Test Repetition (kips)			Mean	STD	COV	Alpha-Setup
	4	5	6				
Confined	26.4	29.3	28.1	27.8	2.1	0.07	
Unconfined	10.2	10.9	12.2	11.1	1.0	0.09	0.40

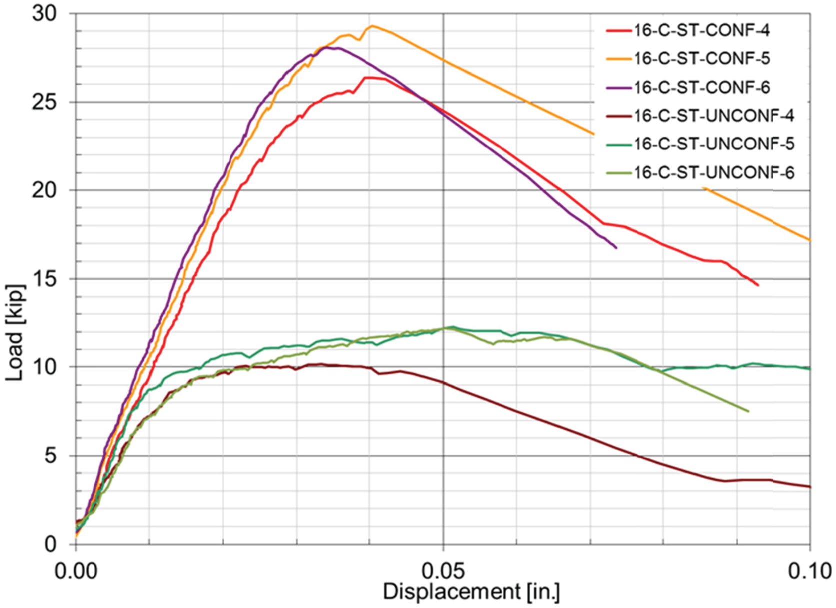


Figure 45. Test series 16 (unconfined setup) short-term verification tests results with adhesive C in higher strength concrete at 80°F (27°C).

discussion, the stress levels were reduced to 70%, 55%, and 40%. Due to the longer than anticipated failure durations, it was decided by the researchers with the approval of the NCHRP panel to test only some series at two stress levels.

Sustained Load Displacement versus Time Test Results

The displacement versus time results for the anchor pullout tests conducted at the University of Florida and the University of Stuttgart are presented in Appendix K. A sample is provided as Figure 46. It can be seen from the sample plot that the higher stress level tests have steeper slopes (creep rate) and fail more quickly than the lower stress level curves with shallower slopes.

Core Sample Analysis

Several anchors were cored and then split open for investigation of the failure surface. Most were anchors that had failed but a few were anchors from tests that were terminated before failure. The photos and discussion can be found in Appendix H. Only a few typical examples will be discussed here.

Several anchor tests that were terminated prior to failure were investigated and two different events occurred when splitting the core sample. The adhesive B samples (Figure 47) fractured through the concrete on one side of the anchor indicating that the adhesive bond between adhesive B and the steel and the concrete as well as the internal cohesive bonds were stronger than the tensile strength of the concrete. Adhesive C samples (Figure 48) separated between the steel and the adhesive indicating that the bond between the adhesive and the concrete was stronger than the bond between the adhesive and the steel.

For short-term and long-term tests where failure occurred, two common failure modes were loss of adhesion with the concrete (Figure 49) and shearing failure along the threads (Figure 50).

A common variant of the adhesive bond failure was seen in many tests in which, in some cases, it appears the adhesion

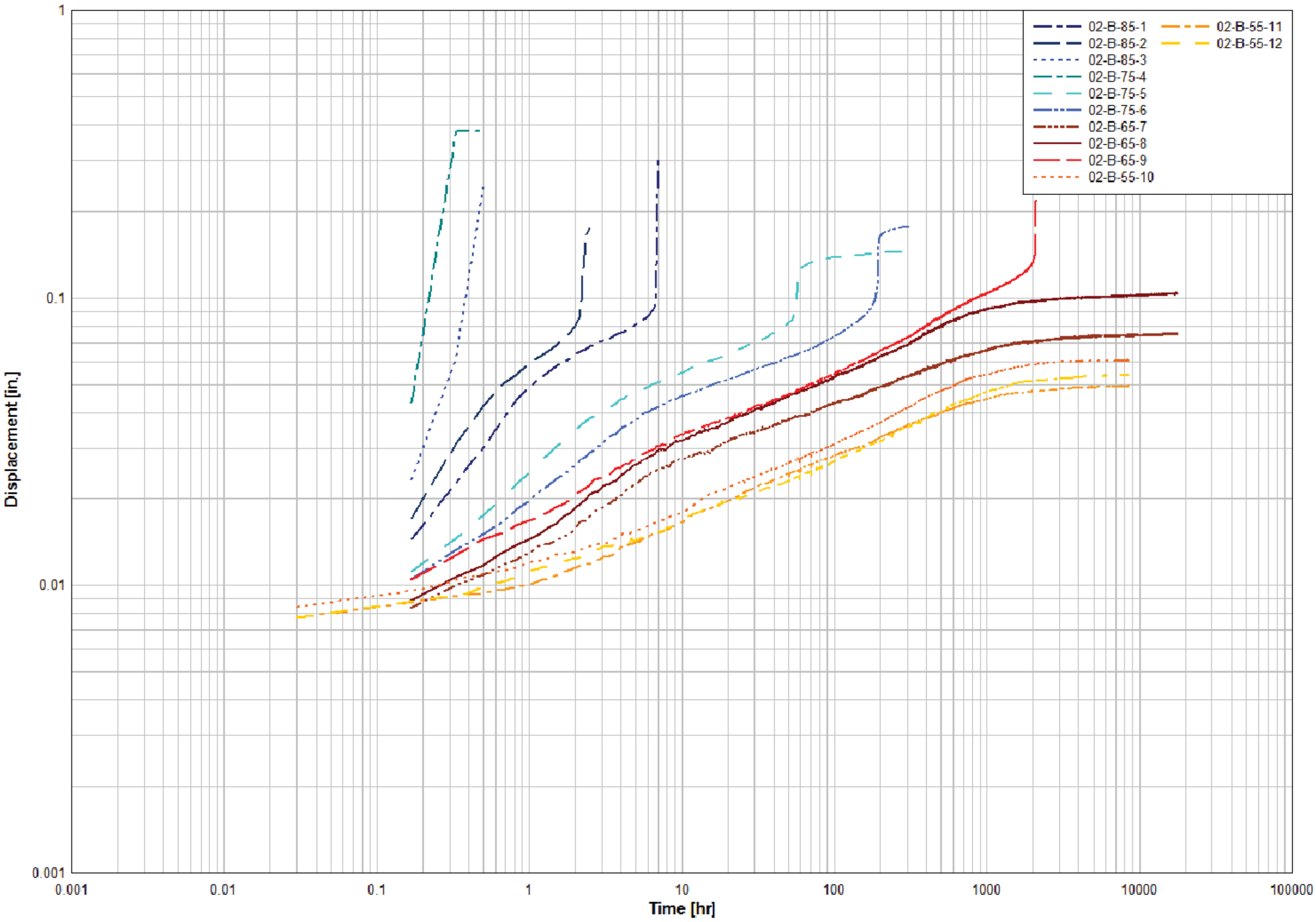


Figure 46. TS02B (US Baseline B) displacement versus time plot.

Figure 47. Typical terminated sample for adhesive B.

Figure 48. Typical terminated sample for adhesive C.

Figure 49. Typical adhesive bond failure.

Figure 50. Typical shearing failure at threads.

Figure 51. "Plug and reattachment" failure with thread separation.

Figure 52. "Plug and reattachment" failure with concrete fracture.

with the concrete failed and a "plug" of the anchor with the adhesive still attached slipped in the hole. In other cases, portions of the adhesive also fractured within the bond line. The adhesive "plug" eventually stopped due to friction and reduction in load as the spring relaxed. As the anchor remained in the chamber, portions of the adhesive "plug" appeared to reattach to the concrete. When the sample was cored and split, either portions of the adhesive detached from the threads (Figure 51) or portions of the concrete fractured (Figure 52).

The reattachment can be supported by the fact that many of the samples in Appendix H show large displacements (½"–1") after failure with one side still attached to the core after splitting. It is not reasonable that the adhesive could displace this much and stay bonded to the concrete and steel. Rather the adhesive would have to debond and/or fracture, shift, and then reattach. Many of the samples remained in the 110°F (43°C) chamber for a few days prior to removal. Additionally, many of the cores were not made until months after the tests concluded. This provided ample time at elevated temperatures for the adhesive to reattach.

Anchor Pullout Testing Stress versus Time-To-Failure Test Results

The stress versus time-to-failure (SvTTF) results for the anchor pullout tests conducted at the University of Florida and the University of Stuttgart are presented in Appendix L.

Model Equation for Stress versus Time-to-Failure Relationship

The SvTTF projection as listed in AASHTO TP 84-10 recommends a logarithmic model. For comparison a logarithmic model ($\sigma = m\ ln(t) + b$) and a power model ($\sigma = At^B$) were both evaluated and they resulted in essentially the same coefficient of determination (R^2). It was decided to use the logarithmic model as recommended in AASHTO TP 84-10.

Exclusion of Short-Term Tests in Stress versus Time-to-Failure Relationship

The short-term tests were initially expected to be included on the SvTTF curve, but based on the distribution of stress along the borehole, analysis of the test results, and investigation of failure modes, it was decided to not include the short-term test results in the SvTTF projection.

Based on analytical work by McVay et al. (1996), Figure 4 to Figure 7 show that at low stress levels (<30% of MSL) the adhesive is still in the elastic range. At about 70% of MSL, the adhesive has undergone inelastic redistribution of stress along the entire length of the anchor. Under high stress level sustained load conditions, the coupling of creep strains caused by the sustained load and strains caused by inelastic redistribution of bond stress seem to hasten the failure.

As an example, Figure 53 and Figure 54 show the results of TS01B (Baseline B) with the short-term tests excluded and

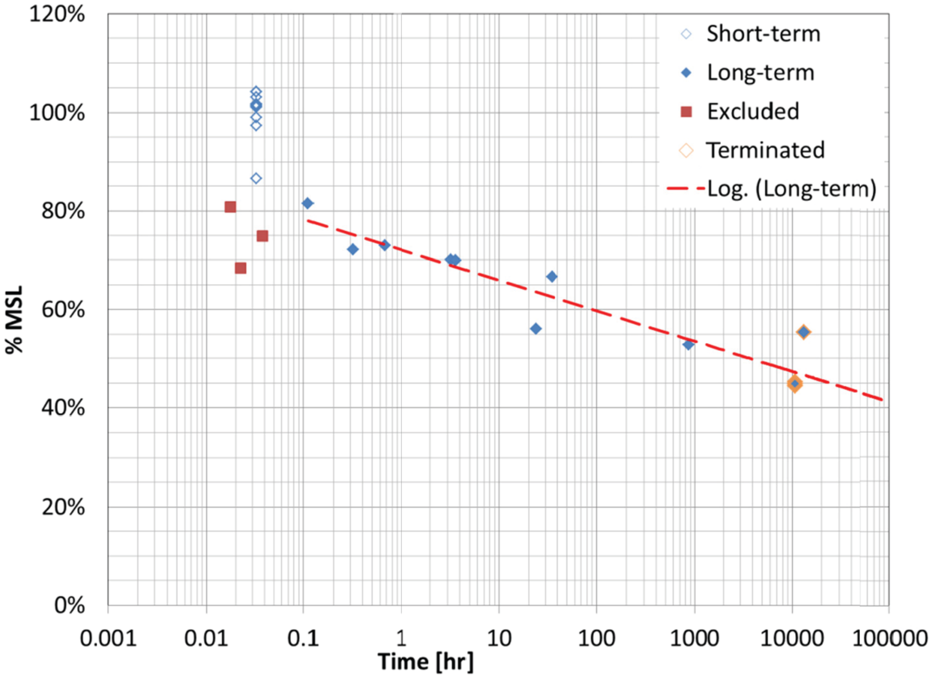


Figure 53. Baseline TS01B SvTTF plot with short-term tests excluded from the projection.

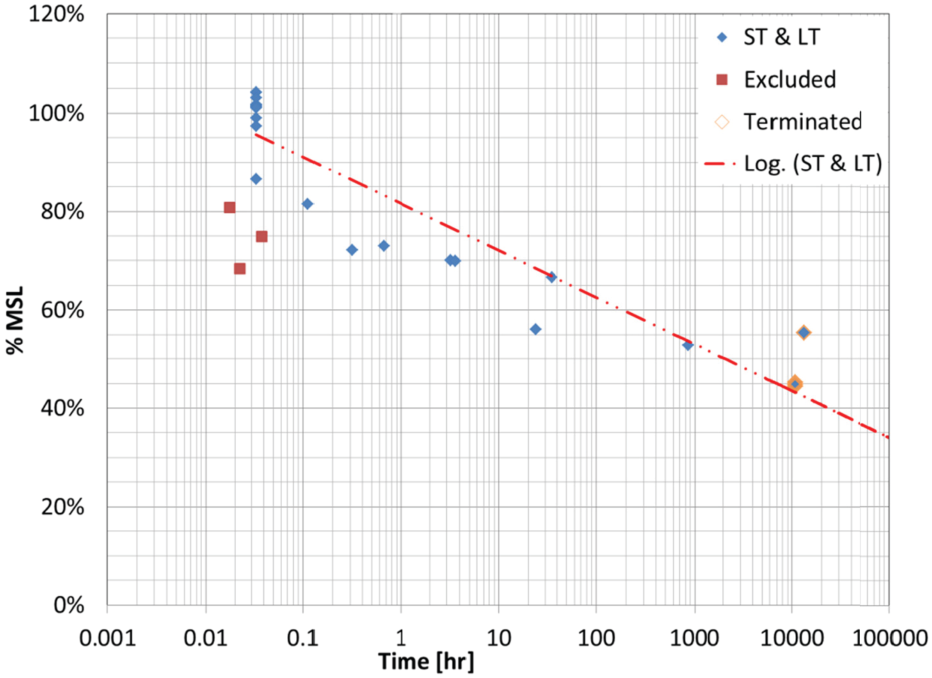


Figure 54. Baseline TS01B SvTTF plot with short-term tests included in the projection (ST = short term, LT = long term).

Table 37. Expected failure stress level at 5-minute load duration for baseline tests with short-term tests excluded in the SvTTF projection.

Test Series	Expected Failure Stress Level at 5-Minute Load Duration (%MSL)
TS01A	78
TS01B	79
TS01C	80
TS02A	71
TS02B	88
TS02C	76
A-combined	75
B-combined	82
C-combined	78

included in the projection, respectively. By inspection it can be seen that the trend of the sustained load tests on Figure 53 does not intersect the data points of the short-term tests at 100% of MSL. Appendix L (pages L-2 to L-7) provides SvTTF figures showing all baseline data with trendlines including and not including the short-term tests.

Using the constants from the regression analysis, the expected failure stress level for a 5-minute load duration for TS01B is 79% of MSL. Table 37 summarizes the expected failure stress levels at a 5-minute load duration from the regression analysis for the six baseline tests and from three baselines created by combining the results from US and UF.

Table 38. Peak displacement data for short-term (ST) and sustained load (LT) tests for UF baselines.

Test Series	ST Mean (in.)	ST COV	LT Mean (in.)	LT COV	Ratio LT/ST
Baseline A	0.043	0.09	0.059	0.15	1.4
Baseline B	0.051	0.08	0.100	0.26	2.0
Baseline C	0.046	0.11	0.102	0.29	2.2

This reduced expected failure stress level for short-duration loads appears to result from a dual requirement placed on the polymer. The magnitude of the load causes the polymer to undergo inelastic deformation as it redistributes the load down the anchor, and the sustained nature of the load causes the polymers to migrate within the adhesive. These two actions occurring simultaneously reduce the capacity.

The lower stress level sustained load tests provide sufficient time for the polymer strands within the adhesive to slide past each other. This is supported by the much larger deformations seen in the sustained load tests than in the short-term tests as polymer strand migration leads to creep deformation and higher rupture displacements. For the UF baseline tests, the peak displacements in the sustained load tests were approximately ⅓ higher than the peak displacements in the short-term tests for adhesive A and double for adhesives B and C (Table 38 and Figure 55). If the peak displacements in the sustained load are compared to the limiting displacement (Δ_{lim}) at loss of adhesion as calculated in ACI

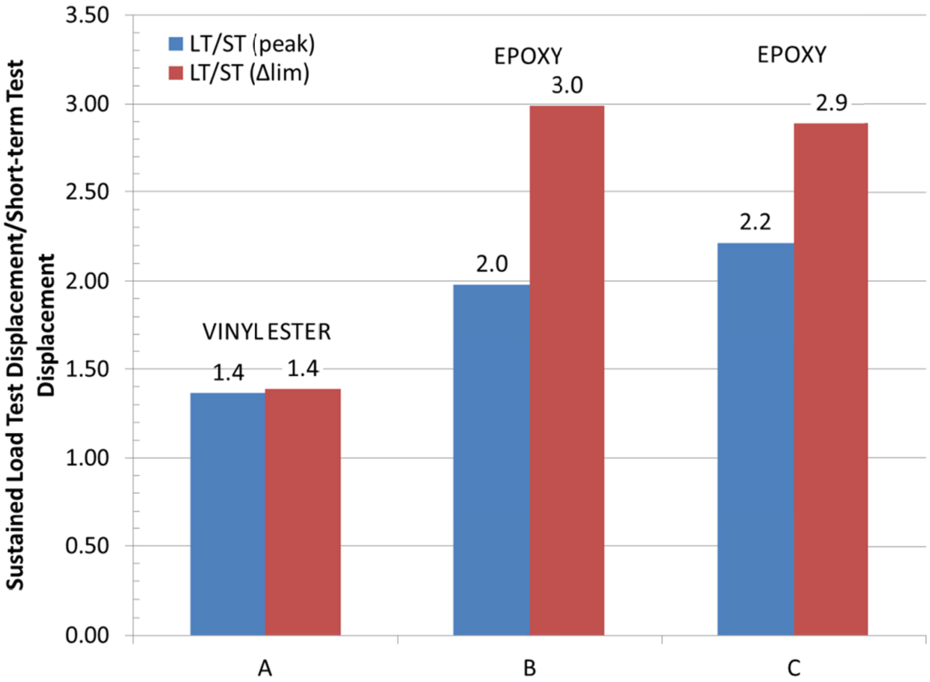


Figure 55. Ratio of sustained load test failure displacements to short-term test failure displacements for UF baselines.

Table 39. Displacement data at loss of adhesion per ACI 355.4 for short-term (ST) tests and peak displacement data for sustained load (LT) tests for UF baselines.

Test Series	ST Mean (in)	ST COV	LT Mean (in)	LT COV	Ratio LT/ST
Baseline A	0.042	0.15	0.059	0.15	1.4
Baseline B	0.034	0.19	0.100	0.26	3.0
Baseline C	0.035	0.14	0.102	0.29	2.9

355.4, the ratio for adhesives B and C approaches 3 (Table 39 and Figure 55).

Figure 56 and Figure 57 present the displacements versus time to failure and %MSL respectively for the short-term and sustained load tests for all three UF baseline tests. These figures show that failure displacements are larger for lower stress levels and longer time to failures.

Based on the above discussion, it was decided to exclude the short-term test results from the SvTTF relationships in anchor tests. Subsequently, the analysis for sustained load sensitivity to various parameters was based on projections derived only from sustained load test results. It should be noted that projections were also performed including short-term tests in the projections for each test series and similar conclusions were drawn.

Figure 58 to Figure 71 present the SvTTF results for test series 3 through 16 respectively with short-term results excluded from the projections. The same graphs as well as the data are presented in Appendix L.

Combined SvTTF Baseline Curves

Figure 72 to Figure 74 present the individual and combined baseline curves from UF and US for the three adhesives, respectively. Since different anchor diameters and embedment depths were used at the two laboratories, the stresses have all been normalized by the average of the 15 short-term bond stresses (10 at UF and 5 at US).

At the time of publication, TS10 had one stress level underway. Due to this limited data, TS10 has a SvTTF chart included in Appendix L, but there was not sufficient data to generate an experimental baseline.

Rejection of Failures During Loading

Several of the tests failed during the loading period prior to reaching the desired sustained load. It was decided that those tests that failed during loading were not reliable and were excluded from the time-to-failure projection.

Tests Terminated Prior to Failure

Several tests were terminated prior to failure per approval by this project's NCHRP panel. These tests were identified as not likely to fail during the remainder of the testing program and their continued monitoring would not provide any more meaningful results than had already been obtained. The tests identified for early termination are listed below and are identified in the SvTTF plots with a diamond and their test durations listed in the tables in Appendix L.

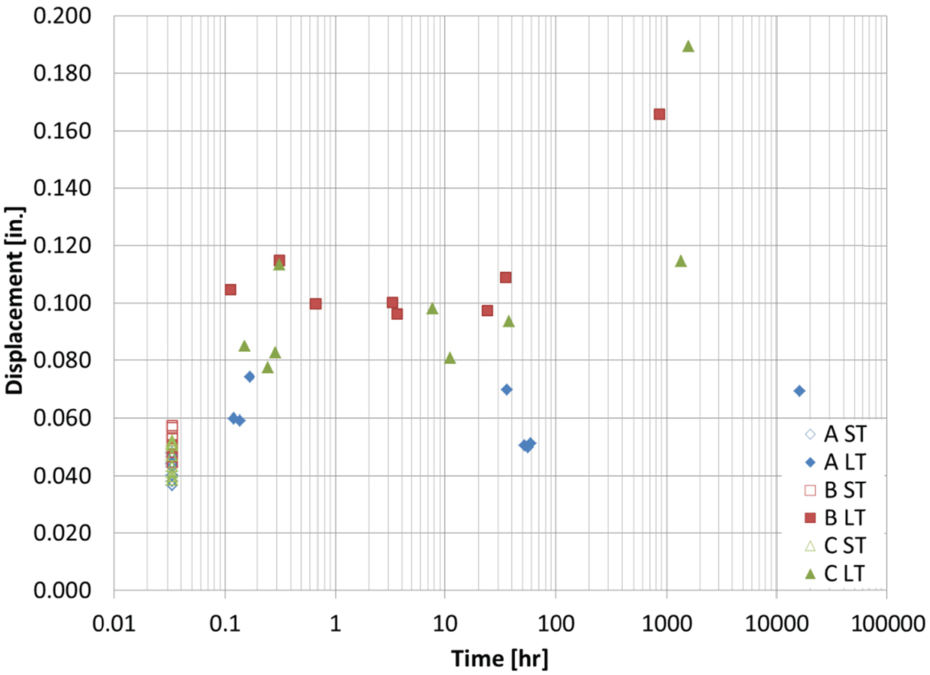


Figure 56. Failure displacement versus time to failure for all three UF baseline tests.

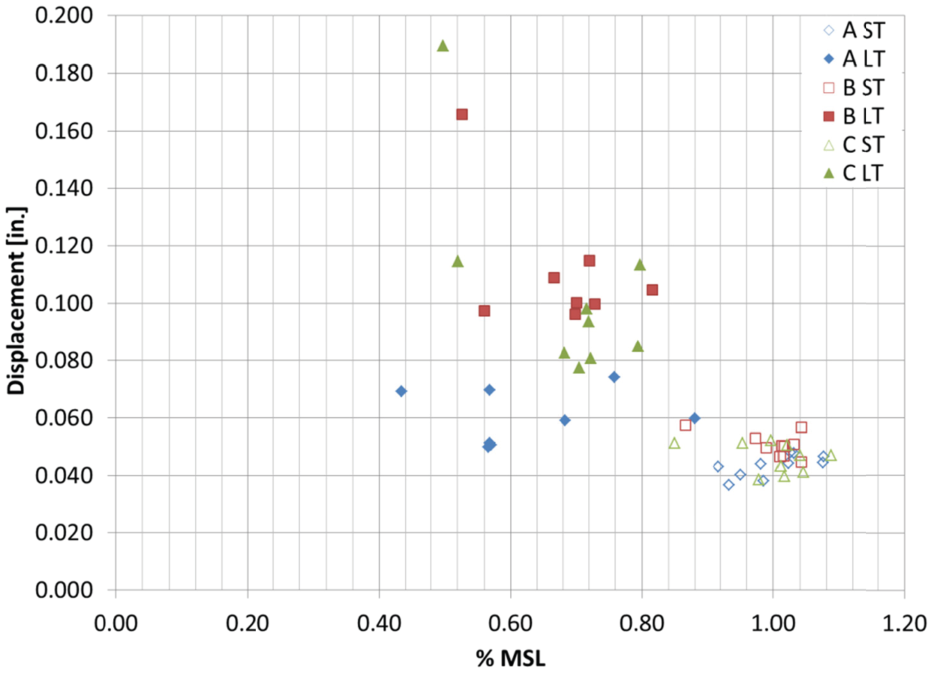


Figure 57. Failure displacement versus %MSL for all three UF baseline tests.

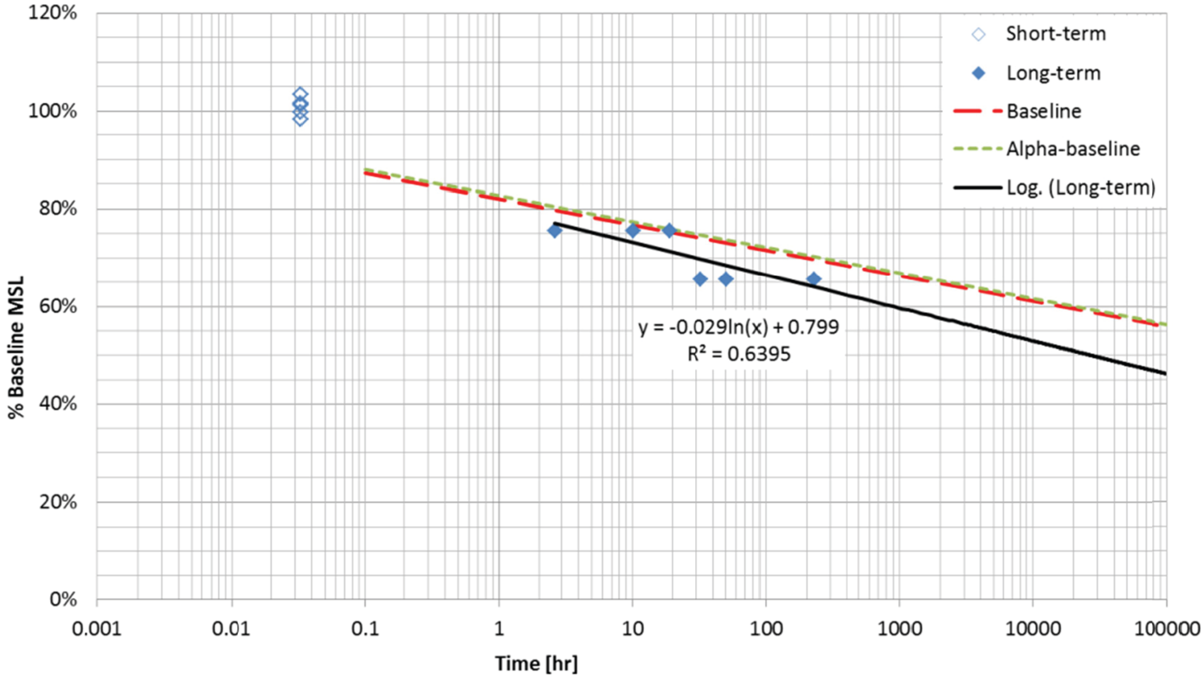


Figure 58. SvTTF TS03-B service temperature (120°F).

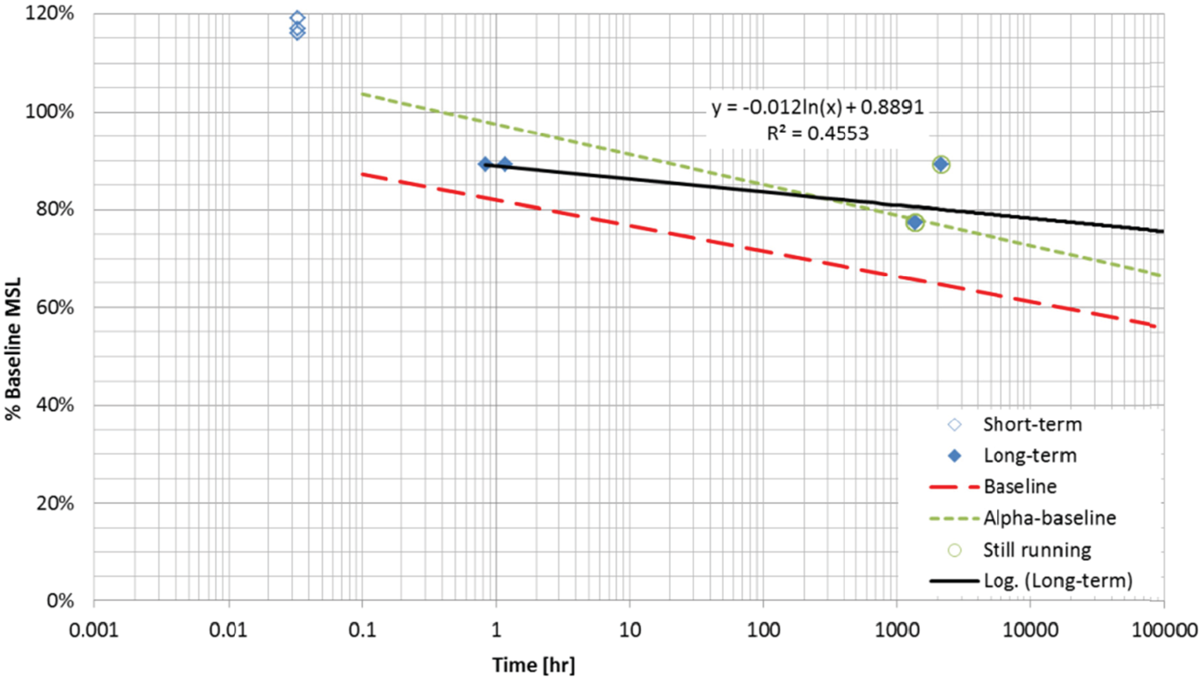


Figure 59. SvTTF TS04-B service temperature (70°F).

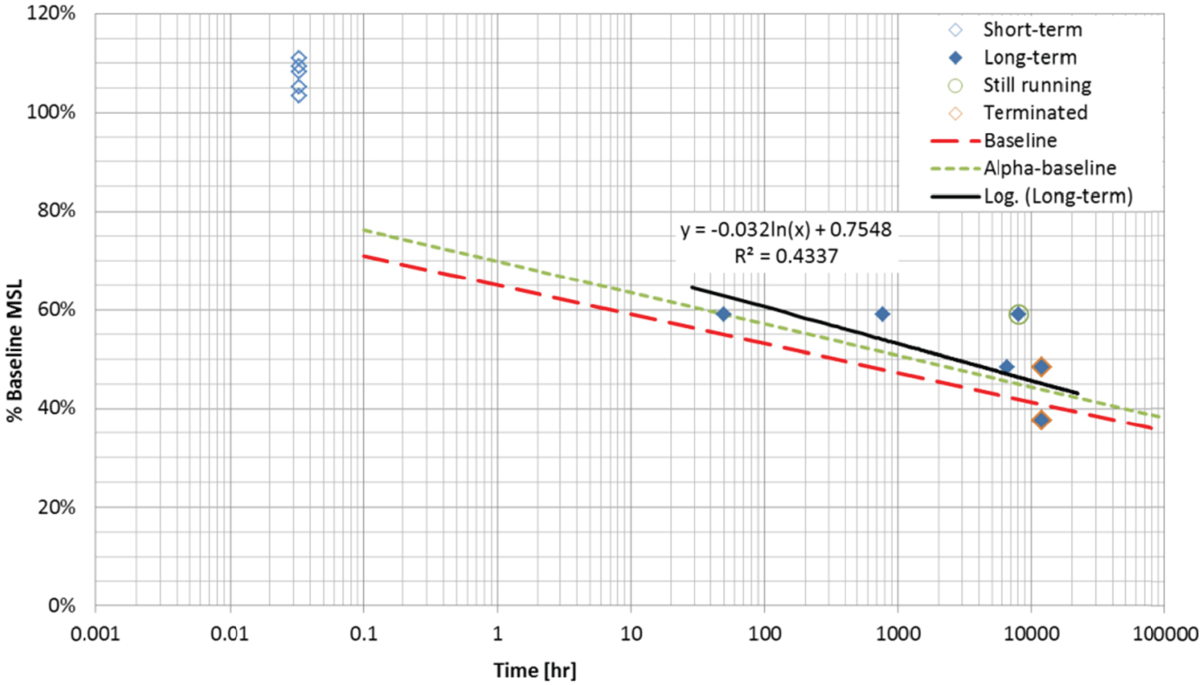


Figure 60. SvTTF TS05-A installation direction (horizontal).

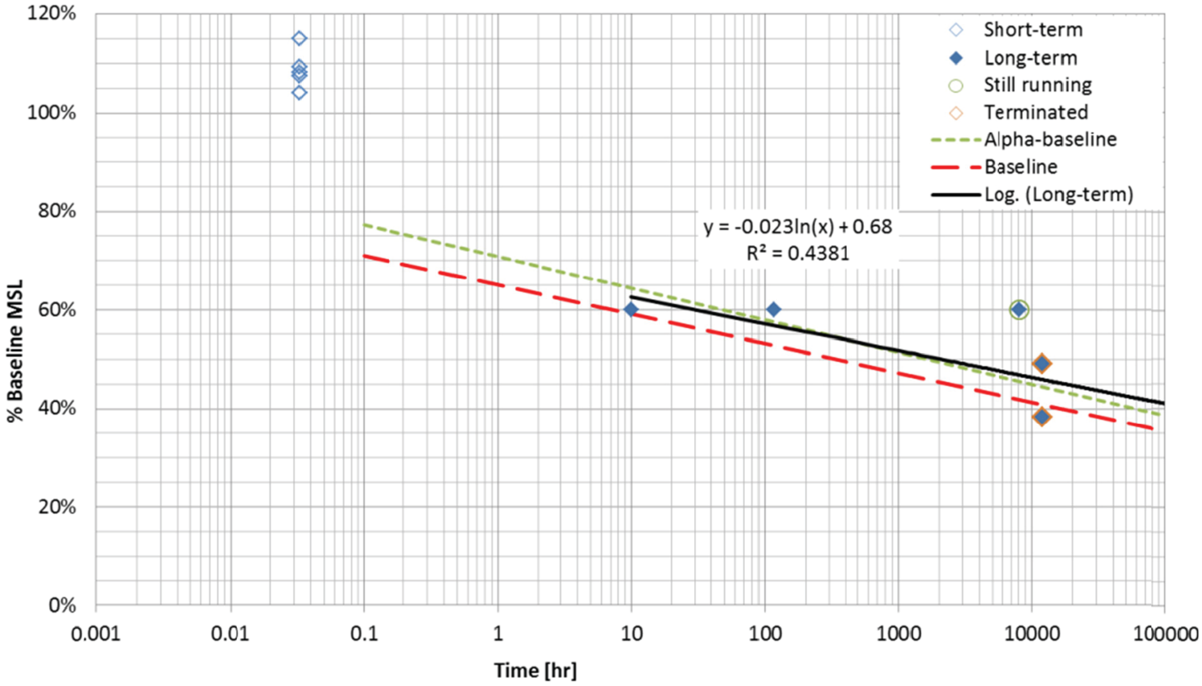


Figure 61. SvTTF TS06-A installation direction (vertical).

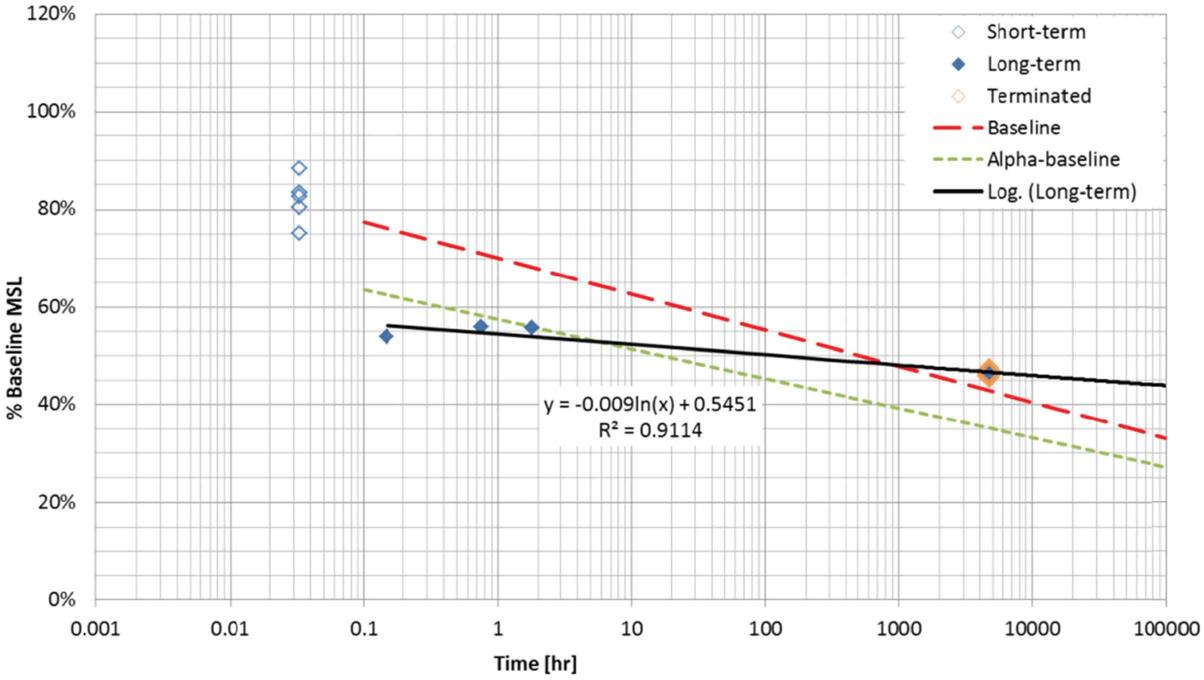


Figure 62. SvTTF TS07-A moisture during installation.

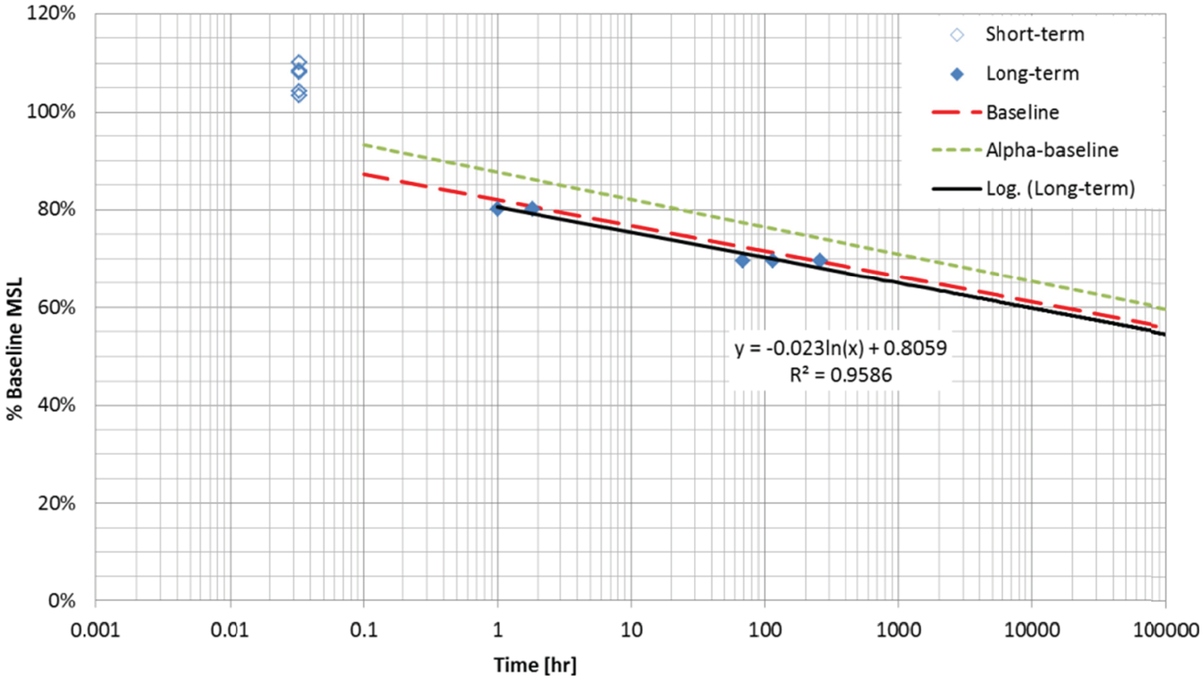


Figure 63. SvTTF TS08-B moisture in service.

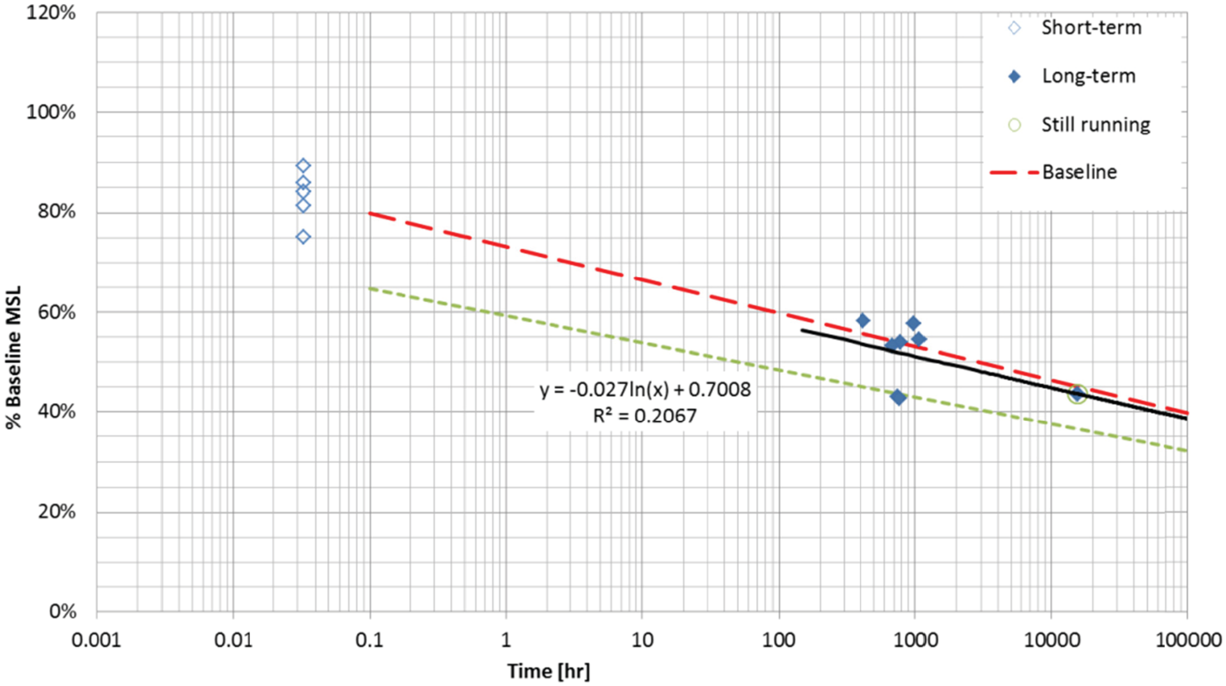


Figure 64. SvTTF TS09-C reduced hole cleaning.

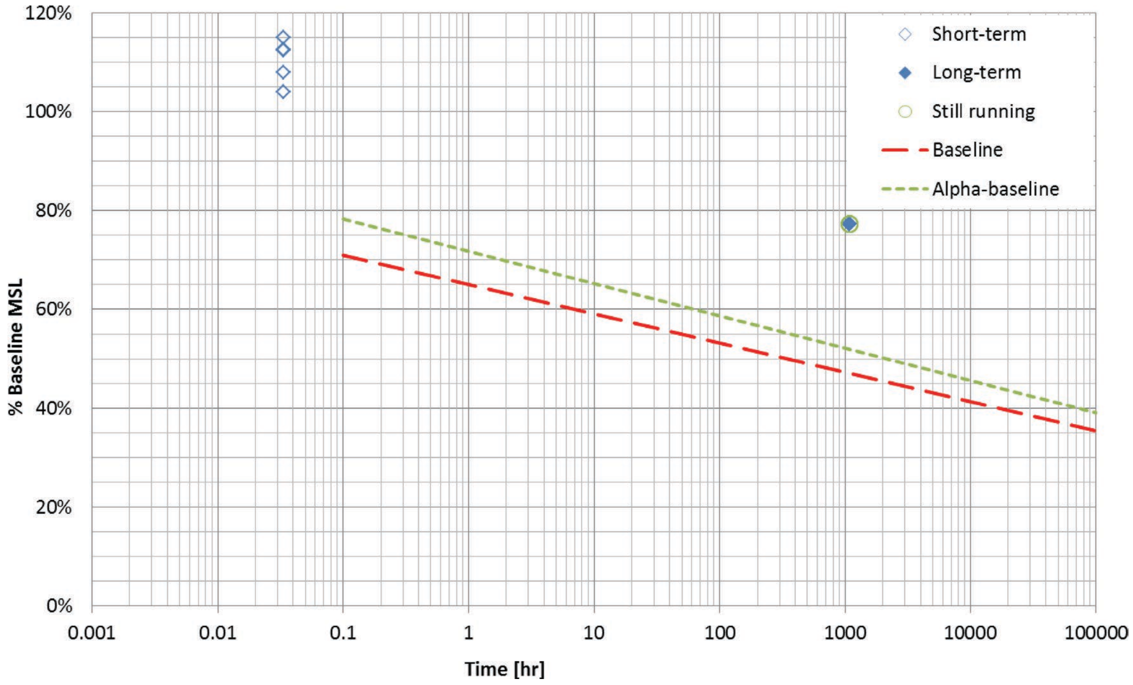


Figure 65. SvTTF TS10-A installation temperature (mfr minimum/mfr minimum).

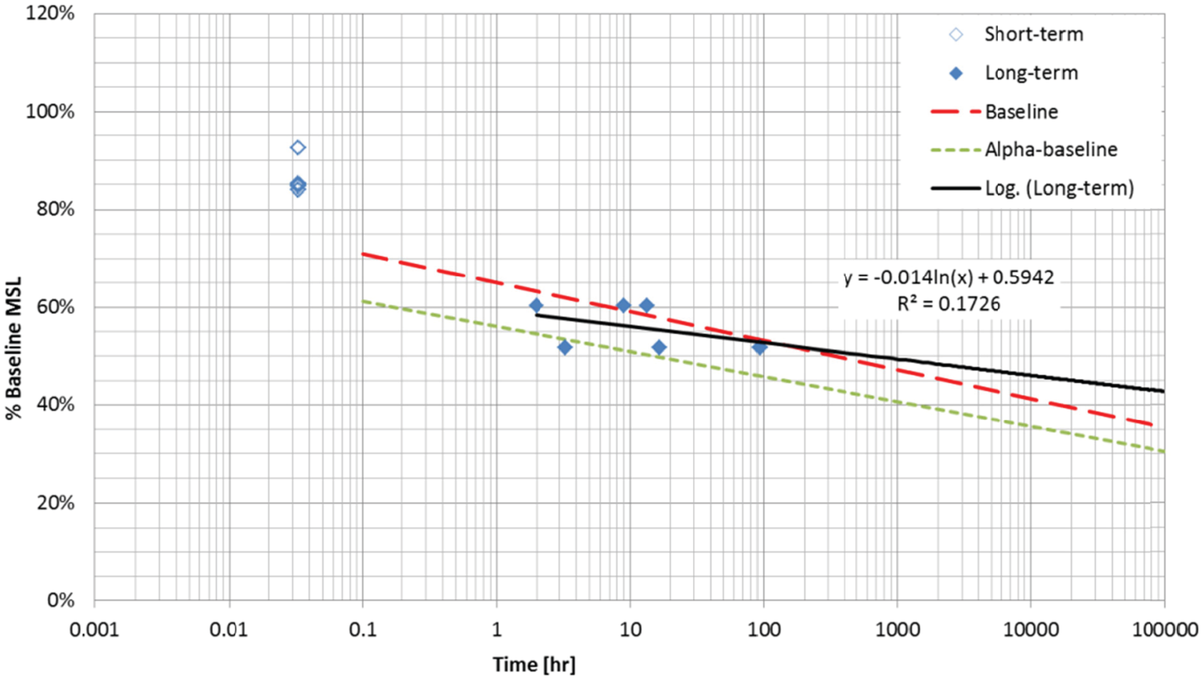


Figure 66. SvTTF TS11-A installation temperature (mfr minimum/110°F).

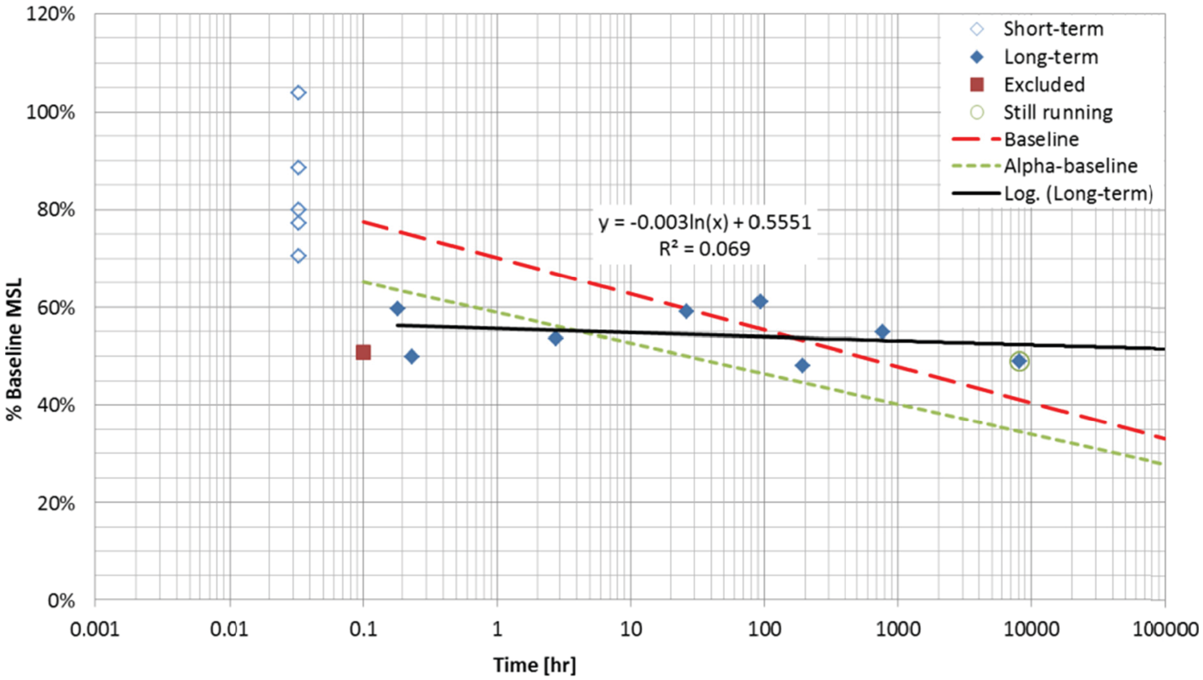


Figure 67. SvTTF TS12-A standard DOT mix.

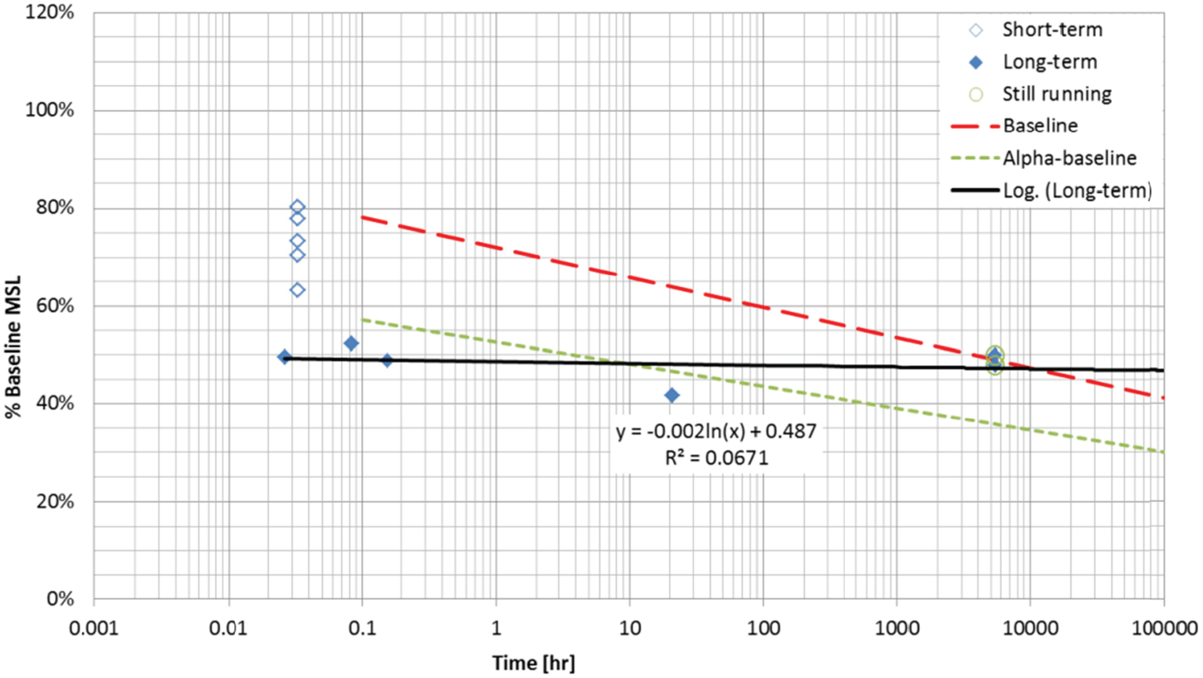


Figure 68. SvTTF TS13-B core drilling.

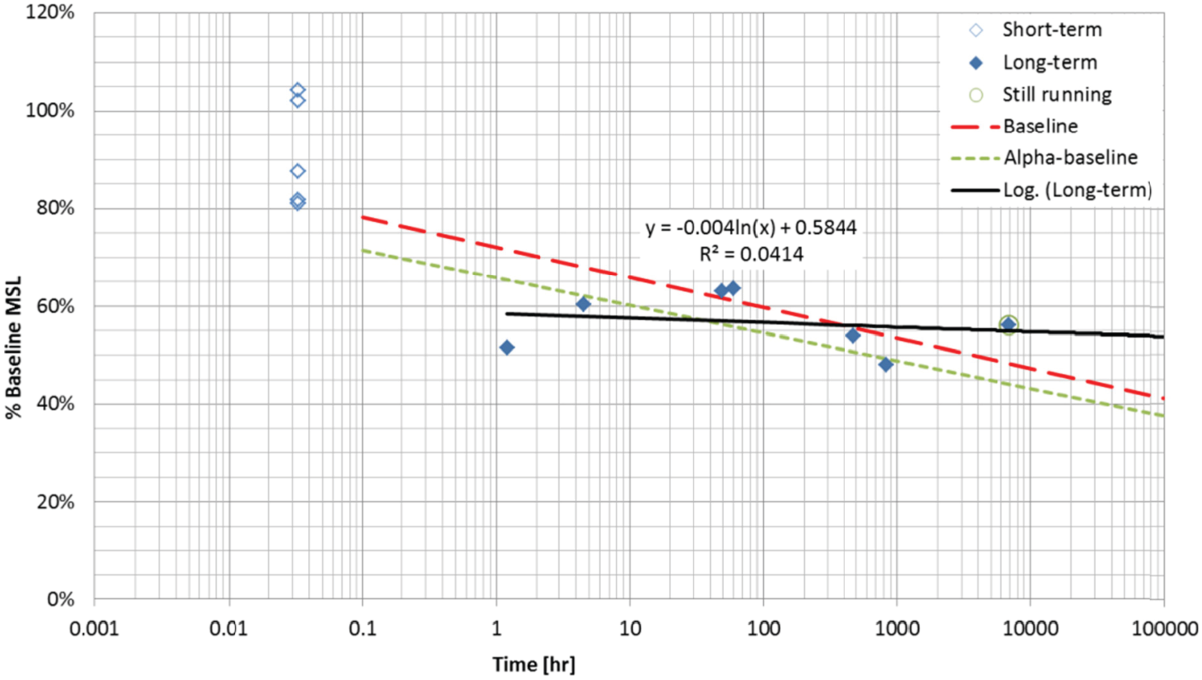


Figure 69. SvTTF TS14-B fly ash.

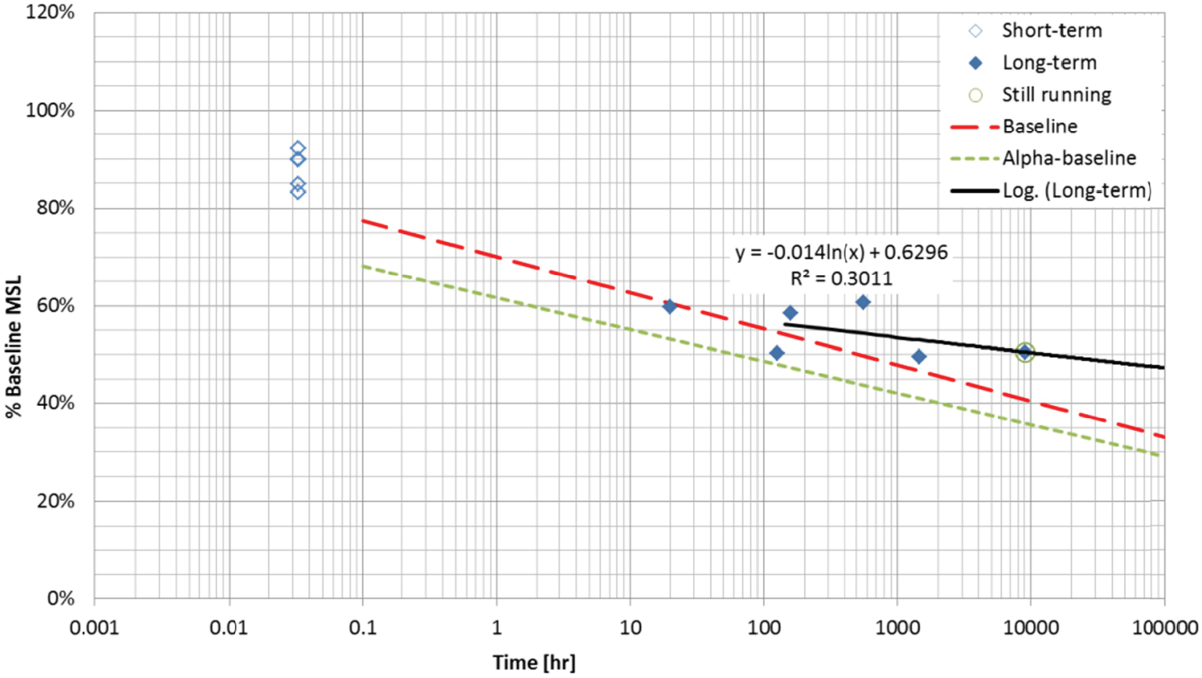


Figure 70. SvTTF TS15-A blast furnace slag.

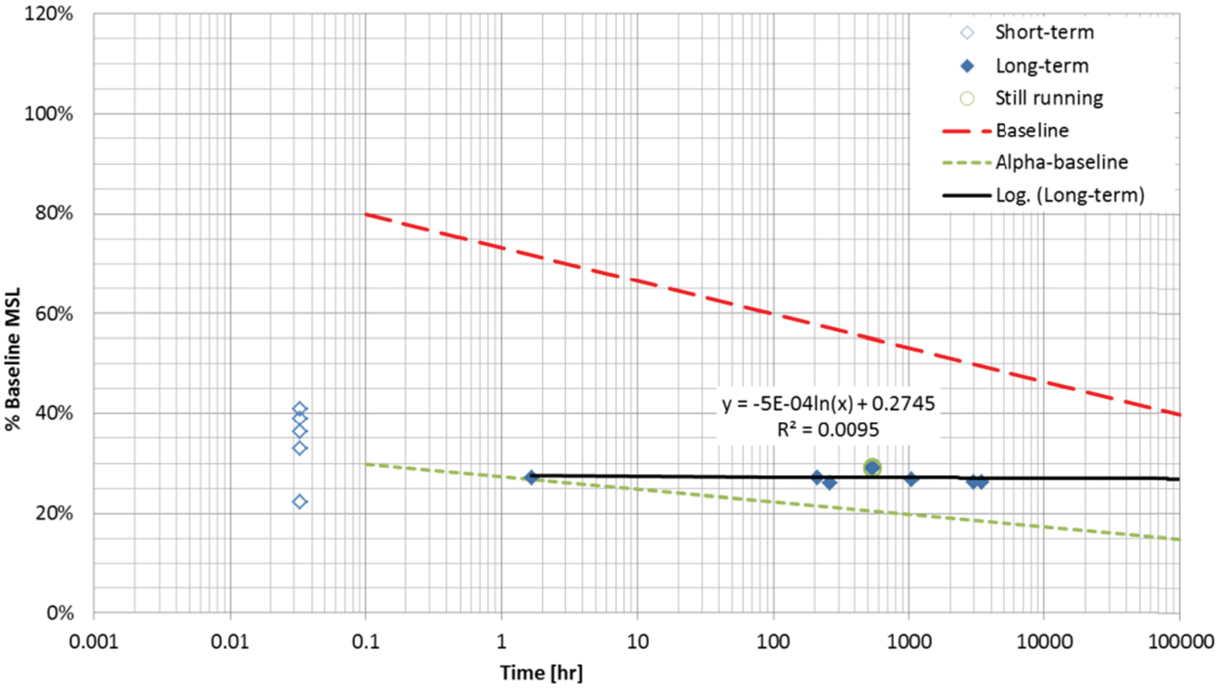


Figure 71. SvTTF TS16-C unconfined setup.

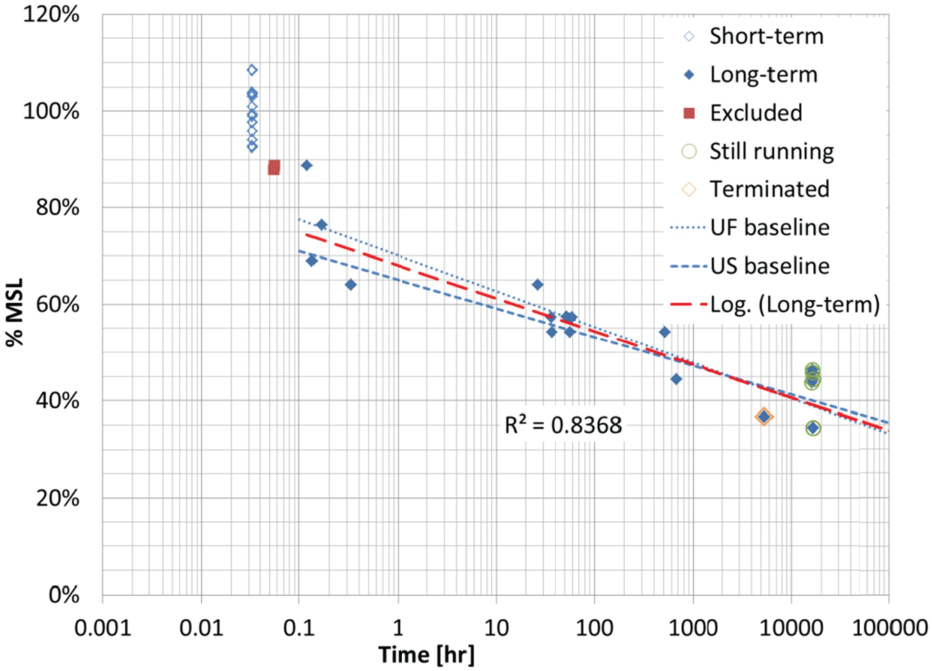


Figure 72. Combined baseline SvTTF for adhesive A normalized by the average bond stress of the short-term tests from UF and US.

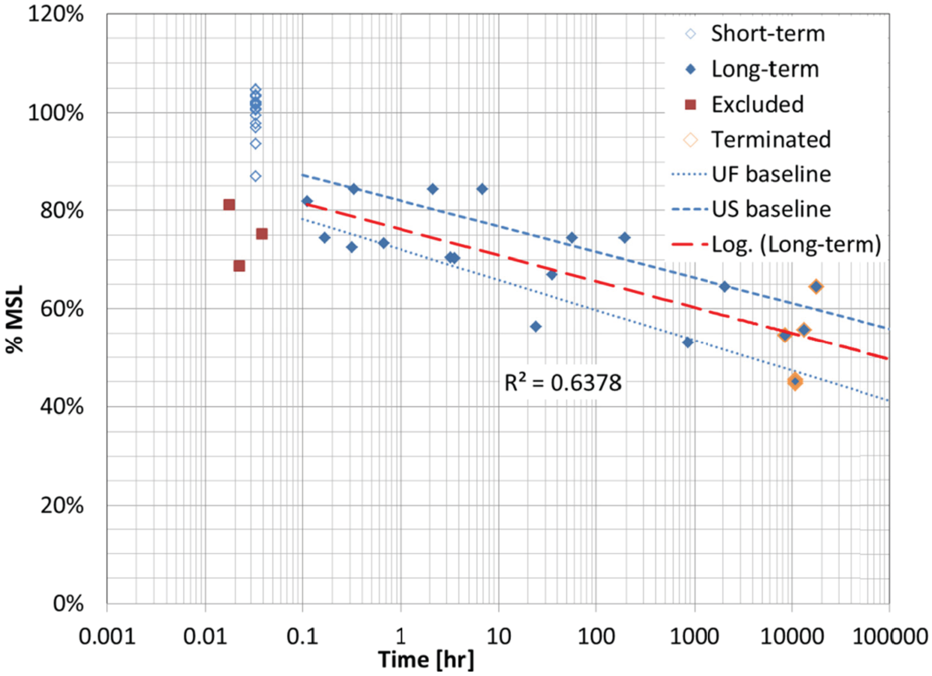


Figure 73. Combined baseline SvTTF for adhesive B normalized by the average bond stress of the short-term tests from UF and US.

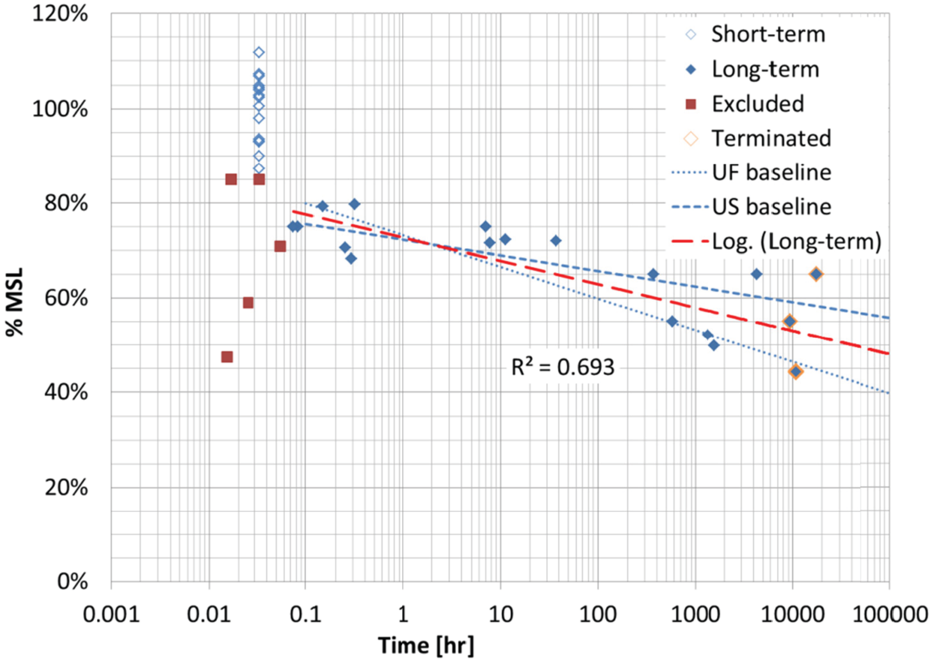


Figure 74. Combined baseline SvTTF for adhesive C normalized by the average bond stress of the short-term tests from UF and US.

Tests Still Running at Time of Publishing

Those tests that were still running at the time this report was completed were included in the SvTTF plots with the current test duration and are identified with a circle and their test durations listed in the tables in Appendix L.

Adhesive-Alone Testing

Short-Term Results

The short-term test results for the dogbone specimens are presented in Appendix I. For the baseline test series, both adhesives A and C exhibited brittle failures. Adhesive B was more ductile, failing at much higher strains and loads. For test series 22 using MPII cure time, adhesive A showed a slight increase in strength. Adhesive B had strengths about one half of what was seen in the week-cured specimens with significant scatter in the results (COV = 0.47) due to the fact that the testing temperature was so close to the glass transition temperature. Adhesive C would break in the grips of the testing machine due to its high brittleness and was therefore unable to be tested.

The alpha-reduction factors for the influence of cure time are presented in Table 40. Adhesives A and B were initially both chosen for sustained load investigation for test series 22, but due to the large ductility in the adhesive B manufacturer-cured samples the tests could not be conducted.

Table 40. Summary of alpha-reduction factors.

Test Series		Adhesive A	Adhesive B	Adhesive C
22	Manufacturer Cure Time	1.05	0.54	---

Note:
Short-term test results for adhesive C were not able to be obtained for the manufacturer cure time due to the brittleness of the material and its tendency to break when loaded into the Instron.

DMTA Results

For the initial characterization of the adhesives, measurements were conducted using a sinusoidally oscillating stress. The resulting strain was measured, and the component of the strain (ε') in-phase with the applied stress (σ) was recorded and used to calculate the storage modulus (G') by:

$$G' = \sigma/\varepsilon'$$

The first set of experiments was a temperature ramp at a speed of 5 degrees per minute at 1 Hz on the DSR machine and the results of samples A, B, and C are shown in Figure 75, Figure 76, and Figure 77, respectively. Adhesive A showed a very broad and slow decrease of its shear storage modulus (G'), which is the typical behavior of a non-crosslinked vinyl ester with wide range of molecular weight distribution. Both adhesives B and C displayed a plateau in their storage modulus at a temperature above their T_g, which indicated a crosslinked system. A narrower half width of the tan delta peak in sample C suggested a more homogenous crosslink network. Crosslinks are chemical bonds formed in the adhesive during the curing reaction that cause the adhesive to harden. Crosslinks restrict molecular motion, and thus crosslinks cause increased resistance to creep.

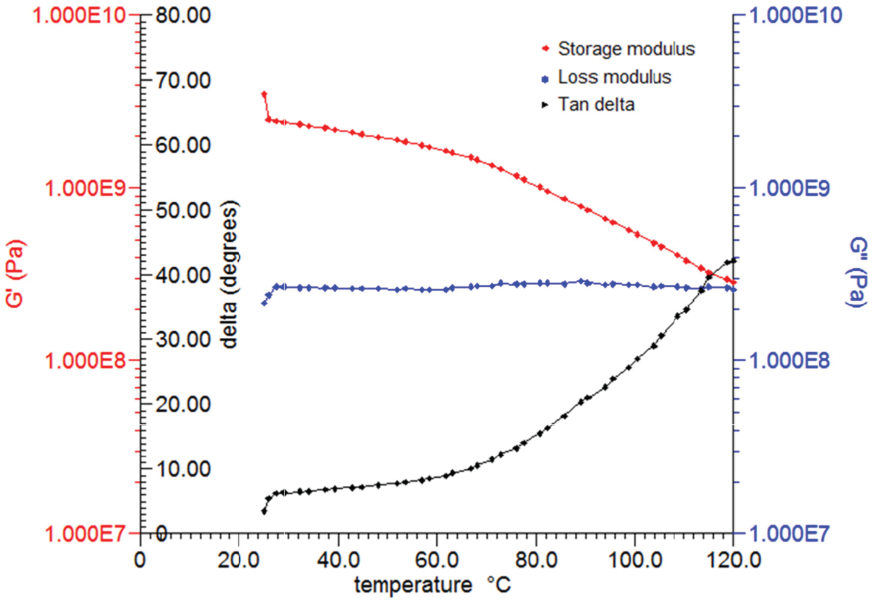


Figure 75. DMTA test results for adhesive A.

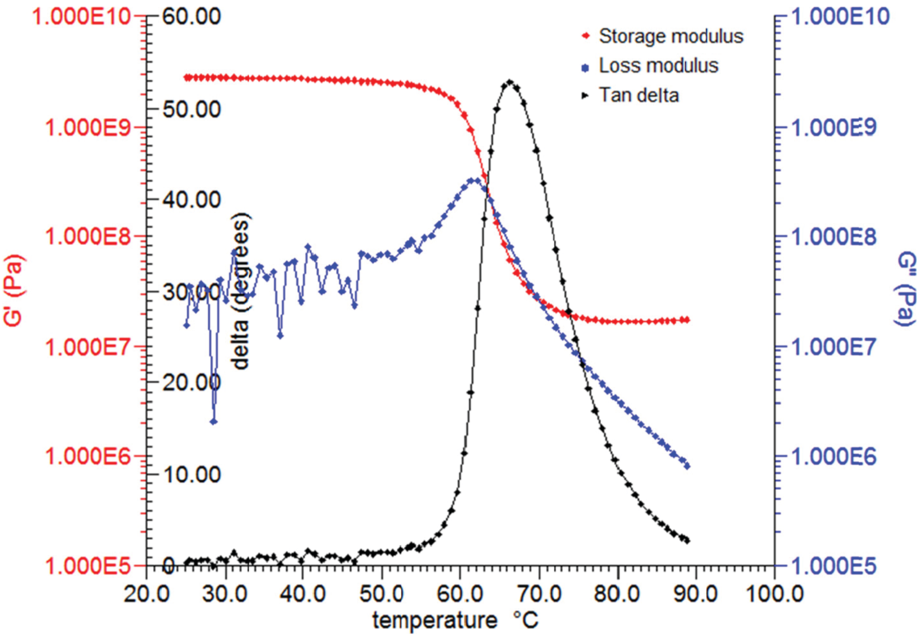


Figure 76. DMTA test results for adhesive B.

A thermogravimetric analysis was conducted on the samples that were heated under air from 68°F to 1,470°F (20°C to 799°C) at a rate of 18°F/min (10°C/min) while recording the weight change. These experiments were done to provide basic characterization of the adhesives. Adhesive polymers will start to decompose into gas at temperatures greater than their decomposition temperature [typically higher than 734°F (390°C)]. The decomposition was considered complete as evidenced by the fact that there was no weight change in the 1,290°F to 1,470°F (699°C to 799°C) range. The inorganic filler loading was calculated as the ratio of the final weight to the initial weight. The inorganic filler loading for the three samples was 60.0% for adhesive A, 38.9% for adhesive B, and 46.4% for adhesive C.

Sustained Load Strain versus Time Results

Figure 78, Figure 79, and Figure 80 present the baseline strain vs. time plots of adhesives A, B, and C obtained through the sustained load creep test on dogbone specimens. Because of the different stress levels, the strain plots are scattered.

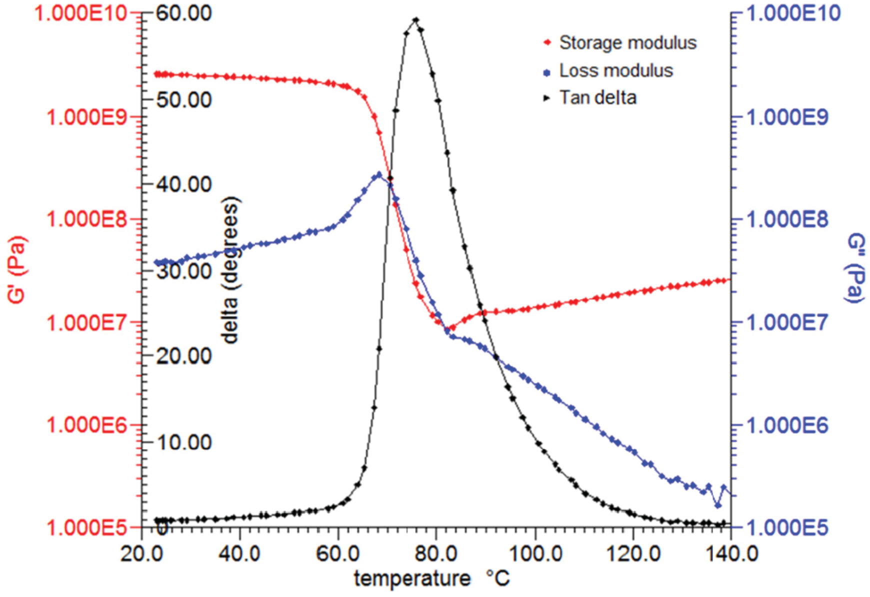


Figure 77. DMTA test results for adhesive C.

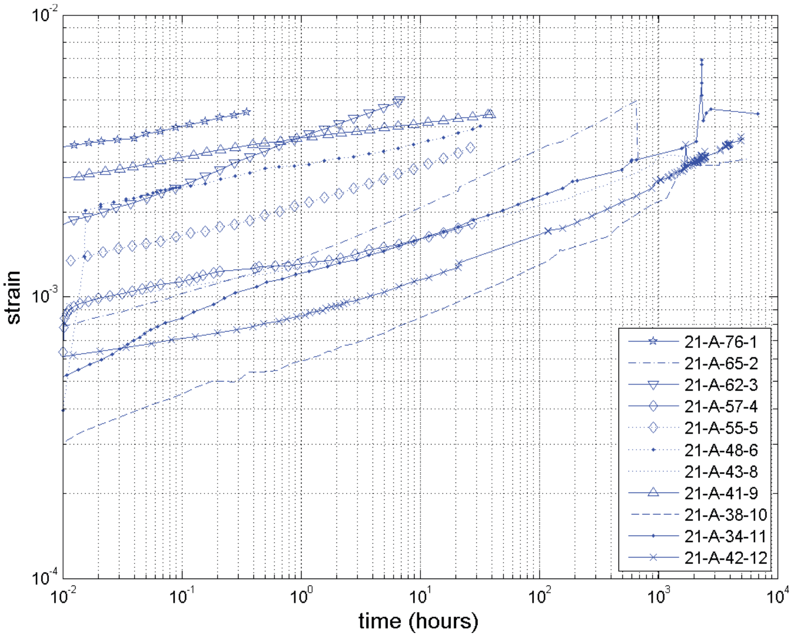


Figure 78. Adhesive A baseline strain vs. time plot for dogbone specimens.

Sustained Load Compliance versus Time Results

Normalizing the strains according to their stress, the compliance vs. time plots for all three adhesives are shown in Figure 81, Figure 82, and Figure 83. As the majority of the compliance curves of adhesive C overlap each other, this gives a good indication that time–temperature superposition should work for adhesive C. For adhesives A and B, the compliance curves at different stress levels differ from each other, indicating a nonlinear creep rate dependence on stress level.

Figure 84 presents the short-term creep response (log-log plot) of adhesive A obtained through DSR creep tests at different temperatures. Figure 85 presents the shifted creep

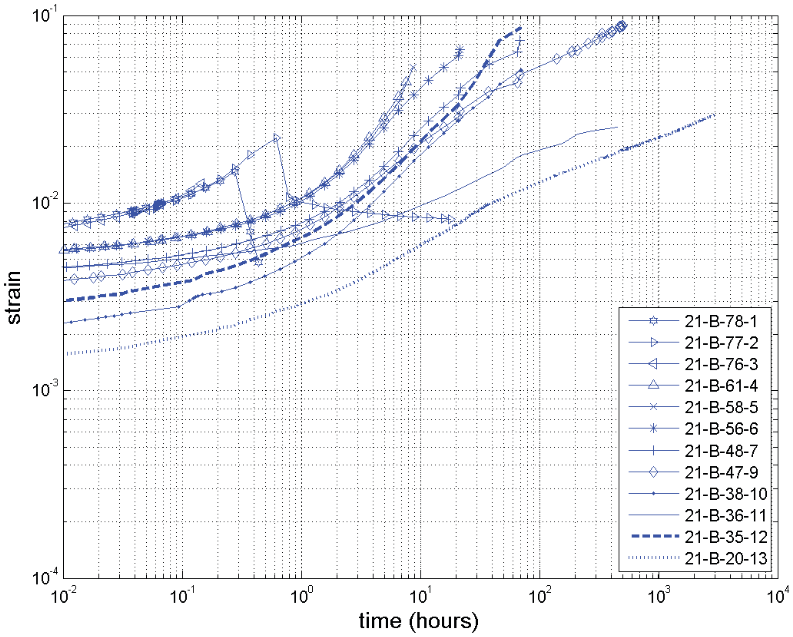


Figure 79. Adhesive B baseline strain vs. time plot for dogbone specimens.

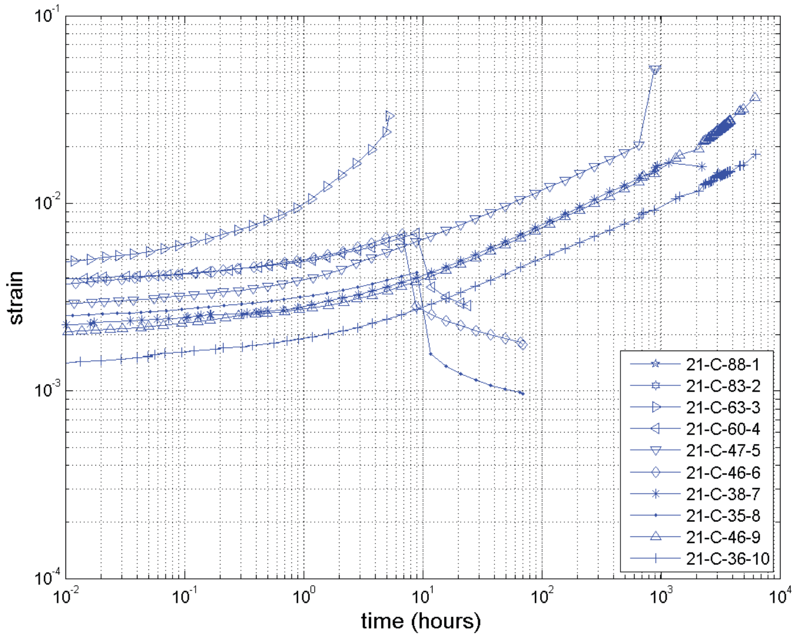


Figure 80. Adhesive C baseline strain vs. time plot for dogbone specimens.

response master curve at 110°F (43°C). Due to the nonlinear behavior observed during the long-term creep test of sample A and B, the short-term creep curves might also be accelerated by the applied stress or the resulted strain. If the shift factors were directly obtained through shift of the creep curve, the shift factor will be coupled with the applied stress during the short-term creep experiment. Since the frequency sweep measurements were conducted at very low strain levels, where the nonlinear behavior's effect is negligible in the linear viscoelastic region, the shift factor for time–temperature superposition was obtained by shifting the frequency sweeps at different temperatures. As a result, eight frequency sweeps from 0.1 Hz to 10 Hz were performed at the same temperature of the sustained load creep tests with a maximum oscillation

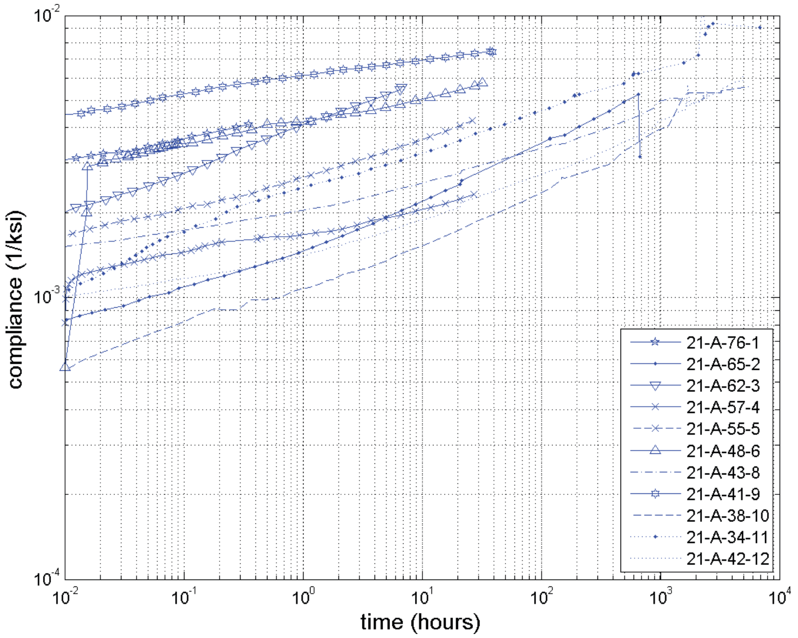


Figure 81. Adhesive A baseline compliance vs. time plot for dogbone specimens.

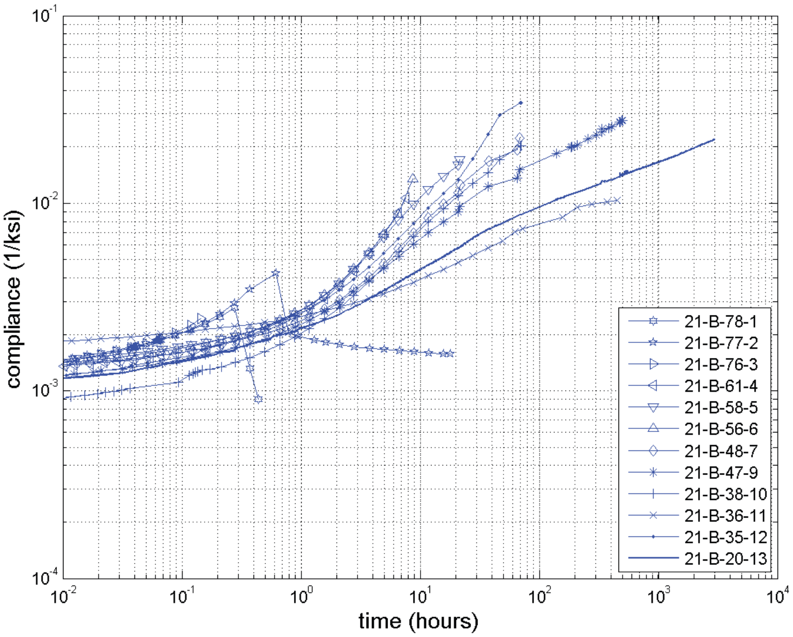


Figure 82. Adhesive B baseline compliance vs. time plot for dogbone specimens.

strain at 0.05% and shifted with 110°F (43°C) as the reference temperature. Using the shift factor obtained this way, the short-term creep tests of adhesive A shown in Figure 84 were shifted accordingly. The resulting master curve is shown in Figure 85.

Figure 86 presents the comparison of the long-term creep compliance curve of adhesive A to the shifted compliance curves from the short-term creep test. Please note that the compliance of the curves from the creep test is the shear compliance and when compared with tensile compliance obtained through the sustained load creep tests, the shear compliance was divided by $2(1 + \nu)$ where ν is the Poisson's ratio of the epoxy (taken as 0.4). From this comparison, it can be seen that the prediction from the DSR creep test captured

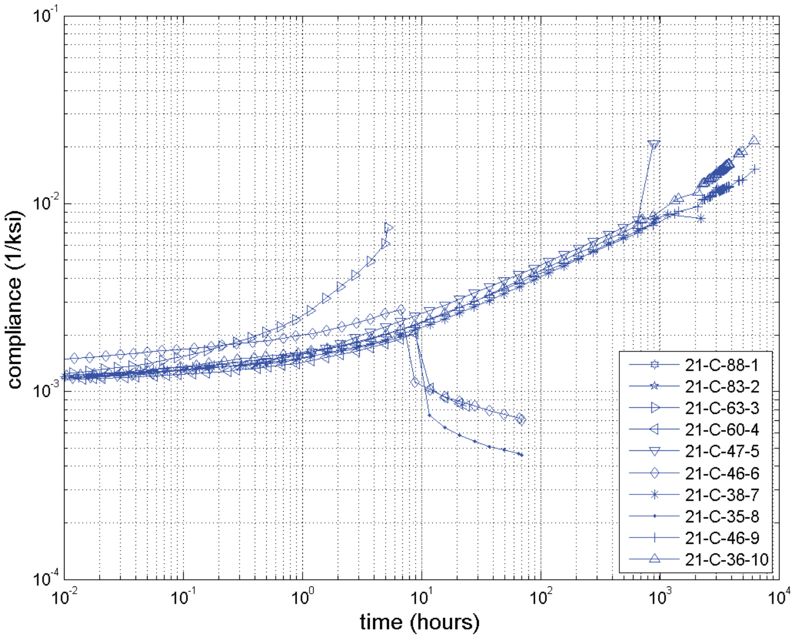


Figure 83. Adhesive C baseline compliance vs. time plot for dogbone specimens.

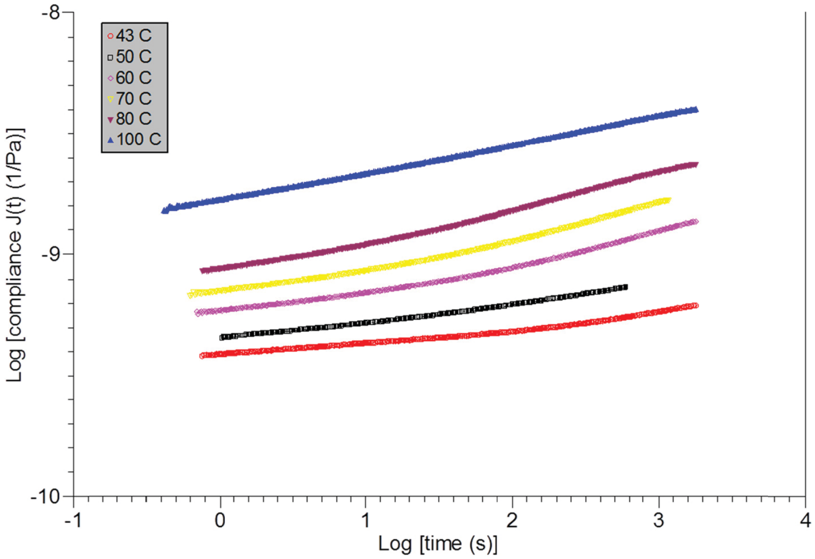


Figure 84. Compliance vs. time plot for DSR creep test of adhesive A at different temperatures.

the overall trend and shape of the adhesive creep. However, due to the dependence of compliance on the stress level, the prediction from the DSR creep test could not be used quantitatively for adhesive A.

Using the same treatment as described above for adhesive A, the short-term DSR creep tests of adhesive B shown in Figure 87 were shifted accordingly. The resulting master curve is shown in Figure 88.

The comparison between the compliance obtained from the sustained load creep test and the compliance predicted from the DSR creep tests is shown in Figure 89. As with adhesive A, the prediction from the DSR creep test could not be used to directly predict the creep behavior of the dogbone. An apparent trend in Figure 89 is, as the load was increased during the long-term test, the compliance increased at higher speeds over time, which should be due to the accelerating of the creep mechanism due to stress.

To investigate if there was any simple stress time superposition relation, five DSR creep tests on adhesive B with shear stress ranging from 72.5; 2,180; 2,900; 3,630 to 5,080 psi (0.5, 15, 20, 25, 35 MPa) were tested on the DSR machine. Any further increase of the test stress level resulted in the failure of the test specimen. The raw and shifted curves are shown in Figure 90 and Figure 91. Only when the horizontal dis-

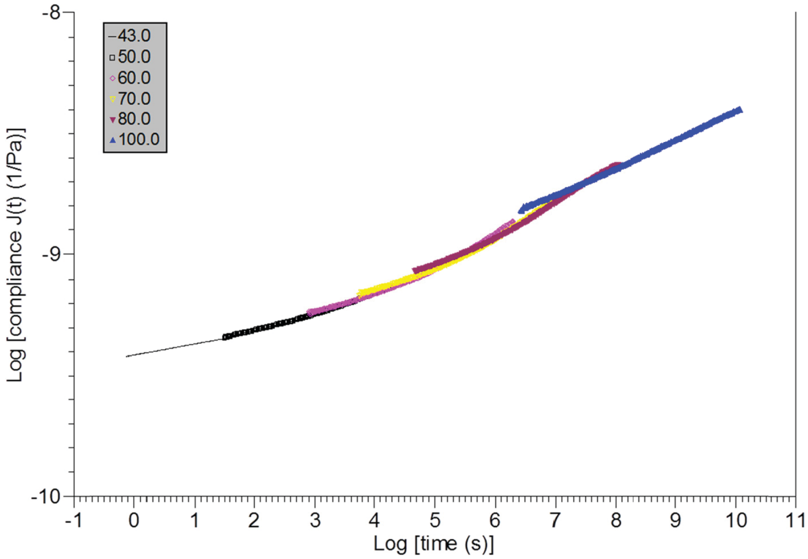


Figure 85. Shifted master compliance curve for adhesive A using 43°C as a reference temperature.

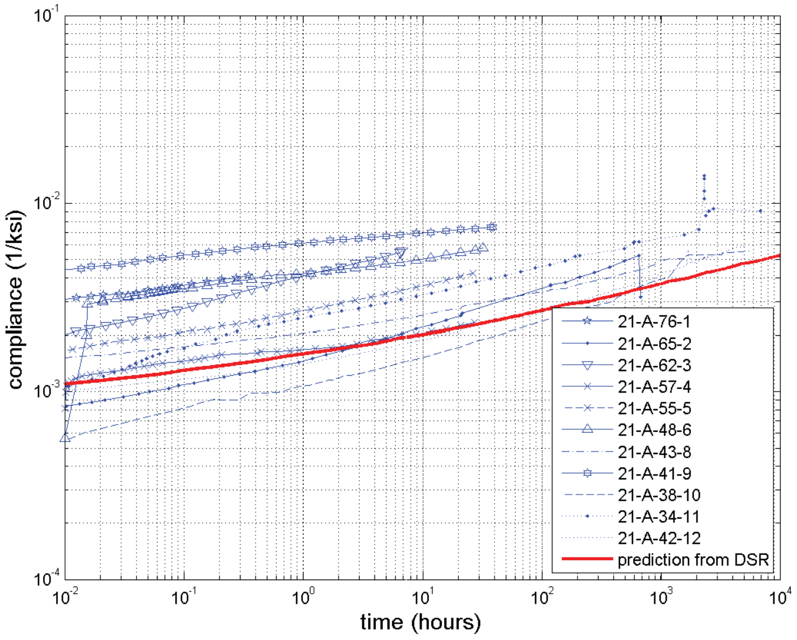


Figure 86. Comparison between predicted compliance from the DSR creep test and the sustained load creep tests on dogbone samples for adhesive A.

tance between the overlapping regions of two curves was a constant can satisfactory superposition be possible. The poor matches of the shifted curve indicated that no simple time–stress superposition relationship existed for adhesive B. In effect, the horizontal distance between any two curves was not a constant but a function of compliance.

The horizontal distance was calculated between any two pairs of compliance curves in Figure 91 resulting in a total of 10 pairs, and this value was plotted against the $\log_{10}$ of the corresponding compliance regions and is shown in Figure 92. Note that if a simple stress–time superposition relation existed, there would be a few horizontal lines at different heights, which depended on the stress level difference. For each curve in Figure 92, three numbers were labeled, indicating the stress levels of the pair of compliance curves (labeled beside each curve) and the difference between the two stress levels (labeled on each curve). Note that here 72.5 psi (0.5 MPa) was treated as 1,450 psi (10 MPa) during the calculation of the

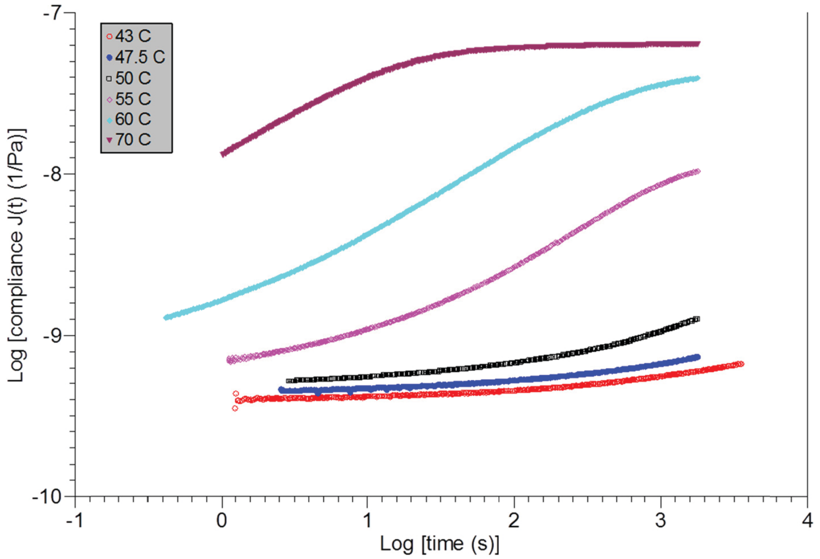


Figure 87. Compliance vs. time plot for DSR creep test of adhesive B at different temperatures.

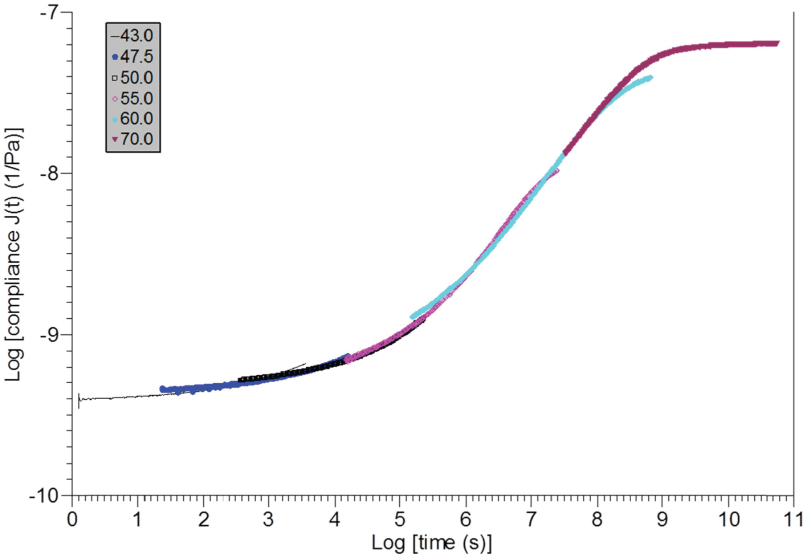


Figure 88. Shifted master compliance curve for adhesive B using 43°C as a reference temperature.

stress difference as the calculated stress difference agreed with the curves they overlapped. A possible reason for the equivalence of 72.5 psi (0.5 MPa) with 1,450 psi (10 MPa) could be that the nonlinear behavior of adhesive B was very low under low load, allowing 72.5 psi (0.5 MPa) to be treated as 1,450 psi (10 MPa) in this analysis. An interesting observation is that the curves with the same stress level difference seem to lie on top of each other. In addition, curves with higher stress level differences had higher shift factors.

Similar treatment was done to the sustained load creep compliance curves of adhesive B, which is shown in Figure 93. Here the sustained load compliance axis was plotted linearly and the logs of the shift factor became a linear function of the compliance after a certain compliance value.

A linear fit was performed for all the plots using the data points where compliance equaled 345 ksi^{-1} (5e-10 Pa^{-1}) and was plotted in green on Figure 93. Depending on the stress level, it took about 2 to 10 hours for the compliance to reach

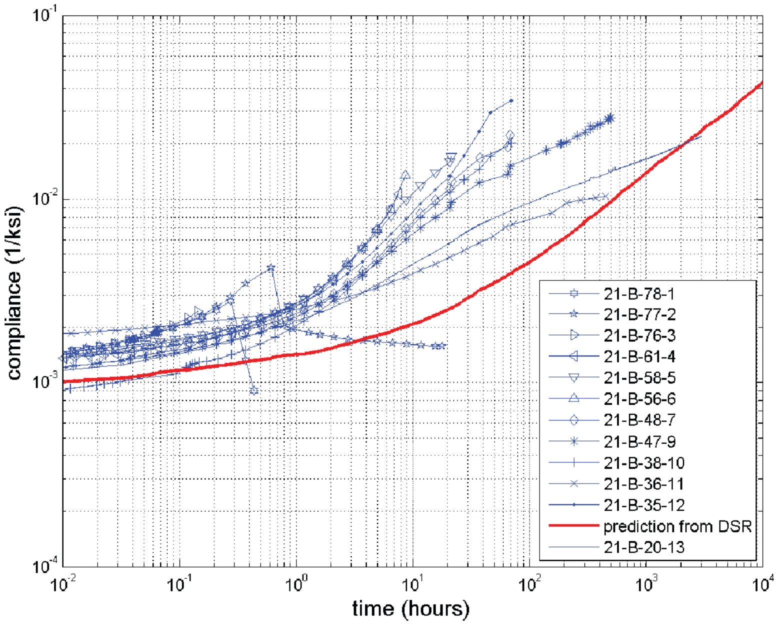


Figure 89. Comparison between predicted compliance from the DSR creep test and the sustained load creep tests on dogbone samples for adhesive B.

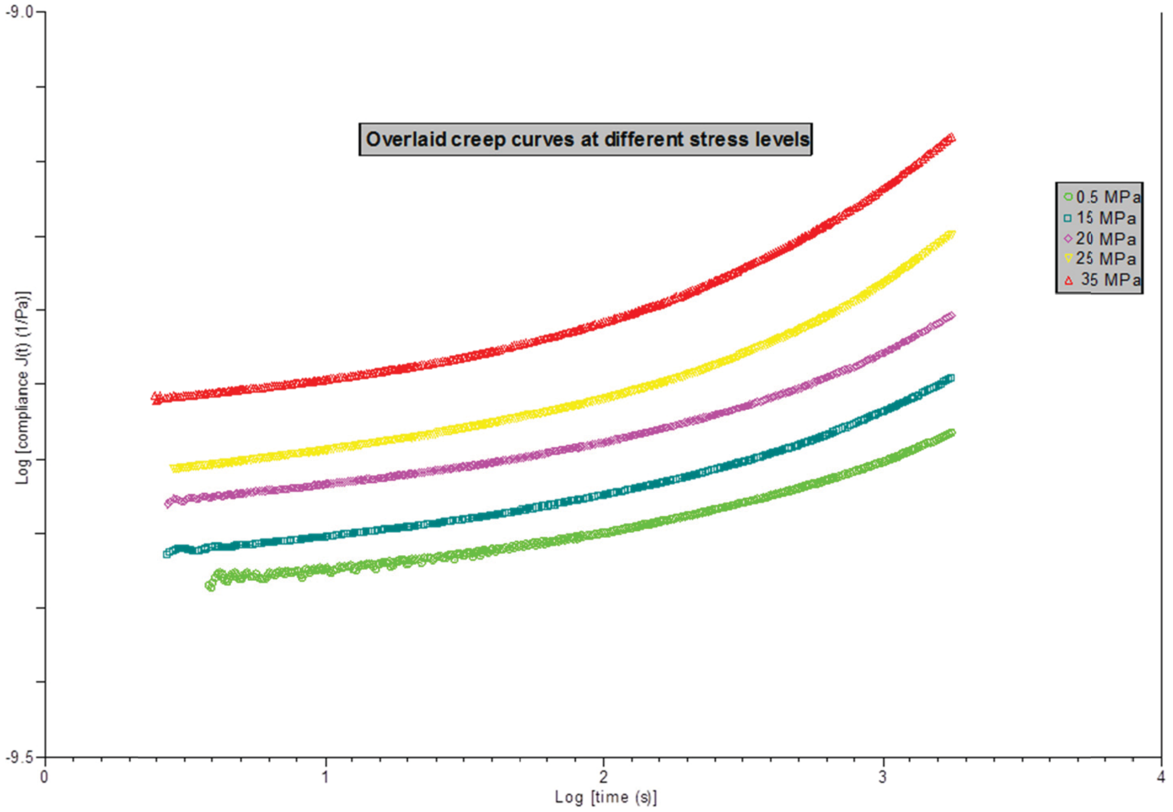


Figure 90. Compliance versus time for the DSR creep test of adhesive B at different stress levels.

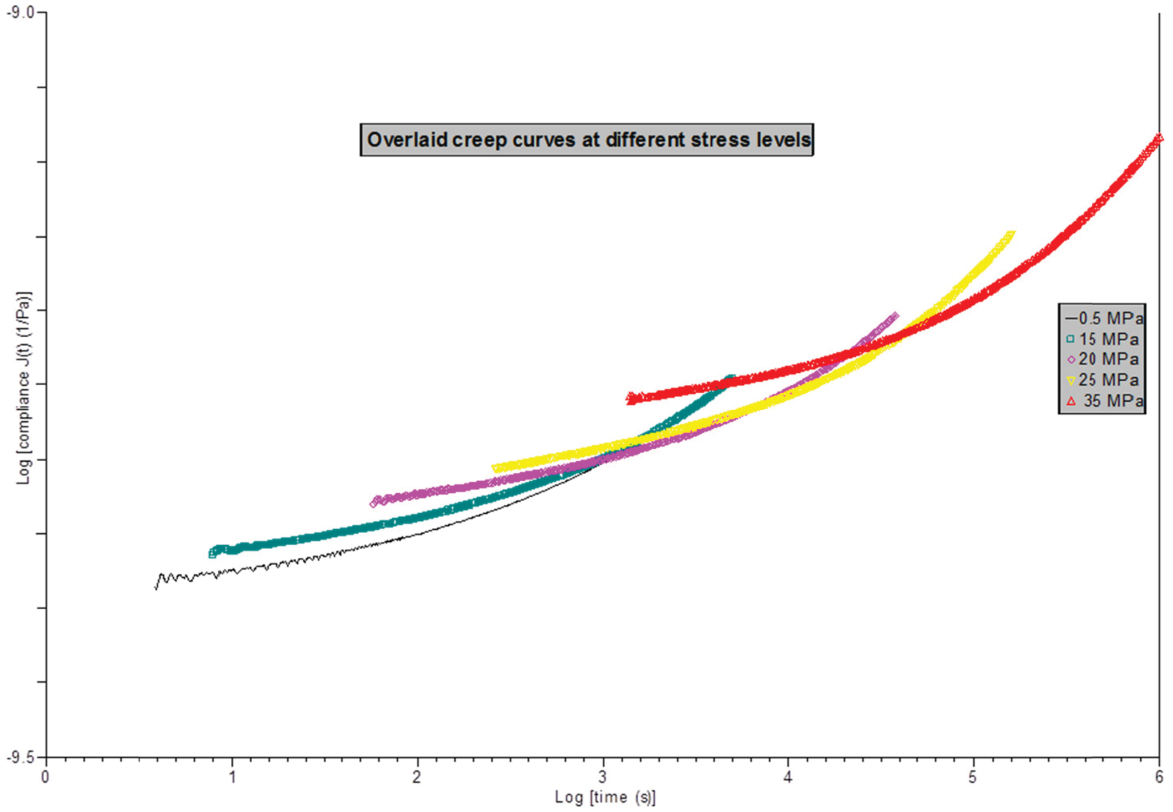


Figure 91. Shifted master compliance curve for adhesive B using 72.5 psi (0.5 MPa) as the reference stress.

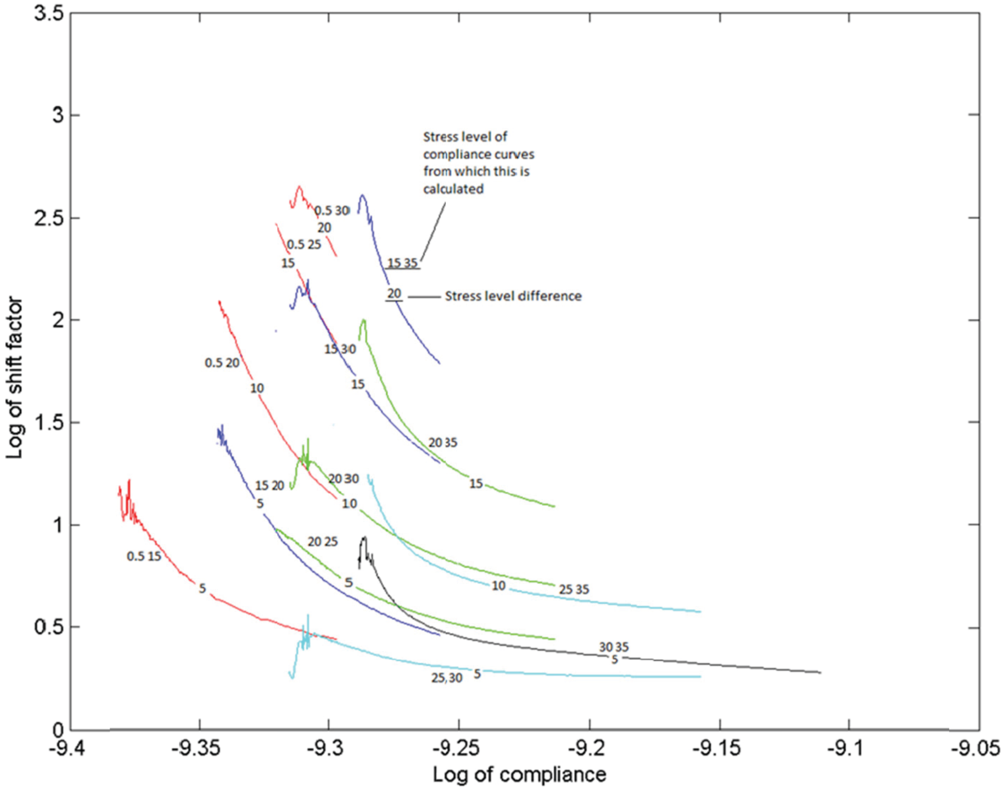


Figure 92. Shifted factor as a function of compliance for each pair of compliance creep curves for adhesive B at different stresses for short-term DSR creep tests.

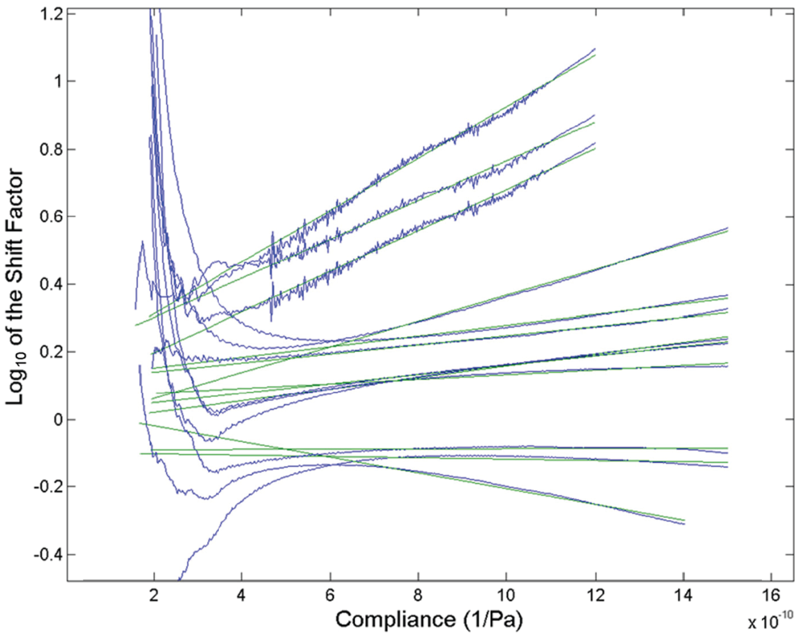


Figure 93. Shifted factor for adhesive B as a function of compliance for each pair of compliance creep curves at different stresses for the sustained load creep drawn in blue semi-log plot. The linear fit of each curve is shown in green (shown in color in online version).

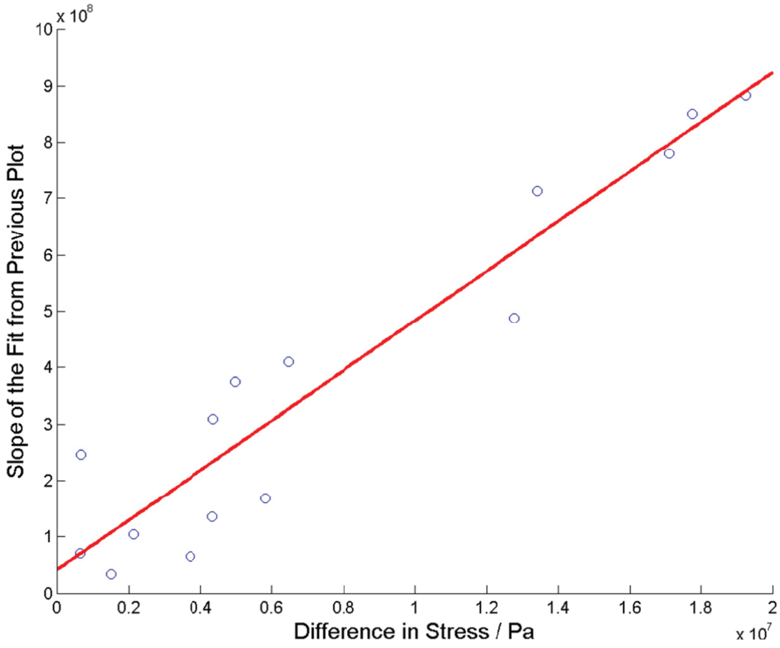


Figure 94. Difference in stress vs. the slope of the fit for each of the plots from Figure 93. The solid line is a linear fit to the data. R^2 = 0.909.

this value. Clearly the curve fits are very good for all curves and all the linear fit plots roughly converge at the origin of the coordinate system. The slope of each curve fit and the stress difference for each of the fits was plotted in Figure 94. A fairly good linear fit was obtained with R^2 value equal to 0.909 and slope = 44.7. In addition, the intercept on the y axis of the linear fit was very close to origin. As a result, we postulate that the shift factor for adhesive B can be approximated as:

$$\log_{10} a = C \times \Delta\sigma \times D \qquad Eq.\,5$$

where a is the shift factor, $\Delta\sigma$ is the difference in stress, D is the compliance at which the shift factor is calculated, and C is a materials dependent constant which can be calculated from the slope of the solid line of Figure 94.

Since the shift factor can be regarded as the viscosity ratio of two tests, from Eq. 5 it can be seen that the viscosity is proportional to e^{τ} which indicates an Eyring type of viscosity stress relationship [Lee et al. (2009)]. If there is no D term in Eq. 5, a simple stress–time superposition is sufficient to describe the stress dependence of the creep behavior. Since stress–time superposition assumed an unchanged creep mechanism, it is believed the presence of a D term indicates that there is a dependence of the underlying creep mechanism on the current state of the polymer during the creep test. The reason is still currently unknown, but the apparent linear relationship of the $\log_{10}$ of the shift factor with D makes this a very interesting problem for further investigation.

Figure 95 shows the DSR creep test for adhesive C and Figure 96 shows the resulting master curve. The shift was conducted by the built-in TTS processing function of the DSR instrument. Very good agreement between the overlapping regions of the shifted curves showed that the time-temperature superposition was valid for adhesive C.

The DSR master creep curve was overlaid with the compliance curves of adhesive C and is shown in Figure 97. The compliance of the sustained load curve did show agreement with the prediction curve at the early stage of creep but the creep predicted from DSR creep test grew faster than the tensile creep, which may be due to additional cure of the long-term sample during the 1,000-hour long creep tests. To test this hypothesis, the DSR creep samples were allowed to cure at 122°F (50°C) for 2 days and the master curves were constructed again as shown in Figure 98. The discrepancy in the master curves and the long-term creep compliance happened 100 hours later than the previous result, which confirmed the effect of the additional curing.

Discussion and Suggestions

Time–temperature superposition can be a powerful tool for accelerated polymer testing. However, for epoxy resins used in commercial adhesive products, due to the complexity of their formulas, one should not assume that time–temperature superposition always works. For adhesive C used in this study, time–temperature superposition appears

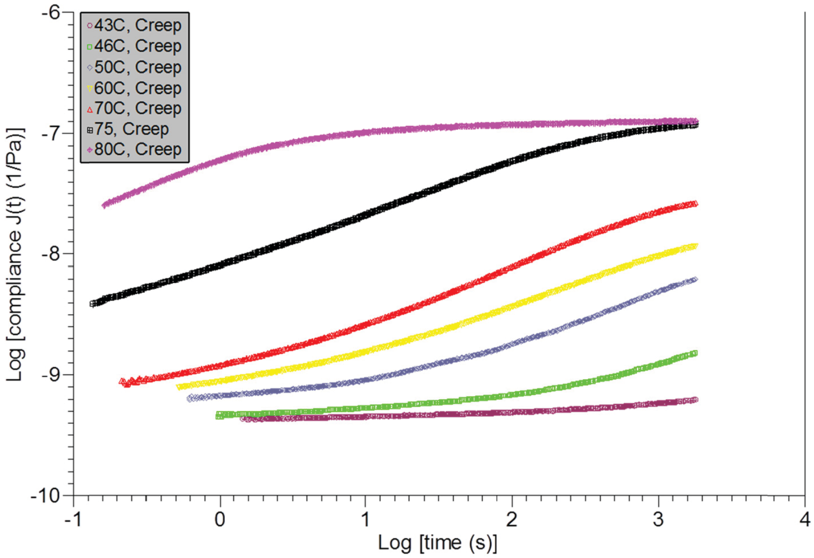


Figure 95. Compliance vs. time for DSR creep test of adhesive C at different temperatures.

to be a reasonable method for long-term creep prediction from very short-term DSR creep tests. As for adhesives A and B, it was observed that linear viscoelastic behavior was not valid and the creep behavior depended on the applied stress. Although the time–stress supposition method was reported to be valid for a few polymers, we found the effect of stress to be more complicated. For adhesive B, the dependence of the shift factor on the stress was quite different between the sustained load creep tests and the short-term DSR creep test. Nevertheless, it was found that after the creep compliance passed a certain point, the relationship between the shift factor, compliance, and stress became simple and apparently followed Eq. 5. As a result, we suggest the following steps to predict the sustained load creep rate from a set of relative short-term tests.

First, construct a master compliance curve from a DSR creep test within the linear viscoelastic range for very low stress levels following the steps as shown in Figure 87 to Figure 88. The duration of each DSR creep test can be as short as 30 minutes.

Second, perform DSR creep tests under different stresses to see if there is any stress dependence on the compliance. If

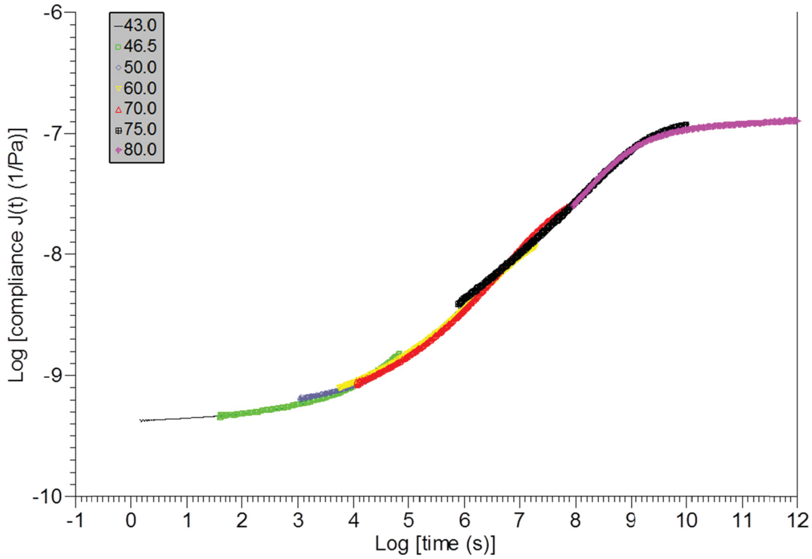


Figure 96. Shifted master compliance curve for adhesive C using 43°C as reference temperature.

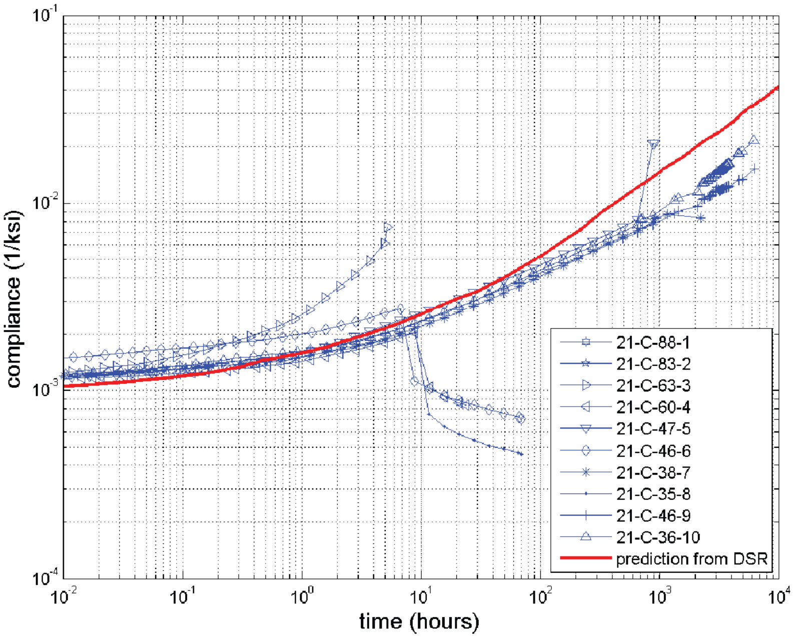


Figure 97. Comparison between predicted compliance from the DSR creep test and sustained load creep tests on dogbone specimens for adhesive C.

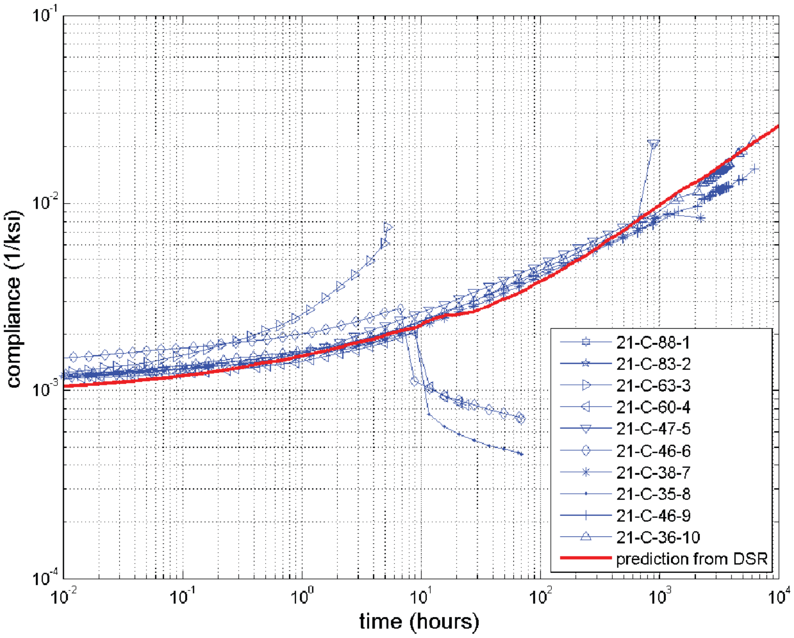


Figure 98. Comparison between predicted compliance from the DSR creep test and sustained load creep tests on dogbone specimens for adhesive C with higher curing temperature.

such dependence does exist, attempt the stress–time supposition first. If successful, measure the short-term creep tests at the desired stress level to obtain the shift factor and shift the master curve from step one accordingly.

If the stress–temperature superposition does not work, it is still possible to predict the sustained load creep rate. In this case, the short-term creep tests must be conducted long enough so that Eq. 5 becomes valid, which can take about 2 to 10 hours based on testing adhesive B. With this data, determine the *C* term in Eq. 5. Combined with the master compliance curve from step one, the sustained load creep rate at any stress level can be obtained. Note that this only predicts creep rate and not time to failure.

Adhesive-Alone Testing to Anchor Pullout Testing Correlation

Sustained Load Test Results

This project investigated the existence of a correlation between the sustained load tests performed on the adhesive anchors in concrete and the dogbone samples. However, a direct comparison cannot be made as the strain in the dogbone specimens is a tensile strain and the strain in the anchor pullout tests is a shear strain calculated as the arctangent of the anchor displacement over the annular gap (Figure 99). The strains calculated in the anchor tests differ from the dogbone specimens by approximately two orders of magnitude. The strain measured in the anchor tests is not a direct measurement of adhesive strain but rather a measurement of the total system. The total displacement measured is composed of the strain in the adhesive as well as the strain in the anchor, and slippage of the adhesive/anchor "plug" within the hole.

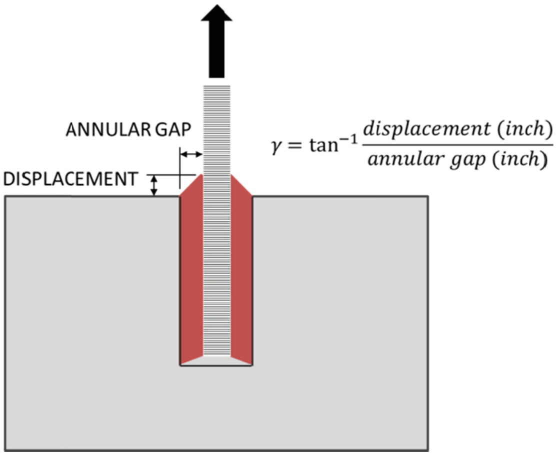


Figure 99. Shear strain in anchor tests.

However, creep compliance curves for the anchor pullout tests were generated and compared the dogbone specimens. Figure 100 to Figure 102 present the creep compliance comparisons for the three adhesives. Only the compliance comparison for adhesive C shows a similar trend between the two sets of tests, although separated by almost two

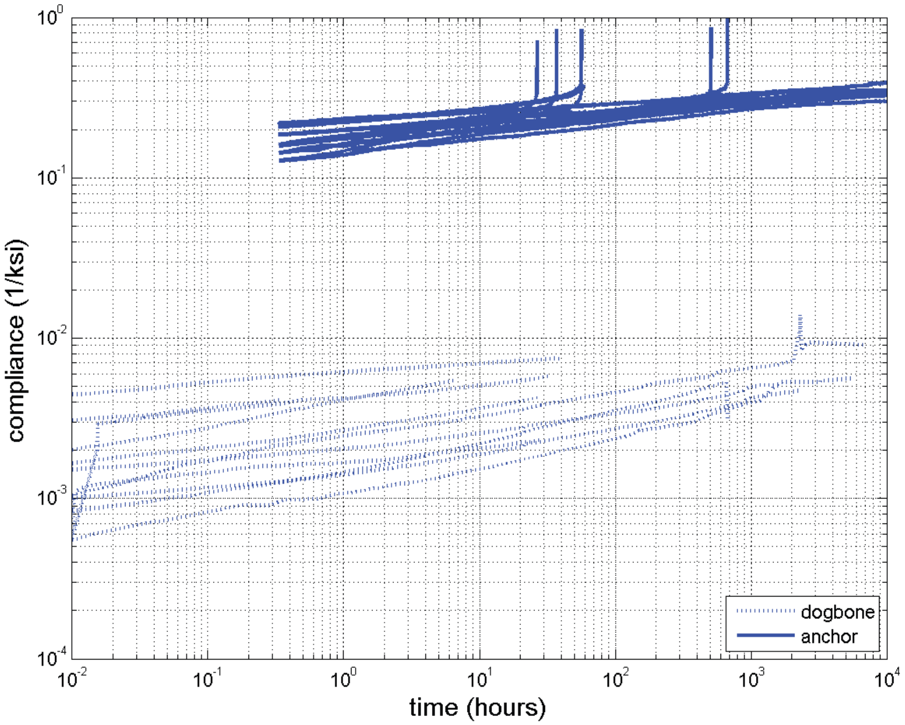


Figure 100. Creep compliance comparison between dogbone and anchor tests for adhesive A.

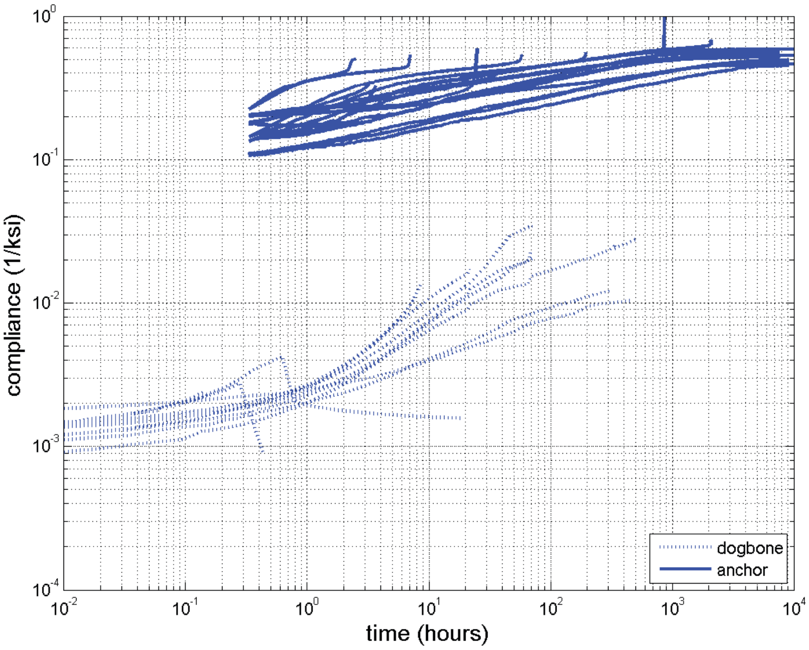


Figure 101. Creep compliance comparison between dogbone and anchor tests for adhesive B.

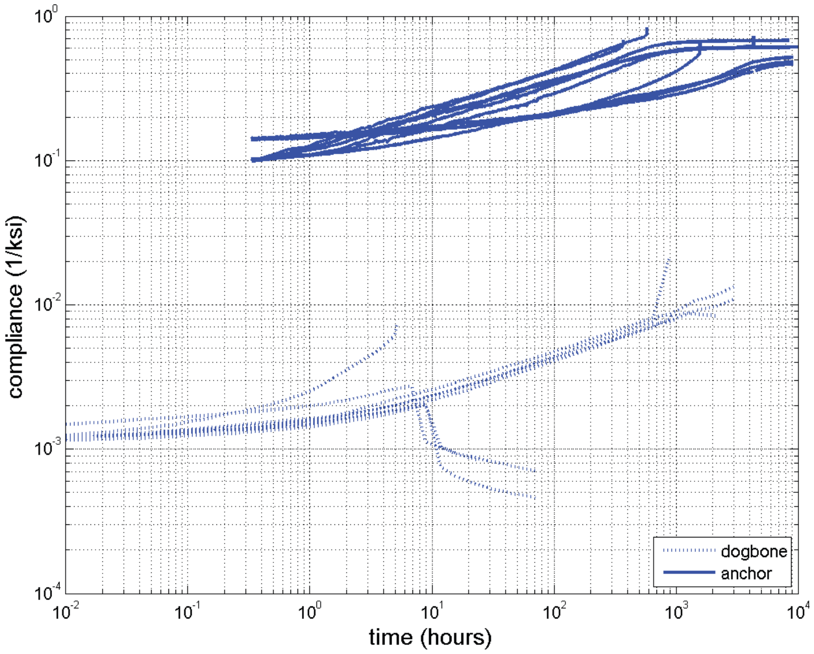


Figure 102. Creep compliance comparison between dogbone and anchor tests for adhesive C.

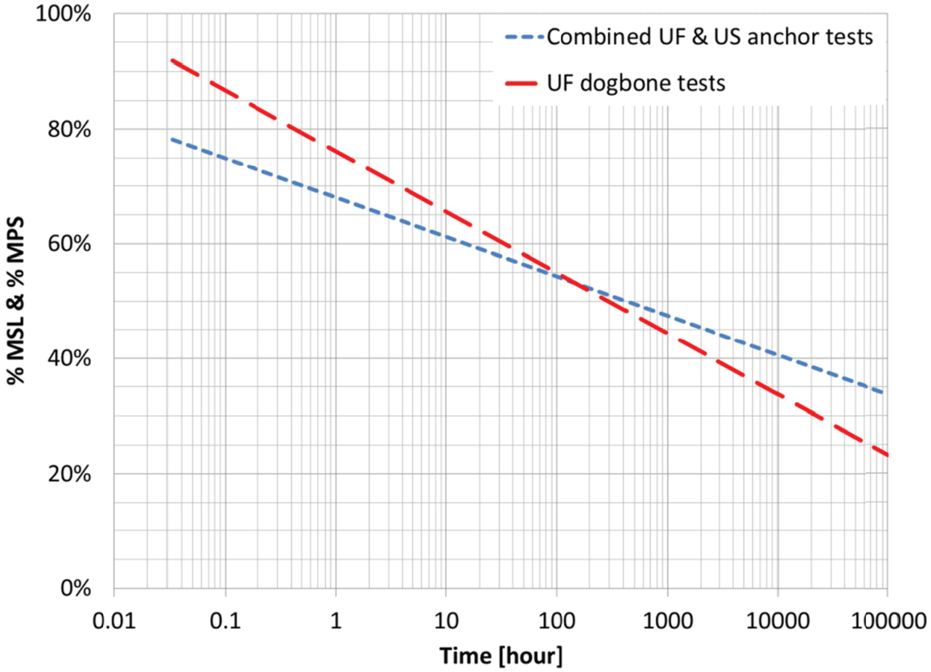


Figure 103. SvTTF comparison between anchor pullout tests and dogbone tests for adhesive A (MPS = mean peak stress).

orders of magnitude. Adhesives A and B do not provide good comparisons.

Stress versus Time-to-Failure Results for Anchor Pullout and Dogbone Tests

Figure 103 to Figure 105 present a comparison of the SvTTF relationships determined from the combined anchor pullout tests and the dogbone tests. The SvTTF curves for the dogbones are presented in Appendix L (series 21 and 22). While the dogbone tests did a very poor job predicting the SvTTF results for adhesives B and C, they did a better job for adhesive A. This is possibly due to the poor adhesion of adhesive A. Adhesive anchor systems with better adhesion can develop more friction along the sides of the hole prior to failure as the adhesive/anchor "plug" will have pieces of concrete attached to it.

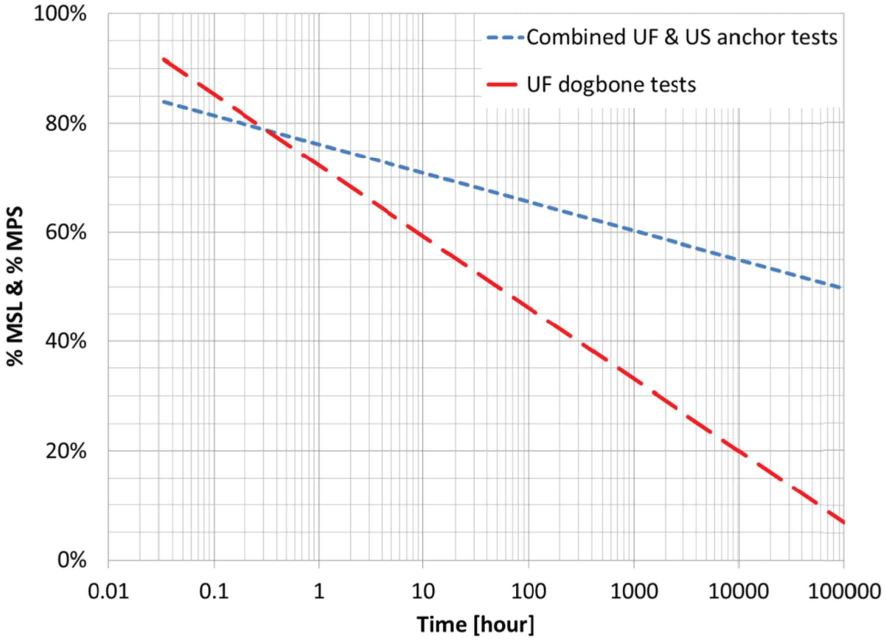


Figure 104. SvTTF comparison between anchor pullout tests and dogbone tests for adhesive B.

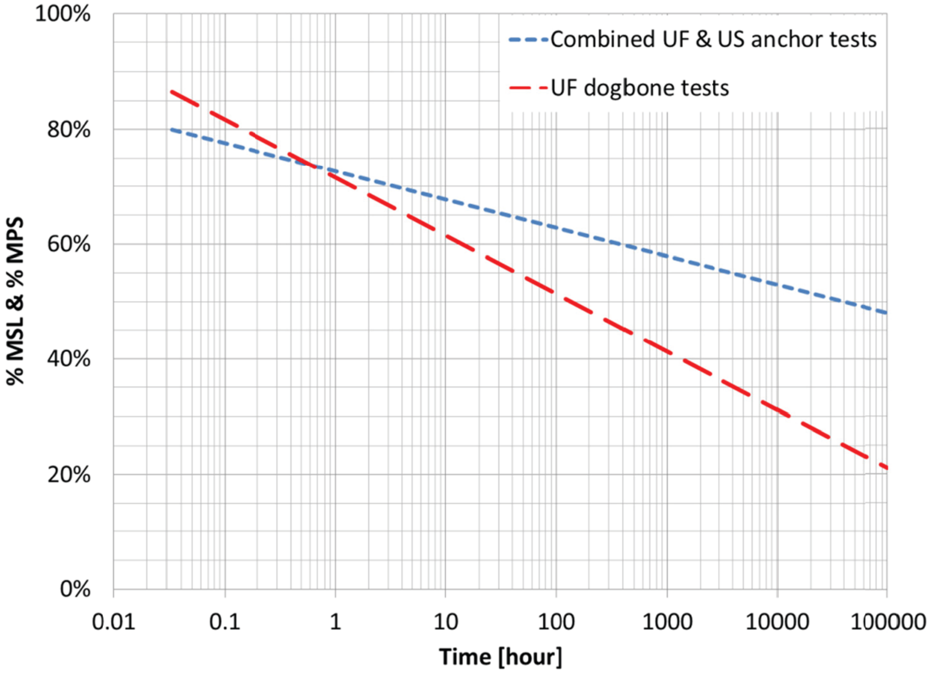


Figure 105. SvTTF comparison between anchor pullout tests and dogbone tests for adhesive C.

Dogbone specimens do not have this additional frictional resistance.

Influence on Sustained Load

As discussed earlier, the influence of a given parameter on sustained load can be evaluated by evaluating the influence ratio. If this influence ratio is less than 1, then the parameter does not have a more adverse effect at that point in time as compared to the short-term effect. Figure 106 presents the results of this analysis for the parameters investigated.

As shown in Figure 106, some short-term tests (TS03, TS05, and TS08) indicated a slight increase in strength for the given parameter. As design standards should not increase the predicted short-term strength due to slight variations above the baseline for certain parameters, it would then seem

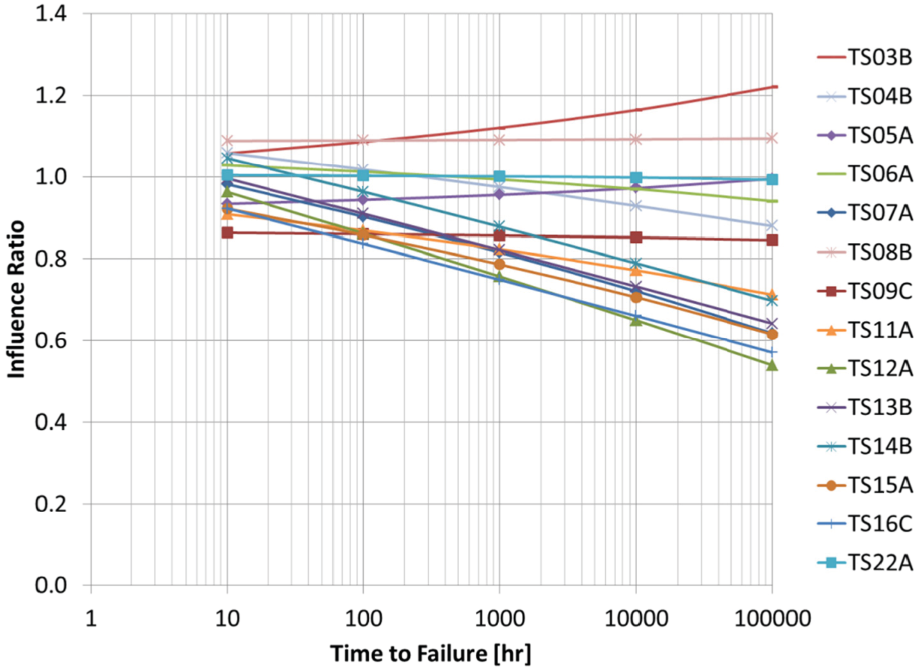


Figure 106. Influence ratio for each test series.

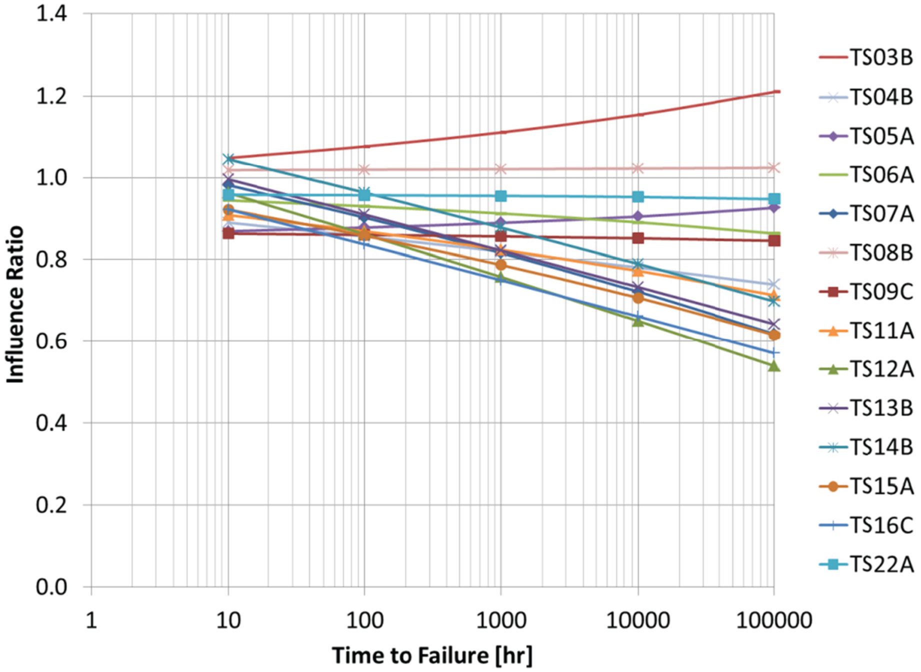


Figure 107. Influence ratio for each test series with the alpha-reduction factor limited to a maximum value of 1.

appropriate to evaluate the influence ratio of these parameters against the baseline and not against an elevated baseline. This is identical to limiting the alpha-reduction factor to a maximum value of 1 (Figure 107). As it is more appropriate for design, the practice of limiting the alpha-reduction factor to 1 in the analysis of sustained load influence ratio was adopted for the remaining analysis and discussion.

For the parameters investigated, most showed a decreasing trend versus time and result in an influence ratio less than 1, indicating that these adhesive products are not affected more adversely by the given parameter under sustained load than under short-term load.

Figure 108 presents the same information for a structure with 15 years at elevated temperature. ACI 355.4 assumes that a structure exceeds 110°F (43°C) for only 20% of its lifetime and, as a result, projects 110°F (43°C) test data to 10 years (20% of 50 years). For an AASHTO lifetime of 75 years, the influence ratio is therefore evaluated at 15 years (20% of 75 years).

Of all the parameters tested, only two were identified as having an adverse effect on the sustained load performance of adhesive anchors: 120°F (49°C) service temperature and manufacturer's cure time. The identification of these two parameters (TS03 and TS22) as having an adverse effect was based on not only the influence ratio but on an overview of the respective test results. The highest three influence ratios were TS03 (1.22), TS08 (1.02), and TS22 (0.95). TS08 (in-service moisture) was not considered as explained below.

Parameters with Adverse Sustained Load Influence

TS03—120°F (49°C) service temperature. As discussed earlier, polymers exhibit high creep deformations at elevated temperatures. It is no surprise that the long-term tests conducted at temperatures above the baseline temperature showed increased creep displacements. TS03 indicates that the stress level predicted by the influence ratio is 122% than that to cause failure at an equivalent lifetime of 75 years.

ACI 355.4 §8.5 provides tension testing at two temperature categories. Temperature Category A stipulates a long-term temperature of 110°F (43°C) and Temperature Category B has a long-term temperature greater than or equal to 110°F (43°C). The current testing temperature for Temperature Category A of 110°F (43°C) was based on temperature measurements provided in a CALTRANS study by Dusel and Mir (1991) of a bridge in Barstow, CA, in which 110°F (43°C) was noted to occur over a few hours during the day. In the CALTRANS study, there were no recordings greater than 115°F (46°C).

If it can be shown that an anchor would be expected to be at or above 120°F (49°C) for significant portions of its service life, it is suggested that AASHTO require the adhesive anchor system to be tested and evaluated for Temperature Category B at a temperature equal to or greater than its highest service temperature.

TS22—cure time. While the influence ratio of TS22 for adhesive A was less than 1 (0.95), the effect of cure time seems to

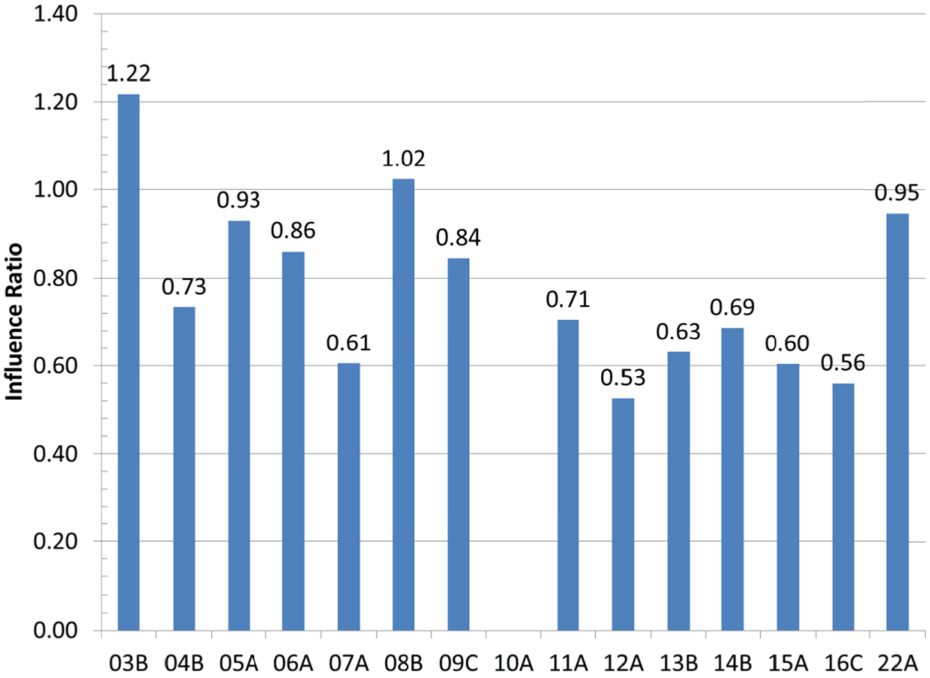


Figure 108. Influence ratio for each test series at 15 years exposure to elevated temperature (75-year design life).

be product specific as adhesive B resulted in an alpha-reduction factor of 0.54 and was unable to be adequately tested for sustained load at manufacturer's cure time to very high deformations. For sustained load applications it is important that the adhesive is sufficiently cured. A practical solution would be to require a cure time for sustained load applications beyond the minimum required by the manufacturer.

Research by Cook and Konz (2001) tested 20 anchor systems at 24 hours and at 7 days. Almost one-half of the systems obtained 90% of the 7-day strength at 24 hours and the average of all 20 obtained 88% of the 7-day strength at 24 hours. ACI 355.4-11 §8.7 has a required test method for cure time at standard temperature in which anchors tested at the manufacturer's minimum cure time must achieve 90% of the strength of anchors tested at the minimum cure time plus 24 hours.

It seems reasonable to require that anchors used in sustained load applications be required to cure for an additional 24 hours beyond the manufacturer's minimum cure time before loading.

Parameters without Adverse Sustained Load Influence

The testing criterion for evaluating influence on sustained load was based on the alpha-reduction factor determined from short-term testing. If the reduction in strength at any point in time was greater than at 2 minutes (short-term test duration) then the parameter was said to have an adverse effect on the sustained load performance. Most of the following test series have the same or more favorable in-service conditions compared to the baseline but vary by installation condition. It appears that once the adhesive has cured, any reduction in strength due to the installation condition can be completely defined by the alpha-reduction factor from short-term testing. As long as the in-service conditions are not worse than the baseline, there should not be any further reduction in strength over the service life.

TS04—70°F (21°C) service temperature. Polymers will exhibit higher creep displacements at higher temperatures, especially as the temperature approaches the glass transition temperature. As discussed above, as long as the in-service conditions remain the same as the baseline, there should not be any further reduction in strength over the service life. In the case of TS04, the in-service temperature is lower than the baseline. A lower in-service temperature is a condition that is more favorable for sustained load performance. With an influence ratio of 0.73, this parameter is considered not adverse to sustained load performance.

TS05—installation direction (horizontal). Quality products, for example, those that have passed ACI 355.4-11 criteria, that are to be used for horizontal installations must have passed the sensitivity to installation direction test (ACI 355.4-11 §7.18). In this test series the short-term load strength of a horizontally installed anchor must be at least 90% of the strength of an anchor installed in the downward direction.

If a product passes this test then installation direction can be considered to not affect the short-term strength. Once the adhesive has cured, if the only difference between an anchor installed horizontally to one installed in the downward direction is orientation (i.e., same concrete, moisture condition, temperature, etc.) then the application of sustained load should reasonably have the same effect for both conditions. Due to the discussion above, with an influence ratio of 0.93, this parameter is considered not adverse to sustained load performance.

TS06—installation direction (vertical). The sensitivity to installation direction test (ACI 355.4-11 §7.18) discussed above also tests for anchors installed vertically. It is believed that vertical installation does not adversely affect the sustained load performance for the same reasons discussed above for horizontal installation (TS05). Due to the discussion above, with an influence ratio of 0.86, this parameter is considered not adverse to sustained load performance.

TS07—moisture at installation. While moisture at installation created a reduction in short-term bond strength ($\alpha = 0.82$), the sustained load performance was no worse than the short-term reduction. This can be explained by the fact that the concrete began to dry after installation and eventually dried out in the 110°F (43°C) chamber. The subsequent in-service conditions were the same as the baseline. With an influence ratio of 0.61, this parameter is considered not adverse to sustained load performance.

TS08—moisture in-service. While the influence ratio is greater than 1 (1.02), the experimental line and the baseline appear to be the same line within scatter of that data (SvTTF curve in Appendix H, page H-13). It is therefore the researchers' opinion that this parameter is considered not adverse to sustained load performance.

TS09—reduced hole cleaning. While reduced hole cleaning created a reduction in short-term bond strength ($\alpha = 0.81$), once the adhesive had cured, the reduction in adhesion due to the presence of dust on the sides of the borehole could be accounted for in the alpha-reduction factor. As time progressed, the amount of adhesion did not change and the reduction in strength over time was no worse than in the short term. Due to an influence ratio of 0.84, this parameter is considered not adverse to sustained load performance.

TS10—installation temperature (mfr minimum/mfr minimum). Currently data is only available for one sustained load stress level (70%MSL) for TS10 and it is not possible to develop an experimental trendline and subsequent influence ratio. However, based on the current results from the 70% stress level tests, it appears that this test series will not have an adverse effect on the sustained load performance. As discussed earlier and illustrated in Figure 14, adhesives respond to temperature slightly differently, but all show a decrease in bond strength as the temperature increases. As seen in Figure 14, it is possible for an anchor installed and tested at a very low temperature to have a higher bond strength than an anchor installed at room temperature and tested at 110°F (43°C) as was the case for the baseline and evidenced by the alpha-reduction factor of 1.10.

TS11—installation temperature [mfr minimum/110°F (43°C)]. It appears from the tests conducted at low temperature that as long as the adhesive is installed at a temperature at or above the minimum permitted by the manufacturer that there are no adverse effects under sustained load compared to the baseline. This was noticed in TS10, which tested at the manufacturer's minimum permitted temperature and in TS11, which tested at 110°F (43°C). It is definite that the adhesive underwent additional cure over the 24 hours as the specimens were conditioned from the installation temperature to the elevated testing temperature. However, the 0.86 alpha-reduction factor indicates that it was not as cured as the baseline that was installed at room temperature. However, the low influence ratio of 0.71 indicates that this parameter is not adverse to sustained load performance.

TS12—DOT concrete mix. As discussed earlier, it appears that as long as the in-service conditions are the same as the baseline, the alpha-reduction factor obtained from short-term testing for the influence of concrete mix is sufficient to conservatively evaluate the sustained load performance. With an influence ratio of 0.53, this parameter is considered not adverse to sustained load performance.

TS13—core drilling. While core drilling created a reduction in short-term bond strength ($\alpha = 0.73$) as time progressed, the reduction in strength over time was no worse than in the short term. It is believed that the short-term reduction is due to reduced friction along the smoother core drilled hole after loss of adhesion. For the lower stresses experienced in the sustained load tests, the anchor is not as dependent on friction along the sides of the hole. With an influence ratio of 0.63, this parameter is considered not adverse to sustained load performance.

TS14—fly ash. It is believed that the addition of fly ash to the concrete mix does not adversely affect the sustained load performance for the same reasons discussed for the DOT mix (TS12). With an influence ratio of 0.69, this parameter is considered not adverse to sustained load performance.

TS15—blast furnace slag. It is believed that the addition of blast furnace slag to the concrete mix does not adversely affect the sustained load performance for the same reasons discussed for the DOT mix (TS12). With an influence ratio of 0.60, this parameter is considered not adverse to sustained load performance.

TS16—unconfined setup. It was shown earlier that the alpha-setup factor of 0.75 is not appropriate for some adhesives. The three adhesives in this study had alpha-setup factors in the range of 0.35 to 0.55. As all the points in the TS16 SvTTF lie above the α_{ST}-baseline, and due to the low influence ratio of 0.56, it appears that sustained load in unconfined setup is not an adverse condition as long as it is assumed that the correct alpha-setup factor for the product is used (i.e., 0.37 not 0.75).

Early-Age Concrete Evaluation

The short-term test load versus displacement and stress versus displacement results for the early-age investigation are presented in Appendix M. The results are summarized in Figure 109, which normalizes the results by the 28-day bond strength.

It appears that on the basis of bond strength alone, adhesive A (vinyl ester) does not show any significant increase after 14 days, and adhesives B and C (epoxies) do not show any significant increase after 7 days.

Discussion of Anomalies

Several of the anchors for adhesive A failed not with a strength type failure but rather a stiffness type failure. Failure was defined as the point when the load–displacement curve dropped below a stiffness of 28.6 kip/in (5 kN/mm) as discussed earlier and illustrated in Figure 38.

Test samples D21-C-ST-4 (Figure 110), D28-C-ST-3, and D28-C-ST-5 all pulled out at very low bond stresses. The anchors were removed from their holes for investigation. It was noticed that the adhesive had not completely cured as it was still tacky with a dark gray glossy color indicating an improper ratio of the hardener and resin. Per NTSB (2007b), excess hardener is evidenced by a pliable consistency and a decrease in bond strength. The anchors of this adhesive that failed at higher bond stresses were also removed and exhibited hard fully cured adhesive with a flat whitish-gray color (Figure 111).

All the holes were cleaned identically per the MPII at the same time. The same adhesive tube was used for all five repetitions for a given test day. The anchors for day 28 used a different tube than those for day 21. These three samples were considered anomalies and were not included in the determination of the mean.

These three test samples were not completely cured due to the previously discussed problem with setting down the cartridge gun during installation.

Temperature and Humidity

The four Sensiron temperature and humidity sensors that were cast in the control slab were destroyed in the casting process. Therefore, the two 9” long PVC pipes with PVDF filters on the embedded ends in each slab were used for temperature

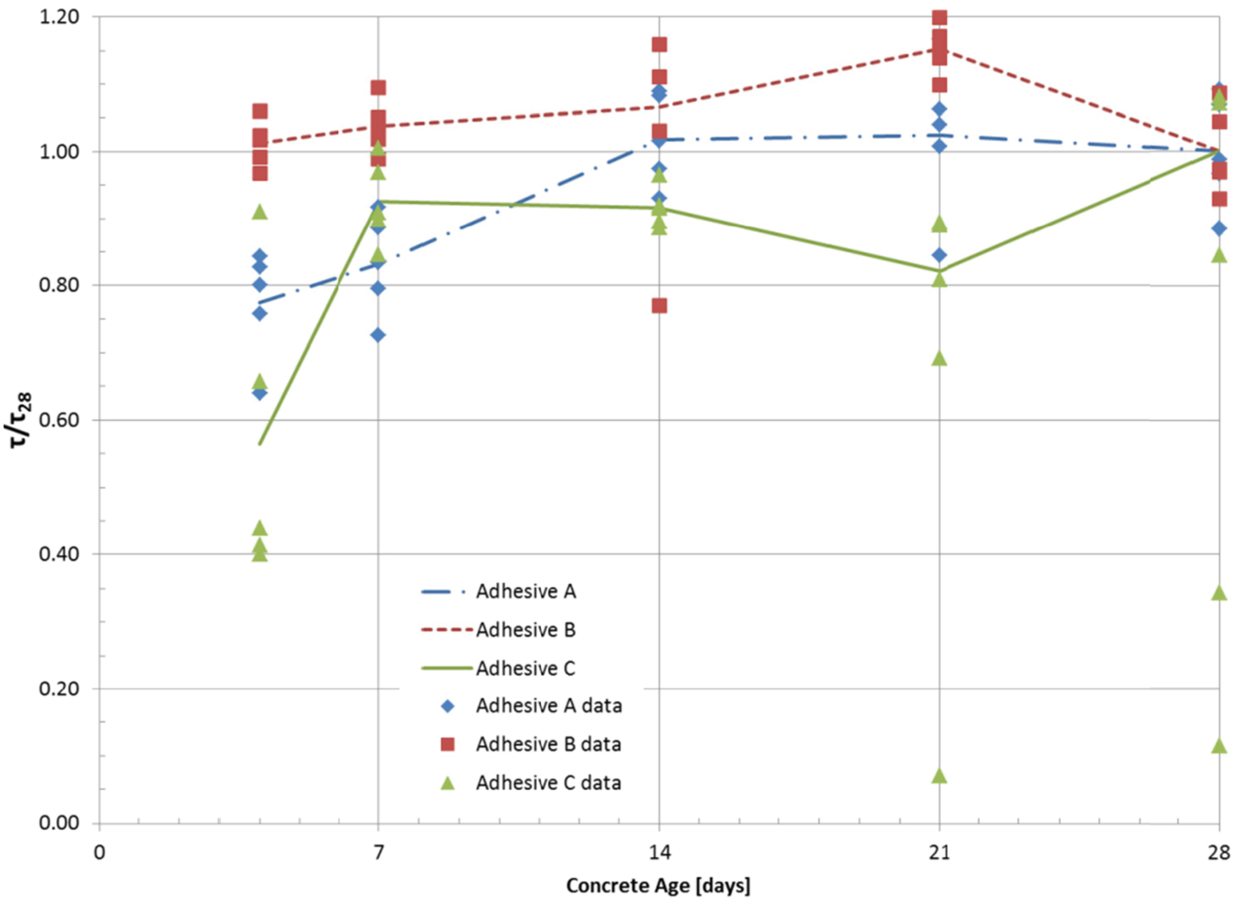


Figure 109. Normalized bond stress (by 28-day value) versus concrete age.

Figure 110. D21-C-ST-4 showing failure surface of incompletely cured specimen.

and humidity monitoring. During testing, two sensors were placed in the two pipes of the control slab and left for the duration of the month-long testing period. The remaining two sensors were placed in the test slab of the anchors being tested.

The temperature readings from the control slab and the individual testing slabs were within a 2°F (1°C) agreement with each during the testing program. The internal concrete temperature for both slabs followed the daily temperature fluctuation of the laboratory and were within 4°F (2°C) (and less than) the ambient temperature of the laboratory. The only exception was that on day 4, the concrete internal temperature was 7°F (4°C) below the ambient temperature of the laboratory. The temperature readings are presented in Table 41.

Table 41. Temperature readings for the early-age concrete evaluation.

Test Day	Control Slab	Test Slab	Ambient
4	78°F (26°C)	77°F (25°C)	84°F (29°C)
7	74°F (23°C)	72°F (22°C)	75°F (24°C)
14	72°F (22°C)	70°F (21°C)	74°F (23°C)
21	73°F (23°C)	73°F (23°C)	75°F (24°C)
28	77°F (25°C)	76°F (24°C)	79°F (26°C)

Figure 111. D21-C-ST-5 showing failure surface of fully cured specimen.

The Sensiron sensors in the control slabs reported a consistent 100% relative humidity (RH) reading for the entire month.

For testing, separate slabs were used for a given day and then discarded. The RH readings from the sensors in the test slabs were all greater than 96%. It seems reasonable that since all the concrete slabs were cast at the same time and kept together prior to testing there would be a consistency in RH readings with each other. However, when the sensors were switched between slabs, the RH reading would be less than the previous slab and would show a sharp increase and it would take several days for the readings to stabilize. Initially, the slabs would be changed out on Monday morning, the anchors installed on Thursday, and tested on Friday. Except for day 14, this did not provide sufficient time for the readings to stabilize prior to testing. In response to this, the slabs for day 28 were changed out on the Friday before testing providing a full week of readings and the RH readings began to stabilize (within the daily fluctuation of the ambient RH) on the testing day. The RH data is presented in Table 42.

It does not seem reasonable that the RH at day 21 should be higher than at day 14 as the RH in concrete should decrease

Table 42. Relative humidity readings for the early-age concrete evaluation.

Test Day	Test Slab Relative Humidity (%)	Ambient Relative Humidity (%)	Comment
4	98.6	40	RH not stabilized
7	96.2	38	RH not stabilized
14	99.4	49	
21	99.8	52	RH not stabilized
28	99.3	53	

over time as hydration progresses and moisture is lost to evaporation at the surface. The datasheet for the sensors indicate that they are accurate to ± 4% RH in the range of 90 to 100% RH.

Based on control slab RH readings of 100% and the limitations of the sensors (tolerance and time to stabilize) the only definitive conclusion that can be drawn from the RH data is that the RH was in the range of 96% to 100%.

Initial Surface Absorption

The initial surface absorption test (ISAT) samples were read at 10 minutes, 30 minutes, and 60 minutes after applying the water. For adhesive anchors, the 10-minute reading is the most relevant reading as the 30-minute and 60-minute readings measure the surface absorption of essentially saturated concrete, which is not a common condition for most adhesive anchor installations. Table 43 presents the 10-minute sample data from the ISAT program as well as the relative humidity recorded during testing. The data is based on three repetitions (one repetition for day three of the formed surface). In order to better evaluate trends, ISAT testing was conducted up to 35 days after casting. Figure 112 presents the ISAT data over the 35 day testing period for the top formed surface and the sides of the hole.

Table 43. ISAT 10-minute sample data and relative humidity for sides of hole and formed surface.

Age (days)	Sides of Hole ($ml/m^2 \cdot s$)	Formed Surface ($ml/m^2 \cdot s$)	Ambient Relative Humidity (%)
3	0.036	0.030*	--
6	0.031	0.047	39
13	0.028	0.097	54
20	0.043	0.094	65
27	0.059	0.080	59
35	0.074	0.092	46

Note:
*All ISAT data is based on an average of three repetitions except for the day-3 sample for the formed surface.

Initially, the surface absorption of the top formed surface and the sides of the hole showed similar rates. The top formed surface drastically increased in surface absorption over the first 2 weeks and then leveled off (within the scatter of the data). For this concrete specimen, as the concrete dehydrated, the top surface increased in absorption but reached equilibrium with the environment after 2 weeks. The surface absorption of the sides of the hole remained fairly consistent over the first 2 weeks as the moisture several inches from the surface was not as easily lost to the environment. Eventually after 2 weeks, the surface absorption began to increase as the process of dehydration slowly dried out deeper and deeper portions of the concrete specimen.

Initial surface absorption is indirectly a measure of internal moisture. If the internal moisture is high, the surface absorption will be lower. Without accurate internal humidity data, the initial surface absorption data is the only indication we have on the relative measure of internal moisture. Based on these tests it appears that there is a threshold of internal moisture above which the bond stress is not affected.

Hardness

The rebound and indention hammers used to determine hardness generated similar trends of increasing hardness over time. Both hammers had conversion charts to predict the 6” cube compressive strength for which the indention hammer had good agreement for the first 14 days and then underestimated the strength. The rebound hammer consistently overestimated the concrete strength. The rebound hammer produced values that were 20% to 45% higher than the indention hammer (Table 44).

Figure 113 presents the data for the hardness tests as well as the compression and split tensile tests. All show similar trends of increasing value over time.

Summary

This chapter presented the findings from the experimental program. The major findings were:

- The ratio of unconfined tests to confined tests (α_{setup}) of 0.75 assumed in ACI 355.4 is not conservative for high-strength adhesives. Test results in this project obtained alpha factors for unconfined setup in the rage of 0.35 to 0.55. These results were confirmed in a series of verification tests.
- Short-term test results should not be included in a stress versus time-to-failure relationship with results from sustained load tests. The short-term tests (which failed

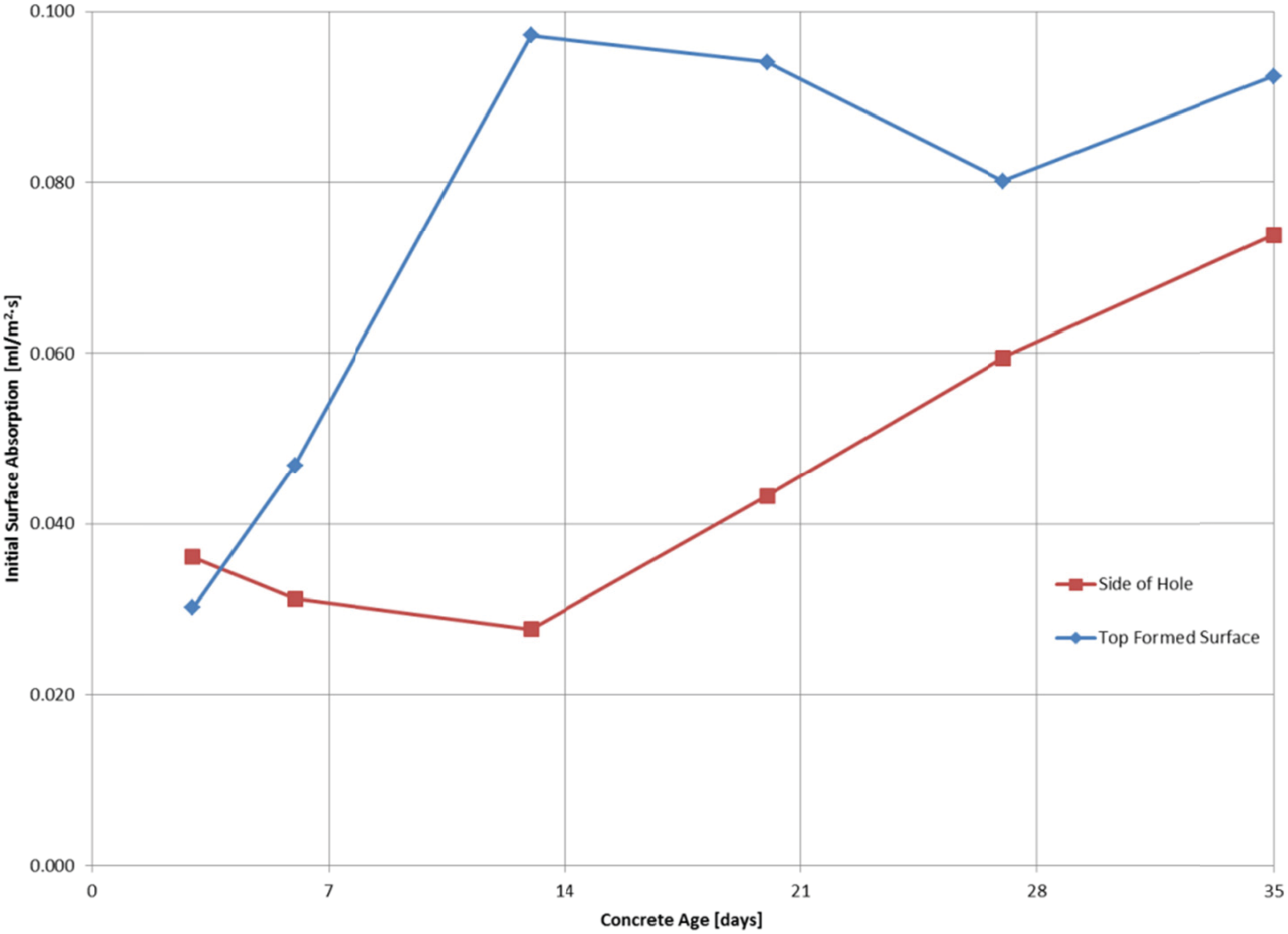


Figure 112. ISAT 10-minute sample data and relative humidity for sides of hole and formed surface.

at 100% MSL and 2 minutes) plotted well above the SvTTF relationship generated from sustained load tests alone. The reduced expected failure stress level for short-duration loads appears to result from a dual requirement placed on the polymer. The magnitude of the load causes the polymer to undergo plastic deformation as it redistributes the load down the anchor, and the sustained nature of the load causes the polymers to migrate within the adhesive. These two actions occurring simultaneously reduce the capacity.

- For the parameters tested in this project, only elevated service temperature [>120°F (>49°C)] and manufacturer's cure time were shown to have an influence on the sustained load performance.
- No consistent correlation between adhesive-alone (dogbone or DSR creep) and anchor creep tests was discovered. Dogbone tensile specimens are poor predictors of long-term and short-term performance, and are not recommended for qualification testing for adhesives for anchors.
- It was shown for the three adhesives tested that the bond strength did not increase significantly after 14 days (adhesive A) and 7 days (adhesives B and C). It is believed that the high level of internal moisture existent in early-age concrete was the leading contributor to lower bond strengths in the earlier-age concrete tests.

Table 44. Rebound and indention hammer results.

Age (days)	Rebound Hammer (psi)	Indention Hammer (psi)	Ratio Rebound/Indention
4	3,480	2,900	1.20
7	4,640	3,400	1.36
14	4,930	3,770	1.31
21	5,000	3,770	1.33
28	5,220	3,630	1.44

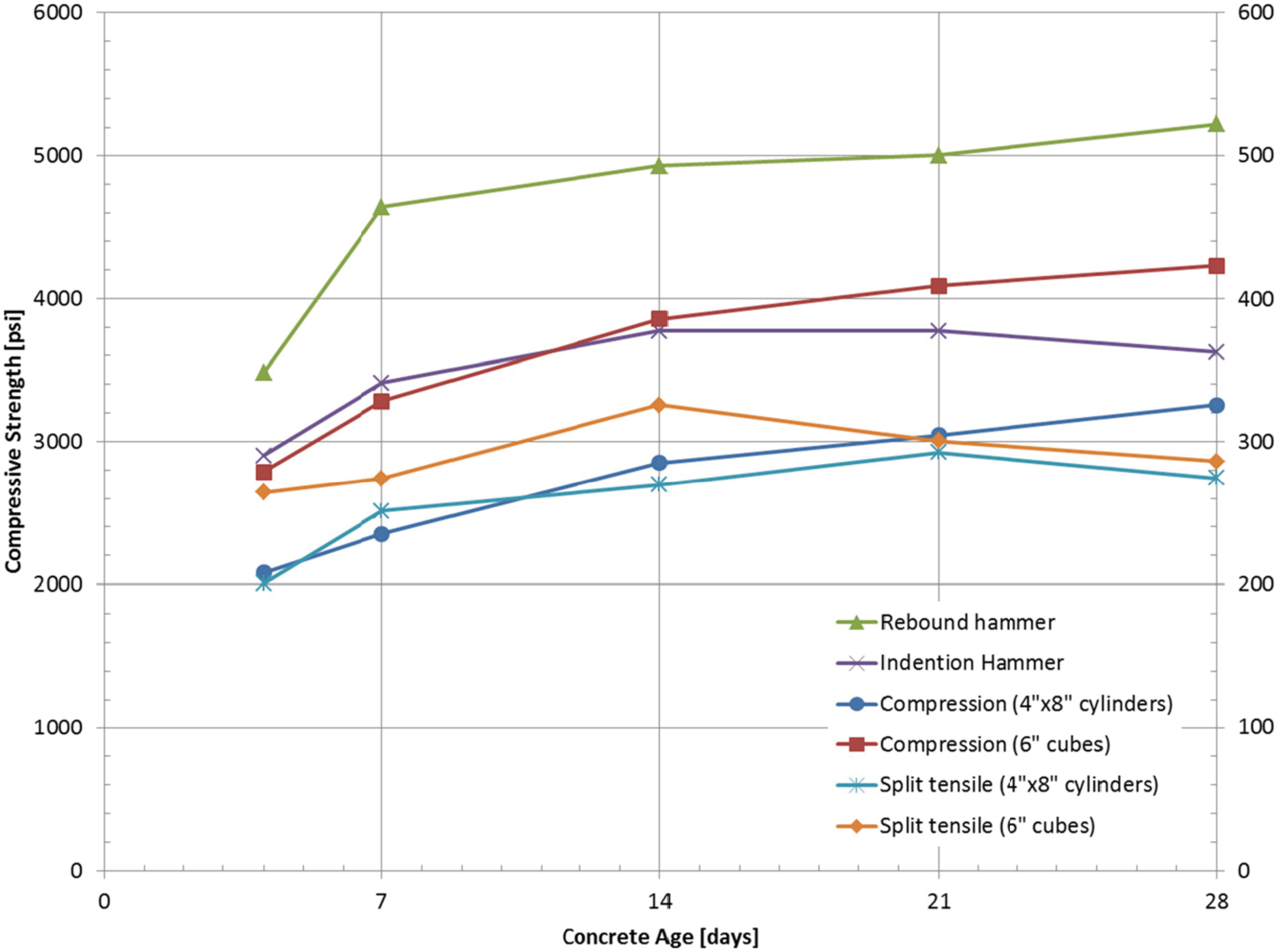


Figure 113. Hardness, concrete compression strength, and split tensile strength versus concrete age.

CHAPTER 4

Proposed AASHTO Specifications

This section presents the proposed specifications for AASHTO relating to material and testing, design, construction, and quality assurance for adhesive anchor systems in concrete. A flowchart is provided in Appendix N to better describe how the various ICC-ES, ACI, and AASHTO standards and specifications fit together and interact.

Material and Testing

ACI 355.4 provides testing and material specifications for adhesive anchors in concrete. This specification includes a large battery of tests and criteria for adhesive anchors in cracked and uncracked concrete. ACI 355.4 has evolved from ICC-ES (1995) AC58, which initially established the acceptance criteria for adhesive anchors in concrete and masonry and eventually from ICC-ES (2008) AC308 for adhesive anchors in concrete alone. Both ICC-ES documents are based on testing methods presented in ASTM E488 and ASTM E1512. ACI 355.4 includes the following mandatory tests for systems approved for use in both cracked and uncracked concrete:

- Reliability Tests:
  - Sensitivity to hole cleaning, dry concrete;
  - Sensitivity to hole cleaning, water-saturated concrete;
  - Sensitivity to mixing effort;
  - Sensitivity to installation, water-saturated concrete;
  - Sensitivity to crack width in low-strength concrete;
  - Sensitivity to crack width in high-strength concrete;
  - Sensitivity to crack width cycling;
  - Sensitivity to freezing/thawing conditions;
  - Sensitivity to sustained load; and
  - Torque test.
- Service-condition Tests:
  - Tension in low-strength concrete,
  - Tension in high-strength concrete,
  - Tension in low-strength cracked concrete,
  - Tension in high-strength cracked concrete,
  - Tension at elevated temperatures,
  - Curing time at standard installation temperature,
  - Resistance to alkalinity,
  - Edge distance in corner condition to develop full capacity,
  - Minimum spacing and edge distance to preclude splitting,
  - Shear capacity of anchor element having a non-uniform cross section, and
  - Round robin tests for regional concrete variation.

ACI 355.4 includes the following optional tests. Anchors not tested for these optional parameters will have limitations placed on their use:

- Reliability Tests:
  - Sensitivity to hole cleaning, water-filled hole;
  - Sensitivity to hole cleaning, submerged concrete;
  - Sensitivity to installation, water-filled hole;
  - Sensitivity to installation, submerged concrete; and
  - Sensitivity to installation direction.
- Service-condition Tests:
  - Tension at decreased installation temperature,
  - Resistance to sulfur,
  - Seismic tension,
  - Seismic shear, and
  - Member minimum thickness.

Testing Specifications (Interim Proposal)

It is proposed that, in the short term, AASHTO adopt the ACI 355.4 testing program for acceptance of adhesive anchors in transportation projects and not develop its own program for several reasons:

- ACI 355.4 has undergone the extensive ANSI consensus review process and has been adopted by other code and standard organizations.

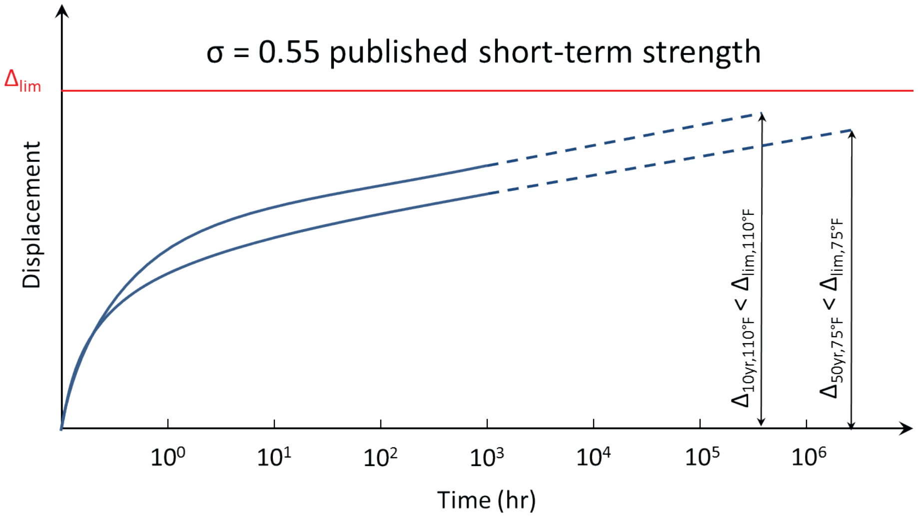


Figure 114. Current ACI 355.4 sustained load test projection.

- This testing program has a very significant cost per product line and it would be prohibitive to require manufacturers to evaluate their products under another testing program for use in transportation projects.
- There are several products on the market that have undergone the extensive testing program specified in ICC-ES AC308, which are currently being evaluated under the slightly modified provisions of ACI 355.4. AASHTO can immediately incorporate these approved products in transportation projects.
- The ACI 355.4 testing method results in a conservative and reasonable reduction factor for use in adhesive anchor design for sustained load as discussed below.

The sustained loading test program in ACI 355.4 subjects an anchor to 55% of the mean static load at standard temperature and at the long-term elevated temperature for 1,000 hours. The displacements from the last 20 days are projected based on a logarithmic trend. The projected displacements at 50 years for the standard temperature test and 10 years for the long-term elevated temperature test must be less than the displacement at loss of adhesion (Δ_{lim}) for their respective short-term tests (Figure 114). Additionally, the residual strength must be at least 90% of the short-term test strength. Anchors that pass these criteria are acceptable for use in concrete structures up to a lifetime of 50 years. The 55% stress level coupled with the displacement criteria results in a 0.55 reduction factor in the ACI 318-11 design provisions for adhesive anchors in sustained load applications.

As AASHTO stipulates structure lifetimes of 75 years as compared to 50 in ACI, a different (lower) modification factor must be specified. One option is to require testing at a lower stress level that will guarantee that the displacement and residual strength criteria are met at 75 years at standard temperature and 15 years at elevated temperature. However, in order to avoid additional testing as discussed above, the SvTTF relationship can be used to determine a reasonable sustained load reduction factor for AASHTO design applications. Table 45 shows that all of the six individual and three combined baseline SvTTF curves project an average drop of 1%MSL between 10 years and 15 years and a drop of 2% between 10 years and 20 years.

It is important to realize that the 55% stress level at which manufacturers conduct their sustained load tests is not actually 55% of the short-term strength. It is common that sustained load tests at 55% of the actual short-term strength will not pass the displacement criterion of the test program. Therefore, manufacturers often downgrade their short-term strength in order to pass the sustained load test. This downgraded short-term strength becomes the new short-term bond

Table 45. Projected stress level at 10 years and drop in stress level for various structure lifetimes from the baseline SvTTF curves.

Baseline Test	10 years (87,600 hrs)	Drop Is %MSL from 10 yrs to 15 yrs	Drop Is %MSL from 10 yrs to 20 yrs
01-A	33	1	3
01-B	42	2	2
01-C	54	1	2
02-A	35	1	1
02-B	56	1	2
02-C	56	1	1
A-combined	33	1	2
B-combined	50	1	2
C-combined	48	1	2

strength that is lowered again to account for other parameters with the end result being that the final published value for bond stress is significantly lower than the actual short-term bond strength. As the test data is protected by the manufacturers, based on our calculations we estimate that the downgraded short-term bond strength is in the range of 65%MSL to 75%MSL and the subsequent sustained load tests are conducted in the range of 35%MSL to 40%MSL. Based on these estimates, the projected stress level to cause failure at 15 years is approximately 1%MSL less than the stress to cause failure at 10 years and 2% less at 20 years.

Therefore, it seems reasonable to specify a reduction factor for AASHTO at 15 years no less than 1%MSL below the 55% stress level at 10 years. In other words, a reduction factor for design of adhesive anchors under sustained load for AASHTO should not be greater than 0.54. To allow for additional conservatism, it is suggested that a reduction factor of 0.50 be used for lifetimes of 75 and 100 years.

A modification to ACI 355.4 §8.5.2.3 has been included to test anchors at temperature category B for long-term temperatures above 120°F.

Additionally, it is proposed that AASHTO require a series of tests to determine the alpha-setup factor for the relationship between unconfined tests to confined tests as opposed to using the default value of 0.75 specified in ACI 355.4 §10.4.5.1.

Finally, a modification to ACI 355.4 §7.9 includes a qualification test for evaluating the effect of pausing during the installation of the adhesive.

Testing Specifications (Proposal to Include SvTTF)

It is proposed that sustained load testing for adhesive anchors eventually transition from the current pass/fail criteria towards an SvTTF approach. AASHTO TP 84-10 was recently created to provide a framework for SvTTF testing for adhesive anchors. AASHTO can either (1) choose to require manufacturers to qualify their products under an AASHTO SvTTF protocol for use in sustained load applications in transportation structures or (2) work with ACI in transitioning the sustained load testing in ACI 355.4 toward an SvTTF testing program. It should be noted that there was a large scatter on time to failure for the same stress level, indicating that several tests will need to be required.

It was shown in Table 38 and Figure 55 that the average creep displacement is 1.3 to 2.2 times the average short-term peak displacement for the three adhesives tested and in Table 39 was shown to be 1.4 to 3.0 times the displacement at loss of adhesion per ACI 355.4. It would be reasonable then to project the displacements for tests that have not failed to a lower bound value of the creep displacements of tests that have failed as opposed to using the displacement limit based on the short-term displacements.

However, if the creep displacement data is normalized by the average creep displacement for each adhesive and pooled together, the resulting lower bound values (using a 5% fractile) of the creep displacement in terms of the short-term displacement for each adhesive is presented in Table 46. The normalized lower bound values for adhesive A are 1 for both approaches and those for adhesives B and C are between 1.2 and 1.8. Based on this analysis, it appears that the ACI 355.4 projection of sustained load test data to the average short-term displacement is a rational approach.

The current projection method does not take into account tertiary creep or rupture but assumes a limit on displacements under sustained load. For example, the three repetitions of the US adhesive C baseline at 65% resulted in three different displacement versus time responses (Figure 115). Repetition 8 exhibited a standard tertiary creep region with rupture at 370 hours. Both repetitions 7 and 9 exhibited a significant reduction in displacement rate between 1,000 and 2,000 hours, possibly indicating that the anchors would cease to displace and sustain the load indefinitely. Repetition 7 has essentially ceased to displace and was terminated at 15,000 hours due to laboratory logistics. However, repetition 9 had a sudden increase in displacement rate after 4,000 hours and ruptured. These three repetitions at the same stress level indicate that a projection

Table 46. Characteristic creep displacement for the three adhesives used in this project.

Adhesive	Lower Bound Creep Displacement/ Average Short-Term Displacement	Lower Bound Creep Displacement/ Average Limiting Displacement
A	1.0	1.0
B	1.2	1.8
C	1.3	1.7

Notes:
Based on a K value (5% probability of nonexceedence with a confidence of 90%) of 1.64.
Characteristic value for adhesive A used the COV for adhesive A.
Characteristic value for adhesives B & C used the pooled COV from all adhesives.

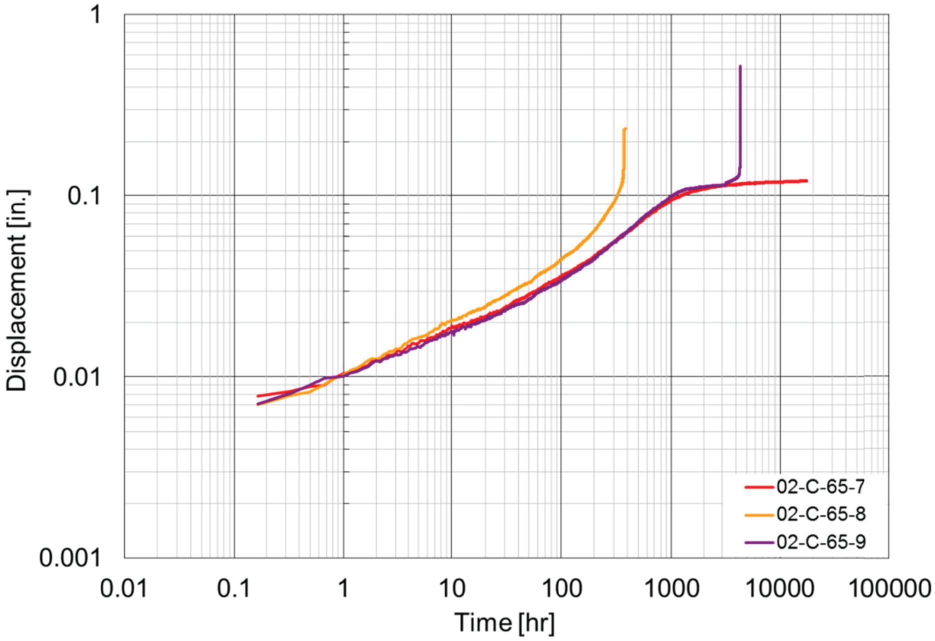


Figure 115. University of Stuttgart baseline tests for adhesive C at 65%MSL.

method assuming continually increasing displacements would not identify these three responses. However, as the displacements seen in these tests are well above the limiting displacement determined by ACI 355.4 the current projection method is conservative.

A benefit of the SvTTF approach is that manufacturers will not have to downgrade their published short-term strength, but can publish their actual short-term strength and a sustained load strength for particular lifetimes.

Based on this research project, a few modifications are proposed for TP 84-10. Section 9.4.2 of TP 84-10 requires two stress levels for sustained load testing (70%–80%) and (60%–70%) of the MSL. Based on the early failures in the sustained load tests and that the regression analysis of the baselines indicates an approximate 80% strength at 5 minutes, it is proposed that the highest sustained load test should be conducted at 70%MSL. Based on the scatter, two other stress levels should be tested at 60% and 50%. Furthermore, as discussed previously, results from short-term tests should not be included in the SvTTF relationship.

It is further proposed that tests should be conducted to failure and the failure times plotted on the SvTTF curve. For those tests that do not fail within a reasonable timeframe, the manufacturer can include these tests on the SvTTF curve at the larger of the following two times:

- The current test duration.
- Projected time to reach the limiting displacement from the short-term tests [which was shown to be essentially the lower bound (5% fractile) of the creep displacement from the sustained load tests that failed]. This projection is to be based on the last 20 days of data (minimum 20 data points).

Furthermore, the manufacturer can opt to continue sustained load testing and update its SvTTF curve in the future providing a higher published sustained load strength.

A proposed Standard Method of Test for Adhesive Anchors in Concrete, which references ACI 355.4-11 and AASHTO TP 84-10, is included in Appendix O.

Material Specifications

A proposed Standard Specification for Adhesive Anchors in Concrete is included in Appendix P.

Design

Design Specifications

The consensus between the NCHRP panel and the researchers was to provide a simplified AASHTO design specification intended to cover the majority of adhesive anchor systems under tensile loading with a few simplifying assumptions. For anchor applications that fall outside the limitations of the AASHTO design specification, the designer is encouraged to refer to ACI 318-11 Appendix D due to the overwhelming time and effort invested in its development. There is precedent from AASHTO to reference ACI documents in regards to anchors as AASHTO (2010b) *LRFD Bridge Design Specifications* §C6.13.2.12 and §C14.8.3.1 currently refers to ACI 318-05 Appendix D for “the global design of anchorage to concrete.”

The following limitations are included in the AASHTO design specification. The commentary in the design specification discusses the justification behind their inclusion.

- Products shall be qualified for use in cracked concrete in accordance with ACI 355.4.
- The effective depth of embedment, h_{ef}, must not be less than $4d_a$, 1⁵/₈", or the minimum stated in the manufacturer's printed installation instructions (MPII).
- The effective depth of embedment, h_{ef}, must be less than or equal to $20d_a$ or the maximum stated in the MPII, whichever is less.
- Edge distance, c, from the center of the anchor to the nearest edge of concrete must not be less than the larger of $6d_a$ or the minimum stated in the MPII.
- Anchors must be installed in holes drilled with a manufacturer approved rotary impact drill or rock drill unless permitted by MPII.
- Concrete must be normal weight concrete.
- The concrete member is considered cracked with normal temperature and shrinkage cracks and with minimum reinforcement.
- The concrete at time of installation shall have a minimum temperature of 50°F (10°C) or that stated in the MPII, whichever is greater.
- Concrete at time of installation shall have a minimum age of 21 days and a minimum compressive strength of 2,500 psi.
- The tensile loading on the group of anchors must be applied centrically to the anchor group.
- Anchors must not be subjected to seismic loads.

The proposed AASHTO Design Specification for Adhesive Anchors is included in Appendix Q.

Design Guidelines

A proposed AASHTO Design Guideline for Adhesive Anchors is provided in Appendix R, which provides a brief orientation on adhesive anchor design and refers the user to ACI 318-11 Appendix D for the extensive commentary on the design of adhesive anchors in concrete. Additionally, two calculation examples (for a single anchor in tension and for a group of anchors in tension) are provided using the proposed AASHTO design specifications for adhesive anchors.

Construction and Quality Assurance

Quality Assurance Guidelines

A Quality Assurance Guideline has been drafted and is included in Appendix S. It is based on information from ACI 355.4, CRSI (2011), Wollmershauser and Mattis (2008), Mattis and Silva (2011), and various manufacturer printed installation instructions (MPII). This document is intended to serve as general information for the installer and inspector. It discusses the various types of adhesives, installation equipment, and storage and handling suggestions. It is also intended to provide the "why" behind the many common installation instructions found in most MPII. As this is a guideline, it is not written in mandatory language and often refers the reader to the MPII for all storage, handling, and installation procedures.

Construction Specifications

Section 29 of the AASHTO 2010 *LRFD Bridge Construction Specifications* currently addresses embedment anchors and includes references to bonded anchors systems and adhesive anchors. Also included are general references to qualification by universal tests standards and certifications by an engineer. ACI 349 Appendix B was previously referenced for embedment anchor details. Section 29 provided a solid framework to include more specific construction specifications related to adhesive anchor systems.

The following briefly discusses the proposed changes to AASHTO 2010 *LRFD Bridge Construction Specifications* Section 29 and are included in underline/strikeout format in Appendix T.

29.2-PREQUALIFICATION

- Includes references to ACI 355.4 for post-installed adhesive anchors.

29.3-MATERIALS

- Adopts the ACI 355.4 definition of acceptable adhesive products. The current definition could inadvertently restrict the use of some products that meet the assessment criteria of ACI 355.4.
- Requires the use only of products that meet the assessment criteria of ACI 355.4.
- Provides a definition of adhesive anchor systems.
- Prohibits the use of bulk adhesive mixed in open containers without automatically controlled metering and mixing of components.
- Includes a statement on storage and discarding of expired product.

29.4-CONSTRUCTION METHODS

- Includes references to the MPII for adhesive anchors related to installation procedures.
- Includes limitation from ACI 355.4 on the minimum age (21 days) and compressive strength (2,500 psi) of concrete for installation of adhesive anchors.

- Includes requirement that adhesive anchors installed in horizontal or upwardly inclined holes shall be installed by ACI/CRSI certified personnel.
- Article C29.4: Discusses MPII, installation limitations, and the ACI/CRSI Adhesive Anchor Installer Certification program.

29.5-INSPECTION AND TESTING

- Requires continuous inspection on adhesive anchors installed in horizontal and upwardly inclined holes.
- Requires adhesive anchors exposed to in-service temperatures ≥120°F (49°C) to be tested and qualified under Temperature Category B at a temperature equal to or greater than the highest in-service temperature.
- Includes requirements for proof testing of adhesive anchors.
- Requires anchors for sustained load applications to not be loaded or torqued until 24 hours after the manufacturer's minimum cure time.

REFERENCES

- Updates the references section to include ACI 318 and ACI 355.4.

Summary

This chapter presented the rationale behind the development of proposed standards and specifications for AASHTO pertaining to the testing, design, construction, and inspection of adhesive anchors in concrete. The proposed drafts are included in Appendixes O through T.

CHAPTER 5

Conclusions and Suggested Research

The objective of this project was to develop recommended standard test methods and specifications, design guidelines and specifications, and quality assurance guidelines and construction specifications for the use of adhesive anchor systems in transportation structures. Development of these tests, specifications, and guidelines was founded on the results of a program of experiments to determine, predict, and verify the sustained load performance of these systems in their different applications and environments.

Conclusions

Anchor Testing

The results from the unconfined short-term tests suggests that the 0.75 ratio of unconfined bond strength to confined bond strength in ACI 355.4-11 to determine the unconfined bond strength from a series of confined tests might be a significant overestimate of unconfined bond strength. Tests on the three high bond strength adhesives in this research project produced factors from 0.37 to 0.53.

Sustained Load Sensitivity

A stress versus time-to-failure approach was used to evaluate the sustained load performance of three adhesive anchor systems in concrete. SvTTF relationships were developed for the baseline (control) and for multiple parameters. An α_{ST}-baseline relationship was developed for each parameter, which assumed that the reduction in strength at any point in time was the same as the reduction in strength experienced in short-term testing. An influence ratio was determined to evaluate sensitivity to sustained loading. For the parameters tested in this project, only elevated service temperature [>120°F (>49°C)] and manufacturer's cure time were shown to have an influence on the sustained load performance.

Sustained Load Testing

The short-term tests (which failed at 100% MSL and 2 minutes) plotted well above the SvTTF relationship generated from sustained load tests alone. The reduced expected failure stress level for short-duration loads appears to result from a dual requirement placed on the polymer. The magnitude of the load causes the polymer to undergo plastic deformation as it redistributes the load down the anchor, and the sustained nature of the load causes the polymers to migrate within the adhesive. These two actions occurring simultaneously reduce the capacity.

Displacements at failure from sustained load tests were 1.3 to 2.2 times larger than peak failure displacements from short-term tests and 1.4 to 2.9 times the limiting displacement at loss of adhesion. The current ACI 355.4 projection method for sustained load displacement projects to a limiting failure displacement from short-term tests. This ACI 355.4 approach was determined to be reasonable as the limiting displacement was essentially a lower bound (5% fractile) of sustained load failure displacements observed in the test program. If an SvTTF approach is adopted, sufficient testing should be required to minimize the influence of test scatter of time to failure for given stress levels.

Adhesive-Alone DSR Creep to Dogbone Testing Correlation

The DSR creep tests and dogbone testing for the three adhesives did not provide consistent correlation. Time–temperature superposition did not work for Adhesives A and B due to nonlinear viscoelastic behavior. Time–stress superposition worked for Adhesive B, but only with a shift factor that was dependent on stress level. There was no good relationship for Adhesive A, which is probably due to a large amount of fillers in the product as determined in the thermogravimetric analysis. However, time–temperature superposition did work very well for Adhesive C due to its linear viscoelastic behavior.

Adhesive-Alone to Anchor Pullout Testing Correlation

No consistent correlation between adhesive-alone (dogbone or DSR creep) and anchor creep tests was discovered. While the dogbone tests did a very poor job predicting the SvTTF results for Adhesives B and C, they did a better job for Adhesive A. This is due to the difference in loading of adhesive anchors and dogbone specimens. The adhesive anchors are confined specimens in a hole loaded under shear. The dogbones are unconfined specimens loaded in pure tension.

This is possibly also due to the poor adhesion of Adhesive A. Adhesive anchor systems with better adhesion can develop more friction along the sides of the hole prior to failure as the adhesive/anchor "plug" will have pieces of concrete attached to it. Dogbone specimens do not have this additional frictional resistance.

In summary, dogbone tensile specimens are poor predictors of long-term and short-term performance, and are not recommended for qualification testing for adhesives for anchors.

Early-Age Evaluation

The effect of early-age concrete on the short-term bond strength for the three adhesives was investigated. ACI 355.4 specifies a 21-day minimum on concrete age for adhesive anchor installations. It was shown that for the three adhesives tested the bond strength did not increase significantly after 14 days (Adhesive A) and 7 days (Adhesives B and C). It is believed that the high level of internal moisture existent in early-age concrete was the leading contributor to lower bond strengths in the earlier-age concrete tests.

Suggestions

Anchor Testing

The alpha-setup factor for the relationship between unconfined to confined bond strength in ACI 355.4-11 should be adjusted or a test series added to determine this relationship for individual products. The results of this research showed that this value can be in the range of 0.35 to 0.55 and is significantly less than the value of 0.75 currently assumed in ACI 355.4-11. It is proposed that AASHTO require testing to verify this value for each adhesive.

Sustained Load Sensitivity

If it can be shown that an anchor would be expected to be at or above 120°F (49°C) for significant portions of its service life, it is proposed that AASHTO require the adhesive anchor system to be tested and evaluated for Temperature Category B at a temperature equal to or greater than its highest service temperature.

Additionally it is suggested that adhesive anchors that will be used for sustained load applications be allowed to cure an additional 24 hours beyond the manufacturer's minimum cure time prior to loading or torquing.

Modifications to AASHTO TP 84-10

Due to scatter in the time to failure at a given stress level, it is proposed that AASHTO TP 84-10 include sustained load tests at three stress levels as opposed to two stress levels. Furthermore, as discussed above, the short-term test results should not be included in the SVTTF curve developed in AASHTO TP 84-10.

Suggested Research

The following topics are suggested for further research.

- Complete reliability study of AASHTO load and resistance factors pertaining to adhesives anchor applications.
- Additional sustained load testing at high stress levels could be performed to better identify the stress versus time to failure relationship within the time to failures of a few hours.
- Adhesive anchor sustained load tests at room temperature at various adhesive cure times could be performed to evaluate the influence of cure time on the sustained load performance.

References

AASHTO (2010a), *LRFD Bridge Construction Specifications,* 2nd edition, American Association of State Highway Officials, Washington, D.C.

AASHTO (2010b), *LRFD Bridge Design Specifications,* 4th edition, American Association of State Highway Officials, Washington, D.C.

AASHTO (2007b), M 235M/M 235-03, *Standard Specification for Epoxy Resin Adhesives,* American Association of State Highway Officials, Washington, D.C.

AASHTO (2010c), TP 84-10, *Standard Method of Test for Evaluation of Adhesive Anchors in Concrete under Sustained Loading Conditions,* American Association of State Highway Officials, Washington, D.C.

AASHTO (2007c), T 333-07, *Standard Method of Test for Linear Coefficient for Shrinkage on Cure of Adhesive Systems,* American Association of State Highway Officials, Washington, D.C.

AASHTO (2008), *Standard Specifications for Transportation Materials and Methods of Sampling and Testing,* 28th edition, American Association of State Highway Officials, Washington, D.C.

AASHTO (2009), *Standard Specifications for Structural Supports for Highway Signs, Luminaires, and Traffic Signals,* 5th edition, American Association of State Highway Officials, Washington, D.C.

ACI 318-11 (2011a), *Building Code Requirements for Structural Concrete,* American Concrete Institute, Farmington Hills, MI.

ACI 349-06 (2006), *Code Requirements for Nuclear Safety-Related Concrete Structures & Commentary,* American Concrete Institute, Farmington Hills, MI.

ACI 355.4 (2011b), *Qualification of Post-Installed Adhesive Anchors in Concrete,* American Concrete Institute, Farmington Hills, MI.

ACI 355.2-07 (2007), *Qualification of Post-Installed Mechanical Anchors in Concrete,* American Concrete Institute, Farmington Hills, MI.

ACI 503.5R-92 (1997), *Guide for the Selection of Polymer Adhesives with Concrete,* American Concrete Institute, Farmington Hills, MI.

Adams, R. D. and Wake, W. C. (1984), *Structural Adhesive Joints in Engineering,* Elsevier Applied Science Publishers, London and New York, pp. 160–162.

Anderson, D. S. (1999), The Effects of Permeability and Water Content on the Adhesive-Bond Strength Between Epoxy Products and Concrete, High Honors Research Report, University of Florida, Gainesville, FL.

ANSI B212.15.1994 (1994), *American National Standard for Cutting Tools—Carbide-Tipped Masonry Drills and Blanks for Carbide-Tipped Masonry Drills,* American National Standards Institute, Washington, D.C.

ASTM A193-12 (2012), *Standard Specification for Alloy-Steel and Stainless Steel Bolting for High Temperature or High Pressure Service and Other Special Purpose Applications,* American Society for Testing and Materials, West Conshohocken, PA.

ASTM A354-11 (2011), *Standard Specification for Quenched and Tempered Alloy Steel Bolts, Studs, and Other Externally Threaded Fasteners,* American Society for Testing and Materials, West Conshohocken, PA.

ASTM A568-09 (2009), *Standard Specification for Steel, Sheet, Carbon, Structural, and High-Strength, Low-Alloy, Hot-Rolled and Cold-Rolled, General Requirements for,* American Society for Testing and Materials, West Conshohocken, PA.

ASTM A615-09 (2009), *Standard Specification for Deformed and Plain Carbon-Steel Bars for Concrete Reinforcement,* American Society for Testing and Materials, West Conshohocken, PA.

ASTM C881/C881M-02 (2002), *Standard Specification for Epoxy-Resin-Base Bonding Systems for Concrete,* American Society for Testing and Materials, West Conshohocken, PA.

ASTM C882-05 (2005), *Standard Test Method for Bond Strength of Epoxy-Resin Systems Used with Concrete by Slant Shear,* American Society for Testing and Materials, West Conshohocken, PA.

ASTM C1074-10 (2010), *Standard Practice for Estimating Concrete Strength by the Maturity Method,* American Society for Testing and Materials, West Conshohocken, PA.

ASTM D471-06 (2006), *Standard Test Method for Rubber Property—Effect of Liquids,* American Society for Testing and Materials, West Conshohocken, PA.

ASTM D638-08 (2008), *Standard Test Method for Tensile Properties of Plastics,* American Society for Testing and Materials, West Conshohocken, PA.

ASTM D648-07 (2007), *Standard Test Method for Deflection Temperature of Plastics Under Flexural Load in the Edgewise Position,* American Society for Testing and Materials, West Conshohocken, PA.

ASTM D1151-00 (2006), *Standard Practice for Effect of Moisture and Temperature on Adhesive Bonds,* American Society for Testing and Materials, West Conshohocken, PA.

ASTM D1875-03 (2008), *Standard Test Method for Density of Adhesives in Fluid Form,* American Society for Testing and Materials, West Conshohocken, PA.

ASTM D2556-93 (2005), *Standard Test Method for Apparent Viscosity of Adhesives Having Shear-Rate-Dependent Flow Properties,* American Society for Testing and Materials, West Conshohocken, PA.

ASTM D2990-01 (2001), *Standard Test Methods for Tensile, Compressive, and Flexural Creep and Creep-Rupture of Plastics,* American Society for Testing and Materials, West Conshohocken, PA.

ASTM D7290-06 (2011), *Standard Practice for Evaluating Material Property Characteristic Values for Polymeric Composites for Civil*

Engineering Structural Applications, American Society for Testing and Materials, West Conshohocken, PA.

ASTM E119-08 (2008), *Standard Test Methods for Fire Tests of Building Construction and Materials,* American Society for Testing and Materials, West Conshohocken, PA.

ASTM E488-96 (2003), *Standard Test Methods for Strength of Anchors in Concrete and Masonry Elements,* American Society for Testing and Materials, West Conshohocken, PA.

ASTM E488-10 (2003), *Standard Test Methods for Strength of Anchors in Concrete Elements,* American Society for Testing and Materials, West Conshohocken, PA.

ASTM E1252-98 (2007), *Standard Practice for General Techniques for Obtaining Infrared Spectra for Qualitative Analysis,* American Society for Testing and Materials, West Conshohocken, PA.

ASTM E1356-08 (2008), *Standard Test Method for Assignment of the Glass Transition Temperatures by Differential Scanning Calorimetry,* American Society for Testing and Materials, West Conshohocken, PA.

ASTM E1512-01 (2001), *Standard Test Methods for Testing Bond Performance of Bonded Anchors,* American Society for Testing and Materials, West Conshohocken, PA.

ASTM E1545-11 (2011), *Standard Test Method for Assignment of the Glass Transition Temperature by Thermomechanical Analysis,* American Society for Testing and Materials, West Conshohocken, PA.

ASTM E1640-09 (2009), *Standard Test Method for Assignment of the Glass Transition Temperature by Dynamic Mechanical Analysis,* American Society for Testing and Materials, West Conshohocken, PA.

ASTM F1080-93 (2008), *Standard Test Method for Determining the Consistency of Viscous Liquids Using a Consistometer,* American Society for Testing and Materials, West Conshohocken, PA.

Caldwell, D. (2001), *Surface Chemical Analysis of Aggregate,* Polymer Solutions Incorporated, Blacksburg, VA.

CALTRANS (2001), CTM681, *Method for Testing Creep Performance of Concrete Anchorage Systems,* California Department of Transportation, Sacramento, CA.

CALTRANS (2006a), CTM438, Method for Determination of Rheological Properties of Chemical Adhesives using a Dynamic Shear Rheometer, California Department of Transportation, Sacramento, CA.

CALTRANS (2006b), *Standard Specifications,* California Department of Transportation, Sacramento, CA.

CALTRANS (2010), *Caltrans Augmentation—Revisions to ICBO-AC58 "Acceptance Criteria for Adhesive Anchors in Concrete and Masonry Elements,"* California Department of Transportation, Sacramento, CA.

Chin, J., Hunston, D., and Forster, A. (2007), *Thermo-Viscoelastic Analysis of Ambient Cure Epoxy Adhesives Used in Construction Applications,* NISTIR 7429, National Institute of Standards and Technology, Washington, D.C.

Cognard, P. (2005), "Technical Characteristics and Testing Methods for Adhesives and Sealants," *Handbook of Adhesives and Sealants,* Vol. 1, Chap. 2, Elsevier, Oxford, UK, pp. 21–99.

Çolak, A. (2001), Parametric Study of Factors Affecting the Pull-Out Strength of Steel Rods Bonded into Precast Concrete Panels, *International Journal of Adhesion and Adhesives,* Vol. 21, No. 6, pp. 487–493.

Çolak, A. (2007), Estimation of Ultimate Tension Load of Methylmethacrylate Bonded Steel Rods into Concrete, *International Journal of Adhesion and Adhesives,* Vol. 27, No. 8, pp. 653–660.

Cook, R. A., Bishop, M. C., Hagedoorn, H. S., Sikes, D. E., Richardson, D. S., Adams, T. L., and DeZee, C. T. (1994), Adhesive-Bonded Anchors: Bond Properties and Effects of In-Service and Installation Conditions, Structures and Materials Research Report No. 94-2, University of Florida, Gainesville, FL.

Cook, R. A., Doerr, G. T., and Klingner, R. E. (1993), Bond Stress Model for Design of Adhesive Anchors, *ACI Structural Journal,* 90(5), pp. 514–524.

Cook, R. A., Konz, R. C., and Richardson, D. S. (1996), Specifications for Adhesive-Bonded Anchors and Dowels, Structures and Materials Research Report No. 96-3, University of Florida, Gainesville, FL.

Cook, R. A., Kunz, J., Fuchs, W., and Konz, R. C. (1998), Behavior and Design of Single Adhesive Anchors Under Tensile Load in Uncracked Concrete, *ACI Structural Journal,* Vol. 95, No. 1, pp. 9–26.

Cook, R. A. and Konz, R. C. (2001), Factors Influencing Bond Strength of Adhesive Anchors, *ACI Structural Journal,* Vol. 98, No. 1, pp. 76–86.

Cook, R. A. and Jain, P. (2005), Effect of Coarse Aggregate on the Strength of Adhesive-Bonded Anchors, Structures and Materials Research Report No. 05-1, University of Florida, Gainesville, FL.

Crawford, R. J. (1998), Mechanical Behaviour of Plastics, *Plastics Engineering,* Chap. 2, Elsevier Butterworth-Heinemann, Oxford, UK and Burlington, MA.

DIN EN 206-1 (2001), *Concrete - Part 1: Specification, performance, production and conformity; English version of DIN EN 206-1,* Deutsches Institut für Normung, Berlin.

Dusel, J. P. and Mir, A. A. (1991), Initial Evaluation of Epoxy Cartridges Used for Anchoring Dowels into Hardened Concrete, Minor Research Report F91TL01, California Department of Transportation, Sacramento, CA.

Eligehausen, R. and Balogh, T. (1995), Behavior of Fasteners Loaded in Tension in Cracked Reinforced Concrete, *ACI Structural Journal,* Vol. 92, No. 3, pp. 365–379.

Eligehausen, R., Cook, R. A., and Appl, J. (2006a), Behavior and Design of Adhesive Bonded Anchors, *ACI Structural Journal,* Vol. 103, No. 6, pp. 822–831.

Eligehausen, R., Mallee, R., and Silva, J. F. (2006b), *Anchorage in Concrete Construction,* Ernst & Sohn, Berlin, Germany, pp. 186.

Eligehausen, R. and Silva, J. (2008), *The Assessment and Design of Adhesive Anchors in Concrete for Sustained Loading,* Hilti Corporation, Schaan, Principality of Liechtenstein, http://www.us.hilti.com/fstore/holus/techlib/docs/technical%20publications/anchoring/hiltiadhesive sustainedloading.pdf.

EN ISO 6988 (1995), Metallic and Other Non-Organic Coatings—Sulfur Dioxide Test with General Condensation of Moisture, International Organization for Standardization, Geneva, Switzerland.

EOTA (1997a), Anchors in General, *ETAG 001 Guideline for European Technical Approval of Metal Anchors for Use in Concrete,* Part 1, European Organisation for Technical Approvals, Brussels.

EOTA (1997b), Design Methods for Anchorages, *ETAG 001 Guideline for European Technical Approval of Metal Anchors for Use in Concrete,* Annex C, European Organisation for Technical Approvals, Brussels.

EOTA (2002), Bonded Anchors, *ETAG 001 Guideline for European Technical Approval of Metal Anchors for Use in Concrete,* Part 5, European Organisation for Technical Approvals, Brussels.

FDOT (2000), FM 5-568, *Anchor System Tests for Adhesive-Bonded Anchors and Dowels,* Florida Department of Transportation, Tallahassee, FL.

FDOT (2007), *Standard Specifications for Road and Bridge Construction,* Florida Department of Transportation, Tallahassee, FL.

FDOT (2009), *Structures Design Guidelines,* Florida Department of Transportation, Tallahassee, FL.

fib (2011), *Design of Anchorages in Concrete,* Federation Internationale du Beton, Lausanne, Switzerland.

Fuchs, W., Eligehausen, R., and Breen, J. E. (1995), Concrete Capacity Design (CCD) Approach for Fastening to Concrete, *ACI Structural Journal,* Vol. 92, No. 1, pp. 73–94.

Hunston, D. T., Carter, W., and Rushford, J. L. (1980), Mechanical Behavior of Plastics, *Mechanical Properties of Solid Polymers as Modeled by a Simple Epoxy,* Chap. 4, Elsevier Butterworth-Heinemann, Oxford, UK and Burlington, MA.

Hunston, D. and Chin, J. (2008), *Characterization of Ambient Cure Epoxies used in the "Big Dig" Ceiling Collapse,* seminar for Virginia Tech Macromolecular Science and Engineering Department, Nov. 5, 2008.

ICC-ES AC58 (2005), *Acceptance Criteria for Adhesive Anchors in Concrete and Masonry Elements,* ICC Evaluation Services, Inc., Whittier, CA.

ICC-ES AC58 (2007), *Acceptance Criteria for Adhesive Anchors in Masonry Elements,* ICC Evaluation Services, Inc., Whittier, CA.

ICC-ES AC308 (2008), *Acceptance Criteria for Post-Installed Adhesive Anchors in Concrete,* ICC Evaluation Services, Inc., Whittier, CA.

IDOT (2007a), *Laboratory Test Procedure for Chemical Adhesives,* Illinois Department of Transportation, Springfield, IL.

IDOT (2007b), *Standard Specifications for Road and Bridge Construction,* Illinois Department of Transportation, Springfield, IL.

IDOT (2008), *Bridge Manual,* Illinois Department of Transportation, Springfield, IL.

ISO/IEC 17011 (2004), *Conformity Assessment—General Requirements for Accreditation Bodies Accrediting Conformity Assessment Bodies,* International Organization for Standardization, Geneva, Switzerland.

ISO/IEC 17020 (1998), *General Criteria for the Operation of Various Types of Bodies Performing Inspection,* International Organization for Standardization, Geneva, Switzerland.

Jazouli, S., Luo, W., Bremand, F., and Vu-Khanh, T. (2005), Application of Time-Stress Equivalence to Nonlinear Creep of Polycarbonate, Polymer Testing, *Polymer Testing,* Vol. 24, pp. 463–467.

Klompen, E. T. J., Engels, T. A. P., van Breemen, L. C. A., Schreurs, P. J. G., Govaert, L. E., and Meijer, H. E. H. (2005), Quantitative Prediction of Long-Term Failure of Polycarbonate, *Macromolecules,* Vol. 38, pp. 7009–7017.

Krishnamurthy, K. (1996), Development of a Viscoplastic Consistent-Tangent FEM Model with Applications to Adhesive-Bonded Anchors, (Dissertation), University of Florida, Gainesville, FL.

Lee, H. N., Paeng, K., Swallen, S. F., and Ediger, M. D. (2009), Direct Measurement of Molecular Mobility in Actively Deformed Polymer Glasses, *Science,* Vol. 323, pp. 231–234.

Mattis, L. and Silva, J. (2011), Special Inspection Guidelines for Expansion and Adhesive Anchors, Concrete Anchor Manufacturers Association, Cleveland, OH, June 2011, 13 pp. (available at www.concreteanchors.org/pubs/htn).

McVay, M., Cook, R. A., and Krishnamurthy, K. (1996), "Pullout Simulation of Postinstalled Chemically Bonded Anchors," *Journal of Structural Engineering,* ASCE, 122(9), 1016–1024.

Mehta, P. K. and Monteiro, J. M. (2006), *Concrete Microstructure, Properties, and Materials,* McGraw Hill. New York, NY. pp. 66.

Messler, R. W. (2004), *Joining of Materials and Structures,* Elsevier Butterworth-Heinemann, Oxford, UK.

Meszaros, J. (1999), Tragverhalten Von Verbunddübeln Im Ungerissenen Und Gerissenen Beton, (Dissertation), University of Stuttgart, Stuttgart, Germany, (in German).

MDOT (2003), *Standard Specifications for Construction,* Michigan Department of Transportation, Lansing, MI.

MDOT (2005), *Bridge Design Manual,* Michigan Department of Transportation, Lansing, MI.

MDOT (2008), "Moratorium on the Use of Adhesive Anchors in Sustained Tensile-Load-Only Overhead Applications," Bureau of Highway Instructional Memorandum 2008-07, Michigan Department of Transportation, Lansing, MI.

MDOT (2009), *Materials Source Guide,* Michigan Department of Transportation, Lansing, MI.

NCHRP (2002), *NCHRP Report 469: Fatigue-Resistant Design of Cantilevered Signal, Sign, and Light Supports,* Transportation Research Board of the National Academies, Washington D.C.

NCHRP (2009), NCHRP Report 639: Adhesive Anchors in Concrete Under Sustained Loading Conditions, Transportation Research Board of the National Academies, Washington D.C.

NTSB (2007a), Ceiling Collapse in the Interstate 90 Connector Tunnel, Boston, Massachusetts, July 10, 2006, NTSB Highway Accident Report HAR-07/02, National Transportation Safety Board, Washington, D.C.

NTSB (2007b), Materials Laboratory Factual Report, NTSB No. HWY 06MH024, Report No. 06-105, National Transportation Safety Board, Washington, DC.

NYSDOT (2008a), *Bridge Manual,* 4th Edition, (1st US Customary Edition), New York State Department of Transportation, Albany, NY.

NYSDOT (2008b), Anchoring Materials—Chemical Curing, NTSB Safety Recommendations, *Engineering Instruction EI 08-012,* New York State Department of Transportation, Albany, NY.

NYSDOT (2008c), *Standard Specifications,* with January 2009 amendments, New York State Department of Transportation, Albany, NY.

PENNDOT (2007), *Design Manual Part 4—Structures,* Publication No. 15M, Vol. 1, Pennsylvania Department of Transportation, Harrisburg, PA.

Rodden, R. (2006), Analytical Modeling of Environmental Stresses in Concrete Slabs, Masters Thesis, University of Illinois at Urbana-Champaign.

SEAOSC (1997), *Standard Method of Cyclic (Reversed) Load Test for Anchors in Concrete or Grouted Masonry,* Structural Engineers Association of Southern California, Whittier, CA.

TxDOT (2004), *Standard Specifications for Construction and Maintenance of Highways, Streets, and Bridges,* Texas Department of Transportation, Austin, TX.

TxDOT (2007a), DMS-6100 Epoxies and Adhesives, *Departmental Material Specifications,* Texas Department of Transportation, Austin, TX.

TxDOT (2007b), *Tex-614-J, Testing Epoxy Materials,* Texas Department of Transportation, Austin, TX.

VDOT (2007a), *Road and Bridge Specifications,* Virginia Department of Transportation, Richmond, VA.

VDOT (2007b), "Sound Barrier Wall Attachments," Instructional and Informational Memorandum, IIM-S&B-40.2, Structure and Bridge Division, Virginia Department of Transportation, Richmond, VA.

VDOT (2008a), "Adhesive Anchors for Structural Applications," Instructional and Informational Memorandum, IIM-S&B-76.2, Structure and Bridge Division, Virginia Department of Transportation, Richmond, VA.

VDOT (2008b), *Inspection Manual,* Virginia Department of Transportation, Richmond, VA.

Vuoristo, T. and Kuokkala, V. (2002), Creep, Recovery and High Strain Rate Response of Soft Roll Cover Materials, *Mechanics of Materials,* Vol. 34, No. 8, pp. 493–504.

Wheeler, A., and Ganji, A. (2004), *Introduction to Engineering Experimentation,* 2nd ed. Prentice Hall, Upper Saddle River, NJ.

Wollmershauser, R., and Mattis, L., Adhesive Anchor Installation and Inspection, *Concrete International,* vol. 30, No. 12, December 2008, pp. 36–40.

WSDOT (2008a), *Bridge Design Manual,* Publication M23-50.02, Washington State Department of Transportation, Olympia, WA.

WSDOT (2008b), *Standard Specifications,* Publication M41-10, Washington State Department of Transportation, Olympia, WA.

WSDOT (2009), *Construction Manual,* Publication M41-01.07, Washington State Department of Transportation, Olympia, WA.

Abbreviations

ACI	American Concrete Institute
ANSI	American National Standards Institute
ASD	Allowable Stress Design
CALTRANS	California Department of Transportation
CRSI	Concrete Reinforcing Steel Institute
DIN	Deutsches Institut für Normung
DMTA	Dynamic Mechanical Thermal Analysis
DSC	Differential Scanning Calorimetry
DSR	Dynamic Shear Rheometer
EOTA	European Organisation for Technical Approvals
ESR	Evaluation Safety Report
ETAG	European Technical Approval Guideline
FDOT	Florida Department of Transportation
fib	Federation Internationale du Beton
FTIR	Fourier transform infrared spectroscopy
ICBO	International Conference of Building Officials
ICC-ES	International Code Council Evaluation Service
IDOT	Illinois Department of Transportation
ISAT	Initial Surface Absorption Test
IWB	Institut für Werkstoffe im Bauwesen
LRFD	Load and Resistance Factor Design
MDOT	Michigan Department of Transportation
mfr	Manufacturer
MPII	Manufacturer’s Printed Installation Instructions
MSL	Mean Static Load
MPS	Mean Peak Stress
NIST	National Institute of Standards and Technology
NYSDOT	New York State Department of Transportation
PENNDOT	Pennsylvania Department of Transportation
PTFE	Polytetrafluoroethylene
QPL	Qualified Products List
RH	Relative Humidity
SEAOSC	Structural Engineers Association of Southern California
SvTTF	Stress versus Time to Failure

TxDOT	Texas Department of Transportation
UF	University of Florida
US	University of Stuttgart
VDOT	Virginia Department of Transportation
WSDOT	Washington State Department of Transportation

APPENDIX A

ACI 355.4 Tables 3.1, 3.2, 3.3, 10.5, and 10.6

Table 3.1—Test program for evaluating adhesive anchor systems in uncracked concrete

Testing				Assessment				
Test no.	Test reference	Purpose	Test parameters	α_{req}	Load and displacement	f_c[*]	h_{ef}[†]	Minimum sample size n_{min}
Reference tests								
1a	Chapter 6	Reference tension in low-strength concrete	Tension, confined, single anchor away from edges	—	—	low	min max	Five per concrete batch
1b	Chapter 6	Reference tension in high-strength concrete	Tension, confined, single anchor away from edges	—	—	high	min	Five per concrete batch
Reliability tests								
2a	7.5	Sensitivity to hole cleaning, dry substrate	Tension, confined, single anchor away from edges	10.4.6	10.4.2 10.4.4	low	max	Five[‡]
2b	7.6	Sensitivity to hole cleaning, installation in water-saturated concrete	Tension, confined, single anchor away from edges	10.4.6	10.4.2 10.4.4	low	max	Five[‡]
2c	7.7	Sensitivity to hole cleaning, installation in a water-filled hole[§]	Tension, confined, single anchor away from edges	10.4.6	10.4.2 10.4.4	low	max	Five[‡]
2d	7.8	Sensitivity to hole cleaning, installation in submerged concrete[§]	Tension, confined, single anchor away from edges	10.4.6	10.4.2 10.4.4	low	max	Five[‖]
2e	7.9	Sensitivity to mixing effort	Tension, confined, single anchor away from edges	10.4.6	10.4.2 10.4.4	low	max	Five[#]
2f[**]	7.10	Sensitivity to installation in water-saturated concrete	Tension, confined, single anchor away from edges	10.4.6	10.4.2 10.4.4	low	max	Five[‡]
2g	7.11	Sensitivity to installation in a water-filled hole[§]	Tension, confined, single anchor away from edges	10.4.6	10.4.2 10.4.4	low	max	Five[‡]
2h	7.12	Sensitivity to installation in submerged concrete[§]	Tension, confined, single anchor away from edges	10.4.6	10.4.2 10.4.4	low	max	Five[‖]
3	7.16	Sensitivity to freezing/thawing conditions	Sustained tension, residual capacity, confined test	0.90	10.4.2 10.4.4 10.10	high	min[††]	Five[#]
4	7.17	Sensitivity to sustained load	Sustained tension, residual capacity, confined test	0.90	10.4.2 10.4.4 10.11	low	min[††]	Five[#]
5	7.18	Sensitivity to installation direction[§]	Tension, confined, single anchor away from edges	0.90	10.4.2 10.4.4 10.12	low	max	Five[#]
6	7.19	Torque test[‡‡]	Application of torque, confined, single anchor away from edges	—	10.8	high	min	Five[‖]
Service-condition tests								
7a	8.4	Tension in low-strength concrete	Tension, unconfined, single anchor away from edges[§§]	—	10.4.2 10.4.4 10.4.5	low	min max	Five[‖]
7b	8.4	Tension in high-strength concrete[‖‖]	Tension, unconfined, single anchor away from edges[§§]	—	10.4.2 10.4.4 10.4.5	high	min	Five[‖]
8a	8.5	Tension at elevated temperatures	Tension, confined, single anchor away from edges	—	10.4.2 10.4.4 10.13	low	min	Five[#]
8b	8.6	Tension at decreased installation temperature[§]	Tension, confined single anchor away from edges	—	10.4.2 10.4.4 10.14	low	min	Five[#]
8c	8.7	Curing time at standard installation temperature	Tension, confined single anchor away from edges	—	10.4.2 10.4.4 10.15	low	min	Five[#]
9a	8.8	Resistance to alkalinity	Slice tests	—	10.16	low	—	Ten[#]
9b	8.8	Resistance to sulfur[§]	Slice tests	—	10.16	low	—	Ten[#]
10	8.9	Edge distance in corner condition to develop full capacity	Tension, unconfined single anchor in corner with proximate edges[##]	—	10.17	low	min max	Four[‖]
11	8.10	Minimum spacing and edge distance to preclude splitting	High installation tension (torque or unconfined tension), two anchors near an edge[##]	—	10.18	low	min	Five[‖]
12	8.11	Shear capacity of steel element having a non-uniform cross section[***]	Shear, single anchor away from edges	—	10.6	low	min	Five[‖]
13	9.1	Round-robin tests for regional concrete variation	Tension, confined and unconfined single anchor away from edges	—	10.4.1	low[†††]	$7d_a$	Five[#]
14	9.2	Minimum member thickness[§]	Installation tests[##]	—	10.7	low	max	Ten[‖]

[*] For definition of high- and low-strength concrete, refer to 4.3.4.

[†] Where MPII specifies multiple embedment depths for single anchor diameter, test anchor at minimum or maximum embedment depth as noted, whereby $h_{ef,max}/h_{ef,min} \leq 5.0$ (4.7.2).

[‡] Test small, medium, and large diameters.

[§] Optional test.

[‖] Test all diameters.

[#] Test the nominal 1/2 in. diameter or the smallest nominal diameter if it is larger than 1/2 in. For overhead and horizontal orientations, test the largest diameter for which recognition is sought. For tests conducted in accordance with 9.1, tests shall be performed with a nominal 1/2 in. anchor only.

[**] Test 2f may be omitted if Test 2g is performed.

[††] Refer to 4.7.2.2.

[‡‡] Refer to 3.4 for multiple anchor element types.

[§§] Alternatively, tests may be performed as confined tests.

[‖‖] Tests are optional if test results of Test 1b can be shown to be statistically equivalent to or greater than the results of Test 1a. If Test 7b is not performed, limit the calculated anchor tension resistance to $f_c' = 2500$ psi regardless of the in-place concrete strength.

[##] Use minimum member thickness h_{min} for these tests.

[***] Test is required only for anchors having a cross-sectional area, within five anchor diameters of the shear failure plane, that is less than that of a threaded bolt having the same nominal diameter as the anchor.

[†††] Test in concrete having a measured compressive strength of 3000 ± 500 psi at the time of testing.

Table 3.2—Test program for evaluating adhesive anchor systems for cracked and uncracked concrete

Testing				Crack width Δ_w, in.	Assessment		f_c[*]	h_{ef}[†]	Minimum sample size n_{min}
Test no.	**Test reference**	**Purpose**	**Test parameters**		α_{req}	**Load and displacement**			
Reference tests									
1a	Chapter 6	Reference tension in low-strength concrete	Tension, confined, single anchor away from edges	—	—	—	low	min max	Five per concrete batch
1b	Chapter 6	Reference tension in low-strength, cracked concrete	Tension, confined, single anchor away from edges	0.012	—	—	low	min	Five per concrete batch
1c	Chapter 6	Reference tension in high-strength concrete	Tension, confined, single anchor away from edges	—	—	—	high	min	Five per concrete batch
1d	Chapter 6	Reference tension in high-strength, cracked concrete[‡]	Tension, confined, single anchor away from edges	0.012	—	—	high	min	Five per concrete batch
Reliability tests									
2a	7.5	Sensitivity to hole cleaning, dry substrate	Tension, confined, single anchor away from edges	—	10.4.6	10.4.2 10.4.4	low	max	Five[§]
2b	7.6	Sensitivity to hole cleaning, installation in water-saturated concrete	Tension, confined, single anchor away from edges	—	10.4.6	10.4.2 10.4.4	low	max	Five[§]
2c	7.7	Sensitivity to hole cleaning, installation in a water-filled hole[‖]	Tension, confined, single anchor away from edges	—	10.4.6	10.4.4 10.4.4	low	max	Five[§]
2d	7.8	Sensitivity to hole cleaning, installation in submerged concrete[‖]	Tension, confined, single anchor away from edges	—	10.4.6	10.4.4	low	max	Five[#]
2e	7.9	Sensitivity to mixing effort	Tension, confined, single anchor away from edges	—	10.4.6	10.4.2 10.4.4	low	max	Five[**]
2f[††]	7.10	Sensitivity to installation in water-saturated concrete	Tension, confined, single anchor away from edges	—	10.4.6	10.4.2 10.4.4	low	max	Five[§]
2g	7.11	Sensitivity to installation in a water-filled hole[‖]	Tension, confined, single anchor away from edges	—	10.4.6	10.4.2 10.4.4	low	max	Five[§]
2h	7.12	Sensitivity to installation in submerged concrete[‖]	Tension, confined, single anchor away from edges	—	10.4.6	10.4.2 10.4.4	low	max	Five[#]
3	7.13	Sensitivity to crack width in low-strength concrete	Tension, confined, single anchor away from edges	0.020	0.80	10.4.4 10.4.4	low	min	Five[§]
4	7.14	Sensitivity to crack width in high-strength concrete[‡]	Tension, confined, single anchor away from edges	0.020	0.80	10.4.2 10.4.4	high	min	Five[§]
5	7.15	Sensitivity to crack width cycling	Sustained tension, single anchor away from edges, residual capacity, confined test	0.004 to 0.012	0.90	10.4.2 10.4.4 10.9	low	min	Five[#]
6	7.16	Sensitivity to freezing/thawing conditions	Sustained tension, residual capacity, confined test	—	0.90	10.4.2 10.4.4 10.10	high	min[‡‡]	Five[**]
7	7.17	Sensitivity to sustained load	Sustained tension, residual capacity, confined test	—	0.90	10.4.2 10.4.4 10.11	low	min[‡‡]	Five[**]
8	7.18	Sensitivity to installation direction[‖]	Tension, confined, single anchor away from edges	—	0.90	10.4.2 10.4.4 10.12	low	max	Five[**]
9	7.19	Torque test[§§]	Application of torque, confined, single anchor away from edges	—	—	10.8	high	min	Five[#]
Service-condition tests									
11a	8.4	Tension in low-strength concrete	Tension, unconfined, single anchor away from edges	—	—	10.4.2 10.4.4 10.4.5	low	min max	Five[#]
11b	8.4	Tension in high-strength concrete[‡]	Tension, unconfined, single anchor away from edges	—	—	10.4.2 10.4.4 10.4.5	high	min	Five[#]
11c	8.4	Tension in low-strength, cracked concrete	Tension, unconfined, single anchor away from edges	0.012	—	10.4.2 10.4.4 10.4.5	low	min	Five[#]
11d	8.4	Tension in high-strength, cracked concrete[‡]	Tension, unconfined, single anchor away from edges	0.012	—	10.4.2 10.4.4 10.4.5	high	min	Five[#]
12a	8.5	Tension at elevated temperatures	Tension, confined single anchor away from edges	—	—	10.4.2 10.4.4 10.13	low	min	Five[**]
12b	8.6	Tension at decreased installation temperature[‖]	Tension, confined single anchor away from edges	—	—	10.4.2 10.4.4 10.14	low	min	Five[**]
12c	8.7	Curing time at standard installation temperature	Tension, confined single anchor away from edges	—	—	10.4.2 10.4.4 10.15	low	min	Five[**]

Table 3.2—Test program for evaluating adhesive anchor systems for cracked and uncracked concrete (cont.)

Testing				Crack width Δ_w, in.	Assessment				
Test no.	**Test reference**	**Purpose**	**Test parameters**		α_{req}	**Load and displacement**	f_c[*]	h_{ef}[†]	**Minimum sample size** n_{min}
13a	8.8	Resistance to alkalinity	Slice tests	—	—	10.16	low	—	Ten[**]
13b	8.8	Resistance to sulfur[‖]	Slice tests	—	—	10.16	low	—	Ten[**]
14	8.9	Edge distance in corner condition to develop full capacity	Tension, unconfined single anchor in corner with proximate edges[##]	—	—	10.17	low	min max	Four[#]
15	8.10	Minimum spacing and edge distance to preclude splitting	High installation tension (torque or unconfined tension) two anchors near an edge[##]	—	—	10.18	low	min	Five[#]
16	8.11	Shear capacity of anchor element having a non-uniform cross section	Shear, single anchor away from edges[***]	—	—	10.6	low	min	Five[#]
17	8.12	Seismic tension[‖]	Pulsating tension, single anchor away from edges	0.020	—	10.4.2 10.4.4 10.19	low	min max	Five[#]
18	8.13	Seismic shear[‖]	Alternating shear, single anchor away from edges	0.020	—	10.20	low	min	Five[§]
19	9.1	Round-robin tests for regional concrete variation	Tension, confined and unconfined single anchor away from edges	—	—	10.4.1	low[†††]	$7d_a$	Five[**]
20	9.2	Minimum member thickness[‖]	Installation tests[##]	—	—	10.7	low	max	Ten[#]

[*] For definition of high- and low-strength concrete, refer to 4.3.4.

[†] Where MPII specify multiple embedment depths for single anchor diameter, test anchor at minimum or maximum embedment depth as noted, whereby $h_{ef,max}/h_{ef,min} \le 5.0$ (4.7.2).

[‡] Tests are optional if test results of Test 1c can be shown to be statistically equivalent to or greater than results of Test 1a. If any of Tests 1d, 4, 11b, and 11d are not performed, limit calculated anchor tension resistance to f'_c = 2500 psi.

[§] Test small, medium, and large diameters.

[‖] Optional test.

[#] Test all diameters.

[**] Test the nominal 1/2 in. (12 mm) diameter or the smallest nominal diameter if it is larger than 1/2 in. (12 mm). For overhead and horizontal orientations, test the largest diameter for which recognition is sought. For tests conducted in accordance with Section 9.1, tests shall be performed with a nominal 1/2 in. anchor only.

[††] Test 2f may be omitted if Test 2g is performed.

[‡‡] Refer to Section 4.7.2.2.

[§§] Refer to Section 3.4 for multiple anchor element types.

[##] Use minimum member thickness h_{min} for these tests.

[***] Test is required only for anchors having a cross-sectional area, within five anchor diameters of the shear failure plane, that is less than that of a threaded bolt having the same nominal diameter as the anchor.

[†††] Test in concrete having a measured compressive strength of 3000 psi ± 500 psi at the time of testing.

Table 3.3—Reduced test program for evaluating adhesive anchor systems in cracked and uncracked concrete

Testing				Crack width Δ_w, in.	Assessment				
Test no.	**Test reference**	**Purpose**	**Test parameters**		α_{req}	**Load and displacement**	f_c[*]	h_{ef}[†]	**Minimum sample size** n_{min}
			Reference tests						
1a	Chapter 6	Reference tension in low-strength concrete	Tension, confined, single anchor away from edges	—	—	—	low	min max	Five per concrete batch
1b	Chapter 6	Reference tension in high-strength concrete	Tension, confined, single anchor away from edges	—	—	—	high	min	Five per concrete batch
			Reliability tests						
2a	7.5	Sensitivity to hole cleaning, dry substrate	Tension, confined, single anchor away from edges	—	10.4.6	10.4.2 10.4.4	low	max	Five[‡]
2b	7.6	Sensitivity to hole cleaning, installation in water-saturated concrete	Tension, confined, single anchor away from edges	—	10.4.6	10.4.2 10.4.4	low	max	Five[‡]
2c	7.7	Sensitivity to hole cleaning, installation in a water-filled hole[§]	Tension, confined, single anchor away from edges	—	10.4.6	10.4.2 10.4.4	low	max	Five[‡]
2d	7.8	Sensitivity to hole cleaning, installation in submerged concrete[§]	Tension, confined, single anchor away from edges	—	10.4.6	10.4.2 10.4.4	low	max	Five[‖]
2e	7.9	Sensitivity to mixing effort	Tension, confined, single anchor away from edges	—	10.4.6	10.4.2 10.4.4	low	max	Five[#]
2f[**]	7.10	Sensitivity to installation in water-saturated concrete	Tension, confined, single anchor away from edges	—	10.4.6	10.4.2 10.4.4	low	max	Five[‡]
2g	7.11	Sensitivity to installation in a water-filled hole[§]	Tension, confined, single anchor away from edges	—	10.4.6	10.4.2 10.4.4	low	max	Five[‡]
2h	7.12	Sensitivity to installation in submerged concrete[§]	Tension, confined, single anchor away from edges	—	10.4.6	10.4.2 10.4.4	low	max	Five[‖]

Table 3.3—Reduced test program for evaluating adhesive anchor systems in cracked and uncracked concrete (cont.)

Testing				Crack width Δ_w, in.	Assessment				Minimum sample size n_{min}
Test no.	**Test reference**	**Purpose**	**Test parameters**		α_{req}	**Load and displacement**	f_c[*]	h_{ef}[†]	
3	7.15	Sensitivity to crack width cycling	Sustained tension, single anchor away from edges, residual capacity, confined test	0.004 to 0.012	0.90	10.4.2 10.4.4 10.9	low	min	Five[‖]
4	7.16	Sensitivity to freezing/thawing conditions	Sustained tension, residual capacity, confined test	—	0.90	10.4.2 10.4.4 10.10	high	min[††]	Five[#]
5	7.17	Sensitivity to sustained load	Sustained tension, residual capacity, confined test	—	0.90	10.4.2 10.4.4 10.11	low	min[††]	Five[#]
6	7.18	Sensitivity to installation direction[§]	Tension, confined, single anchor away from edges	—	0.90	10.4.2 10.4.4 10.12	low	max	Five[#]
7	7.19	Torque test[‡‡]	Application of torque, confined, single anchor away from edges	—	—	10.8	high	min	Five[‖]
Service-condition tests									
8a	8.4	Tension in low-strength concrete	Tension, unconfined, single anchor away from edges	—	—	10.4.2 10.4.4 10.5	low	min max	Five[‖]
8b	8.4	Tension in high-strength concrete[§§]	Tension, unconfined, single anchor away from edges	—	—	10.4.2 10.4.4 10.5	high	min	Five[‖]
9a	8.5	Tension at elevated temperatures	Tension, confined single anchor away from edges	—	—	10.4.2 10.4.4 10.13	low	min	Five[#]
9b	8.6	Tension at decreased installation temperature[§]	Tension, confined single anchor away from edges	—	—	10.4.2 10.4.4 10.14	low	min	Five[#]
9c	8.7	Curing time at standard installation temperature	Tension, confined single anchor away from edges	—	—	10.4.2 10.4.4 10.15	low	min	Five[#]
10a	8.8	Resistance to alkalinity	Slice tests	—	—	10.16	low	-	Ten[#]
10b	8.8	Resistance to sulfur[§]	Slice tests	—	—	10.16	low	-	Ten[#]
11	8.9	Edge distance in corner condition to develop full capacity	Tension, unconfined single anchor in corner with proximate edges[##]	—	—	10.17	low	min max	Four[‖]
12	8.10	Minimum spacing and edge distance to preclude splitting	High installation tension (torque or unconfined tension), two anchors near an edge[##]	—	—	10.18	low	min	Five[‖]
13	8.11	Shear capacity of anchor element having a non-uniform cross section	Shear, single anchor away from edges[***]	—	—	10.6	low	min	Five[‖]
14	9.1	Round-robin tests for regional concrete variation	Tension, confined and unconfined single anchor away from edges	—	—	10.4.1	low[†††]	$7d_a$	Five[#]
15	9.2	Minimum member thickness[§]	Installation tests[##]	—	—	10.7	low	max	Ten[‖]

[*] For definition of high- and low-strength concrete, refer to 4.3.4.

[†] Where MPII specify multiple embedment depths for single anchor diameter, test anchor at minimum or maximum embedment depth as noted, whereby $h_{ef,max}/h_{ef,min} \leq 5.0$ (4.7.2).

[‡] Test small, medium, and large diameters.

[§] Optional test.

[‖] Test all diameters.

[#] Test nominal 1/2 in. diameter or smallest nominal diameter if it is larger than 1/2 in. For overhead and horizontal orientations, test largest diameter for which recognition is sought. For tests conducted in accordance with 9.1, tests shall be performed with nominal 1/2 in. anchor only.

[**] Test 2f may be omitted if Test 2g is performed.

[††] Refer to 4.7.2.2.

[‡‡] Refer to 3.4 for multiple anchor element types.

[§§] Tests are optional if test results of Test 1b can be shown to be statistically equivalent to or greater than results of Test 1a. If Test 8b is not performed, limit calculated anchor tension resistance to $f_c' = 2500$ psi.

[##] Use minimum member thickness h_{min} for these tests.

[***] Test is required only for anchors having cross-sectional area within five anchor diameters of the shear failure plane that is less than that of threaded bolt having same nominal diameter as anchor.

[†††] Test in concrete having measured compressive strength of 3000 ± 500 psi at time of testing.

Table 10.5—Anchor categories for adhesive anchors subject to installation conditions according to Table 10.7*

Anchor category	Threshold value of α_{req} for selected reliability tests				
	Reliability test numbers according to Table 3.1, Table 3.2, or Table 3.3				
	2a	2b	2c†	2d†	2e
1	0.95	0.90	0.90	0.90	0.95
2	0.80	0.75	0.75	0.75	0.80
3	0.70	0.65	0.65	0.65	0.70

*(periodic special inspection)

†Optional tests; refer to Table 10.7 for permissible combinations.

Table 10.6—Anchor categories for adhesive anchors subject to installation conditions according to Table 10.8*

Anchor category	Threshold value of α_{req} for selected reliability tests							
	Reliability test numbers according to Table 3.1, Table 3.2, or Table 3.3							
	2a	2b	2c†	2d†	2e	2f‡§	2g†§	2h†§
1	0.80	0.75	0.75	0.75	0.80	0.90	0.90	0.90
2	0.70	0.65	0.65	0.65	0.70	0.75	0.75	0.75
3	0.60	0.55	0.55	0.55	0.60	0.65	0.65	0.65

*(continuous special inspection and on-site proof loading program)

†Optional tests; refer to Table 10.8 for permissible combinations.

‡If Test 2g is performed, then Test 2f may be omitted.

§Omission of less severe tests is permitted in specific cases: for example, if the desired category is fulfilled with the results of Tests 2b, 2c, and 2d, then Tests 2f, 2g, and 2h may be omitted.

APPENDIX B

ACI–AASHTO Resistance Factor Investigation

COMPARISON OF ACI AND AASHTO NOMINAL AND FACTORED RESISTANCES

This document compares the nominal and factored resistances of various concrete structures and steel anchor bolts as determined by ACI and AASHTO. In this document the following abbreviations are used:

- ACI = ACI 318-11 (2011) *Building Code Requirements for Structural Concrete.*
- AASHTO = AASHTO (2010) *LRFD Bridge Design Specifications*, Fifth Edition.

DESIGN APPROACH

In all structural design calculations, the loads, Q, must be less than or equal to the resistance R (Eqn. 1). Due to varying levels of uncertainty, modification factors are applied to both sides of the equation (Eqn. 2). Both AASHTO and ACI follow this approach, but the values of the modification factors vary.

$$loads \leq resistance \qquad \text{(Eqn. 1)}$$

$$\eta \cdot \gamma \cdot Q \leq \varphi \cdot R_n \qquad \text{(Eqn. 2)}$$

The factored resistance, R_r, is comprised of resistance factors, φ, and the nominal resistance, R_n (Eqn. 3).

$$R_r = \varphi \cdot R_n \qquad \text{(Eqn. 3)}$$

Note, ACI and AASHTO use different terminology for the LRFD design which is summarized in Table 1. This document adopts the AASHTO terminology.

Table 1: ACI and AASHTO LFRD terminology.

Term	ACI	AASHTO
R_r or $\varphi \cdot R_n$	Design strength	Factored resistance
φ	Strength reduction factor	Resistance factor
R_n	Nominal strength	Nominal resistance

As the factored resistance, R_r, is comprised of resistance factors, φ, and the nominal resistance, R_n, this document will evaluate both separately. First equations related to several general concrete design situations will be compared followed by a comparison of the equations for bolt shear and tension.

CONCRETE DESIGN COMPARISON

Nominal Resistance

The following compares the nominal resistances for concrete flexure, shear, compression, and bearing.

Nominal Flexural Resistance

Both AASHTO and ACI assume the Whitney stress block for flexural design and use the same definition for the factor, β_1, which relates the depth of the equivalent rectangular compressive stress block to neutral axis depth.

Nominal Shear Resistance Provided by the Concrete

For non-prestressed sections and using the simplified procedures in ACI §11.2.1.1 and AASHTO §5.8.3.4.1 the equations for nominal shear resistance provided by the concrete are:

$$V_c = 2\lambda\sqrt{f'_c}\,b_w d \qquad \text{ACI Eqn. 11-3}$$

$$V_c = 0.0316\beta\sqrt{f'_c}b_v d_v \qquad \text{AASHTO Eqn. 5.8.3.3-3}$$

If we assume normal weight concrete, then λ=1. In the ACI equation, f'_c is in terms of psi but is in terms of ksi in the AASHTO equation. If AASHTO Eqn. 5.8.3.3-3 is converted to terms of psi, the equation would need to be multiplied by $\sqrt{1000}$. The factor β is defined as 2.0 in AASHTO §5.8.3.4.1. With these assumptions and adjustments, the shear capacity provide by concrete for both standards reduces to:

ACI Eqn. 11-3

$$V_c = 2\sqrt{f'_c}\,b_w d$$

AASHTO Eqn. 5.8.3.3-3

Nominal Uniaxial Compressive Resistance

For non-prestressed sections, both ACI §10.3.6 and AASHTO §5.7.4.4 define the uniaxial compressive resistance for sections with spiral and tie reinforcement as:

Spiral reinforcement $$P_n = 0.85\left[0.85f'_c\left(A_g - A_{st}\right) + f_y A_{st}\right]$$ ACI Eqn. 10-1
AASHTO Eqn. 5.7.4.4-2

Tie reinforcement $$P_n = 0.80\left[0.85f'_c\left(A_g - A_{st}\right) + f_y A_{st}\right]$$ ACI Eqn. 10-1
AASHTO Eqn. 5.7.4.4-2

Nominal Bearing Resistance

Both ACI §10.14 and AASHTO §5.7.5 define the bearing resistance as:

$$P_n = 0.85f'_c A_1 m$$

ACI §10.14
AASHTO Eqn. 5.7.5-2

The modification factor, m, is allowed by both ACI and AASHTO. The factor *m* is illustrated in Figure 1 and expressed by both as:

$$m = \sqrt{\frac{A_2}{A_1}} \leq 2.0$$

ACI §10.14
AASHTO Eqn. 5.7.5-3

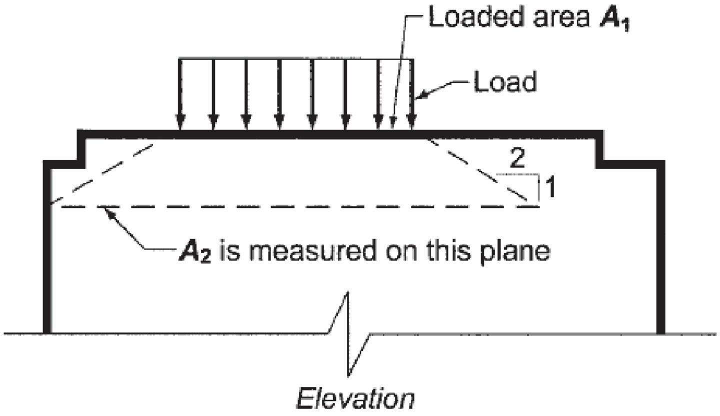


Figure 1: Calculation of area A_2 (courtesy ACI).

Summary

The above study shows that the nominal flexural, shear, axial compressive, and bearing resistances are identical as calculated by ACI and AASHTO.

Resistance Factors

The resistance factors as listed by ACI and AASHTO for several common conditions are presented in Table 2.

Table 2: Comparison of ACI strength reduction factors and AASHTO resistance factors.

Factor	ACI 318-11		AASHTO	
Tension controlled section	0.90	9.3.2.1	0.90	5.5.4.2.1
Compression-controlled sections (Spiral reinforcement)	0.75	9.3.2.2	0.75	5.5.4.2.1
Compression-controlled sections (Tie reinforcement)	0.65	9.3.2.2	0.75	5.5.4.2.1
Shear (normal weight)	0.75	9.3.2.3	0.90	5.5.4.2.1
Shear (lightweight)	0.60[1]	9.3.2.3	0.70	5.5.4.2.1
Bearing	0.65	9.3.2.4	0.70	5.5.4.2.1

Note:

1. Assuming an average value of $\lambda = 0.80$ from ACI 8.6.1, and for comparison with AASHTO, the ACI phi factor reported in this table is $\varphi' = \varphi\lambda = (0.75)(0.80) = 0.60$.

Factored Resistance

Since the nominal resistances, R_n, for flexure, shear, axial compression, and bearing are identical as determined by ACI and AASHTO, the factored resistances, R_r, will only vary by their resistance factors. Therefore, the ratios of the factored resistance determined by ACI and AASHTO are presented in Table 3.

Table 3: Ratio of factored resistance determined by ACI to AASHTO.

Factor	ACI/AASHTO
Tension controlled section	1.00
Compression-controlled sections (Spiral reinforcement)	1.00
Compression-controlled sections (Tie reinforcement)	0.87
Shear (normal weight)	0.83
Shear (lightweight)	0.86
Bearing	0.93

Summary

For all the cases evaluated, ACI is either identical to or more conservative than AASHTO in determining the nominal and factored resistances.

STEEL TENSILE DESIGN COMPARISON

Nominal Resistance

The equations for the tensile strength of an anchor (or bolt) as computed by ACI 318-11 and AASHTO are shown below:

$$N_{sa} = A_{se,N} f_{uta} \qquad \text{ACI (D-2)}$$

$$T_n = 0.76 A_b F_{ub} \qquad \text{AASHTO (6.13.2.10.2-1)}$$

Both f_{uta} and F_{ub} are the specified minimum tensile strength of the anchor. ACI limits this to 125,000 psi or 1.9fya. $A_{se,N}$ is the effective cross-sectional area of the anchor while A_b is the gross area of the anchor corresponding to the nominal diameter. $A_{se,N}$ is defined by ANSI/ASME B1.1 for threaded rods and headed bolts in Eqn. 4 where d_a is the anchor diameter and n_t is the number of threads per inch. Values of $A_{se,N}$ are readily tabulated as in AISC (2005) *Steel Construction Manual*.

$$A_{se,N} = \frac{\pi}{4}\left(d_a - \frac{0.9743}{n_t}\right)^2 \qquad \text{(Eqn. 4)}$$

Table 4 shows that the 0.76 multiplier in AASHTO to compute the effective cross-sectional area from the nominal area is a reasonable approximation.

Table 4: Comparison of effective and gross cross-sectional areas.

Bolt diameter (in.)	**$A_{se,N}$ (in.^{2})**	**A_b (in.^{2})**	**$A_{se,N}/A_b$**
⅝	0.226	0.307	0.74
¾	0.334	0.442	0.76
⅞	0.462	0.601	0.77
1	0.606	0.785	0.77
1 ⅛	0.763	0.994	0.77
1 ¼	0.969	1.23	0.79
1 ⅜	1.16	1.49	0.78
1 ½	1.41	1.77	0.80
1 ¾	1.90	2.41	0.79
2	2.50	3.14	0.80

Note:
Values obtained from AISC (2005) *Steel Construction Manual*, 13th Edition Table 7-18.

Resistance Factors

For steel tensile failure, in ACI §D.4.3 the resistance factors are 0.75 for ductile steel elements and 0.65 for brittle steel elements. In AASHTO §6.5.4.2 the resistance factors are 0.80 for all bolt types.

Factored Resistance

For ductile anchors the ratio of the factored resistances calculated by ACI to AASHTO are presented in Table 5 for various bolt diameters.

Table 5: Ratio of factored resistance for steel strength in tension as computed by ACI and AASHTO for ductile steel elements.

Bolt diameter (in.)	$\varphi N_{sa(ACI)}/\varphi T_{n(AASHTO)}$
⅝	0.91
¾	0.93
⅞	0.95
1	0.95
1 ⅛	0.95
1 ¼	0.97
1 ⅜	0.96
1 ½	0.98
1 ¾	0.97
2	0.98

Note:

- The resistance factors used are φ=0.75 for ACI design equation and φ=0.80 for AASHTO design equation.
- $F_{ub} = f_{uta}$.

Summary

The above ratio of factored resistances calculated by ACI to AASHTO varies between 0.91 and 0.98 over the selected range of anchor diameters.

STEEL SHEAR DESIGN COMPARISON

Nominal Resistance

The equations for the shear strength of an anchor as computed by ACI are shown below:

Cast-in headed stud $V_{sa} = A_{se,V} f_{uta}$ ACI (D-28)

Cast-in headed bolt and hooked bolt anchors and for post-installed anchors where sleeves do not extend through the shear plane	$V_{sa} = 0.60 A_{se,V} f_{uta}$	ACI (D-29)
For post-installed anchors where sleeves extend through the shear plane	$V_{sa} = ACI\ 355.2$ or $V_{sa} = 0.60 A_{se,V} f_{uta}$	ACI §D.6.1.2(c)

ACI §D.6.1.3 also reduces the shear strengths determined above with a 0.80 multiplier when anchors are used with built-up grout pads.

The value of f_{uta} is as defined earlier. $A_{se,V}$ is calculated per Eqn. 4 and is identical to $A_{se,N}$.

The 0.60 multiplier in ACI (D-29) is based on the understanding that the shear strength is 60% of the tensile strength. Cast-in headed studs do not have the 0.60 multiplier as they have higher shear strengths attributed to the fixity of the weld between the bolt and the baseplate as discussed in ACI §RD.6.1.2. ACI §D.6.1.2(c) provides for the shear strength to be determined from tests in accordance with ACI 355.2-07 due to special shaft geometries, configurations, and the presence or absence of sleeves found in anchor bolt applications apart from the regular threaded rods and bolts addressed in AISC (2005) Table 7-18.

The equations for the shear strength of an anchor as computed by AASHTO are shown below:

Where threads are excluded from the shear plane	$R_n = 0.48 A_b F_{ub} N_s$	AASHTO (6.13.2.7-1) AASHTO (6.13.2.12-1)
Where threads are included in the shear plane	$R_n = 0.38 A_b F_{ub} N_s$	AASHTO (6.13.2.7-2)

Resistance Factors

In ACI §D.4.3 the resistance factors are 0.65 for ductile steel elements and 0.60 for brittle steel elements. Based on the definition for ductile steel element in ACI §D.1, A307 and F1554 (within the range of bolt diameters listed) are considered ductile steel elements. In AASHTO §6.5.4.2 the resistance factors are 0.75 for A307 and F1554 bolts. These resistance factors are summarized in Table 6.

Table 6: ACI 318-11 and AASHTO resistance factors for steel shear strength by bolt type.

Bolt	ACI	AASHTO
A307	0.65	0.75
F1554	0.65	0.75

Factored Resistance

For ductile anchors ratio of the factored resistances determined by ACI (D-29) to AASHTO (6.13.2.7-2) with threads included in the shear plane are presented in Table 7.

Table 7: Ratio of factored resistance for steel strength in shear as computed by ACI and AASHTO for A307 & F1554 bolts.

Bolt diameter (in.)	$\varphi V_{sa(ACI)}/\varphi R_{n(AASHTO)}$
⅝	1.01
¾	1.03
⅞	1.05
1	1.06
1 ⅛	1.05
1 ¼	1.08
1 ⅜	1.07
1 ½	1.09
1 ¾	1.08
2	1.09

Note:

- The resistance factors used are:
    - φ=0.65 for ACI 318-11 design equation.
    - φ=0.75 for AASHTO design equation.
- $F_{ub} = f_{uta}$..
- Assumes one shear plane.

Summary

The above ratio of factored resistances calculated by ACI to AASHTO over a range of anchor diameters varies between 1.01 and 1.09 for A307 and F1554 bolts.

COMBINED SHEAR AND TENSION

ACI provides a tri-linear expression in §D.7.1 for the interaction between shear and tension. AASHTO §6.13.2.11 provides an elliptical curve but allows for no reduction of the tensile load when $V_u/V_n \leq 0.33$ (or when $V_u/\varphi V_n \leq 0.44$ assuming $\varphi = 0.75$). ACI's approach is equal to or more conservative than AASHTO's up until $V_u/\varphi V_n = 0.98$ as illustrated in Figure 2.

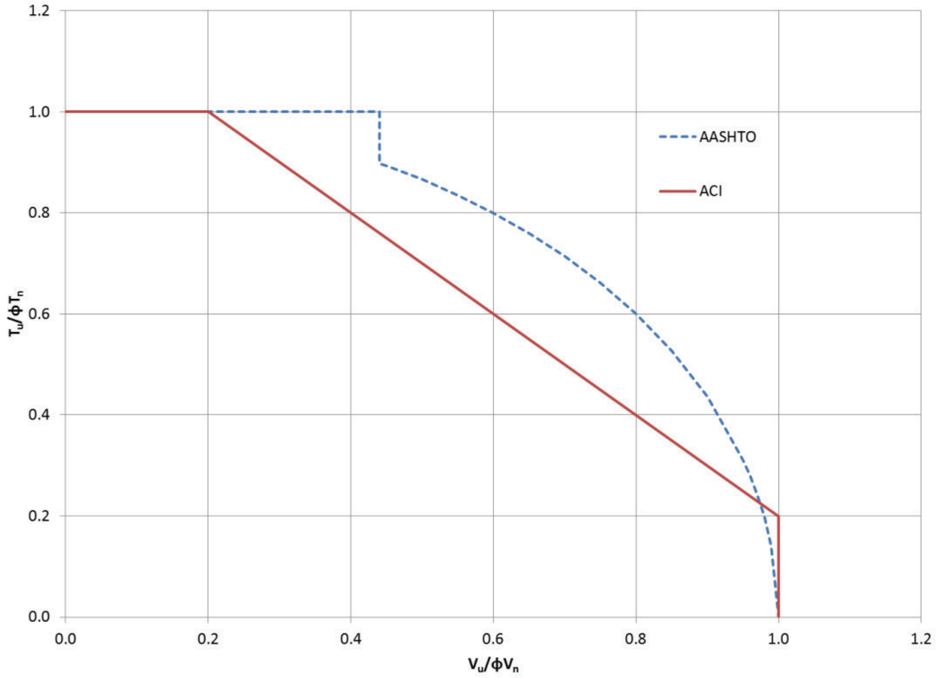


Figure 2: Comparison of ACI and AASHTO tensile-shear interaction equations.

ACI §RD.7 allows for any interaction expression which has been verified by test data, so either expression should be acceptable. However, it must be pointed out that the values used in the interaction expression are the limiting tension and shear limit states for the overall anchor design. While it is preferable that the limit states are steel failure, it is possible that the other limit states discussed in ACI Appendix D might control and should be used in the shear-tension interaction.

CONCLUSION

In conclusion, based on the comparison of the design approaches in ACI and AASHTO for concrete design and steel tension and shear design it would be acceptable to determine both the nominal and factored resistances of anchorage to concrete based on the design provisions from ACI Appendix D for use in designs in which the loads and other limit states were determined by the AASHTO.

APPENDIX C

Anchor Pullout Tests—University of Florida

ANCHOR PULLOUT TESTS—UNIVERSITY OF FLORIDA

Test apparatus

This section describes the test apparatus used for the short-term and sustained load (creep) tests. For each case, the "standard" apparatus is described that was used in the majority of the test series and variations for specific test series are discussed later.

Short-Term Test Apparatus

The short-term confined testing apparatus conformed to the requirements in ASTM E488. The testing apparatus for the short-term test (Figure 1) used a 6" x 6" x 0.03" thick Teflon PTFE (Polytetrafluoroethylene) confining sheet placed under an 8" x 8" x 5/8" thick steel confining plate. The confining sheet was used to correct for any surface irregularities in the concrete. A 1-1/4" hole was drilled though the center of the confining sheet and confining plate to fit around the anchor in accordance with ASTM E488. Two 3" x 5" x 1/4" rectangular steel tubes 8" long were placed parallel to each other on either side of the anchor. A 10" x 10" x 1" thick steel plate with a 2-3/4" diameter hole in the center was placed on the rectangular steel tubes to support an Enerpac model RCH-603 Holl-O-Cylinder hydraulic ram (60 ton). A Houston Scientific Model 3500 100-kip load cell was placed on top of the ram sandwiched between four 3" x 3" x 1/4" square plates (two above and two below) with a 1-1/8" diameter hole in the center. A washer and a nut were placed above the square plates.

The 5/8" diameter anchor was fed through an 11/16" diameter hole in a non-rigid coupler and secured with a nut. The oversized hole in the coupler prevented bending forces from being transferred from the coupling rod to the anchor. A 1" diameter loading rod was threaded into a hole in the top of the coupler and passed through the ram and load cell and was secured at the top with a washer and two nuts.

A 2" x 16" x ¼" steel flat bar was welded to the bottom of the coupler and BEI Duncan Electronics model 9610 linear motion position sensors (linear-pots) were secured to each end of the flat bar equidistant from the center line of the anchor. The linear-pots were oriented downwards and measured displacement between the flat bar and the surface of the concrete. The linear-pots were oriented in this manner so that as the flat bar raised, the plunger extended, ensuring that the linear-pot was not damaged if the anchor failed drastically. A 2" x 2" x ¾" steel baseplate was placed on top of the concrete surface underneath each linear-pot plunger to raise the initial bearing point of the plunger and to provide a smooth measuring surface.

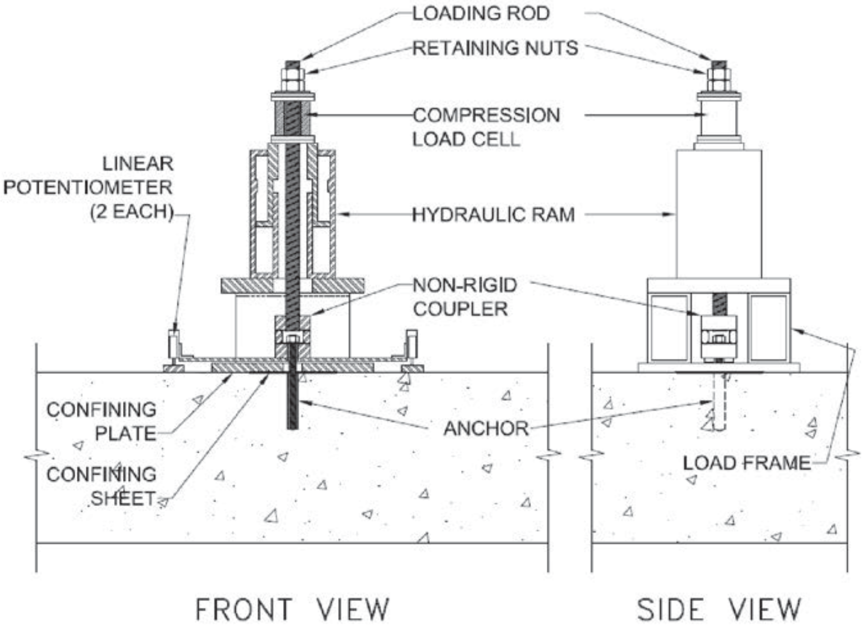


Figure 1: Short-term confined test apparatus.

Test Series 16 (Unconfined) Short-term Test Apparatus

The short-term confined testing apparatus conformed to the requirements in ASTM E488. The 6” x 6” x 0.03” thick Teflon PTFE (Polytetrafluoroethylene) confining sheet and the 8” x 8” x 5/8” thick steel confining plate were not used in this test series. The 3” x 5” x 1/4” rectangular steel tubes were placed parallel to each other on either side of the anchor no closer than two times the embedment depth. An 18” x 18” x 1” thick steel plate with a 2-3/4” diameter hole in the center was placed on the rectangular steel tubes to support an Enerpac model RCH-603 Holl-O-Cylinder hydraulic ram (60 ton). Figure 2 shows the modifications to the short-term test apparatus for test series 16.

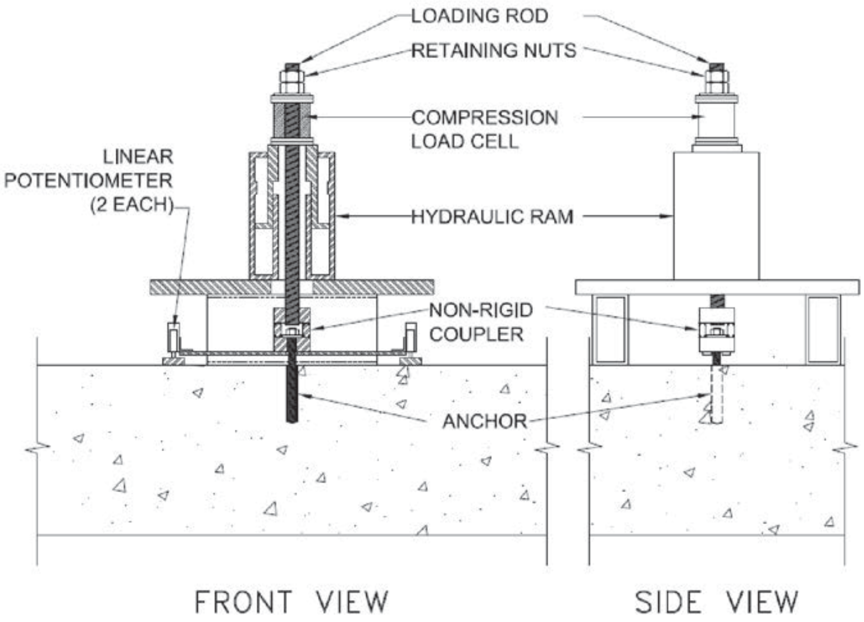


Figure 2: Test series 16 short-term unconfined test apparatus.

Standard Sustained Load (Creep) Test Apparatus

The sustained load confined testing apparatus conformed to the requirements in ASTM E488 and ASTM E1512. Other testing apparatus exist (e.g. cantilevered dead load testing machines) and can be used as long as they conform to the requirements in ASTM E488 and ASTM E1512. The testing apparatus for the sustained load (creep) test (Figure 3) used the same Teflon PTFE (Polytetrafluoroethylene) confining sheet and steel confining plate as in the short-term load test apparatus. Existing steel frames from previous sustained load tests conducted at the University of Florida by Cook et al. (1996) were used to contain compression springs to apply the sustained load. Springs were chosen instead of a hydraulic ram for these sustained load tests in order to reduce the chance of loss of load caused by a hydraulic leak.

The springs used were provided by the Florida Department of Transportation (FDOT) State Materials Office in Gainesville, Florida. Two sets of steel wire springs (large and small) were used individually or in parallel. The large springs were approximately 5.5” in diameter by 8” in uncompressed height and had an average approximate spring stiffness of 10.2 kips/in. and a working load range up to 16 kips. The small springs were approximately 3” in diameter by 8” in uncompressed heights and had an average spring stiffness of 3.2 kips/in. and a working load range up to 5 kips. For loads up to 15 kips, the large springs were used individually, for loads between 16 kips and 21 kips the large and small springs were used in parallel with an average combined spring stiffness of 13.4 kips/in.

The 5/8” diameter anchor was connected to the 1” diameter loading rod by means of the same non-rigid coupler as in the static load test apparatus. Linear-pots were used to measure displacement in the same configuration as in the static load test apparatus.

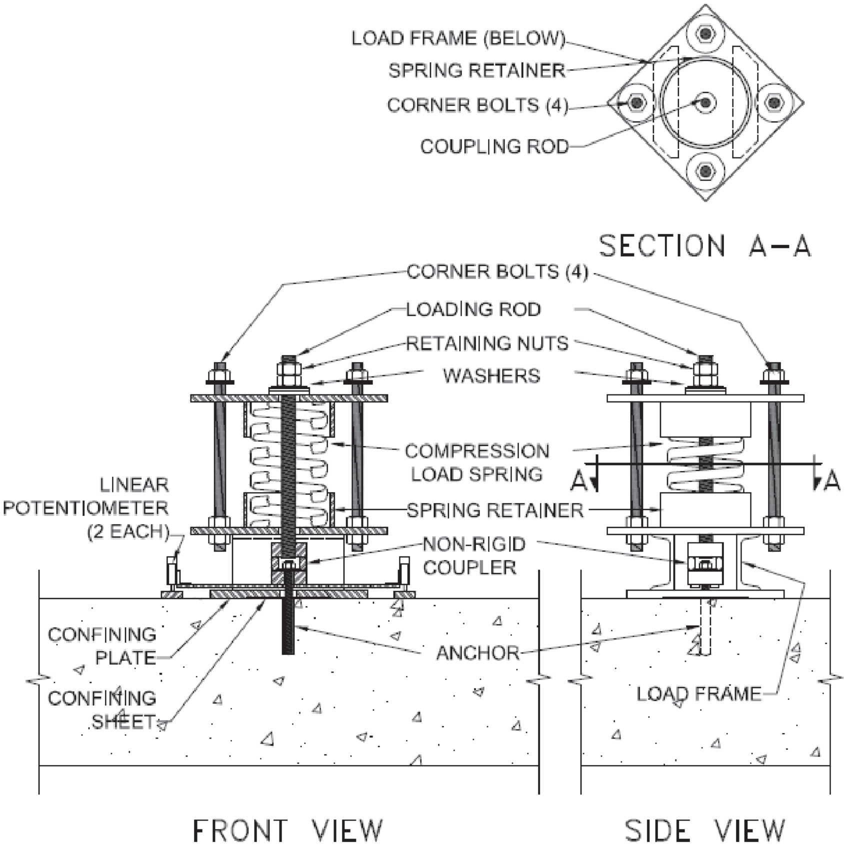


Figure 3: Sustained load (creep) confined test apparatus.

A hydraulic jack chair of four parallel Central Hydraulics Model 95979 20-kip rams with a 7/16” throw was used in order to smoothly and quickly apply the sustained loavd to the anchor. During loading, a load cell on top of the hydraulic jack chair measured the transfer of force from the spring to the anchor. Once the desired load was achieved, a nut was tightened on top of the spring below the hydraulic jack chair and the pressure in the rams was released. The use of the hydraulic jack chair allowed for one load cell to be used for all tests. A test frame with the hydraulic jack chair is shown in Figure 4.

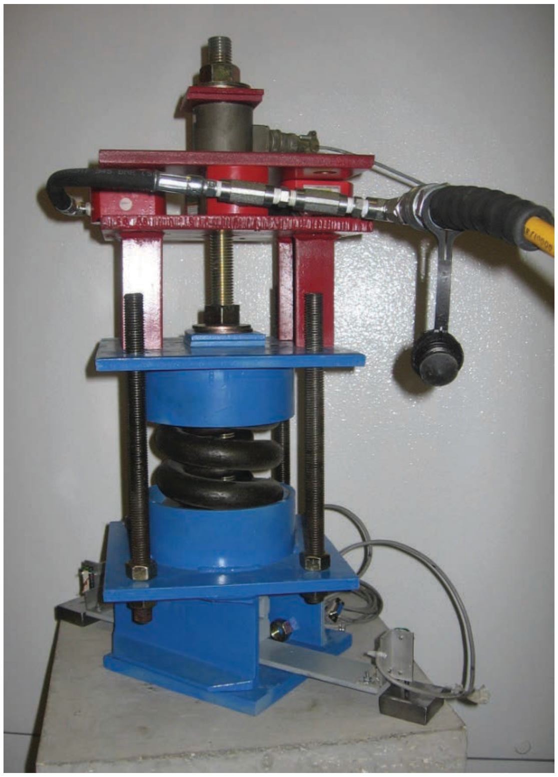


Figure 4: Test frame with hydraulic jack chair.

To prevent the test apparatus from falling over due to the dynamic load on the frame caused by an anchor pullout, the test frames were secured to the concrete blocks with loading straps.

Test Series 16 (Unconfined) Sustained Load Test Apparatus

The sustained load unconfined testing apparatus conformed to the requirements in ASTM E488 and ASTM E1512. The 6” x 6” x 0.03” thick Teflon PTFE (Polytetrafluoroethylene) confining sheet and the 8” x 8” x 5/8” thick steel confining plate were not used in this test series. The 3” x 5” x 1/4” rectangular steel tubes were placed parallel to each other on either side of the anchor no closer than two times the embedment depth. An 18” x 18” x 1” thick steel plate with a 2-3/4” diameter hole in the center was placed on the rectangular steel tubes to support the load frame. Figure 5 shows the modifications to the sustained load (creep) test apparatus for test series 16.

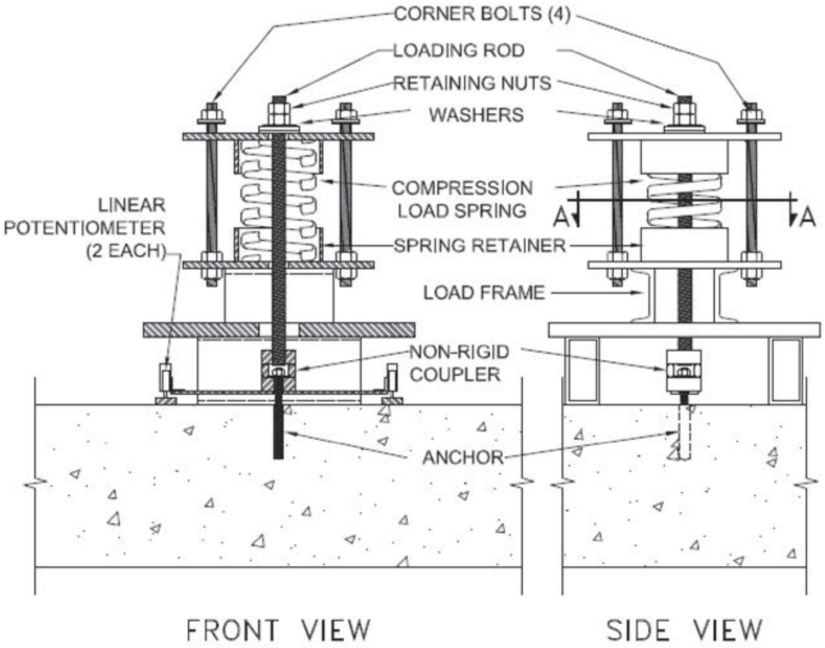


Figure 5: Test series 16 sustained load (creep) unconfined test apparatus.

Specimen preparation

The test specimens consisted of three parts; the concrete test member, the adhesive, and the anchor rod.

Concrete Test Member

The concrete test members for the short-term tests were poured in 60” x 16” x 12” forms. Minimal reinforcement of two #3 60 ksi steel reinforcing bars were placed longitudinally 5” from the bottom of the slab with approximately 1” cover. Four ½” diameter PVC pipes were placed at mid-height which allowed for ½” diameter rods to later be passed through the concrete test member in order to accommodate handling.

The concrete test members for the sustained load (creep) tests were poured in 16” x 16” x 12” forms. No reinforcement was provided. Two ½” diameter PVC pipes were placed at mid-height in order to accommodate handling.

All the forms used in this project were made of high density overlay plywood and were assembled with threaded rod and wing nuts, which allowed for multiple uses due to the large number of test members required. Since only twenty sustained load tests could be conducted simultaneously, the production of the concrete test specimens (Figure 6) was staggered in eleven separate pours denoted as concrete series A–J. The pour dates and number of test blocks produced in each series are listed in Table 1. In order to provide a smooth testing surface, the blocks were cast upside down against the high density overlay plywood. After the first pour, it was decided to place a 1/8" thick sheet of Teflon PTFE (Polytetrafluoroethylene) at the bottom of the form to provide an even smoother surface and ensure against a lesser quality surface in the later pours.

Figure 6: Concrete test specimens being cast.

Table 1: Concrete pour details.

Concrete Mix	**Pour Date**	**Number of Short-term Test Members**	**Number of Sustained load Test Members**	**Notes**
A	May 18, 2010	3	12	
B	May 26, 2010	3	12	
C	June 2, 2010	3	12	
D	June 15, 2010	3	8	
E	June 22, 2010	3	9	
F	June 29, 2010	3	9	
G	July 27, 2010	3	9	
H	August 3, 2010	3	12	20% Fly Ash
I	August 10, 2010	3	12	50% Blast Furnace Slag
J	March 25, 2011	3	12	Standard DOT Mix

The concrete for mixes A–I were batched, mixed, and placed at the Florida Department of Transportation (FDOT) State Materials office in Gainesville, FL. Concrete with round river gravel without any admixtures (except for series H and I, which included 20% fly ash and 50% blast furnace slag respectfully) was specified with a mean compressive strength between 4000 and 6000 psi during testing. All of the materials were batched by weight. Moisture samples were taken of the coarse aggregate (#7 and #89 stone) and allowed to dry in one of two Blue M large ovens (Figure 7) at 230°F (110°C) for 24 hours in order to determine the percent moisture. The sand was oven dried in the same ovens at 230°F (110°C) for 24 hours. Concrete was mixed in a Lancaster 27 CF counter current batch concrete mixer (Figure 8) and discharged into a large hopper and then placed into the forms with shovels and vibrated with an electric vibrator. Due to the size of the concrete mixer and forms, the concrete for each series was made in three batches. Plastic properties (slump, percent air, temperature, and unit weight) were evaluated and 4” x 8” cylinders were made for each batch of every series.

Figure 7: Ovens.

Figure 8: Mixer.

The concrete for mix J was batched and mixed by Florida Rock Industries, a local ready-mix plant and placed at the University of Florida (UF) Structures Laboratory in Gainesville, FL. Mix J was designed by the NCHRP panel and included granite aggregate, water reducer, fly ash, and air entrainment.

The mix designs and plastic properties for concrete series A–J are included in Appendix G.

Following the pour, the concrete was covered with plastic for 24 hours. After the first 24 hours, the concrete was covered with wet tarps and plastic and maintained wet for 5 days. The cylinders were capped with plastic lids. After 6 days the forms were removed and the cylinders demolded. The concrete test members and cylinders were maintained in the UF structures laboratory thereafter.

Concrete compressive strength was determined by testing the cylinders in general accordance with ASTM C39 on a Test Mark Model CM-5000-DG compression machine (Figure 9) calibrated in August 2009 and August 2010 located at the FDOT State Materials Office in Gainesville, FL. The cylinders were ground smooth on a Hi-Kenma cylinder grinding machine (Figure 10) prior to testing. A concrete strength-age relationship was determined for each series by testing 4” x 8” cylinders at 7, 14, 28, 56, 112, 224, and 448 days or at the end of testing for that series, whichever came first. The average compressive strength for each series is presented in Table 2.

Figure 9: Compression machine.

Figure 10: Cylinder grinding machine.

Adhesive

The three adhesive products were stored in an environmentally controlled room maintained within the temperature and humidity range specified by the manufacturers prior to installation.

Table 2: Concrete series average compressive strength.

		Average Compressive Strength (psi)								
Concrete Series	Pour Date	7 day	14 day	28 day	56 day	112 day	224 day	448 days	Final[8]	No of days[9]
A	May 18, 2010	3180	3930	4200	4350	4480	4460[2]	3870[3]	4210	679
B	May 26, 2010	3170	3950	4260	4390	[4]	[4]	[4]	4100	671
C	June 2, 2010	3260	3840	4410	4340[1]	4210	4140	3830	3960	664
D	June 15, 2010	3180	4080	4320	4800	[4]	[4]	[4]	4740	651
E	June 22, 2010	3130	3790	4210	4430	[4]	[4]	[4]	4570	644
F	June 29, 2010	2660	3670	4050	4290	4500	[4]	[4]	4310	637
G	July 27, 2010	3100	3810	4260	4720	4650	4570	[4]	4470	609
H (FA[5])	August 3, 2010	2220	3010	3610	3810	3500	3760	[4]	3540	602
I (BFS[6])	August 10, 2010	1710	2740	3240	3460	3000	3020	[4]	2700	595
J (DOT[7])	March 25, 2011	4530	5490	5940	5930	5310	5540	[10]	4830	368

[1] Test conducted at 55 days.

[2] Test conducted at 231 days.

[3] Test conducted at 251 days.

[4] Not enough samples to conduct tests at these times, last group of three samples held until end of project.

[5] FA = Fly Ash.

[6] BFS = Blast Furnace Slag.

[7] DOT = Department of Transportation concrete mix.

[8] Samples tested at end of project on March 27, 2012.

[9] Number of days since casting for final compression test.

[10] Test at 448 days not conducted.

Anchor Rods

The anchor rods were ASTM A354 grade BD 5/8” diameter 11 threads per inch (UNC) steel threaded rod fabricated by Glaser & Associates from Martinez, CA. This grade of steel has a specified yield strength of 130 ksi and a specified tensile strength of 150 ksi. The anchor rods were cut to a length of 5.75” from 6” stock and their ends ground and chamfered with a bench grinder and steel brush to remove burrs and to clean up the threads in order to install the nuts. The anchors were stored in a sealed bucket in oil-soaked shredded paper to prevent rusting. Prior to installation, the rods were cleaned with acetone, allowed to air dry, and protected with paper until installed.

Instrumentation

Measurement

Displacement. Direct measurement of the anchor displacement was not possible due to the location of the test apparatus. Therefore, a 16” x 2” x ¼” ASTM A36 steel flat bar was attached to the bottom of the non-rigid coupler that connected the anchor to the 1” diameter loading rod (See Figure 1–Figure 5). Two BEI Duncan Electronics model 9610 linear motion position sensors (linear-pots) were fixed to this flat bar, one on each end, equidistant from the centerline of the anchor. The displacement was calculated as the average of the two linear-pot measurements.

Load. The tension in the anchor was measured indirectly as a compressive reaction of either the hydraulic ram or the compression spring in the test apparatus. For the short-term tests, the load was measured by a Houston Scientific Model 3500 100-kip load cell excited by a 10VDC amplifier with a gain of 500. For the short-term (creep) tests, the loads were measured by the same Houston Scientific load cell during loading. Once the load was applied to the anchor, the load cell was removed and the load was monitored by the spring stiffness and displacement.

Temperature. Temperature in each concrete test slab was measured by National Semiconductor LM35 Precision Centigrade Temperature Sensors. The temperature sensors were located 2 inches deep in the top of the concrete test specimen placed in 1/2” diameter holes drilled just prior to conditioning and sealed with rubber grommets to allow for reuse. Ambient air temperature in the test chamber was measured by a Cincinnati Sub-Zero EZT-560i Environmental Chamber Controller installed in the Cincinnati Sub-Zero Model WM-STH-1152-2-H/AC Walk-In Stability Chamber. Analog cards installed in the Cincinnati Sub-Zero EZT-560i Environmental Chamber Controller provided an analog signal output allowing the ambient air temperature to be monitored by the data acquisition system.

Humidity. Relative humidity in the test chamber was measured by a Cincinnati Sub-Zero EZT-560i Environmental Chamber Controller installed in the Cincinnati Sub-Zero Model WM-STH-1152-2-H/AC Walk-In Stability Chamber. Analog cards installed in the Cincinnati Sub-Zero EZT-560i Environmental Chamber Controller provided an analog signal output allowing the humidity to be monitored by the data acquisition system.

Time. Time was measured using the computer’s internal clock.

Instrument Calibration

Displacement. The linear motion position sensors were calibrated against a Fowler digital caliper over their full range of 1” at 1/8” increments. The measurements were adjusted for variations in power supply voltage and normalized to a 10 volt power supply.

Load. The Houston Scientific Model 3500 100-kip load cell was calibrated in July 2010 at the Florida Department of Transportation State Materials Office in Gainesville, FL on a Test Mark Model CM-5000-DG compression machine. The load cell was calibrated over a range of 0 to 80 kips with nine data points.

The compression springs were calibrated in June 2010 on an INSTRON System 3384 150 kN universal testing machine to determine their stiffness and working load. The large springs were calibrated individually over a range of 0 to 15 kips with about 500 data points. For loads above 15 kips, the large and small springs were calibrated in parallel over a range of 0 to 20 kips with about 630 data points. The large springs had an average stiffness of 10.2 kips/in. and a COV of 0.03. The large and small springs together had an average stiffness of 13.4 kips/in. and a COV of 0.02. The average drop in load between the end of loading and rupture was around 3%.

Temperature. The National Semiconductor LM35 Precision Centigrade Temperature Sensors factory calibration was validated in June 2010 against a high quality mercury thermometer over a temperature range of 100°F to 120°F (43°C to 49°C). The temperature sensor in the test chamber was calibrated by the factory.

Humidity. The humidity sensor in the test chamber was calibrated by the factory.

Environmental control

Standard Temperature

An air conditioned space was used to store and condition the adhesive at 75ºF ±10ºF (24°C ±5°C) and 50% ±10% relative humidity.

When conditions allowed, the test slabs were stored prior to installation and testing on the shop floor of the UF Structures Laboratory at 75ºF ±10ºF (24°C ±5°C) and 50% ±10% relative humidity.

Elevated Temperature

A 12' by 12' by 8' tall Cincinnati Sub-Zero Model # WM-STH-1152-2-H/AC Walk-In Stability Chamber (Figure 11) was used to condition and test at the elevated testing temperature of 110ºF +10ºF/-0ºF (43ºC +5ºC/-0ºC) and below 40% relative humidity for the short-term and sustained load (creep) test. The chamber has a temperature range of -20°C to 60°C (-4°F to

140°F) and a relative humidity range of 10% to 95%. The chamber was equipped with a CSZ EZT-560i Touch Screen Controller to monitor and control the temperature and humidity.

Figure 11: Walk-in stability chamber.

The concrete test specimens were placed on furniture dollies in order to facilitate test rotation and to raise them off the ground by a few inches to promote better air flow and a uniform temperature within the concrete. The stability chamber was able to simultaneously house 20 sustained load anchor pullout test specimens and one short-term anchor pullout test specimen on the floor. Shelves were built along the walls to house the 16 adhesive-only test frames. Figure 12 and Figure 13 show the testing chamber with 20 sustained load tests running (2 not visible). A short-term testing slab is in the foreground. Figure 14 shows the layout of the anchor pullout test specimens in the stability chamber.

Figure 12: Left side of testing chamber.

Figure 13: Right side of testing chamber.

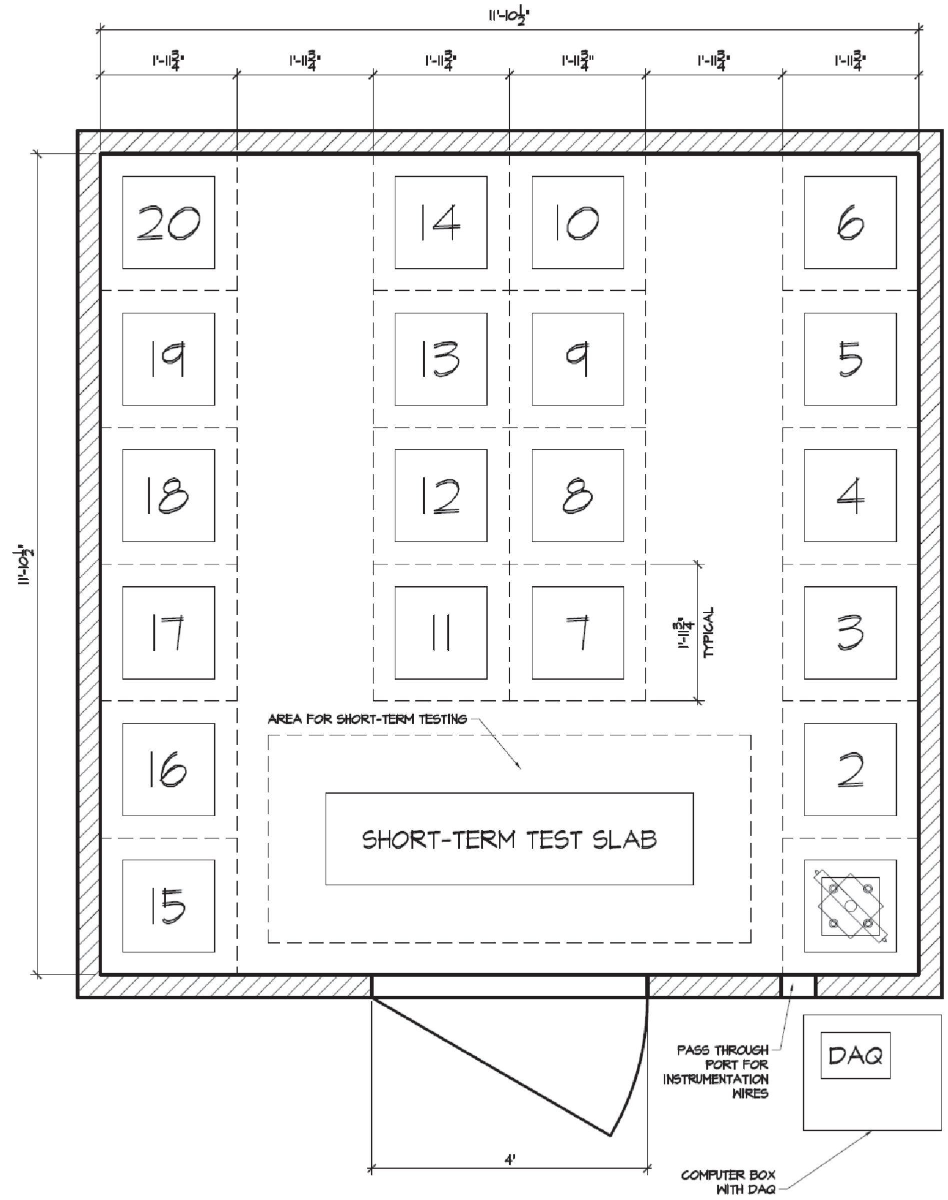


Figure 14: Layout of anchor pullout test frames in the stability chamber.

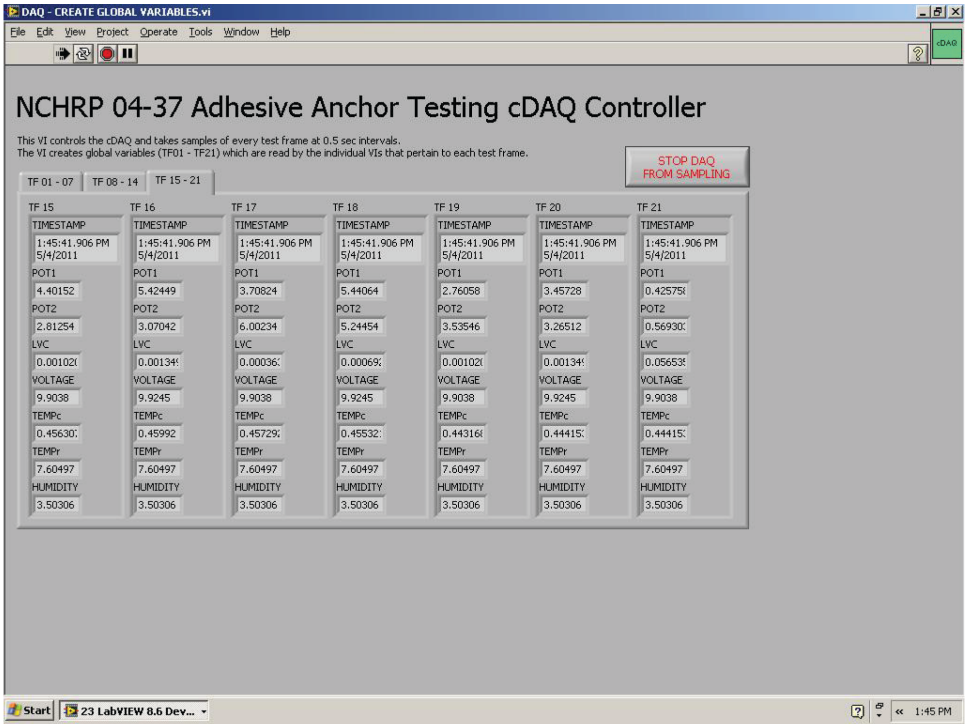
Data management and acquisition

During the testing and conditioning of the test slabs to the elevated temperature, a Microsoft compatible computer ran several National Instruments LabVIEW 8.6 software programs developed to collect, record, and display the data. Measured values included load, displacement, temperature, humidity, and time. Data acquisition was performed with a National Instruments NI cDAQ-9172 chassis with several National Instruments NI 9205 modules to interface with the instrumentation.

Due to minor fluctuations in the 10 volt power supply, the LabVIEW programs recorded the power supply voltage with each data reading and the position readings were appropriately adjusted to a normalized ten volt power supply.

Data Sampling Program

A LabVIEW 8.6 program (Figure 15) was developed to centrally sample data for every test. This program provided a half second time averaged record sampled at 2000 Hz. Global variables for each of the twenty sustained load test frames and the one short-term test frame were updated every half second to the computer memory to be read when needed by the separate LabVIEW programs for each test frame. Each global variable included a timestamp, and the voltage readings for the two linear-pots, power supply, load cell, concrete temperature sensor, and environmental chamber temperature and humidity.



NCHRP 04-37 Adhesive Anchor Testing cDAQ Controller

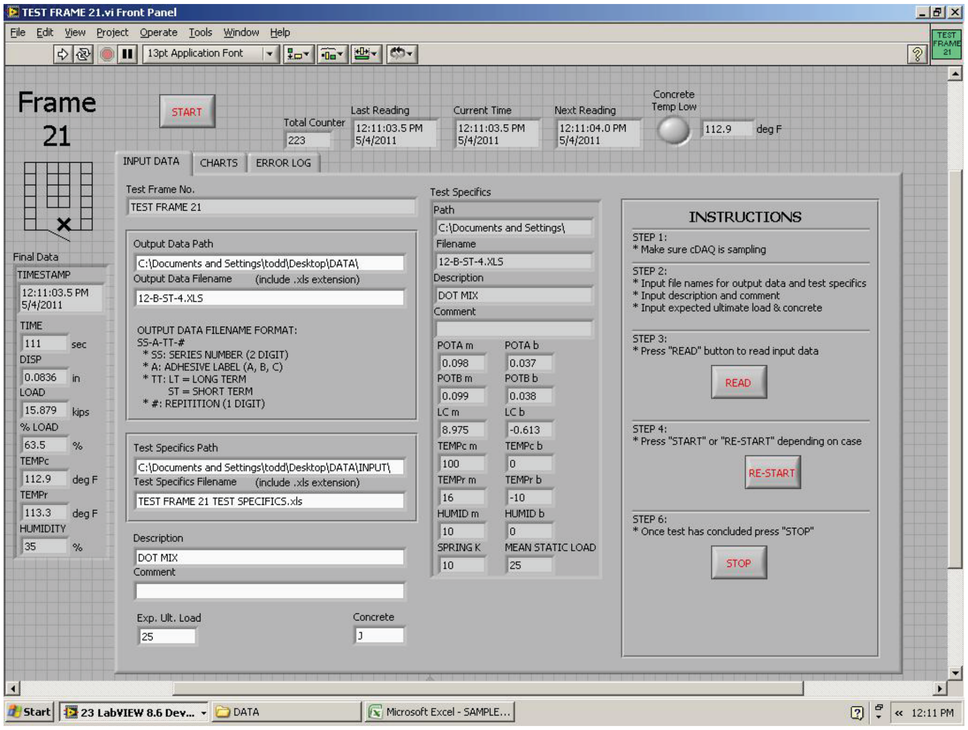
This VI controls the cDAQ and takes samples of every test frame at 0.5 sec intervals.
The VI creates global variables (TF01 - TF21) which are read by the individual VIs that pertain to each test frame.

	TF 15	TF 16	TF 17	TF 18	TF 19	TF 20	TF 21
TIMESTAMP	1:45:41.906 PM 5/4/2011	1:45:41.906 PM 5/4/2011	1:45:41.906 PM 5/4/2011	1:45:41.906 PM 5/4/2011	1:45:41.906 PM 5/4/2011	1:45:41.906 PM 5/4/2011	1:45:41.906 PM 5/4/2011
POT1	4.40152	5.42449	3.70824	5.44064	2.76058	3.45728	0.42575
POT2	2.81254	3.07042	6.00234	5.24454	3.53546	3.26512	0.56930
LVC	0.00102	0.00134	0.00036	0.00069	0.00102	0.00134	0.05653
VOLTAGE	9.9038	9.9245	9.9038	9.9245	9.9038	9.9245	9.9038
TEMPc	0.45630	0.45992	0.45729	0.45532	0.44316	0.44415	0.44415
TEMPr	7.60497	7.60497	7.60497	7.60497	7.60497	7.60497	7.60497
HUMIDITY	3.50306	3.50306	3.50306	3.50306	3.50306	3.50306	3.50306

Figure 15: Data sampling LabVIEW program.

Short-term test program

A LabVIEW 8.6 program (Figure 16 & Figure 17) developed for this project was used for the short-term tests. Load, displacement, temperature, and humidity readings were recorded at half second intervals. A load versus displacement curve was displayed on the screen for real-time feedback. Load rate control was monitored by plotting the actual load rate from the hydraulic hand pump against an ideal load rate to cause bond failure of the expected load in 120 seconds on a load versus time graph. This real-time plot was used to assist the pump operator in applying a constant load rate. The latest data readings were displayed on the screen and each data reading was automatically recorded in a Microsoft Excel spreadsheet.



Total Counter: 223

Last Reading: 12:11:03.5 PM 5/4/2011

Current Time: 12:11:03.5 PM 5/4/2011

Next Reading: 12:11:04.0 PM 5/4/2011

Concrete Temp Low: 112.9 deg F

Final Data

TIMESTAMP: 12:11:03.5 PM 5/4/2011

TIME: 111 sec

DISP: 0.0836 in

LOAD: 15.879 kips

% LOAD: 63.5 %

TEMPc: 112.9 deg F

TEMPr: 113.3 deg F

HUMIDITY: 35 %

Test Frame No.: TEST FRAME 21

Output Data Path: C:\Documents and Settings\todd\Desktop\DATA\

Output Data Filename (include .xls extension): 12-B-ST-4.XLS

OUTPUT DATA FILENAME FORMAT:
SS-A-TT-#
* SS: SERIES NUMBER (2 DIGIT)
* A: ADHESIVE LABEL (A, B, C)
* TT: LT = LONG TERM
ST = SHORT TERM
* #: REPITITION (1 DIGIT)

Test Specifics Path: C:\Documents and Settings\todd\Desktop\DATA\INPUT\

Test Specifics Filename (include .xls extension): TEST FRAME 21 TEST SPECIFICS.xls

Description: DOT MIX

Comment:

Exp. Ult. Load: 25

Concrete: J

Test Specifics

Path: C:\Documents and Settings\

Filename: 12-B-ST-4.XLS

Description: DOT MIX

Comment:

POTA m	POTA b
0.098	0.037

POTB m	POTB b
0.099	0.038

LC m	LC b
8.975	-0.613

TEMPc m	TEMPc b
100	0

TEMPr m	TEMPr b
16	-10

HUMID m	HUMID b
10	0

SPRING K	MEAN STATIC LOAD
10	25

INSTRUCTIONS

STEP 1:
* Make sure cDAQ is sampling

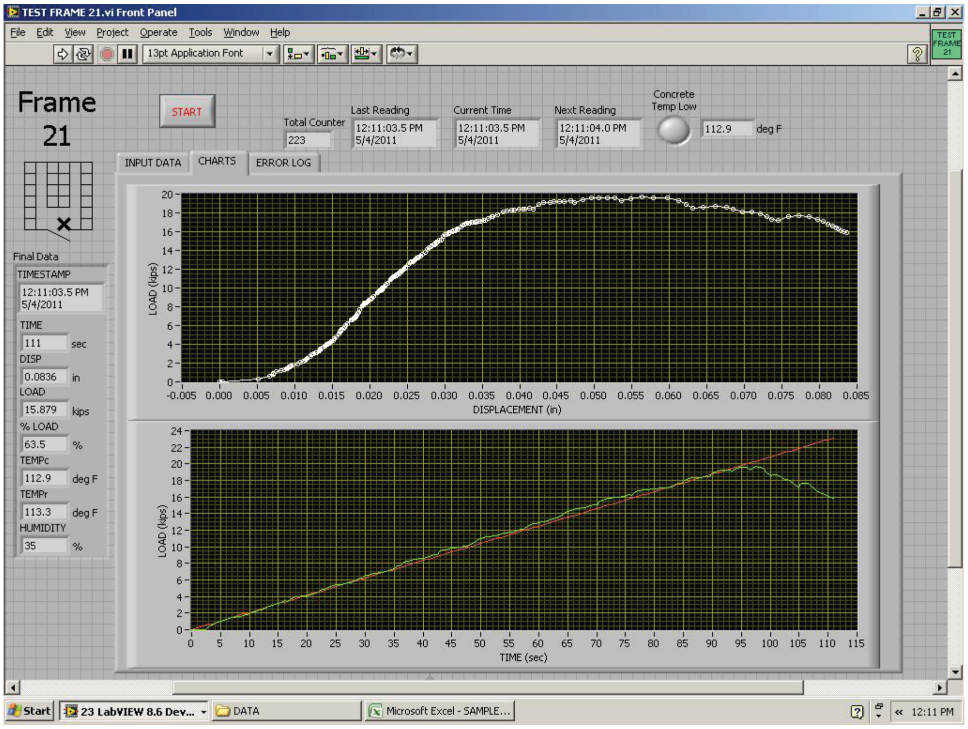
STEP 2:
* Input file names for output data and test specifics
* Input description and comment
* Input expected ultimate load & concrete

STEP 3:
* Press "READ" button to read input data

STEP 4:
* Press "START" or "RE-START" depending on case

STEP 6:
* Once test has concluded press "STOP"

Figure 16: Short-term test LabVIEW program (main screen).



Frame 21

Total Counter: 223

Last Reading: 12:11:03.5 PM 5/4/2011

Current Time: 12:11:03.5 PM 5/4/2011

Next Reading: 12:11:04.0 PM 5/4/2011

Concrete Temp Low: 112.9 deg F

Final Data

TIMESTAMP: 12:11:03.5 PM 5/4/2011

TIME: 111 sec

DISP: 0.0836 in

LOAD: 15.879 kips

% LOAD: 63.5 %

TEMPc: 112.9 deg F

TEMPr: 113.3 deg F

HUMIDITY: 35 %

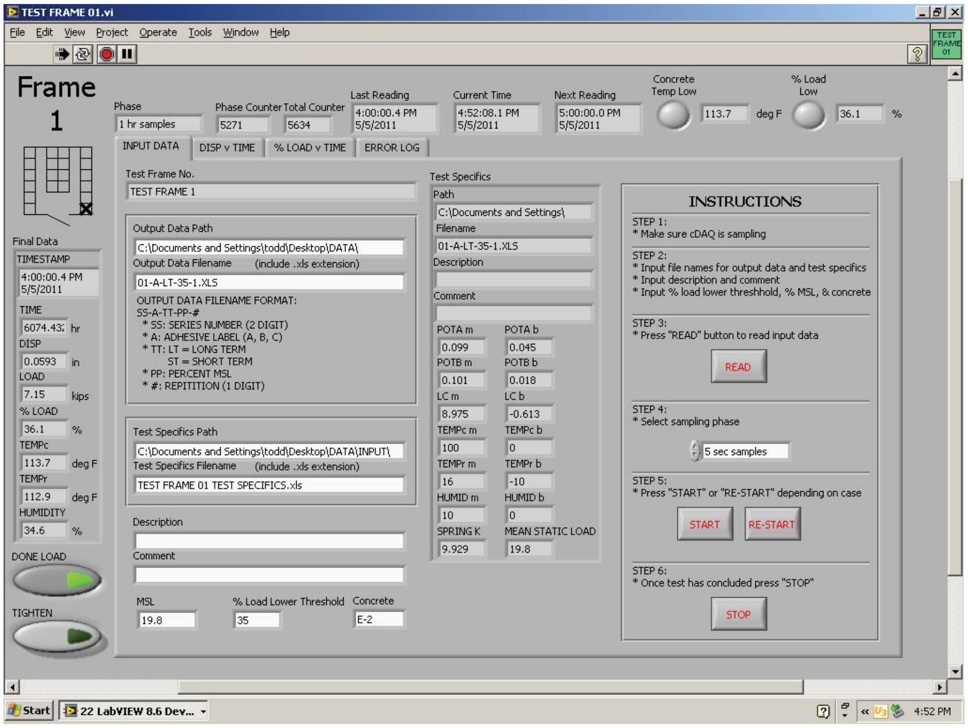
Figure 17: Short-term test LabVIEW program (chart page).

Long-Term (Creep) Test Program

A LabVIEW 8.6 program (Figure 18 to Figure 20) developed for this project was used for the sustained load (creep) test. Load, displacement, temperature, and humidity readings were recorded at progressively longer intervals over the course of the test as discussed previously.

If it became necessary to apply additional load to the anchor during the test, the program entered a tightening phase in which data was recorded every half second. Once tightening was completed, the program began sampling every 5 seconds and proceeded through the previously discussed sampling schedule.

A displacement versus time curve (Figure 19) for each anchor and a percent mean static load versus time curve (Figure 20) were displayed on the screen for real-time feedback. The latest data readings were displayed on the screen and each data reading was automatically recorded in a Microsoft Excel spreadsheet.



Phase 1 hr samples
Phase Counter 5271
Total Counter 5634
Last Reading 4:00:00.4 PM 5/5/2011
Current Time 4:52:08.1 PM 5/5/2011
Next Reading 5:00:00.0 PM 5/5/2011
Concrete Temp Low 113.7 deg F
% Load Low 36.1 %

Final Data
TIMESTAMP 4:00:00.4 PM 5/5/2011
TIME 6074.432 hr
DISP 0.0593 in
LOAD 7.15 kips
% LOAD 36.1 %
TEMPc 113.7 deg F
TEMPr 112.9 deg F
HUMIDITY 34.6 %

Test Frame No. TEST FRAME 1

Output Data Path C:\Documents and Settings\todd\Desktop\DATA\
Output Data Filename (include .xls extension) 01-A-LT-35-1.XLS

OUTPUT DATA FILENAME FORMAT:
SS-A-TT-PP-#
* SS: SERIES NUMBER (2 DIGIT)
* A: ADHESIVE LABEL (A, B, C)
* TT: LT = LONG TERM
ST = SHORT TERM
* PP: PERCENT MSL
* #: REPITITION (1 DIGIT)

Test Specifics Path C:\Documents and Settings\todd\Desktop\DATA\INPUT\
Test Specifics Filename (include .xls extension) TEST FRAME 01 TEST SPECIFICS.xls

Description
Comment

MSL 19.8
% Load Lower Threshold 35
Concrete E-2

Test Specifics
Path C:\Documents and Settings\
Filename 01-A-LT-35-1.XLS
Description
Comment

POTA m	POTA b
0.099	0.045
POTB m	POTB b
0.101	0.018
LC m	LC b
8.975	-0.613
TEMPc m	TEMPc b
100	0
TEMPr m	TEMPr b
16	-10
HUMID m	HUMID b
10	0
SPRING K	MEAN STATIC LOAD
9.929	19.8

INSTRUCTIONS

STEP 1:
* Make sure cDAQ is sampling

STEP 2:
* Input file names for output data and test specifics
* Input description and comment
* Input % load lower threshhold, % MSL, & concrete

STEP 3:
* Press "READ" button to read input data

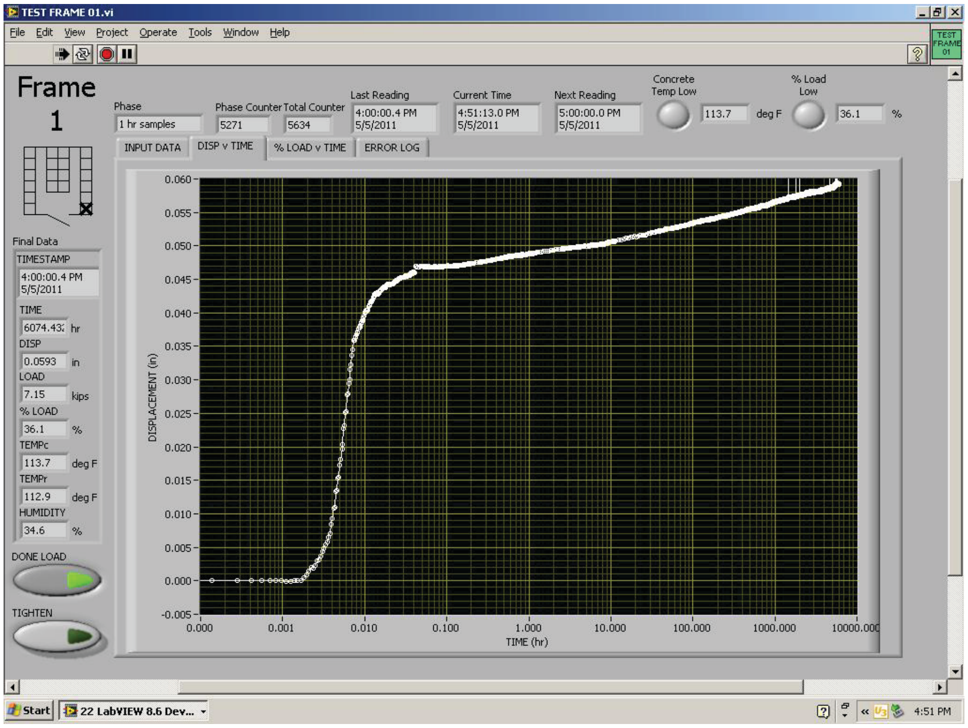
STEP 4:
* Select sampling phase

5 sec samples

STEP 5:
* Press "START" or "RE-START" depending on case

STEP 6:
* Once test has concluded press "STOP"

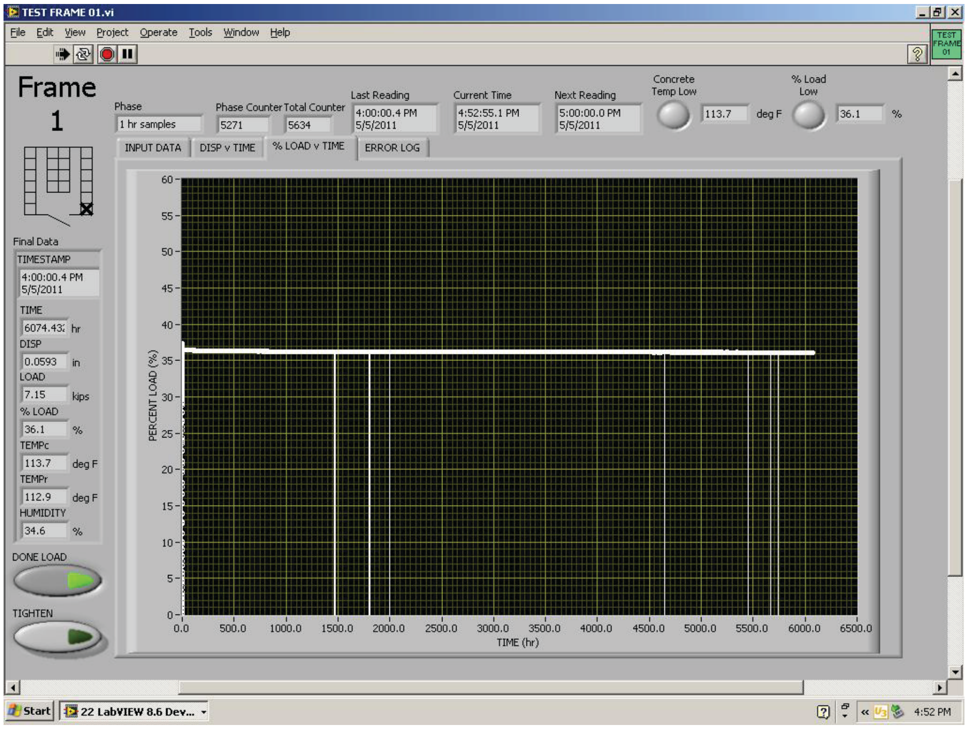
Figure 18: Sustained load test LabVIEW program (main screen).



Phase 1 hr samples
Phase Counter 5271
Total Counter 5634
Last Reading 4:00:00.4 PM 5/5/2011
Current Time 4:51:13.0 PM 5/5/2011
Next Reading 5:00:00.0 PM 5/5/2011
Concrete Temp Low 113.7 deg F
% Load Low 36.1 %

Final Data
TIMESTAMP 4:00:00.4 PM 5/5/2011
TIME 6074.432 hr
DISP 0.0593 in
LOAD 7.15 kips
% LOAD 36.1 %
TEMPc 113.7 deg F
TEMPr 112.9 deg F
HUMIDITY 34.6 %

Figure 19: Sustained load test LabVIEW program (displacement plot).



Phase: 1 hr samples
Phase Counter: 5271
Total Counter: 5634
Last Reading: 4:00:00.4 PM 5/5/2011
Current Time: 4:52:55.1 PM 5/5/2011
Next Reading: 5:00:00.0 PM 5/5/2011
Concrete Temp Low: 113.7 deg F
% Load Low: 36.1 %

Final Data
TIMESTAMP: 4:00:00.4 PM 5/5/2011
TIME: 6074.43: hr
DISP: 0.0593 in
LOAD: 7.15 kips
% LOAD: 36.1 %
TEMPc: 113.7 deg F
TEMPr: 112.9 deg F
HUMIDITY: 34.6 %

Figure 20: Sustained load test LabVIEW program (percent load plot).

Test Specimen Conditioning Program

A LabVIEW 8.6 program developed for this project was used to monitor the test specimen during conditioning. Concrete specimen temperature as well as the temperature and humidity of the environmental chamber were recorded at five minute intervals. A concrete specimen temperature versus time graph was displayed on the screen for real-time feedback. The latest data readings were displayed on the screen and each data reading was automatically recorded in a Microsoft Excel spreadsheet. Since the three large concrete test specimens used for the test series 1 (baseline) short-term tests were conditioned simultaneously, one concrete test specimen was monitored during conditioning and all three were checked prior to testing.

Installation procedure

The standard installation procedure is described below and was followed for test series 1, 12, 14, 15, and 16. Exceptions to this standard installation procedure as used in test series 7, 9, and 13 follow.

Standard Baseline Installation Procedure

All anchors were installed according to the manufacturer's specifications. The holes were created with a 3/4" (11/16" for adhesive A) carbide tipped concrete bit as specified by the manufacturer and a Hilti model TE52 hammer drill. A drilling jig (Figure 21) with a depth stop was used to ensure that the holes were drilled perpendicular to the surface of the concrete and to the correct depth.

Figure 21: Drilling rig and hammer drill.

The spoil at the concrete surface was removed with a vacuum prior to cleaning the holes. The holes were cleaned according to the MPII which generally included blowing with oil-free compressed air, brushing with a steel brush provided by the manufacturer, and then blowing again with compressed air until no dust was discharged. Durations and numbers of brushing/blowing cycles varied by manufacturer, but for each case the holes were cleaned according to the MPII. Details of the full cleaning procedure are listed in Table 3.

Table 3: Full hole cleaning procedures per MPII.

Adhesive A	Adhesive B	Adhesive C
Blow with compressed air (4x)	Blow with compressed air (2x)	Blow with compressed air (4x)
Brush with drill (4x)	Brush by hand (2x)	Brush with drill (1x)
Blow with compressed air (4x)	Blow with compressed air (2x)	Blow with compressed air (4x)
		Brush with drill (1x)
		Blow with compressed air (4x)
		Brush with drill (1x)
		Blow with compressed air (4x)
		Brush with drill (1x)
		Blow with compressed air (4x)

To prevent dust from blowing into the operator's mouth and eyes, an adaptor for the vacuum (Figure 22) was used to capture the dust ejected from the hole when blowing with compressed air. This adaptor attached to the vacuum hose and allowed the compressed air nozzle to be easily inserted and removed.

Once clean, masking tape was placed over the hole to ensure that dust and humidity did not enter the hole prior to installation of the adhesive anchor. In all cases the time between cleaning and installation was not more than a few minutes. A hole was gently cut in the masking tape prior to installation.

The adhesive products were dispensed with a manufacturer supplied cartridge gun. According to the manufacturer's specifications, several squeezes of adhesive were discharged and disposed of before dispensing into the holes to ensure that the adhesive was of uniform color and consistency indicating that it was properly/thoroughly mixed.

The anchors were wiped clean with acetone and allowed to air dry. The anchors were then attached to an "embedment depth chair" (Figure 23) set for the appropriate embedment depth of 3-1/8". The chair rested on the face of the concrete test specimen ensuring the proper embedment depth and did not interfere with the adhesive squeeze out. The anchor rod was rotated counterclockwise and jiggled while it was installed in the hole until the legs of the "chair" came to bear on the concrete. The anchors were left undisturbed during the specified gel/working time and the adhesive was allowed to cure for seven days prior to conditioning. Excess adhesive was carefully chipped away from around the anchor prior to conditioning. The masking tape left around the hole prevented the concrete from being removed during chipping.

Figure 22: Vacuum adaptor.

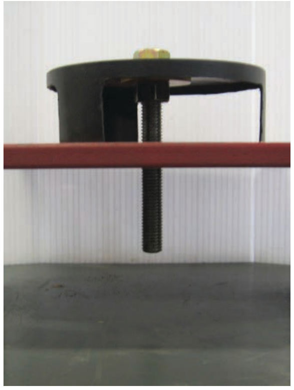


Figure 23: Embedment depth chair.

Test Series 7 (Moisture during Installation) Installation Procedure

This installation procedure was adapted from ACI 355.4 section 7.10 and 7.6.

The holes were initially drilled to roughly half the final diameter using a 3/8" diameter carbide tipped concrete bit. A water dam (Figure 24) constructed out of 2x4 dimensional lumber was secured to the top of the concrete test specimens with silicon. The holes were filled with water and the test specimens were covered with 3" of water for a minimum of eight days (192 hours).

Following eight days of saturation, the water was drained and the standing water was vacuumed out of the holes and the installation procedure then followed the above described standard baseline installation procedure.

Figure 24: Water dam for test series 7 installation.

Test Series 9 (Reduced Hole Cleaning) Installation Procedure

ACI 355.4 section 7.5 defines a reduced hole cleaning effort as 50% of the full hole cleaning procedure. The standard installation procedure was followed except that the cleaning effort was modified to the procedures described in Table 4.

Table 4: Reduced hole cleaning procedures.

Adhesive A	Adhesive B	Adhesive C
Blow with hand pump (2x)	Blow with hand pump (1x)	Blow with compressed air (2x)
Brush with drill (2x)	Brush by hand (1x)	Brush by hand (1x)
Blow with hand pump (2x)	Blow with hand pump (1x)	Blow with compressed air (4x)
		Brush by hand (1x)
		Blow with compressed air (4x)

Test Series 13 (Type of Drilling) Installation Procedure

The holes were created with a 3/4” (11/16” for adhesive A) diamond core bit using a Hilti model DD130 core drill. A drilling rig (Figure 25) was used to ensure that the holes were drilled perpendicular to the surface of the concrete. The drilling rig was secured to the concrete specimen with ratchet tie-down straps. The cores were wet-drilled by use of a water jacket attached to the chuck of the drill. Efforts were made to reduce the amount of excess water on the concrete specimens. A water collector (Figure 26) connected to a wet vacuum surrounded the bit to collect water during drilling.

Figure 25: Core drill for test series 13.

Tape was placed on the core drill to indicate the proper depth during drilling. The holes were drilled to a depth of 4-½” to ensure that the core cylinders would break below the required embedment depth. The cylinders were broken off by inserting a small screwdriver in the hole and gently prying the cylinders loose. An extraction tool (Figure 27) was used to remove the cylinder pieces from the hole.

Standing water was removed using a wet vacuum with a narrow hose attachment. The holes were then flushed twice using a ½” diameter rubber hose at normal street water pressure and the excess water was captured with the water collector, then brushed twice, and then flushed twice again until the water ran clear. Finally, the standing water was removed with a wet vacuum.

The holes were cleaned according to the MPII as presented in Table 3. The holes were then dried with compressed air by inserting and removing a special air nozzle tip (Figure 28) two times.

Figure 26: Water collector.

Figure 27: Extraction tool.

Figure 28: Air nozzle.

The holes were covered with masking tape to ensure that dust and humidity did not enter the hole prior to installation of the adhesive anchors. The anchor installation proceeded as described earlier in the standard installation procedure.

Specimen conditioning

Upon completion of the 7 day adhesive curing period, the test specimens were wheeled into the 110ºF (43ºC) 35% humidity environmental test chamber on dollies for conditioning. The temperature of the concrete test specimen and the environmental chamber as well as the humidity in the environmental chamber were monitored and recorded. Testing began upon completion of the 24 hour conditioning period in the environmental test chamber.

Testing procedure

The standard testing procedures for the short-term and sustained load (creep) tests are described below which was followed for test series 1, 7, 9, 12, 13, 14, and 15. Exceptions to these standard testing procedures as used in test series 16 follow.

Short-Term Test Procedure

A 0.03” thick PTFE confining sheet and steel 5/8” thick confining plate were placed over the anchor and the non-rigid coupler was attached to the anchor. A 1/16” to 1/8” gap was left between the confining plate and the coupler to allow for rotation of the coupler in order to prevent bending forces from being transferred between the anchor and the loading rod. The short-term test apparatus was placed over the anchor as discussed earlier. Steel spacers were placed under the linear potentiometers so that the initial position reading was in the 0.300”–

0.500” range (this was done because the position readings at the far extremes of the instrument are less accurate).

The Enerpac model RCH-603 Holl-O-Cylinder (60 ton) hydraulic ram was placed on the frame and connected to the Enerpac model P802 (10,000 psi) hydraulic hand pump. The loading rod was then connected to the coupler. The Houston Scientific Model 3500 100-kip load cell was placed on top of the ram sandwiched between four 1/4” plates (two above and two below). The loading rod nut was hand tightened to remove slack in the system.

The LabVIEW 8.6 program was started to confirm that the program was functioning correctly and that the linear-pot values were within acceptable ranges.

The program was then reset and the test was started. Pumping did not start until after a few seconds in order to read the initial load reading and to allow the program to zero out the initial load cell and linear-pot readings in order to calculate load and displacement.

The anchors were loaded at a constant load rate. The operator adjusted the pump rate to conform to an ideal pump rate that would cause failure at the expected load within 120 seconds by following the ideal load rate curve on the load versus time plot on the screen.

The operator was only in the environmental chamber to disconnect and connect the testing apparatus to the anchors. The pumping and test observation was conducted outside the chamber.

The LabVIEW 8.6 program automatically recorded the test data in a MS Excel spreadsheet.

Test Series 16 (Unconfined) Test Procedure

The above procedure was followed with the following exceptions:

- The PTFE confining sheet and 5/8” thick steel confining plate were eliminated.
- The test frame supports were placed no closer than two times the embedment depth from the anchor.

Standard Sustained Load (Creep) Test Procedure

The tests began by placing the 0.03” thick PTFE confining sheet, 5/8” thick steel confining plate, coupler, and linear potentiometers as described in the short-term test procedure.

The compression springs were compressed in an INSTRON System 3384 150KN universal loading machine and the load was monitored with the on-screen display from the universal testing machine. Once the desired load was obtained, the four corner bolts on the test frame were hand tightened to maintain the load.

The compression spring frame was placed over the anchor and the loading rod was connected to the coupler. Two ¼” steel plates and a washer were placed on top of the test frame and a nut was loosely placed on top. The entire assembly was rolled into the testing chamber on a dolly for conditioning.

Once the 24 hour condition period elapsed, the hydraulic jack chair (Figure 4) was placed over the loading rod and a ½” steel loading plate was placed on top.

The Houston Scientific Model 3500 100-kip load cell was placed on top of the loading plate sandwiched between four ¼” plates (two above and two below). Another nut was placed on top and hand tightened.

The LabVIEW 8.6 program was started to confirm that the program was functioning correctly and that the linear-pot values were within acceptable ranges.

The program was then reset and the test was started. The data acquisition system initially entered a loading cycle in which the load was monitored by the load cell. The load was applied by pumping the ENERPAC P-14 hand pump, which displaced the top plate of the test frame, causing the load to be transferred from the corner bolts to the loading rod. After the desired load was reached, the nut at the top plate of the test frame was hand tightened and the program exited the loading cycle. The pressure was released from the hand pump and the hydraulic jack chair and load cell were removed from the test frame. The load was thereafter calculated from the spring stiffness and anchor displacement.

If it became necessary to add load during the duration of the test, the hydraulic jack chair and load cell were placed on top of the test frame as described above. The program entered a tightening phase in which the load was monitored once again by the load cell and the spring stiffness and displacement. The greater of the two values was used as the load on the anchor. Once the desired load was achieved, the nut on the top plate of the test frame was hand tightened, the pressure was released from the pump, and the test continued as described above.

The LabVIEW 8.6 program automatically recorded the test data in an MS Excel spreadsheet.

Test Series 16 (Unconfined) Test Procedure

The above procedure was followed with the following exceptions:

- The PTFE confining sheet and 5/8” thick steel confining plate were eliminated.
- The test frame supports were placed no closer than two times the embedment depth from the anchor.
- The compression spring frame was placed on top of a steel plate that rested on the test frame supports.

Post-Test Procedure

A few of the anchors were cored with a 2-½” diameter concrete cylinder core bit using a Cincinnati Bickford coring machine. The resulting cores were saw cut on each side to the depth of the anchor and then split open. The resulting concrete core provided a more detailed investigation of the failure mode and is discussed in Chapter 3. Photos were taken of the cores and are presented in Appendix H.

APPENDIX D

Anchor Pullout Tests—University of Stuttgart

ANCHOR PULLOUT TESTS—UNIVERSITY OF STUTTGART

This section presents the test program conducted at the University of Stuttgart Intsitüt für Werkstoffe im Bauwesen (IWB) to investigate the effect of various parameters on the sustained load performance of three adhesive anchor systems.

Test apparatus

This section describes the test apparatus used for the short-term and sustained load (creep) tests.

Short-Term Test Apparatus

The testing apparatus for the short-term test used a 3.5" diameter x 0.04" thick Teflon PTFE (Polytetrafluoroethylene) confining sheet with a 1" diameter hole in the middle placed under a circular 1.7" thick steel confining plate with a clearance hole of 0.8" (Figure 1). The confining sheet was used to correct for any surface irregularities in the concrete.

Figure 1: Test specimen with PTFE sheet and confining plate installed.

Figure 2: Transducer mount on top of the test specimen.

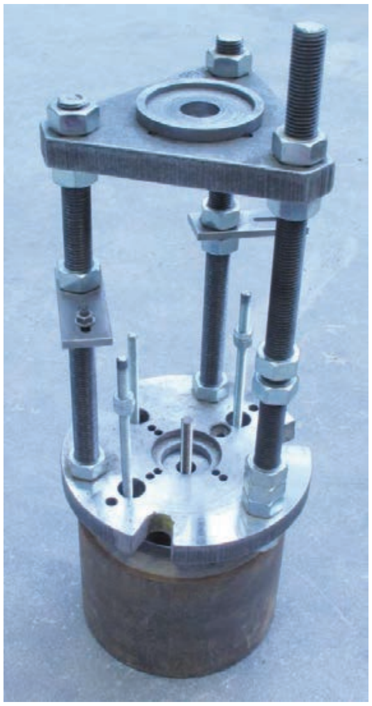


Figure 3: Tripod on top of the test specimens.

The transducer mount was placed on top of the test specimen before the tripod for the hydraulic ram and the load cell was installed (Figure 2). The tripod consisted of an upper triangular steel plate connected to a lower circular steel plate by three M24 threaded rods at a distance of 14” (Figure 3).

Figure 4: Hydraulic ram and load cell on top of the tripod.

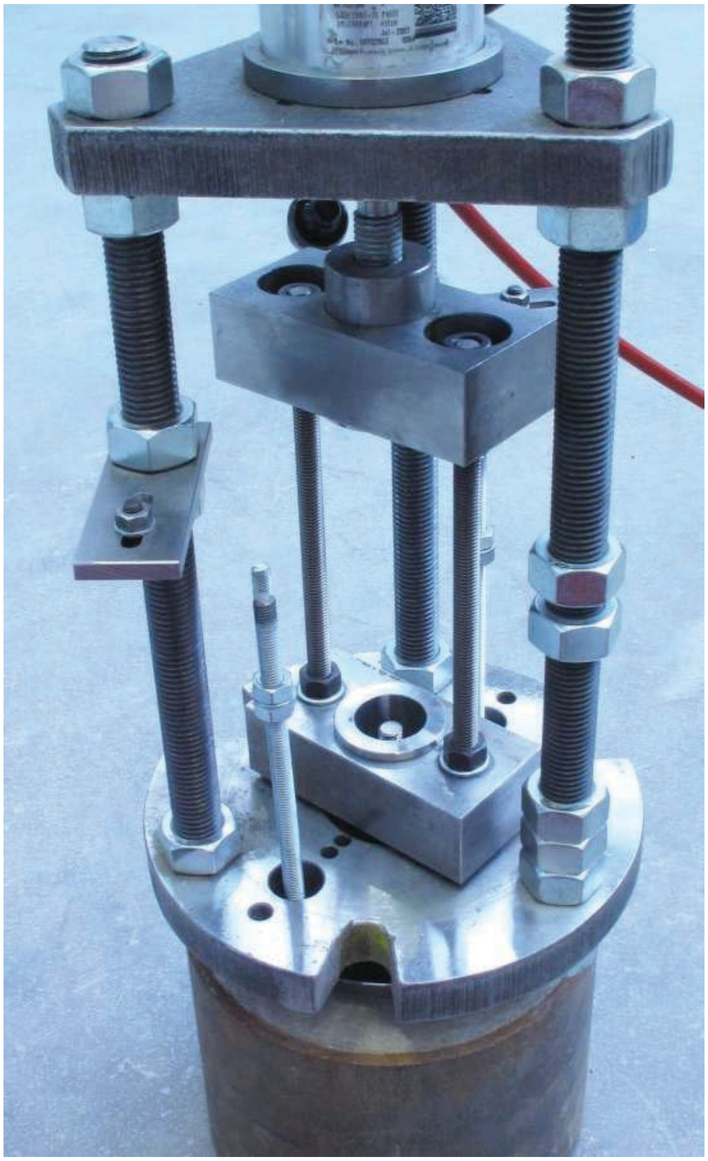


Figure 5: Coupler installed between loading rod and anchor.

A LUKAS Model LZOH 10/50-20 22-kip hydraulic ram and a HBM model C6 45-kip load cell were attached on top of the tripod, using self-centering steel adapters. A M20 threaded loading rod was passed through the ram and load cell and was secured at the top with a washer and a nut (Figure 4). At the bottom, the loading rod was connected to the coupler which was connected to the anchor (Figure 5). The coupler provided a non-rigid connection between the anchor and the loading rod by utilizing axial spherical plain bearings at all connections except the connection to the loading rod. The coupler also allowed for the positioning of the linear transducer directly on top of the anchor (direct measuring).

Transducer mount. Figure 6 shows the transducer mount on top of the test specimen with the linear transducer installed.

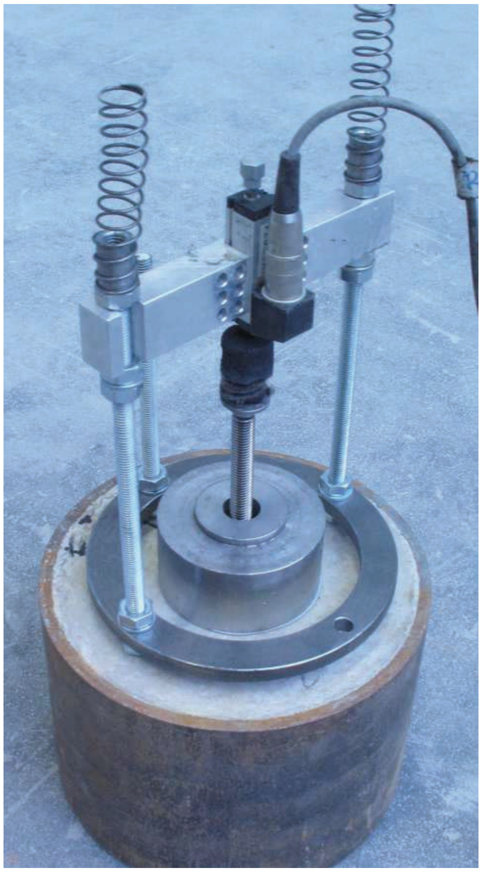


Figure 6: Transducer mount.

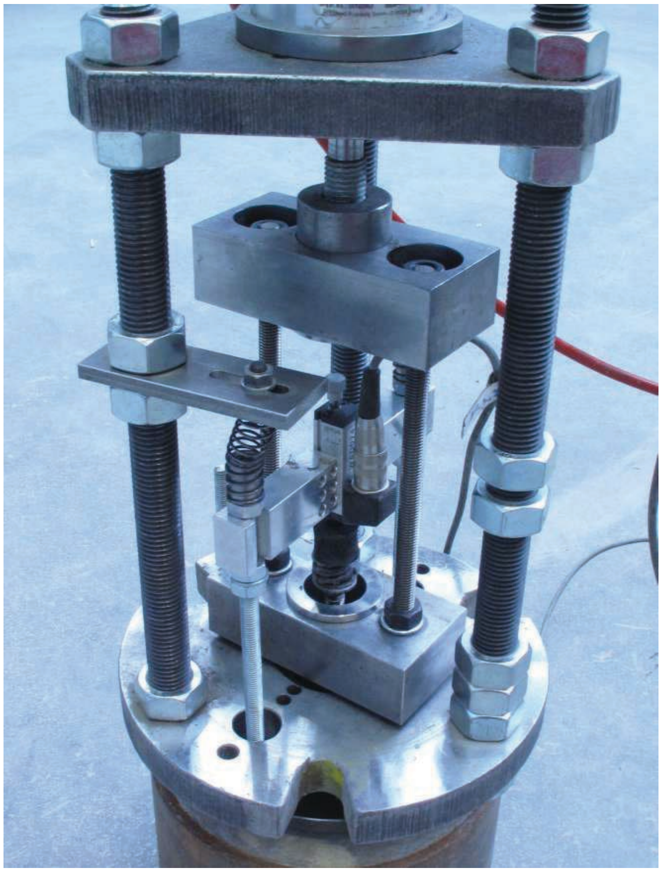


Figure 7: Transducer mount and transducer installed.

The transducer was clamped into an aluminum cross-beam that was mounted on a steel ring with two threaded rods. The threaded rods penetrated the ring and served as feet for the mount. With an additional threaded rod, the steel ring worked as a tripod. The mount (without cross-beam and transducer) was placed directly on the concrete surface before the tripod of the hydraulic ram and the load cell was installed.

Figure 7 shows the transducer mount after the installation of the tripod. The cross-beam with the transducer was adjusted, fixed to the mount, and locked with two size M10 nuts. Two coil springs were placed on the locknuts and connected to two levers attached to the tripod. The springs would push the mount downward to the concrete surface keeping it in position without transferring vibrations or horizontal loads from the test rig to the transducer during loading. Except for the springs, the transducer mount had no contact to the rest of the test rig.

Standard Sustained Load (Creep) Test Apparatus

The testing apparatus for the sustained load (creep) tests used the same Teflon PTFE (Polytetrafluoroethylene) confining sheet. Instead of the steel confining plate that was used in the short-term load test apparatus, a two-part confining plate was used for the sustained load tests to make the installation of the test specimens easier. The dimensions of the confinement sheet and plate were unchanged.

The equipment for sustained load testing of bonded anchors at the IWB, University of Stuttgart, was developed by IWB personnel in 2008. Two different types of heating chambers were developed. Figure 8 shows the large heating box with two back-to-back heating chambers. Each heating chamber contained three single test rigs. There were six large heating boxes installed at the IWB with a total number of 36 test rigs.

Figure 9 shows the small heating chamber that contained a single test rig. There were 26 small heating chambers installed at the IWB.

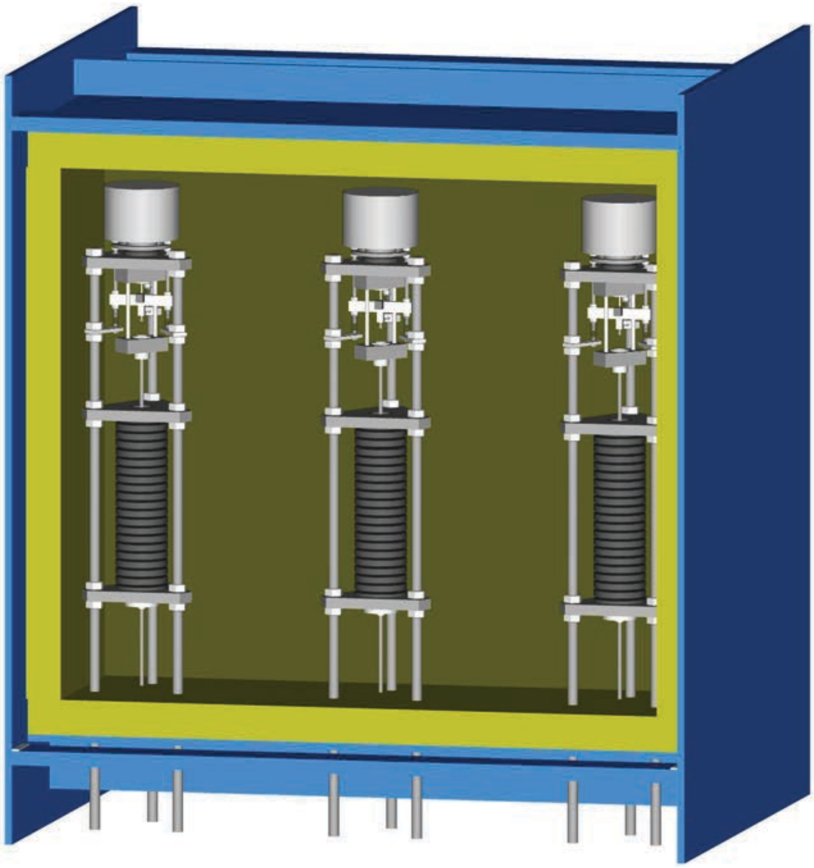


Figure 8: Illustration of the large heating chamber (containing three test rigs).

Figure 9: Small heating chamber (containing a single test rig).

To apply the sustained loads, large packages of disc springs were used (Figure 10). They provided low spring stiffness, which minimized the loss of load when the anchors displaced.

The disc springs were manufactured by Schnorr GmbH, Sindelfingen. The item numbers of the types used are 021 400 (6” x 3” x 0.31,” max. ~ 20 kips) and 021 350 (6” x 3” x 0.23,” max. ~ 11 kips). The spring characteristics are shown in Figure 11.

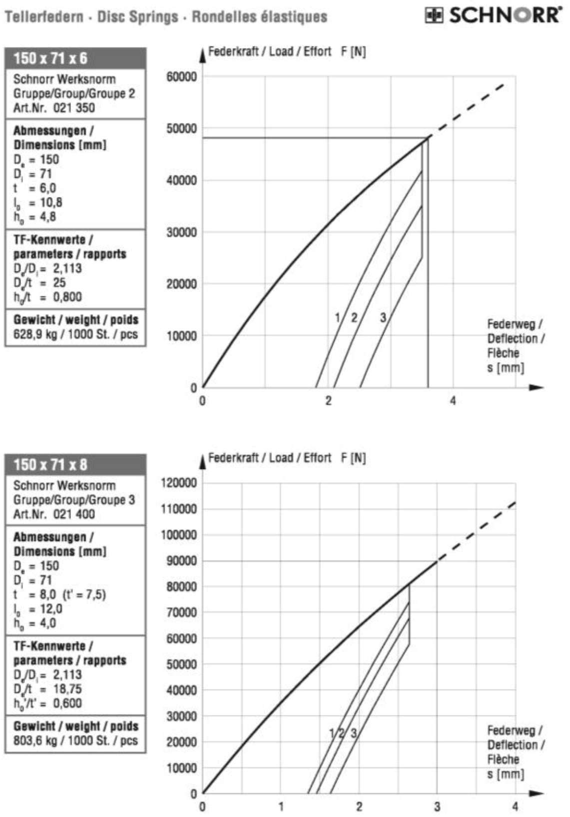


Figure 10: Disc-spring package.

Figure 11: Disc-spring characteristics.

A spring package usually consisted of at least 28 disc springs. Before the packages could be used for the tests, they were loaded for several days with the required test load to avoid any relaxation effect of the springs during testing.

The M12 diameter anchor was connected to the M20 diameter loading rod by means of the same non-rigid coupler as in the static load test apparatus. Linear-pots were used to measure displacement in the same configuration as in the static load test apparatus.

Figure 12: Loading system.

Figure 13: Loading system installed.

A special loading system was developed to apply the loads to the spring packages (Figure 12). Two LUKAS Model LFC 23/11 (50 kip) hydraulic rams were placed on top of a Burster Model 8526 22-kip load cell. It was designed to avoid any effects to the applied loads from deformations of the test rig and to avoid any risk to the operator in case of failing during the loading process. No loss of load had to be taken into account due to unloading of the loading system.

During loading, the load cell measured the transfer of force from the spring to the anchor. Once the desired load was achieved, the nut between coupler and anchor was tightened and the pressure in the rams was released.

Specimen preparation

The test specimens consisted of three parts; the concrete test member, the adhesive, and the anchor rod.

Concrete Test Member

The concrete test members for the short-term tests and the sustained load (creep) tests were poured in steel cylinders with an 8” inner diameter, 6” height, and a wall thickness of ¼” (Figure 14). No reinforcement was used. In addition, 30” x 30” x 6” concrete slabs were cast from the same batches for additional tests for test series 05, 06, and for extras. The pour dates and number of test blocks produced in each series are listed in Table 1.

Figure 14: Typical concrete test specimen.

Table 1: Concrete pour details.

Concrete Mix	Pour Date	Number of Cylindrical Test Members	Number of Sustained Load Test Members	Notes
A	April 07, 2010	85	6	-
B	September 17, 2010	100	3	-

The concrete for all mixes was batched, mixed, and placed by Friedrich Rau GmbH & Co. KG, Ebhausen, according to DIN EN 206-1. Concrete with round river gravel without any admixtures was specified with a mean compressive strength between 4000 and 6000 psi during testing. All of the materials were batched by weight. After mixing the concrete was placed into the steel cylinders with shovels and vibrated on a vibration table. Due to size of the concrete mixer, the concrete for the research project was made in two batches. The concrete mix designs are included in appendix G.

Following the pour, the concrete was cured according to DIN EN 206-1 for 28 days. Concrete compressive strength was determined by testing the cubes in general accordance with DIN EN 206-1 on a Toni-Technik model 1515 compression machine at the laboratory of the IWB, University of Stuttgart (Figure 15). The average compressive strength for each series is presented in Table 2 and Table 3.

Figure 15: Compression machine.

Table 2: Concrete series US-A average compressive strength.

Concrete Series	Pour Date	Average Compressive Strength (psi)					
		7 day	28 day	41 day	82 day	86 day	462 day[1]
A	April 07, 2010	3902	-	5279	5656	6280	5787

[1] Due to the unexpected long test period, the last group of four test samples of the first batch had to be used for compression testing when series S5 and S6 were started. The compressive strength at the end of the project has to be estimated (e.g. according to Weber, 1979).

Table 3: Concrete series US-B average compressive strength.

Concrete Series	Pour Date	Average Compressive Strength (psi)		
		7 day	28 day	538 day
B	Sept. 17, 2010	3031	4279	6193

Adhesive

The same three adhesives identified earlier were used. The three adhesive products were stored at the laboratory of the IWB. Because it was not possible to environmentally control the whole laboratory the adhesives had to be conditioned to the specified setting temperature prior to every installation. This conditioning was done in a Noske-Kaeser Model KSP 502/40 H climate chamber at the laboratory.

Anchor Rods

Size M12 threaded rods and nuts were used as specified in ISO 1502. The steel grade was 12.9, which corresponds to 174 ksi ultimate strength and 157 ksi yield strength. The rods were galvanized to prevent rusting and to ensure nearly identical surface properties for all tests, even if the batch or the manufacturer changed during the project. They were delivered by Ferdinand Gross GmbH & Co. KG of Leinfelden-Echterdingen. The anchor rods were cut to a length of 6.7” from 39” stock and their ends ground. The bottom end of the anchor was ground to a 45° cone (Figure 16) in order to fit into a centering guide placed at the bottom of the drilled hole (except for test series 5 and 6). Prior to installation, the rods were cleaned with acetone and allowed to air dry.

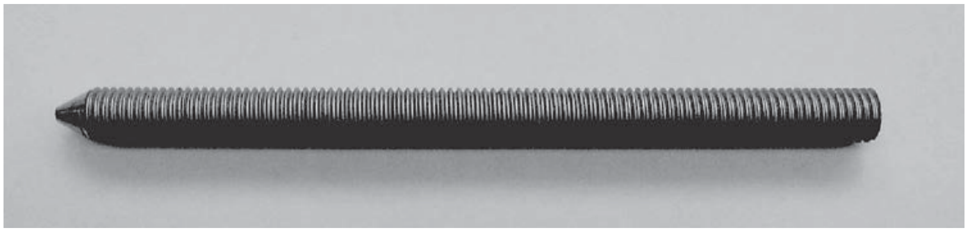


Figure 16: Anchor showing 45° cone to fit into centering guide.

Instrumentation

Measurement

Displacement. A direct measurement of the anchor displacement was measured with Novotechnik model TRS25 potentiometric linear transducers.

Load. The tension in the anchor was measured indirectly as a compressive reaction of either the hydraulic ram or the compression spring in the test apparatus. For the short-term tests, the load was measured by a HBM Model C6 45 kip load cell connected to the HBM Model Spider-8 data acquisition system. The data logging was done with a PC using DIAdem 10. For the sustained load (creep) tests, the loads during the loading process were measured by a Burster Model 8526 22 kip load cell. Once the load was applied to the anchor, the loading system including the load cell was removed. After removing the load cell, it was not possible to monitor the loads that were actually applied to the anchor without disturbing the tests. However, the stiffness of the spring packages was chosen to limit the loss of load to 2% for an anchor movement of 0.04.”

Temperature. The temperature of the test specimens could not be measured directly during the tests. Due to the small specimen size, a hole could not be drilled without affecting the load distribution inside the specimens. To guarantee that the required temperatures were reached before loading transfer, the required conditioning times were determined in advance using a thermocouple-equipped anchor set into a standard test specimen. This temperature calibration specimen was connected to the HBM Model Spider 8 data acquisition system and calibrated using a Testo Model t110 digital thermometer, calibrated on October 08, 2009 and October 24, 2011. The data logging was performed with a PC running DIAdem 10.

Ambient air temperature in each test chamber was measured and controlled by GEFRAN Model 400-DR-1 temperature controllers. The temperature sensors attached to the controllers were Electrotherm Type K2RS PT100 sensors. All heating systems, consisting of sensor, controller, and heating elements were calibrated using the temperature calibration specimen. It was not possible to monitor the temperature of each chamber. The function of the temperature controllers were checked periodically with a calibrated Testo Model t110 digital thermometer.

Humidity. The relative humidity within the test chambers could not be measured and controlled.

Time. Time was measured using the computer’s internal clock.

Instrument Calibration

Displacement in short-term tests. The Novotechnik Model TRS25 potentiometric linear transducer used in the short-term tests was calibrated on May 26, 2010, using the Mitutoyo Gauge Block Set No. BM3-32-1/PD, calibrated on April 2008.

Displacement in sustained load tests. The Novotechnik Model TRS25 potentiometric linear transducer used in the sustained load test could not be calibrated as the creep displacements that occur in sustained load tests were below the accuracy guaranteed by the manufacturer. The accuracy was also affected by the increased temperature. Therefore all measured creep displacements could only be judged qualitatively. All transducers used for long-term testing were checked for proper functioning before each test. The measurements were adjusted for variations in power supply voltage and normalized to a 9 volt power supply.

Load. The Burster Model 8526 22 kip load cell of the loading system for the sustained load tests was periodically calibrated against one of three HBM Model C6 45 kip load cells that were used in the short-term tests and for the loading of the disc-spring packages in the sustained load tests. The HBM load cells were calibrated on October 28, 2009 & October 17, 2011 (ID no.: KMD006), December 11, 2009 & December 13, 2009 (ID no.: KMD009) and July 12, 2010 (ID no.: KMD010) at the MPA Stuttgart (Material Testing Institute University of Stuttgart) according to DKD standards (Deutscher Kalibrierdienst). The spring packages were not calibrated as all loads were applied using a calibrated load cell. For determining the loss of load due to anchor movement the spring constants provided by the manufacturer were used.

Compressive Strength. The compressive strength of concrete cubes was tested on a Toni-Technik Model 1515 compression machine, calibrated on September 11, 2008 and September 13, 2010 at the MPA Stuttgart (Material Testing Institute University of Stuttgart) according to DKD standards (Deutscher Kalibrierdienst).

Temperature. For the conditioning of the test specimens prior to the installation of the anchors and for conditioning at elevated test temperature in the short-term test, the Noske-Kaeser Model KSP 502/40 H climate chamber was used, calibrated on August 06, 2008 and August 18, 2010.

For the periodical checking of the temperature of the heating chambers, the Testo Model t110 digital thermometer was used, factory calibrated on October 08, 2009 and October 24, 2011 according to DKD standards (Deutscher Kalibrierdienst). The temperature sensors in the test chambers were not calibrated separately but in combination with their controller and heating elements, using an original test specimen with a thermocouple-equipped anchor installed. This temperature calibration specimen was calibrated against the Testo Model t110 digital thermometer.

Humidity. There were no humidity sensors installed.

Environmental control

Standard Temperature

The adhesive was stored at the laboratory of the IWB without special air conditioning. The temperature was 73°F ±9°F (23°C ±5°C). Prior to installation, the test specimens, the anchors, and the adhesives were conditioned in the Noske-Kaeser Model KSP 502/40 H climate chamber (Figure 17). The chamber had a temperature range of -40°F to 356°F (-40°C to 180°C).

Elevated Temperature

The Noske-Kaeser Model KSP 502/40 H climate chamber was used for conditioning of the test specimens prior to every installation and for elevated testing temperatures in short-term tests.

Figure 17: Climate chamber.

Data management and acquisition

Generally a Microsoft compatible computer was used for the data acquisition. For short-term testing, National Instruments data acquisition software DIAdem10 was installed with special drivers for the HBM Model Spider-8 data acquisition system. The measured values included load and displacement.

For sustained load testing, the Measure Foundry 5 data acquisition software from Data Translation was used together with the Data Translation DT9803 USB-connected measuring device. A special setup was developed at the IWB to automatically acquire and log the data. Measured values included the power supply voltage (9 volt), transducer voltage, and time. The voltage of the transducers represented the relative position of the transducers, whereas 0V represented the minimum transducer position and 9V represented the maximum transducer position. No calculations were performed before logging. Generally the logging interval was 10 minutes.

Due to minor fluctuations in the 9 volt power supply, the Data Translation program recorded the power supply voltage with each data reading and the readings of the transducer positions were appropriately adjusted to a normalized 9 volt power supply.

Data Acquisition Software for Short-term Tests

For short-term testing, DIAdem 10 was used, published by National Instruments (Figure 18). A load versus displacement curve was displayed on the screen for real-time feedback. Load, displacement, and time readings were recorded at a frequency of 5 Hz and stored as a Microsoft Excel file for analyzing.

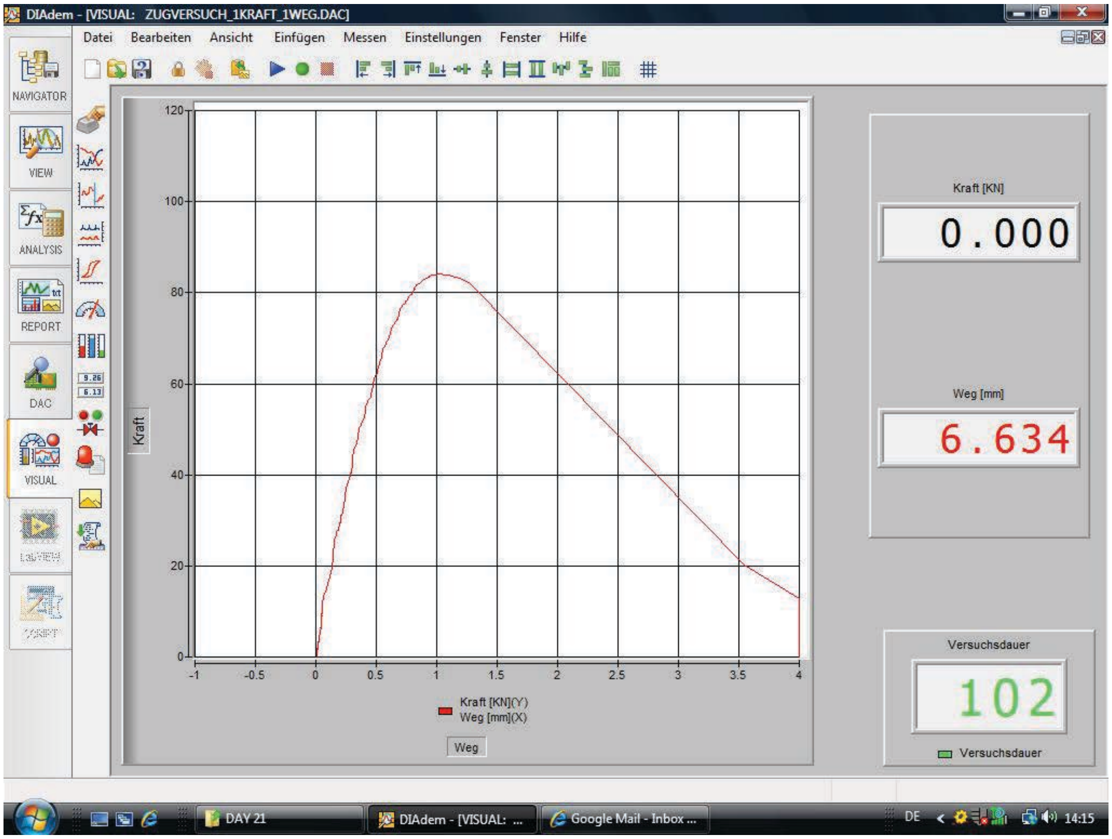
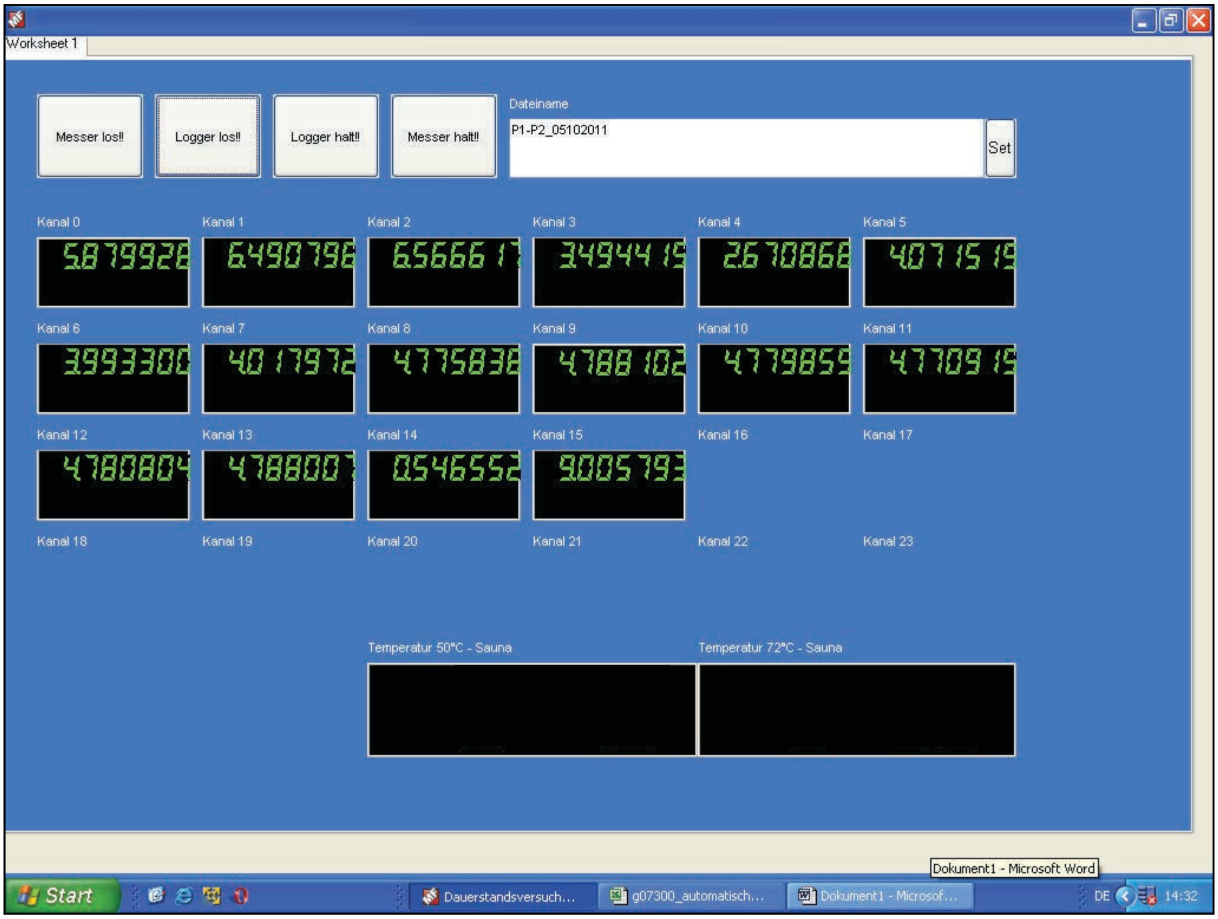


Figure 18: Screenshot of NI Diadem 10.2 data acquisition program.

Data Acquisition Software for Sustained Load (Creep) Tests

For sustained load testing, Measure Foundry 5 was used, designed especially for the data acquisition devices from Data Translation. It used a graphical programming interface that gave access to every function of the measuring device and let the user build customized setups. Since most of the test chambers were not located in the IWB laboratory, the tests could not be observed daily. Therefore it was decided to build a very robust setup that only triggered the data acquisition of the measuring device in a 10 minute interval and wrote the transferred data as a simple ASCII-file to the hard disk (Figure 19). Further analysis was done in a second process using Microsoft Excel.



Dateiname
P1-P2_05102011

```
Kanal 0    Kanal 1    Kanal 2    Kanal 3    Kanal 4    Kanal 5
5.87992    6.49079    6.56661    3.49441    2.67086    4.07151
Kanal 6    Kanal 7    Kanal 8    Kanal 9    Kanal 10   Kanal 11
3.99330    4.01797    4.77583    4.78810    4.77985    4.77091
Kanal 12   Kanal 13   Kanal 14   Kanal 15
4.78080    4.78800    0.54655    9.00579
```

Figure 19: Sustained load test setup, built with Data Translation Measure Foundry 5 (screen shot).

Installation procedure

The standard installation procedure is described below which was followed for test series 2, 3, 4, 5, 6, 8, 10 and 11.

Standard Baseline Installation Procedure

All anchors were installed according to the MPII. The holes were created with a 0.55” (14mm) carbide tipped concrete bit as specified by the manufacturer and a Hilti Model TE36 hammer drill. A drilling jig (Figure 20) with a depth stop was used to ensure that the holes were drilled perpendicular to the surface of the concrete and to the correct depth. The holes were drilled 0.6” deeper than then embedment depth to allow for the placement of a centering guide at the bottom of the hole.

The spoil at the concrete surface was removed with a vacuum prior to cleaning the hole. The holes were cleaned according to the MPII, which generally included blowing with oil-free compressed air, brushing with a steel brush provided by the manufacturer, and then blowing again with compressed air until no dust was discharged from the hole. Durations and numbers of brushing/blowing cycles varied by manufacturer, but for each case the holes were cleaned according to the MPII.

To prevent dust from blowing into the operator’s mouth and eyes, an adaptor for the vacuum (Figure 21) was used to capture the dust ejected from the hole when blowing with compressed air. This adaptor attached to the vacuum hose and allowed the compressed air nozzle to be easily inserted and removed.

Figure 20: Drilling rig and hammer drill.

Figure 21: Vacuum adaptor.

Prior to installation, a centering tool (Figure 22 and Figure 23) was inserted into the hole and a concentric circle was drawn on the surface of the concrete to aid in centering the anchor. A plastic centering guide (Figure 24) was placed in the bottom of the hole.

Figure 22: Centering tool.

Figure 23: Centering tool inserted in hole.

The adhesive products were dispensed with a manufacturer supplied cartridge gun. According to the MPII, several squeezes of adhesive were discharged and disposed of before dispensing into the holes to ensure that the adhesive was of uniform color and consistency indicating that it was properly/thoroughly mixed.

The anchors were wiped clean with acetone and allowed to air dry. The anchor rod was rotated counterclockwise and jiggled while it was installed in the hole until the tip of the anchor seated into the centering guide at the bottom of the hole. Excess adhesive was wiped from the surface and the centering ring coated with wax to prevent adhering with the adhesive (Figure 25) was placed over the anchor and the anchor was centered and plumbed vertical. The anchors were left undisturbed during the specified gel/working time and the adhesive was allowed to cure for seven days prior to conditioning.

Figure 24: Centering guide with anchor.

Figure 25: Anchor with centering ring.

Exceptions to the Standard Baseline Installation Procedure

All tests of series 5 and 6 were conducted without using a centering guide. All of the tests of series 10 and 11 were installed at 32°F (0°C).

Specimen conditioning

Upon completion of the 7 day adhesive curing period, the temperature conditioning started. Usually the conditioning took 18 hours. Immediately after conditioning the short-term tests were conducted and the sustained load tests were loaded.

Testing procedure

The standard testing procedures for the short-term and sustained load (creep) tests are described below which were followed for test series 2, 3, 4, 5, 6, 8, 10, 11

Short-Term Test Procedure

Immediately prior to testing, the test specimen was removed from the climate chamber and exposed to normal ambient temperature. To avoid non-admissible loss of temperature the installation of the test apparatus described below was finished within 120 seconds. A 0.04” thick PTFE confining sheet and 1.7” thick circular steel confining plate were placed over the anchor. The measuring mount for the linear transducer was placed on top of the concrete surface with the anchor centered in the middle of the base ring. The tripod, the LUKAS Model LZOH 10/50-20

22-kip hydraulic ram, the HBM Model C6 45-kip load cell and the loading rod were placed together on top of the confining plate. The coupler was attached to the anchor and connected to the loading rod. Finally the cross bar with the transducer installed was attached to the measuring mount and the coil springs were installed to keep the measuring mount in position. The hydraulic ram was connected to an electrically operated hydraulic pump installed inside a measuring cabinet. The transducer and the load cell were connected to a HBM Spider 8 data acquisition system installed inside the measuring cabinet, connected to a PC running DIAdem under Microsoft Windows-Vista. The software was initialized with the appropriate sensor parameters (calibration factors, etc.) and checked for proper functioning.

The anchors were loaded at a constant pump rate (i.e., displacement-controlled). The pump rate was adjusted to get failure within 60 to 180 seconds as specified in the ETAG001.

The DIAdem program automatically recorded the test data in a proprietary format. After finishing the tests, the data was exported to a MS Excel spreadsheet.

Standard Sustained Load (Creep) Test Procedure

The disc-spring packages were compressed using the same LUKAS LZOH 10/50-20 22-kip and HBM Model C6 45-kip load cells that were used in the short-term tests and placed into the test rig between two triangular steel plates (Figure 26).

Both steel plates were aligned by the same size M30 treaded rods that passed through holes in each corner of the plates surrounding the disc-spring package. Both triangular steel plates could be locked with M30 nuts in any desired vertical position along the M30 treaded rods. To compress the spring packages, the upper steel plate was locked and the lower steel plate pushed upwards. When the desired load was reached, the lower steel plate was locked and the pressure in the hydraulic ram released. In the following paragraph, the set of triangular steel plates with the compressed disc spring package fixed in between is referred to as the “spring frame”.

After the spring frame was adjusted, a third triangular steel plate was installed to the top of the test rig and fixed with M30 nuts in the same way. From above, the same measuring mount that was used in the short-term tests was attached upside-down to the third steel plate. The test specimen was placed upside-down on top of the third steel plate in the same manner, with the PTFE confining sheet and the two-part steel confining plate placed in between. The coupler was installed to the anchor as described in the short-term tests. The loading rod was passed through the spring package and the upper end was connected to the bottom of the coupler. A nut was attached to the lower end of the loading rod and hand tightened, bearing against the lower triangular steel plate of the spring frame.

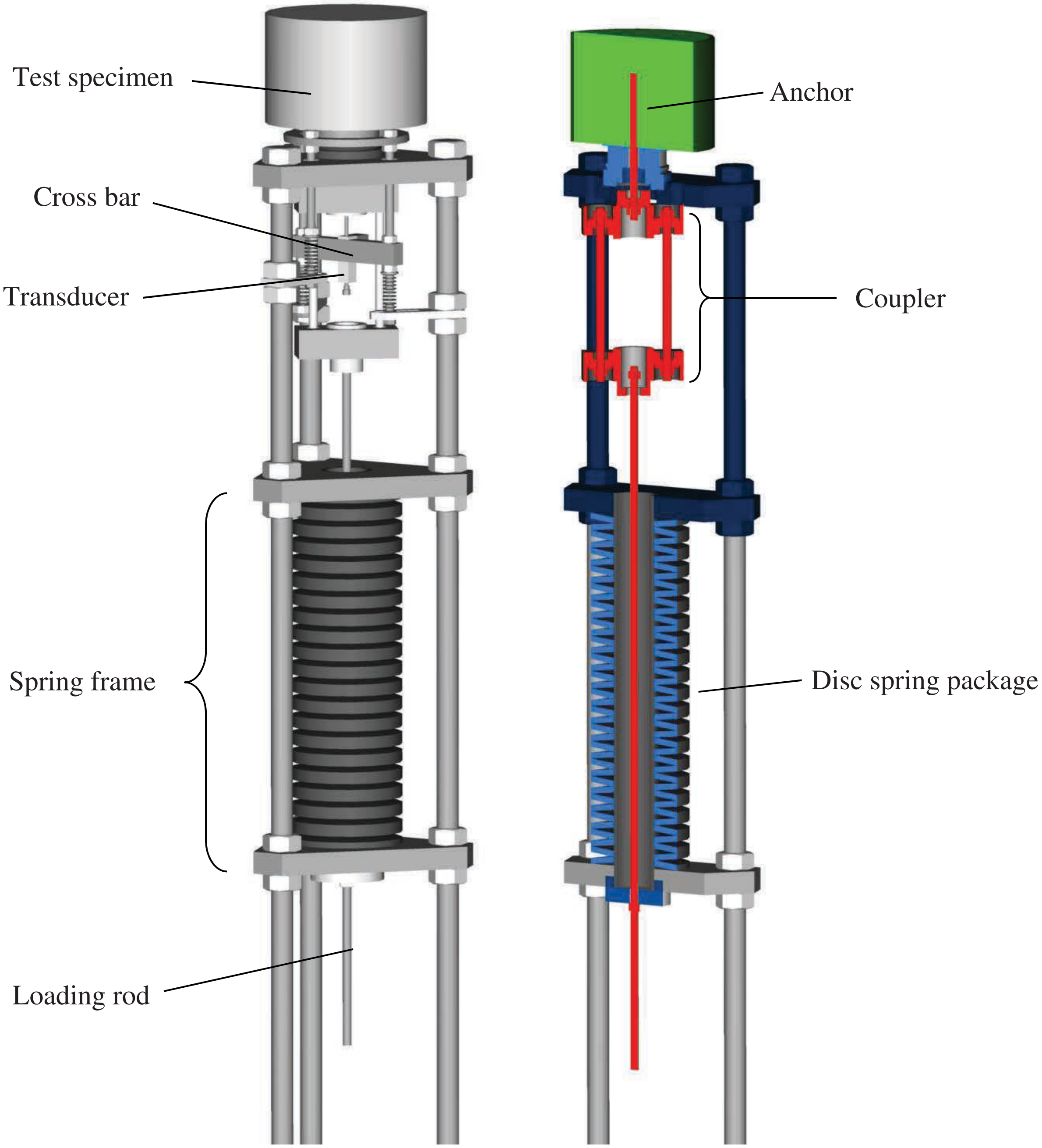


Figure 26: Illustration of the test rig with a vertical cut.

Finally the cross bar with the transducer installed was attached to the measuring mount and the coil springs were installed pushing the measuring mount against the concrete surface keeping it in position during testing. After installation, the temperature was raised to the test temperature.

Once the conditioning period elapsed, the loading system was attached to the lower end of the loading rod bearing against the lower steel plate of the spring frame. The load was applied to the anchor with a hand operated hydraulic pump. Once the preload force of the spring package was reached, the M30 nuts that supported the lower steel plate of the spring frame were loosened and screwed downwards before the nut at the lower end of the loading rod was screwed upwards against the lower steel plate of the spring frame and hand tightened. Finally the pressure was released from the hydraulic rams and the loading system was detached. During the loading procedure, the load was permanently observed using the Burster Model 8526 22-kip load cell (which is an integrated part of the loading system) and the HBM Spider 8 data acquisition system.

Exceptions to the Standard Baseline Testing Procedure

All of the tests of series 3 were conducted at 120°F (49°C) and those of series 4 were conducted at 70°F (21°C). All of the tests of series 8 were conducted in moist concrete during service. The specimens were watered for 24 hrs. Immediately after the watering process, the test specimens were put into plastic bags to prevent them from drying. The anchors were guided through small holes in the plastic bags so that the loading equipment could be attached to the anchors as usual. After heating up the specimens and loading the anchors, the specimens could be checked anytime and rewetted if necessary through the mouth of the bag. All of the tests for series 10 were conducted at 32°F (0°C).

Post Test Procedure

After sustained load failure occurred the anchors could not be extracted from the test specimens by pulling them out without destroying the remaining mortar shell that surrounds the anchor. Instead the anchors were extracted by splitting the test specimens as follows. The concrete cylinder was pressed out of the surrounding steel ring using a hydraulic ram. A 1” diameter hole was drilled into the concrete at a distance of 0.8” from the anchor. With a special wedge that is usually used to generate cracks in concrete slabs, the concrete cone was split in half. Usually the anchor could be extracted now with some gentle strokes of a hammer perpendicular toward the head of the anchor. Once the anchor was separated from the concrete the actual failure could be determined.

APPENDIX E

Adhesive-Alone Tests—University of Florida

ADHESIVE-ALONE TESTS—UNIVERSITY OF FLORIDA

This chapter presents the test program conducted at the University of Florida to investigate the isolated sustained load and short-term creep behavior of the adhesive alone.

Test apparatus

This section describes the test apparatus used for the dogbone and DMTA and creep testing.

Dogbone Short-term Testing Apparatus

The short-term testing was done on an INSTRON 5582 load frame (Figure 1) with a load cell capacity of 2250 pounds. The temperature of the sample was controlled by an oven accessary (Figure 2).

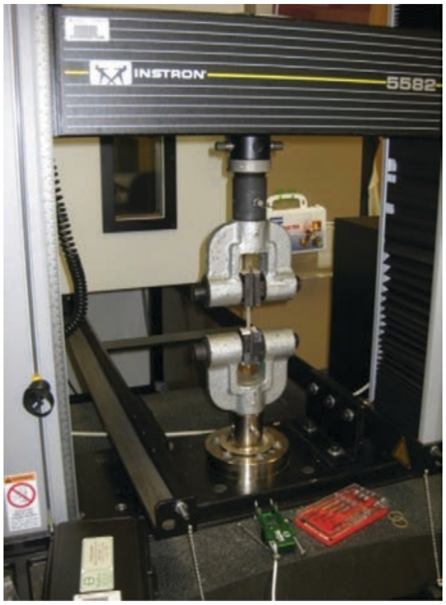


Figure 1: INSTRON tensile testing machine.

Figure 2: The oven, which pulls forward around the INSTRON, used to keep the samples at temperature.

Dogbone Sustained Load (Creep) Testing Apparatus

The sustained load creep tests were done on custom built test frames (Figure 3). The sample was suspended from the frame by an eyehook. The load was applied to the sample through a 24” long lever arm with a 10:1 ratio and was transferred to the dogbone sample through a hook on the lever arm as well. The self-weight of the lever arm resulted in around 80 pounds of base load on the sample and additional weight could be added to the end of the lever arm.

Each test frame had two grips used to clamp the dogbone sample shown in Figure 4. A jig was used to ensure a consistent clamping position of the dogbone. In addition, 60 grit sandpaper was inserted between the grip and the dogbone to increase the friction and prevent slippage between the dogbone and the grips. Once the dogbone sample was clamped by hand tightening the screws on the grips, the sample was then inserted into the test frames between the two hooks mentioned above. Prior to loading, the upper eyehook's height was adjusted until the lever arm was horizontal. With the lever arm supported, the lower hook would become disengaged. Such a design ensured the dogbone sample would not be subjected to a load prior to testing. During testing, as the dogbone elongated during creep, the lever arm would gradually displace downwards.

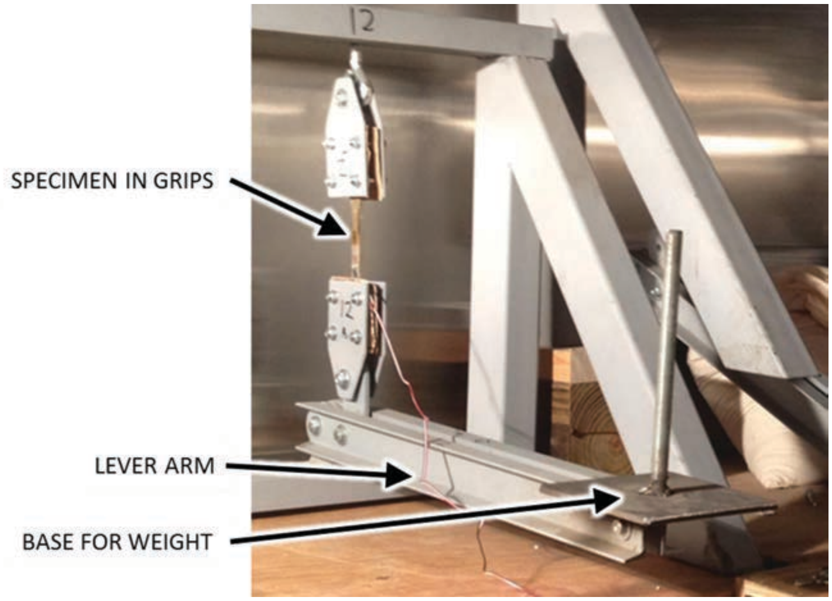


Figure 3: Test frames for sustained load dogbone testing.

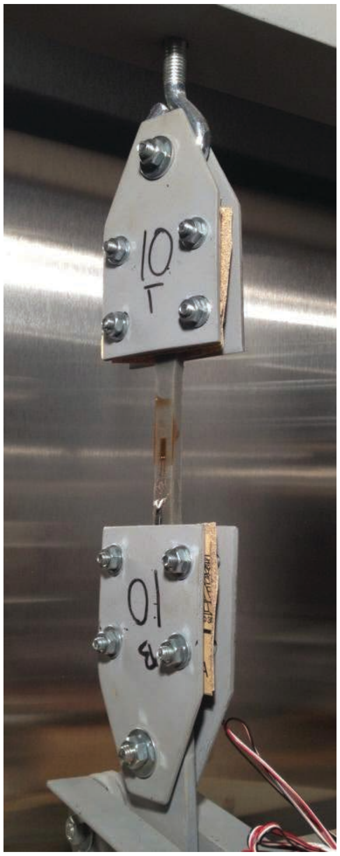


Figure 4: Dogbone specimen loaded in grips.

DSR Machine

The DMTA and creep tests were performed on a TA Instrument's AR-EX2000 DSR machine with a rectangular torsional grips and an environmental test chamber (ETC). The heating of the ETC was achieved through a peltier element and the ETC was air cooled by a Thermo Cube is 10-300A-1-AR system. Figure 5 shows the DSR machine with the ETC open for sample loading.

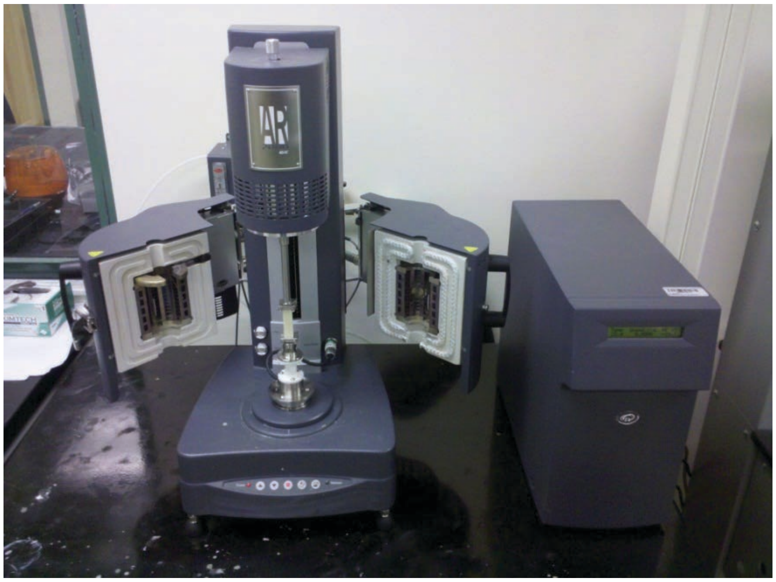


Figure 5: DSR machine.

Specimen fabrication

This section describes the fabrication of specimens used for the dogbone and DMTA and creep testing.

Adhesive

The same three adhesives identified earlier were used in this portion of the project. The three adhesive products were stored in an environmentally controlled room maintained within the temperature and humidity range specified by the manufacturers prior to installation.

Dogbone Sample

The silicone molds (Figure 6) for the dogbone samples were made from Dow Corning Silastic E RTV Silicone Rubber with dogbone shaped steel blanks. The steel dogbones were machined according to the Type I dogbone shape specified in ASTM D638. Once the silicone was cured, the steel dogbones were removed.

Figure 6: Silicon molds for casting dogbone specimens.

The dogbone samples were cast into the pre-made silicone molds directly from the tube. Due to the viscosity difference between the three adhesive, there was a slight difference in preparing the exposed smooth surface. Adhesives A and B were allowed to overflow the mold and a razor blade was used to screed the excessive adhesive in one pass thereby leaving a smooth surface. Later it was decided that such a procedure resulted in too rough a surface for Adhesive A and the procedure was modified as follows. Once overfilled, a piece of glass was pressed against the mold to squeeze the excessive adhesive out. Since Adhesive A showed almost no adhesion to glass, the glass was detached easily after the sample cured. Adhesive C was too sticky for any overfill-screed processing. Fortunately it was found that Adhesive C would slowly flow before gelation and the final procedure for making Adhesive C was to carefully control the amount of the adhesive injected into the mold and let the adhesive flow under gravity and form the smooth surface.

Specimens for DMTA and Creep Testing

The specimens for DMTA and creep testing (Figure 7) on the DSR machine were rectangular thin sheets with a thickness ranging around 0.039” (1.00mm), width of approximately 0.35” (9mm) and a length of approximately 2” (50mm). These sizes were chosen based on recommendations from the DSR equipment manufacturer. The precise control of the thickness of the specimen was very important for the accuracy of the measurement and every effort was made to ensure the sample thickness variation was within ±0.0008” (±0.02mm) throughout the sample length. A thin sheet was first made by casting a quantity of adhesive into an aluminum plate and placing spacers of 0.039” (1.00mm) thickness (glass slides were used) around edges of the plates. Another aluminum plate was placed on top of adhesive and pressed to squeeze out the excess adhesive. When the adhesive sheet was cured, the specimens were cut into small rectangular strips by a precision diamond saw. Again due to the different adhesion behavior of samples, the processing of the thin sheets was slightly different. For Adhesive A, it was found that it did not adhere to the aluminum plate and they were therefore directly placed onto the aluminum plate. For Adhesives B and C, the aluminum plate was coved by a thin cyclic olefin copolymer sheet prior to casting the adhesives.

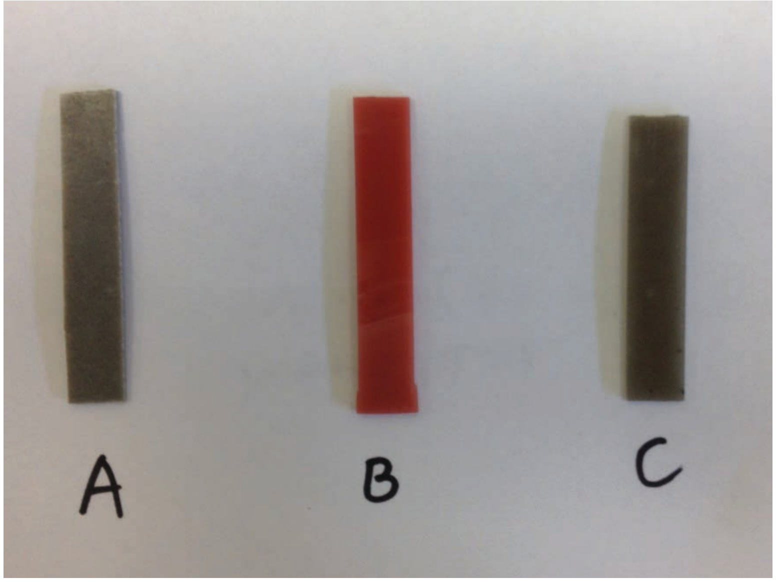


Figure 7: DMTA and DSR creep specimens.

Instrumentation

This section describes the instrumentation used for the dogbone and DMTA and creep testing.

Measurement

Strain. The creep of the dogbone sample was measured with strain gauges. All strain gauges were purchased from Micro-Measurement. The gauge designation was C2A-XX-250LW-350 for Adhesives A and C while adhesive B used EP-08-250-BF-350. Both types of strain gauges had an initial resistance of 350 ohm and a gauge factor slightly larger than 2 (2.09 for B and 2.12 for A and C). The strain gauges used for Adhesive B could detect strain up to 20% while for Adhesives A and C the strain gauges had a limit of 3%. The measurement of the strain gauge resistance was through a quarter-bridge setting.

The strain of the short-term tests was measured by an INSTRON 2630-115 extensometer attached to the sample surface along the loading direction.

Load. The tension in the dogbones was measured indirectly from a relationship to the load applied to the end of the lever arm. For the short-term tests, the loads were measured directly by a load cell.

Temperature. Ambient air temperature in the test chamber was measured by a Cincinnati Sub-Zero EZT-560i Environmental Chamber Controller installed in the Cincinnati Sub-Zero Model WM-STH-1152-2-H/AC Walk-In Stability Chamber. Analog cards installed in the Cincinnati Sub-Zero EZT-560i Environmental Chamber Controller provided an analog signal output allowing the ambient air temperature to be monitored by the data acquisition system.

Humidity. Relative humidity in the test chamber was measured by a Cincinnati Sub-Zero EZT-560i Environmental Chamber Controller installed in the Cincinnati Sub-Zero Model WM-STH-1152-2-H/AC Walk-In Stability Chamber. Analog cards installed in the Cincinnati Sub-Zero EZT-560i Environmental Chamber Controller provided an analog signal output allowing the humidity to be monitored by the data acquisition system.

Time. Time was measured using the computer’s internal clock.

Instrument Calibration

Strain. The extensometer was automatically calibrated with the built-in function of the measurement software.

Load. The INSTRON 5582 calibrated its load cell electronically by the built-in software function before every set of tests. The load cell was allowed to warm up for 15 minutes before calibration. Each test frame lever arm was calibrated with an Omega Engineering, Inc. Model ICCA-10K 10-kip load cell in order to determine the load applied to a dogbone specimen due to the addition of load on the end of the lever arm. The load cell was calibrated on an INSTRON System 3384 150 kN universal testing machine.

Temperature. The National Semiconductor LM35 Precision Centigrade Temperature Sensors factory calibration was validated in June 2010 against a high quality mercury thermometer over a temperature range of 100°F to 120°F (43°C to 49 °C). The temperature sensor in the test chamber was calibrated by the factory.

Humidity. The humidity sensor in the test chamber was calibrated by the factory.

DSR Machine. The system inertial and rotational friction mapping was done with the built-in function of the DSR machine software daily before every set of experiments. The stiffness of the DSR machine geometry was provided by the manufacture.

Environmental control

This section describes the environmental control for the dogbone tests. The environment for the DMTA and creep tests was controlled via the testing device.

Standard Temperature

An air conditioned space was used to store and condition the adhesive and the dogbone specimens at 75ºF ±10ºF (24ºC ±5ºC) and 50% ±10% relative humidity. Temperature was controlled by a Frigidaire air conditioner.

Elevated Temperature

A 12’ by 12’ by 8’ tall Cincinnati Sub-Zero Model # WM-STH-1152-2-H/AC Walk-In Stability Chamber was used to condition and test at the elevated testing temperature of 110ºF +10ºF/-0ºF (43ºC +5ºC/-0ºC)and below 40% relative humidity for the sustained load (creep) test. The chamber was purchased and installed in the fall of 2009. The chamber had a temperature range of -20°C to 60°C (-4°F to 140°F) and a relative humidity range of 10% to 95%. The chamber was equipped with a CSZ EZT-560i Touch Screen Controller to monitor and control the temperature and humidity.

The dogbone test specimens were placed in test frames located on shelves 5 feet high in order to provide space for anchor testing below (Figure 8 and Figure 9).

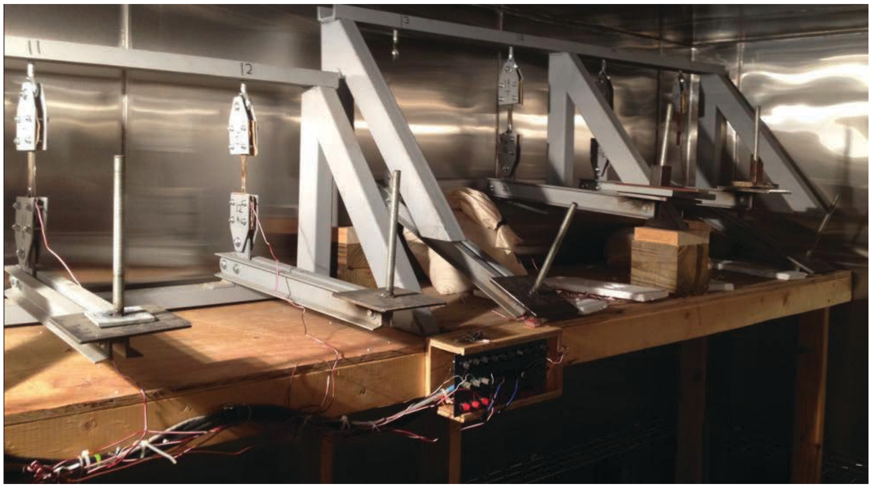


Figure 8: Left side of testing chamber.

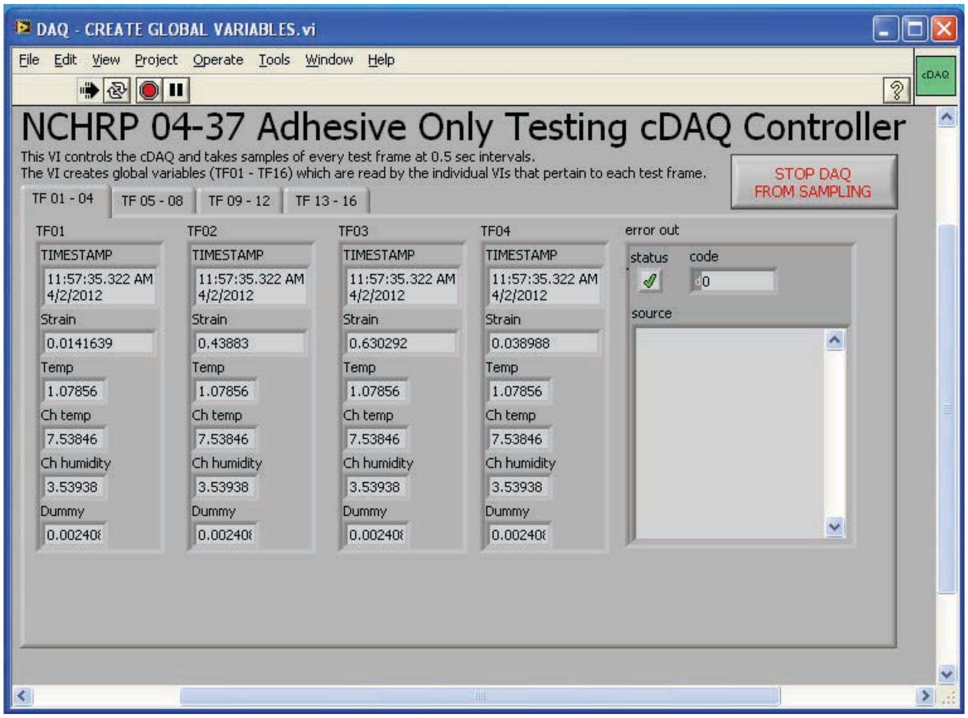
Figure 9: Right side of testing chamber.

Data management and acquisition

During the testing and conditioning of the test slabs to the elevated temperature, a Microsoft compatible computer ran several National Instruments LabVIEW 8.6 software programs developed by the author to collect, record, and display the data. Measured values included load, displacement, temperature, humidity, and time. Data acquisition was performed with a National Instruments NI cDAQ-9172 chassis with several National Instruments NI 9219 modules and a NI 9205 module to interface with the instrumentation. Data acquisition for the DSR creep tests was conducted directly by the DSR machine.

Data Sampling Program

A LabVIEW 8.6 program (Figure 10) was developed to centrally sample data for every test. This program provided a half-second time averaged record sampled at 2000 Hz. Global variables for each of the sixteen sustained load test frames were updated every half second to the computer memory to be read when needed by the separate LabVIEW programs for each test frame. Each global variable included a timestamp, strain, and environmental chamber temperature and humidity.



NCHRP 04-37 Adhesive Only Testing cDAQ Controller

This VI controls the cDAQ and takes samples of every test frame at 0.5 sec intervals.
The VI creates global variables (TF01 - TF16) which are read by the individual VIs that pertain to each test frame.

	TF01	TF02	TF03	TF04
TIMESTAMP	11:57:35.322 AM 4/2/2012	11:57:35.322 AM 4/2/2012	11:57:35.322 AM 4/2/2012	11:57:35.322 AM 4/2/2012
Strain	0.0141639	0.43883	0.630292	0.038988
Temp	1.07856	1.07856	1.07856	1.07856
Ch temp	7.53846	7.53846	7.53846	7.53846
Ch humidity	3.53938	3.53938	3.53938	3.53938
Dummy	0.00240	0.00240	0.00240	0.00240

error out
status ✓
code 0
source

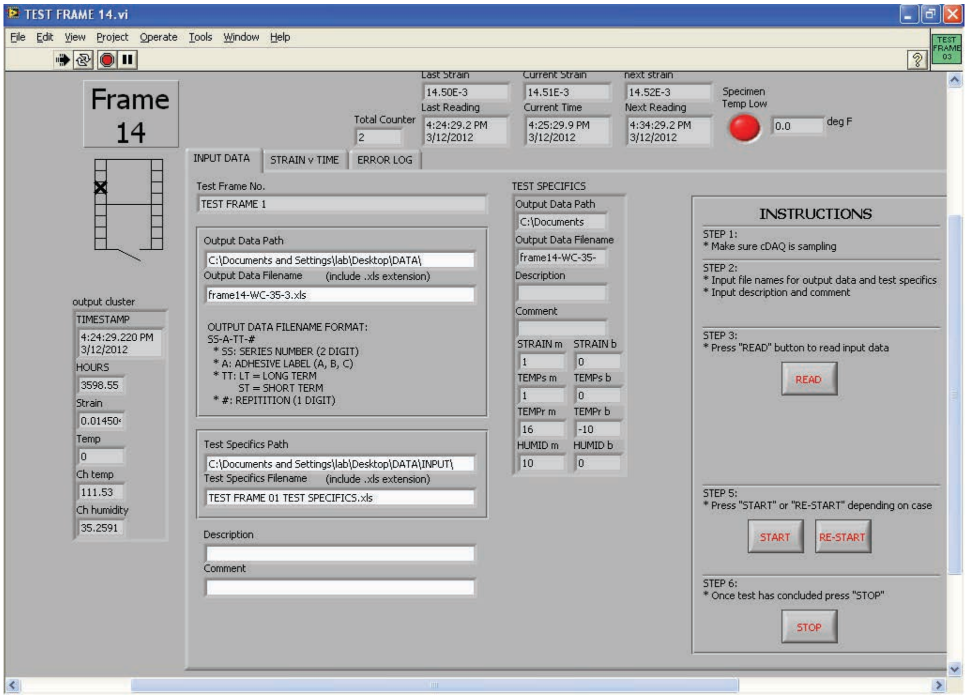
Figure 10: Data sampling LabVIEW program.

Long Term (Creep) Test Program

A LabVIEW 8.6 program (Figure 11) developed for this project was used for the sustained load (creep) test. Strain, temperature, and humidity readings were recorded at one of the following two conditionings:

- If the difference between the last recorded strain and current reading was larger than 2E-6.
- Every ten minutes if no change in strain larger than 2E-6 occurred.

A strain versus time curve (Figure 12) for each dogbone specimen was displayed on the screen for real-time feedback. The latest data readings were displayed on the screen and each data reading was automatically recorded in a Microsoft Excel spreadsheet.



Last Strain: 14.50E-3
Current Strain: 14.51E-3
next strain: 14.52E-3
Total Counter: 2
Last Reading: 4:24:29.2 PM 3/12/2012
Current Time: 4:25:29.9 PM 3/12/2012
Next Reading: 4:34:29.2 PM 3/12/2012
Specimen Temp Low: 0.0 deg F

output cluster
TIMESTAMP: 4:24:29.220 PM 3/12/2012
HOURS: 3598.55
Strain: 0.01450
Temp: 0
Ch temp: 111.53
Ch humidity: 35.2591

Test Frame No.: TEST FRAME 1

Output Data Path: C:\Documents and Settings\lab\Desktop\DATA\
Output Data Filename (include .xls extension): frame14-WC-35-3.xls

OUTPUT DATA FILENAME FORMAT:
SS-A-TT-#
 * SS: SERIES NUMBER (2 DIGIT)
 * A: ADHESIVE LABEL (A, B, C)
 * TT: LT = LONG TERM
 ST = SHORT TERM
 * #: REPITITION (1 DIGIT)

Test Specifics Path: C:\Documents and Settings\lab\Desktop\DATA\INPUT\
Test Specifics Filename (include .xls extension): TEST FRAME 01 TEST SPECIFICS.xls

Description:
Comment:

TEST SPECIFICS
Output Data Path: C:\Documents
Output Data Filename: frame14-WC-35-
Description:
Comment:

STRAIN m	STRAIN b
1	0
TEMPs m	TEMPs b
1	0
TEMPr m	TEMPr b
16	-10
HUMID m	HUMID b
10	0

INSTRUCTIONS

STEP 1:
* Make sure cDAQ is sampling

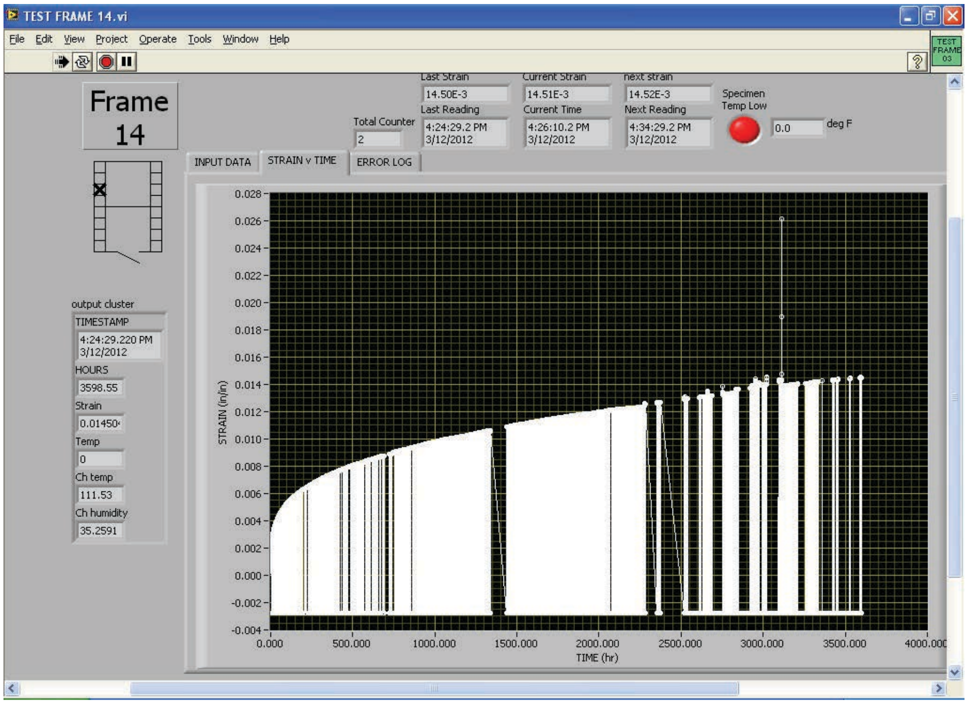
STEP 2:
* Input file names for output data and test specifics
* Input description and comment

STEP 3:
* Press "READ" button to read input data

STEP 5:
* Press "START" or "RE-START" depending on case

STEP 6:
* Once test has concluded press "STOP"

Figure 11: Sustained load test LabVIEW program (main screen).



Last Strain: 14.50E-3
Current Strain: 14.51E-3
next strain: 14.52E-3
Total Counter: 2
Last Reading: 4:24:29.2 PM 3/12/2012
Current Time: 4:26:10.2 PM 3/12/2012
Next Reading: 4:34:29.2 PM 3/12/2012
Specimen Temp Low: 0.0 deg F

output cluster
TIMESTAMP: 4:24:29.220 PM 3/12/2012
HOURS: 3598.55
Strain: 0.01450
Temp: 0
Ch temp: 111.53
Ch humidity: 35.2591

Figure 12: Sustained load test LabVIEW program (strain plot).

Specimen preparation procedure

The standard specimen preparation procedure is described below for the dogbone specimens and the DMTA and creep specimens.

Dogbone Specimen Preparation

To prepare the dogbones for strain gauges, the center of the dogbone was first degreased using isopropyl alcohol, and then polished successively using 120 and 300 grit sandpaper in the presence of the conditioning solvent from Micro-Measurement. After polishing, neutralizing solvent was applied to adjust the pH of the dogbone surface for optimal strain gauge adhesion.

The strain gauge was attached to the degreased and polished dogbone along the principle strain direction using adhesive tape first for easy handling of the strain gauge. Extra care was taken during the handling of the strain gauges to ensure the strain gauges were never touched directly by fingers. After partly peeling away the adhesive tape along with the strain gauge, a thin layer of the M-bond 10 adhesive from Micro-Measurement was applied underneath the strain gauge to permanently attach it to the dogbone sample. The M-bond 10 adhesive was allowed to cure in the test chamber for two hours before the dogbone specimens were loaded.

DMTA and Creep Specimen Preparation

For samples A and B, the thin sheets made for DMTA and creep testing were cut into the specimen strips after proper curing. For sample C, small white spots due to improper mixing were commonly present and care was taken to ensure that the final specimen strips were free of these imperfections.

Specimen conditioning

This section discusses the specimen conditioning for the dogbone and DMTA and creep test specimens.

Dogbone Short-Term Testing

The short-term testing specimens were conditioned the same as the sustained load testing specimens as described below.

Dogbone Sustained Load (Creep) Testing

Upon completion of the seven day adhesive curing period, the test specimens for test series 21 were placed into the 110ºF (43ºC) 35% humidity environmental test chamber for conditioning. The temperature of the environmental chamber as well as the humidity in the environmental chamber were monitored and recorded. Testing began upon completion of the 24 hour conditioning period in the environmental test chamber.

DMTA and Creep Testing

The conditioning of the DMTA and creep testing samples and the sustained load (creep) test samples were all at 24 hours. After 12 hours of conditioning inside the environmental test chamber the DMTA and creep testing samples were removed and cut into small specimen strips. After cutting, the specimens were returned to the environmental test chamber for the remaining 12 hours of the 24 hour conditioning duration. Testing began after the completion of conditioning.

Testing procedure

The standard testing procedures for the short-term tests, sustained load (creep) tests, and DMTA and creep tests are described below.

Dogbone Short-Term Test Procedure

Once the samples were conditioned, the area where the sample was clamped by the grip was roughed by sand paper and the samples were moved into the oven of the INSTRON for several minutes to reach 110°F (43°C). The samples were clamped between the grip with sand paper for increased friction and a stable grip during test. An extensometer was then clipped onto the sample. Once the samples were loaded, they were allowed to equilibrate with the temperature for an additional five minutes. The extensometer was calibrated and both the extensometer and the load cell were zeroed. After entering the test speed and sample dimensions of the dogbone in the testing software, the test was started.

Dogbone Sustained Load (Creep) Test Procedure

Once the dogbone specimens were conditioned and the strain gauges were attached, they were placed in the testing frame without additional weight placed on the lever arm and the lever arm was immediately supported so that no load was applied to the dogbone sample. The top eyehook was adjusted so that the initial position of the lever arm was horizontal as confirmed by a tubular spirit level. While still supported, additional steel weights as determined from the calibration factors were applied to the lever arm. Subsequently, the strain gauge was connected to the data acquisition hardware. Finally, the testing began as one person removed the support underneath the lever arm while another person started the data acquisition process in LabVIEW.

DMTA and Creep Test Procedure

After the torsional grip was mounted in the DSR machine, calibration tests for the system inertial and rotational friction mapping were performed. The grips were then brought to within 0.1” (3mm) of each other and the software was allowed to determine the zero position of the grip gap, which corresponded to the length of the sample during testing. The dimension of the conditioned test strip was first measured and inputted into the DSR machine software and then placed into the grip and tightened to 5.3 in-pounds (60 cm-N) using a torque screwdriver. A 0.03” (0.75mm) spacer was used to align the specimen per recommendations of the DSR machine manufacturer. Next, the ETC was closed and the temperature inside set to the desired experimental temperature through the DSR machine software. Once the temperature stabilized, the specimen would be conditioned at the temperature for 10 minutes before testing. Based on a preliminary test, the dynamic storage modulus of the specimen became stable after 10 minutes of conditioning at the test temperature, which indicated the 10 minutes condition time is sufficient for the relatively thin specimen strips to reach the stable test temperature. Throughout the test, a 0.07±0.4 pound (0.3±0.2 N) tension force was applied to the specimen to compensate for any thermal expansion.

Each creep test was 30 minutes in duration. The test specimen dimensions were entered into the DSR software and the shear stress was precisely controlled by the DSR software. The DSR machine recorded the radial displacement of one end of the strip in relation to the other end and automatically calculated the conversion of strain and compliance.

APPENDIX F

Early-Age Concrete Evaluation—University of Stuttgart

EARLY-AGE CONCRETE EVALUATION—UNIVERSITY OF STUTTGART

This section presents the test program conducted at the IWB laboratory of the University of Stuttgart to investigate the effect of early-age concrete on the short-term performance of three adhesive anchor systems.

Test Apparatus

This section describes the test apparatus used for early-age concrete evaluation used at the IWB laboratory of the University of Stuttgart.

Short-Term Anchor Pullout Test Apparatus

The testing apparatus for the short-term test (Figure 1) used a 3.5” diameter x 0.04” thick Teflon PTFE (Polytetrafluoroethylene) confining sheet with a 1” diameter hole in the middle placed under an 1.2” thick steel equilateral triangle (12” sides) confining plate. The confining plate had an insert with a 13/16” (20 mm) diameter hole to fit around the anchor. The confining sheet was used to correct for any surface irregularities in the concrete. A tripod was placed on the confining plate which supported a 22-kip hydraulic ram, bearing plate, 45-kip load cell, and a ball and socket hinge plate. The anchor was connected to a pulling assembly through a 0.55” (14 mm) hole and secured with two high-strength nuts. The pulling assembly was connected to a 5/8” (16 mm) diameter loading rod which passed though the ram, load cell, and ball and socket hinge above and was secured with a nut.

A separate rig (Figure 2) held an LVDT which was connected via a steel cable to a magnet placed on top of the anchor.

Figure 1: Short-term testing apparatus.

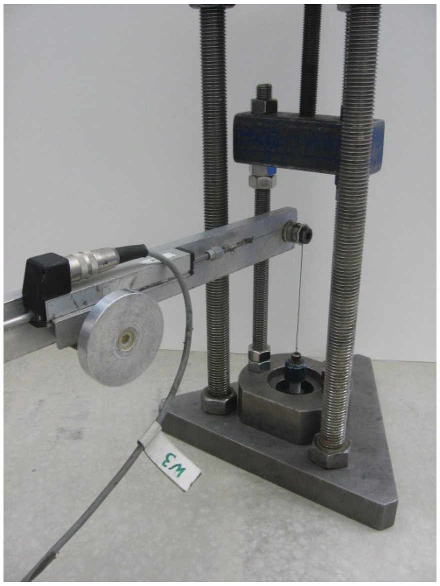


Figure 2: LVDT rig.

Initial Surface Absorption Test Apparatus

An initial surface absorption test (ISAT) apparatus (Figure 3) provided by IMPACT Test Equipment Ltd. was used to evaluate the initial absorption of the top formed surface of the concrete as well as the surfaces of the drilled hole. This apparatus consisted of a reservoir of water which maintained an 8" (200 mm) head above the surface of the concrete. The reservoir was attached to a 3.3" (85 mm) diameter clear cap secured to the surface of the concrete by a clamp and screws with plastic inserts. A small capillary tube was also connected to the cap in order to provide precise measurements of water flow at specific times.

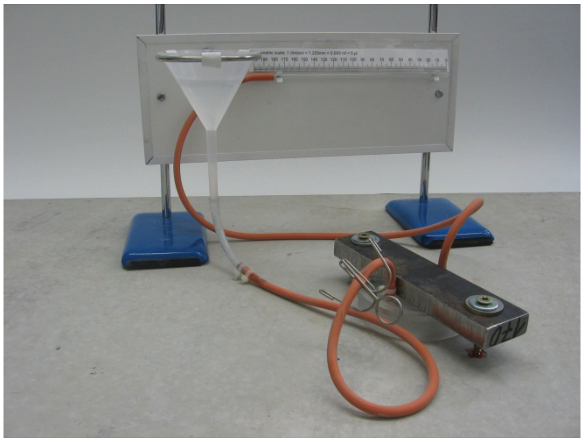


Figure 3: ISAT equipment.

Rebound Hammer

A rebound hammer by Suspa DSI GmbH (Figure 4) was used to measure the concrete hardness. This hammer would drive a weight into the surface of the concrete by means of a spring and record the rebound distance. A scale on the side of the hammer could be used to determine the “hardness” in terms of a 6” cube compressive strength.

Indention Hammer

An indention hammer (Figure 5) was also used to measure the concrete hardness. This hammer would drive a 0.4” (10 mm) diameter ball into the surface of the concrete by means of a spring. The average diameter of the indention would be measured and a graph could be consulted to determine the “hardness” in terms of a 6” cube compressive strength.

Figure 4: Rebound hammer.

Figure 5: Indention hammer.

Specimen preparation

The test specimens consisted of three parts; the concrete test member, the adhesive, and the anchor rod.

Concrete Test Member

The concrete test members for the early-age concrete investigation tests were poured in 50” x 50” x 16” high density overlay plywood forms. Minimal reinforcement of two 6 mm steel reinforcing bars were placed along the top and bottom edges for crack control. Two ¾” diameter by 9.5” long PVC pipes with PVDF filter covers were placed in one corner at 1.5” and 3” from the top test surface to allow for temperature and humidity sensors to be placed later. Four temperature and humidity sensors were cast into one slab but were destroyed during casting.

All the test blocks were cast on July 8, 2011 at the Friedrich Rau GmbH & Co precast concrete plant in Ebhausen, Germany. In order to provide a smooth testing surface the blocks were cast upside down against the high density overlay plywood.

Concrete with round river gravel without any admixtures was specified with a mean compressive strength between 3630–5080 psi during testing. The slump measured 1.5” and the casting temperature was 68°F (20°C). Both 4” x 8” cylinders and 6” cubes were cast.

On July 9, 2011, the day after casting, the forms were removed and the slabs were shipped to the IWB laboratory in Stuttgart, Germany on July 11, 2011, the third day after casting. The concrete test members were maintained in the IWB laboratory thereafter. The 4” x 8” cylinders and 6” cubes were delivered to the MPA laboratory at the University of Stuttgart for compression and split-tensile testing.

Concrete compressive strength was determined by testing both the 4” x 8” cylinders in general accordance with ASTM C39 and the 6” (15 cm) cubes in general accordance with DIN EN 12390-3. Split-tensile strength was determined by testing both the 4” x 8” cylinders in general accordance with ASTM C496 and the 6” cubes in general accordance with DIN EN 12390-6. The compression and split-tensile tests were conducted at the MPA testing laboratory at the University of Stuttgart on a Form+Test Prüfsysteme universal testing machine (Figure 6) calibrated by MPA in May 2011. The cylinders were ground smooth on a Form+Test Seidner cylinder grinding machine (Figure 7) prior to testing. Concrete compression and split-tensile versus age relationships were determined by testing at 4, 7, 14, 21, and 28 days.

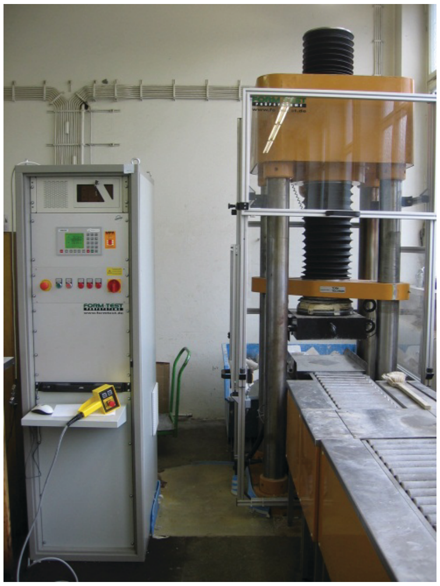


Figure 6: MPA universal testing machine.

Figure 7: MPA cylinder grinding machine.

Table 1 and Table 2 present the compression strength and split-tensile strength results respectfully for the 4” x 8” cylinders and 6” concrete cubes. Moist cured cubes typically test abou 15% stronger than moist cylinders [Mehta and Monteiro (2006)] due to more confinement based on their geometry. The cubes and cylinders in this test program tested from 30% to 40% higher than the cylinders. This can be explained by the fact that these specimens were all air cured and the different volume to surface area ratio of the two different specimens. Cubes have a larger volume to surface area and thus will dry more slowly than cylinders resulting in higher compressive strengths.

Table 1: Early-age concrete compression strength results.

Age (days)	**4” x 8” Cylinders (psi)**	**6” Cubes (psi)**	**Ratio Cubes/Cylinders**
4	2,080	2,790	1.34
7	2,350	3,280	1.40
14	2,850	3,860	1.35
21	3,040	4,090	1.35
28	3,250	4,230	1.30

Table 2: Early-age concrete split-tensile strength results.

Age (days)	4" x 8" Cylinders (psi)	6" Cubes (psi)	Ratio cubes/cylinders
4	200	260	1.30
7	250	270	1.08
14	270	330	1.22
21	290	300	1.03
28	270	290	1.07

Adhesive

The same three adhesives identified earlier were used in this portion of the project. The three adhesive products were stored in the IWB laboratory and maintained within the temperature and humidity range specified by the manufacturers prior to installation.

Anchor Rods

The anchor rods were 14.9 [203 ksi (1400 MPa) 90% yield strength] ½" (12 mm) diameter steel threaded rod fabricated by Hersteller. This grade of steel has a specified yield strength of 183 ksi and a specified tensile strength of 203 ksi. The anchor rods were cut to a length of 6.7" from 8" stock and the top end ground and chamfered with a bench grinder and steel brush to remove burrs and to clean up the threads in order to install the nuts. The bottom end of the anchor was ground to a 45° cone (Figure 8) in order to fit into a centering guide placed at the bottom of the drilled hole.

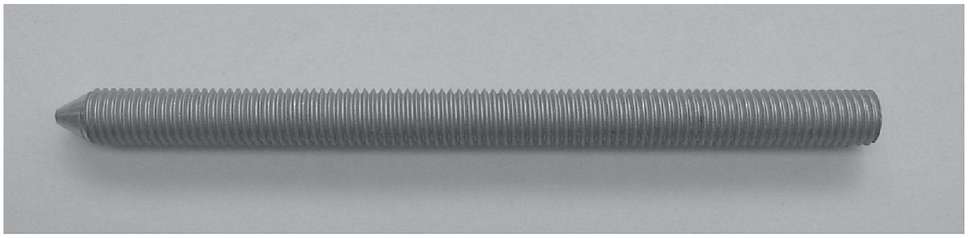


Figure 8: Anchor showing 45° cone to fit into centering guide.

Instrumentation

Measurement

Displacement. Direct measurement of the anchor displacement was measured by a Novotechnik LVDT. The LVDT was mounted in a separate rig and connected via a steel cable to a magnet placed on the top of the anchor (Figure 2).

Load. The tension in the anchor was measured indirectly as a compressive reaction of the hydraulic ram in the test apparatus. The load was measured by a Hottinger Baldwin Messtechnik 45-kip load cell. The load cell was excited and measured by the NI Diadem software.

Temperature and Relative Humidity. Internal temperature and relative humidity in each concrete test slab was measured by Sensiron SHT71 temperature and humidity sensors. Four sensors were cast within one control slab and two empty PVC pipes were cast into every test slab to allow for later insertion and removal of additional sensors if necessary.

The four Sensiron SHT71 sensors cast directly into the concrete slab were constructed similar to those as discussed by Rodden (2006). Each sensor was placed in a 4” long ¾” diameter PVC pipe. One end was covered with a Polyvinyldenfluorid (PVDF) filter by Thomapor with 0.2μm openings. The other end was packed with foam insulation and a PVDE disk to provide a backing for a silicon seal. The entire assembly (Figure 9) was later wrapped with duct tape for extra protection. The pipes were tied to rebar and the centerlines were placed 1.5” and 3” below the top of the testing surface, 2-¼” from each other, with the center of the entire assembly 8” from the corner (Figure 10).

Two 9.5” long by ¾” diameter PVC tubes with same PVDF filter on one end and covered with duct tape were cast in each test slab. The pipes were attached to a plastic plate with holes taped over and connected to the side of the form. The pipes were tied to rebar and the centerlines were placed at 1.5” and 3” below the top of the testing surface and 9.5” and 10.5” from the corner of the slab (Figure 10). The Sensiron SHT71 sensors were inserted into the test slab after casting and several days prior to testing and packed with foam insulation and sealed with duct tape.

The sensors were monitored by the Sensiron EK-H4 evaluation kit and recorded to a text file.

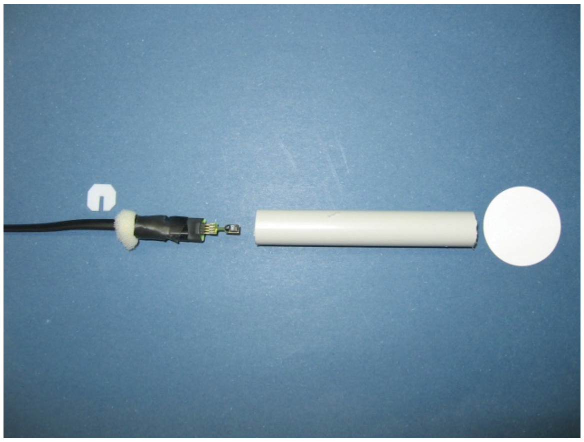


Figure 9: Sensiron sensor assembly.

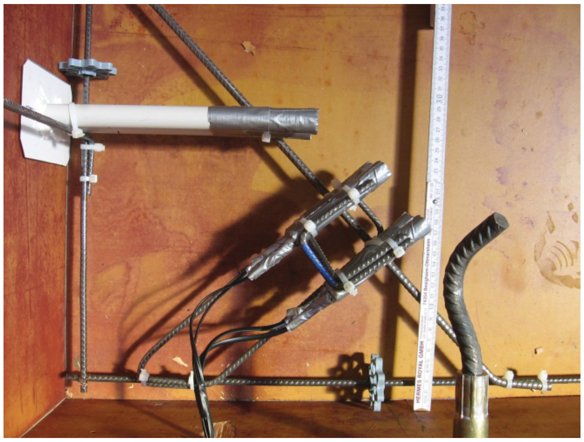


Figure 10: PVC pipes and Sensiron sensors placed in forms prior to casting.

Ambient temperature and relative humidity of the laboratory were monitored and recorded by a Lufft Opusio sensor at 10 minute intervals.

Time. Time was measured using the computer's internal clock.

Instrument Calibration

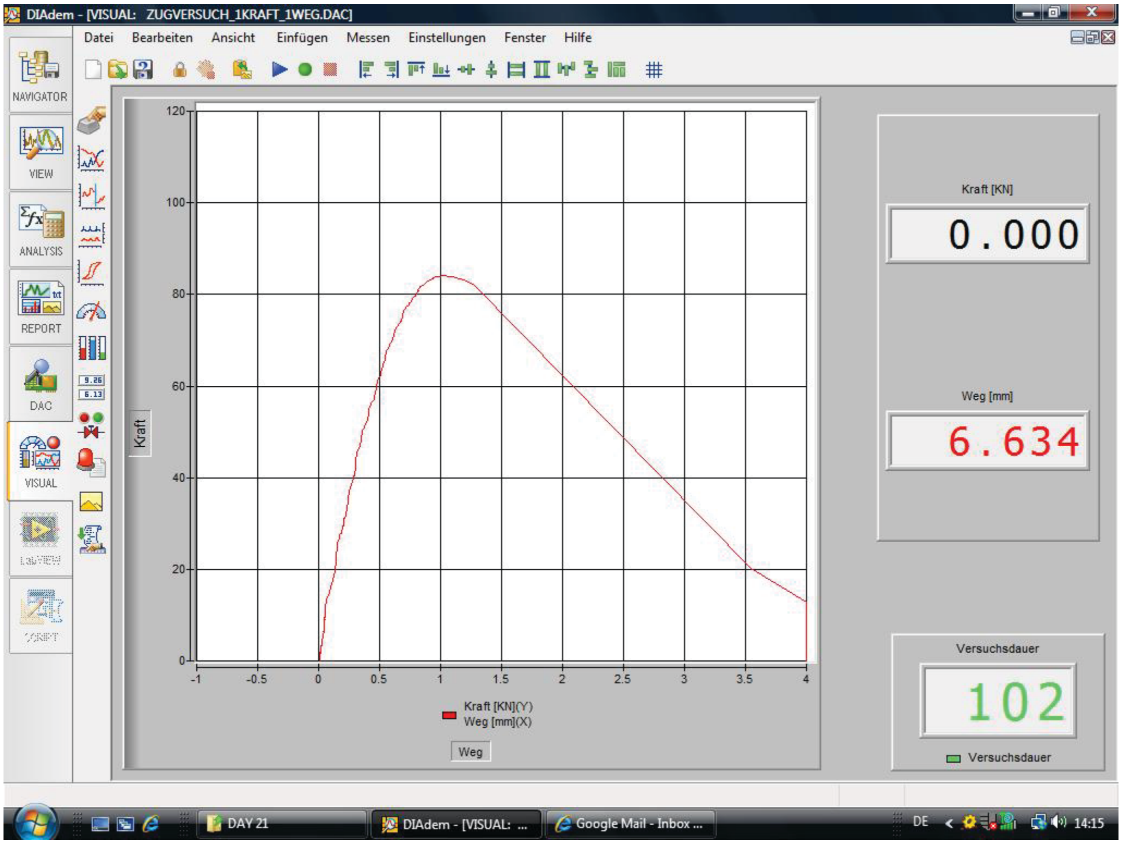
Displacement. The LVDTs were calibrated by IWB every 3 months against calibrated ceramic gages over their working range of 10 mm at 2 mm increments.

Load. The Hottinger Baldwin Messtechnik 45-kip load cell was calibrated on December 11, 2009, by MPA. The load cell was calibrated over a range of 0 to 45 kips with data points every 4.5 kips.

Temperature and Humidity. The Sensiron SHT71 temperature and humidity sensors were calibrated by the factory. The Lufft Opusio ambient temperature and humidity sensor was calibrated by IWB on January 22, 2010 against a TESTO calibrated temperature gage.

Data management and acquisition

An NI Diadem 10.2 program (Figure 11) was used for the short-term tests in one of five test cabinets, which included a computer, data acquisition hardware, and two hydraulic pumps. Load and displacement were recorded at 0.2 second intervals and a load versus displacement curve was displayed on the screen for real-time feedback. Load was applied by a hydraulic pump and controlled by valves integral with the test cabinet. The latest data readings were displayed on the screen and the data was recorded to a Microsoft Excel spreadsheet following the test.



Kraft [KN] 0.000

Weg [mm] 6.634

Versuchsdauer 102

🟩 Versuchsdauer

Figure 11: Screenshot of NI Diadem 10.2 data acquisition program.

Installation procedure

The installation procedure generally followed the procedure described in the section "Anchor Pullout Tests—University of Stuttgart" except the anchors were allowed to cure for 24 hours prior to testing.

Testing procedure

Short-Term Test Procedure

A 0.04" thick PTFE confining sheet and 1.2" thick steel confining plate with 13/16" (20 mm) diameter hole insert were placed over the anchor and the pulling assembly was attached to the anchor. A 3/16" gap was left between the confining plate and the pulling assembly to allow for rotation of the coupler in order to prevent bending forces from being transferred between the anchor and the loading rod. The short-term test apparatus was placed over the anchor as discussed earlier.

The Lukas Hydraulik GmbH 22-kip hydraulic ram was placed on the tripod and connected to the test cabinet hydraulic pump. The loading rod was then connected to the coupler. The Hottinger Baldwin Messtechnik 45-kip load cell was placed on top of a loading plate on top of the ram. A ball and socket hinge was placed on top of the load cell and the loading rod nut was hand tightened to remove slack in the system. A magnet was placed on top of the anchor and connected to a Novotechnik LVDT mounted in a separate rig via a cable

The load and displacement values were the zeroed in the NI Diadem 10.2 program.

The test was started and load rate was controlled by the operator to achieve a failure in one to three minutes.

Initial Surface Absorption Test Procedure

Initial surface absorption was measured in general accordance with BS 1881 using an ISAT apparatus provided by IMPACT Test Equipment Ltd. A 3.3" (85 mm) diameter plastic cap was clamped to the top surface of the concrete with a steel bar using screws and plastic inserts. This cap was connected via rubber tubes to a reservoir of water and a capillary tube. The reservoir maintained an 8" (200 mm) head of water during the duration of the test. At 10 minutes, 30 minutes, and 60 minutes the tube connecting the reservoir to the cap was clamped allowing water to flow into the cap from a capillary tube. A scale created from the calibration procedure in BS 1881 was used to determine the amount of water entering the cap over a 1 minute period. Three repetitions of were conducted on the top formed surface of the concrete test block.

A modified ISAT was developed to determine the initial surface absorption of the sides and bottom of a hole drilled in concrete. Three 0.55" (14 mm) diameter by 4.5" (115 mm) deep holes were drilled and cleaned according to the cleaning procedure for adhesive A. The 3.3" (85mm) diameter cap was clamped over a hole and the same procedures for the above-described ISAT were performed. The initial surface absorption of the sides and bottom of the drilled hole were determined by removing the influence of the top formed surface of the concrete specimen based on the tests performed on the top surface only.

An allowance was made for the chipped area around the top of the hole (Figure 12) as this surface would be more similar to the side of the hole than to the top formed surface. The diameter of the chipped area was measured in four directions (Figure 13) and their results averaged to determine an equivalent circular area.

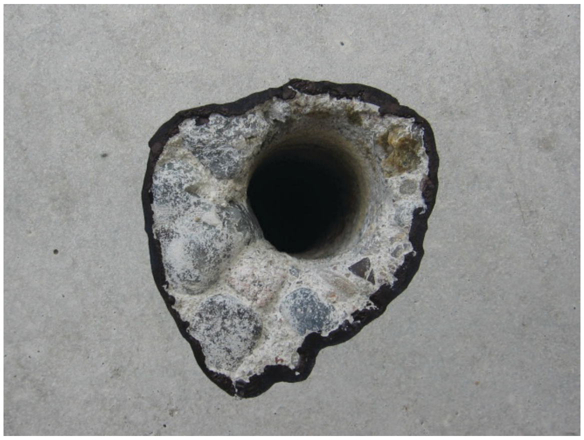


Figure 12: Chipped area around top of hole.

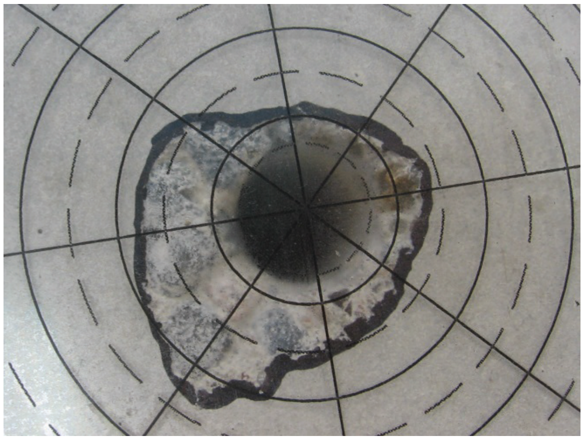


Figure 13: Jig to measure the diameter of the chipped area in four directions.

The initial surface absorption is defined as "the rate of flow of water into concrete per unit area at a stated interval from the start of the test and at a constant applied head" (BS 1881). BS 1881 presents the standard initial surface absorption test (ISAT). The ISAT is intended to be used on a flat surface of concrete. Below is the rationale behind the development of a modified ISAT of bore holes for adhesive anchor testing.

In general, the initial surface absorption can be calculated as:

$$I = \frac{V}{A \cdot t} \qquad \textit{Eqn. 1}$$

where:

- I = initial surface absorption [ml/m^2·s],
- V = volume of water measured in the capillary [ml],
- A = surface area through which water is passing [m^2], and
- t = measured time interval (60 seconds) [s].

For the standard ISAT on the top formed surface of concrete the equation can be written as:

$$I_1 = \frac{V_1}{A_1 \cdot t} \qquad \textit{Eqn. 2}$$

where:

- I_1 = initial surface absorption of the top formed surface [ml/m^2·s],
- V_1 = volume of water measured in the capillary [ml],
- A_1 = surface area of the reservoir [m^2], and
- t = measured time interval (60 seconds) [s].

For adhesive anchor applications it is desirable to determine the initial surface absorption of the surfaces of the drilled hole. In order to determine this, the ISAT reservoir was placed over a hole drilled in concrete and the initial surface absorption of the water passing through the combined surface area of the top formed surface and the surfaces of the drilled hole is defined as:

$$I_2 = \frac{V_2}{A_2 \cdot t} \qquad \textit{Eqn. 3}$$

where:

- I_2 = initial surface absorption of the top formed surface and hole combined [ml/m^2·s],
- V_2 = volume of water measured in the capillary [ml],
- A_2 = surface area of the top formed surface and the hole combined [m^2], and
- t = measured time interval (60 seconds) [s].

During drilling it is common that the top surface of the concrete chip or spall around the edge of the hole. For this reason it is desirable to divide the total surface area (A_2) into distinct areas (Figure 14):

$$A_2 = A_S + A_C + A_H \qquad \textit{Eqn. 4}$$

where:

- A_S = area of the unchipped top formed surface,
- A_C = chipped area of the spalled top surface around the hole due to drilling, and
- A_H = area if the sides and bottom of the drilled hole.

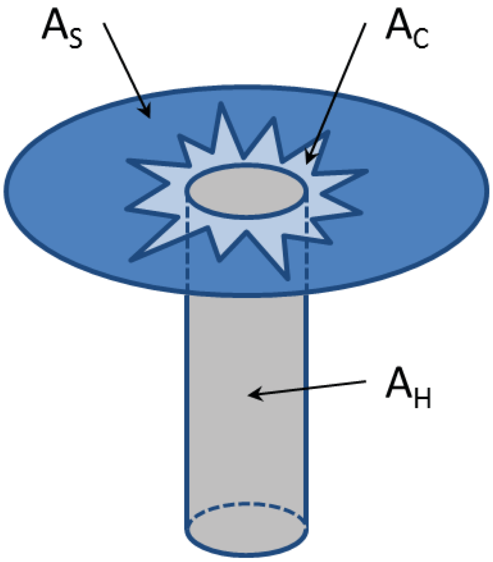


Figure 14: A_2 sub-areas.

It is reasonable that the initial surface absorption of the surfaces of the drilled hole (A_H) is different than that of the top formed surface (A_S). Furthermore, it was assumed that the chipped area (A_C) is more similar to that of the sides and bottom of the drilled hole (A_H) than to the top surface of the concrete (A_S). Therefore the areas A_C and A_H can be combined into another area (A_{CH}) where:

$$A_{CH} = A_C + A_H \qquad \textit{Eqn. 5}$$

where:

- A_{CH} = area of the chipped surface and drilled hole.

This combined area (A_{CH}) will have a distinct initial surface absorption (I_{CH}) different than that of the top surface of the concrete (I_S). It is also reasonable then to assume that the initial surface absorption (I_1) is the same as the initial surface absorption of the unchipped top surface portion (I_S), or,

$$I_1 = I_S \qquad \textit{Eqn. 6}$$

Substituting Eqn. 2 and Eqn. 3 into Eqn. 6,

$$\frac{V_1}{A_1 \cdot t} = \frac{V_S}{A_S \cdot t} \qquad \textit{Eqn. 7}$$

Solving for V_S,

$$V_S = \left[\frac{A_S}{A_1}\right] V_1 \qquad \textit{Eqn. 8}$$

It is obvious that the total volume of water (V_2) is the sum of the volume of water passing through the distinct parts of the wetted surface, or,

$$V_2 = V_S + V_C + V_H \qquad \textit{Eqn. 9}$$

where:

- V_S = volume of water passing through the unchipped top formed surface,
- V_C = volume of water passing through the chipped area of the spalled top surface around the hole, and
- V_H = volume of water passing through the area if the sides and bottom of the drilled hole.

Combining V_C and V_H,

$$V_2 = V_S + V_{CH} \qquad \textit{Eqn. 10}$$

where:

- V_{CH} = volume of water passing through the area of the chipped surface and drilled hole.

Substituting Eqn. 8 into Eqn. 10,

$$V_2 = \left[\frac{A_S}{A_1}\right] V_1 + V_{CH} \qquad \textit{Eqn. 11}$$

Rearranging,

$$V_{CH} = V_2 - \left[\frac{A_S}{A_1}\right] V_1 \qquad \textit{Eqn. 12}$$

Referring to Eqn. 1, the initial surface absorption of the chipped are and the hole can be written as,

$$I_{CH} = \frac{V_{CH}}{A_{CH} \cdot t} \qquad \textit{Eqn. 13}$$

Substituting Eqn. 12 and Eqn. 5 into Eqn. 13, the initial surface absorption of the surface of the drilled hole plus the chipped area around the edge of the hole can be defined as:

$$I_{CH} = \frac{V_2 - \left[\frac{A_S}{A_1}\right] V_1}{[A_C + A_H] \cdot t} \qquad \text{Eqn. 14}$$

Rebound Hammer Test Procedure

Concrete hardness was measured with a rebound hammer in general accordance with ASTM C805 using a Suspa DSI GmbH Original Schmidt hammer. The hammer was used in the vertically downward position in the general location of the installed anchors. These tests were conducted after the anchor pullout tests in case the hammer caused cracking in the early-age concrete. The average of ten readings was reported and a 6” cube concrete compressive strength was estimated using a scale provided by the manufacturer.

Indention Hammer Test Procedure

Concrete hardness was also measured with an indention hammer in general accordance with DIN 4240. The hammer was used in the vertically downward position on the full load setting in the general location of the installed anchors. These tests were conducted after the anchor pullout tests in case the hammer caused cracking in the early-age concrete. As allowed by the test standard, carbon paper was used to better distinguish the indention. Two orthogonal diameters were measured of each indention and their values averaged. The average of twenty readings was reported and a 6” cube concrete compressive strength was estimated using a scale provided by the manufacturer.

APPENDIXES G–M

Appendixes G–M are not printed herein but are available on the NCHRP Project 04-37 web page at http://apps.trb.org/cmsfeed/trbnetprojectdisplay.asp?projectid=2495. The appendices are titled as follows:

APPENDIX G: Concrete Mix Designs
APPENDIX H: Adhesive Anchor Post-Test Split-Core Investigations
APPENDIX I: Short-Term Test Results
APPENDIX J: Time to Rupture versus Time to Tertiary Creep Comparison
APPENDIX K: Sustained Load Creep Test Results
APPENDIX L: Stress versus Time-to-Failure Plots
APPENDIX M: Early-Age Concrete Investigation Short-Term Test Results

APPENDIX N

AASHTO Standards and Specifications Flowchart

NCHRP 04-37	AASHTO ADHESIVE ANCHOR FLOWCHART – INTRODUCTION AND LEGEND	PAGE 1/4

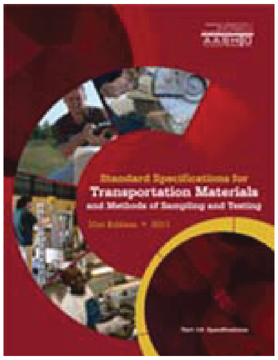
FLOWCHART OVERVIEW

The following pages present the proposed process for an adhesive anchor system to become approved for use by AASHTO through testing via ACI 355.4 and possible additional AASHTO SvTTF tests, effectively designed using the proposed AASHTO design provisions or ACI 318-1 Appendix D, installed per the proposed AASHTO construction specifications and ACI 355.4 requirements, and inspected.

Below is a schematic of the overall process with page references to more detailed flowchart diagrams.


START
TESTING (page 2)
DESIGN (page 3)
CONSTRUCTION & INSPECTION (page 4)
FINISH

LEGEND OF STANDARDS AND SPECIFCATIONS USED IN FLOWCHARTS



AASHTO Standard Specifications for Transportation Materials & Methods of Sampling and Testing


ICC EVALUATION SERVICE

ACCEPTANCE CRITERIA FOR POST-INSTALLED ADHESIVE ANCHORS IN CONCRETE ELEMENTS

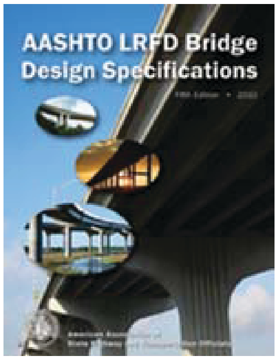
AC308

Approved June 2011

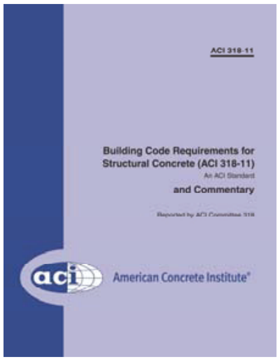
Previously approved November 2009, June 2009, October 2008, August 2008, May 2008, February 2008, January 2008, October 2007, June 2007, February 2007, June 2006

PREFACE

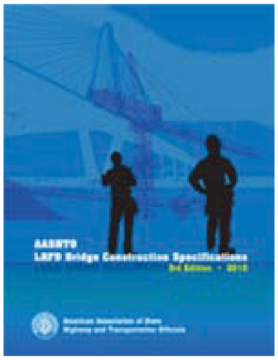
ICC-ES AC308 testing criteria



AASHTO LRFD Bridge Design Specifications

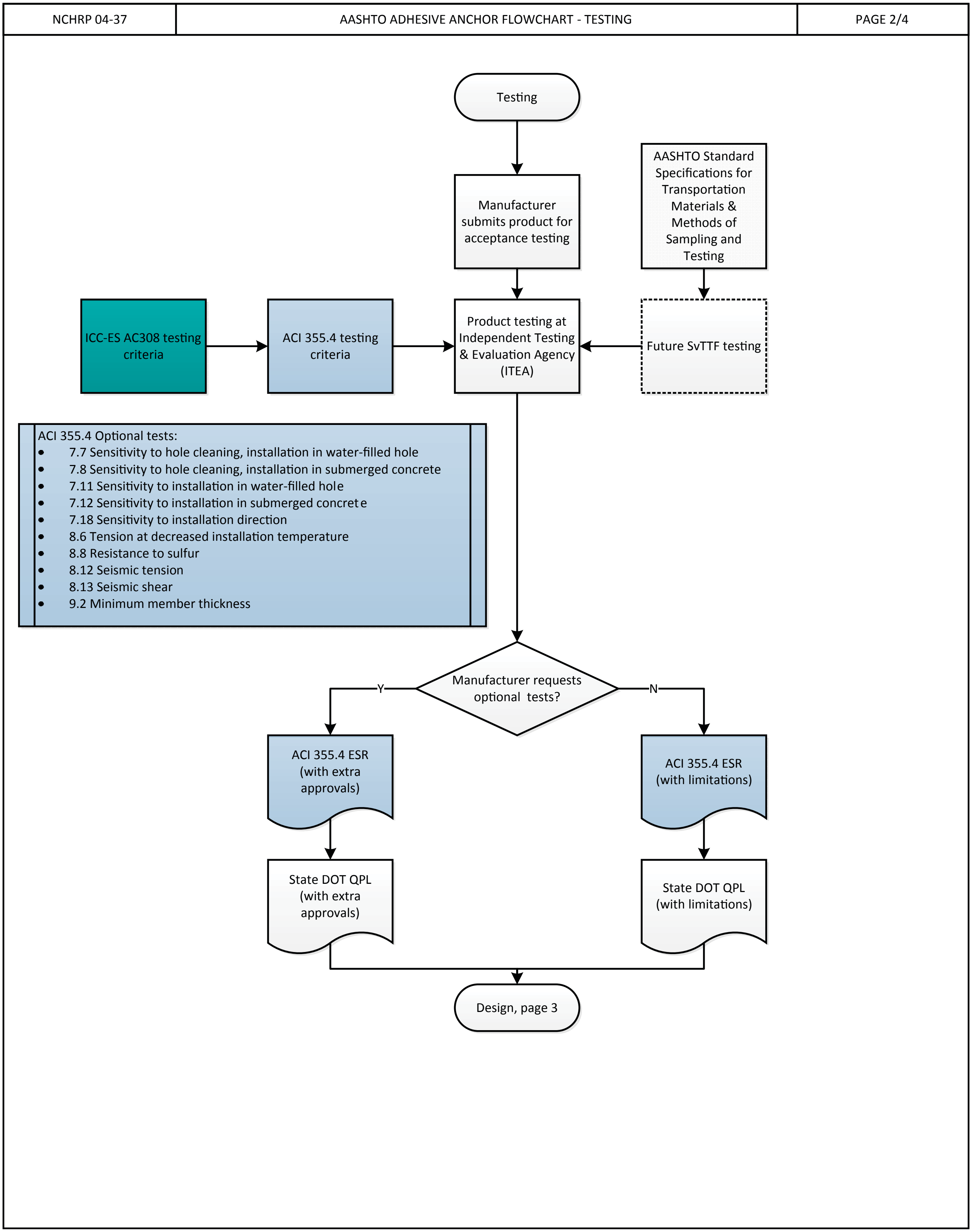


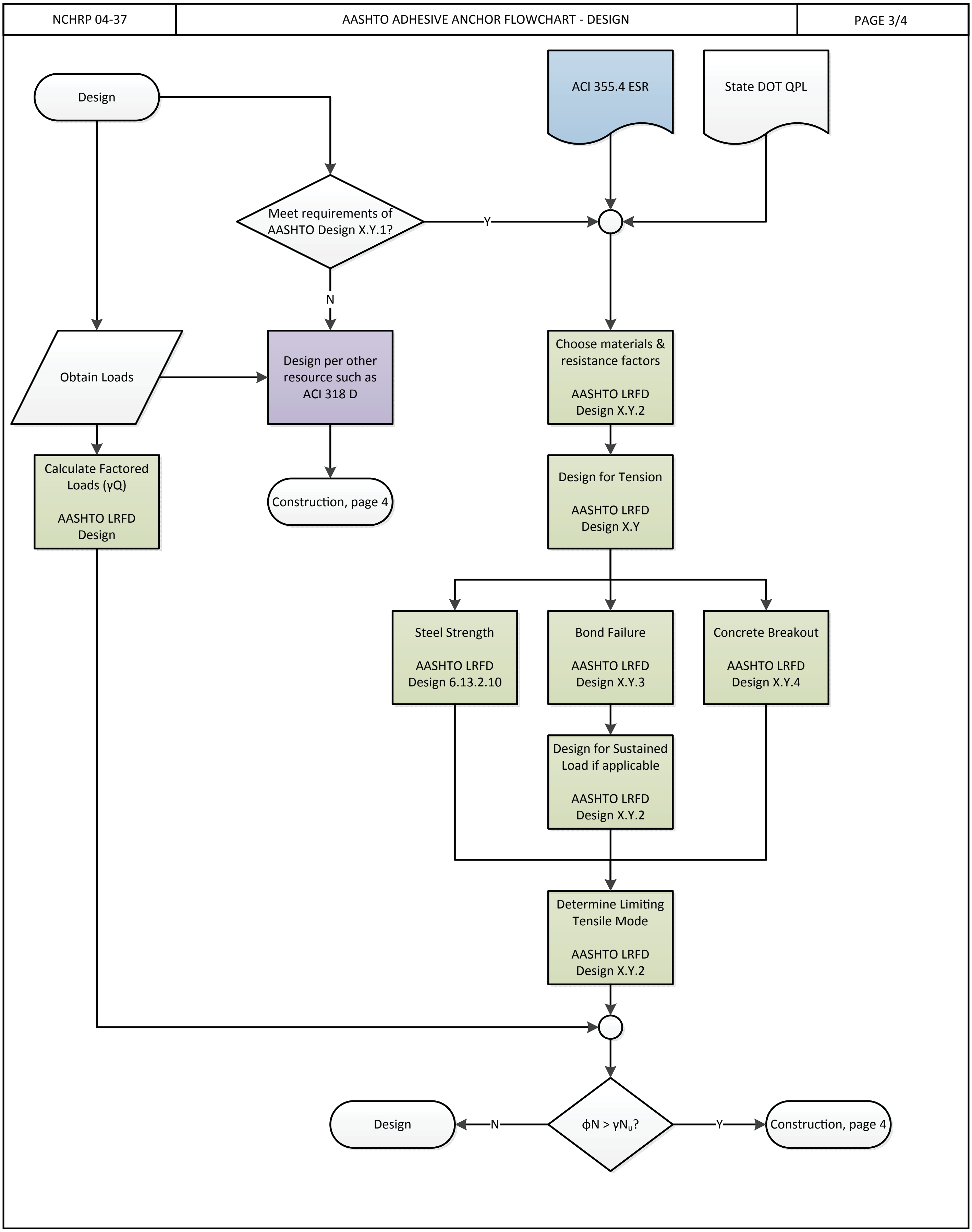
318-11 Building Code Requirements for Structural Concrete

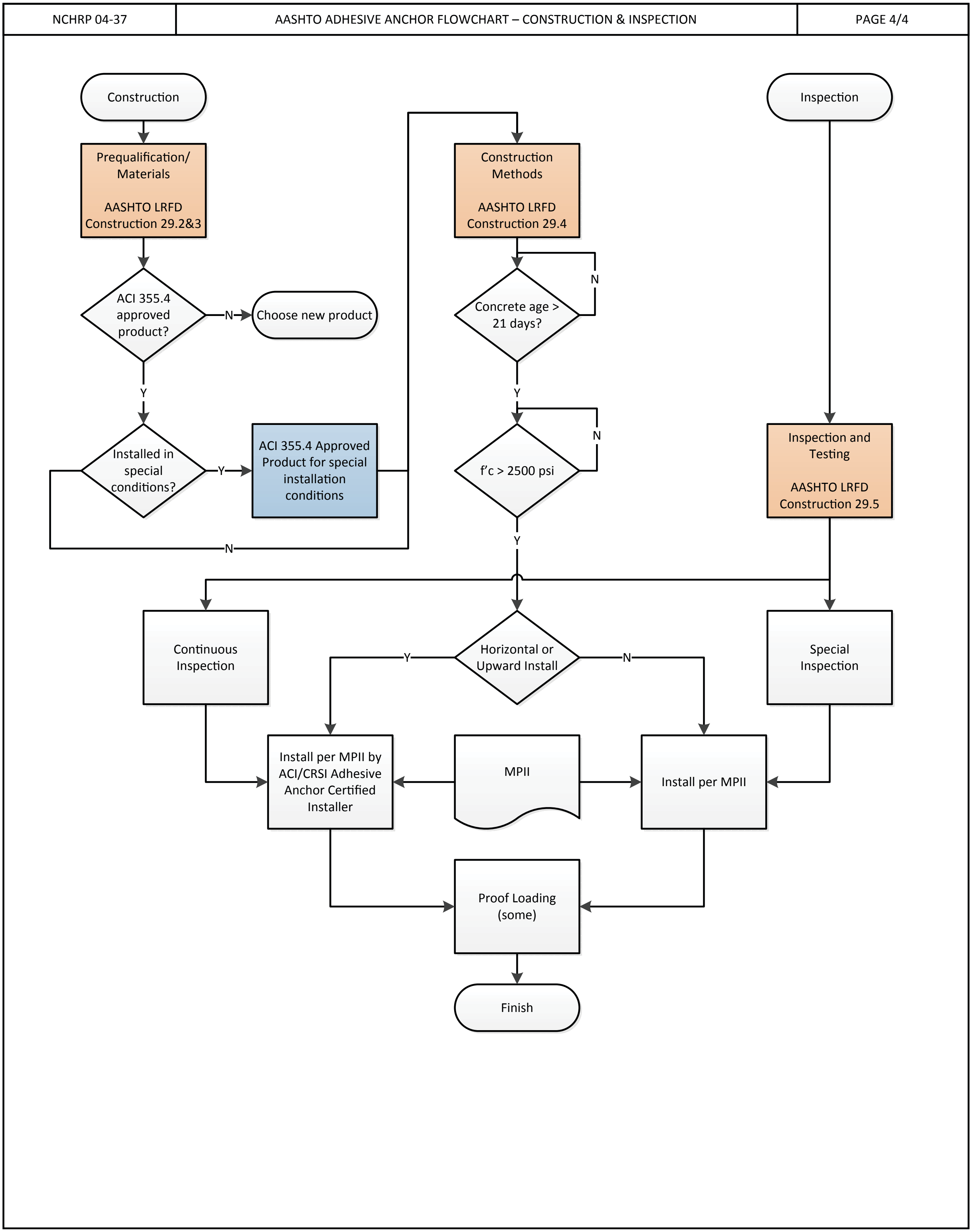


AASHTO LRFD Bridge Construction Specifications

ACI 355.4 qualification procedure


NCHRP 04-37
AASHTO ADHESIVE ANCHOR FLOWCHART - TESTING
PAGE 2/4
Testing
Manufacturer submits product for acceptance testing
AASHTO Standard Specifications for Transportation Materials & Methods of Sampling and Testing
ICC-ES AC308 testing criteria
ACI 355.4 testing criteria
Product testing at Independent Testing & Evaluation Agency (ITEA)
Future SvTTF testing
ACI 355.4 Optional tests:
- 7.7 Sensitivity to hole cleaning, installation in water-filled hole
- 7.8 Sensitivity to hole cleaning, installation in submerged concrete
- 7.11 Sensitivity to installation in water-filled hole
- 7.12 Sensitivity to installation in submerged concrete
- 7.18 Sensitivity to installation direction
- 8.6 Tension at decreased installation temperature
- 8.8 Resistance to sulfur
- 8.12 Seismic tension
- 8.13 Seismic shear
- 9.2 Minimum member thickness
Manufacturer requests optional tests?
Y
N
ACI 355.4 ESR (with extra approvals)
ACI 355.4 ESR (with limitations)
State DOT QPL (with extra approvals)
State DOT QPL (with limitations)
Design, page 3


NCHRP 04-37
AASHTO ADHESIVE ANCHOR FLOWCHART - DESIGN
PAGE 3/4
Design
ACI 355.4 ESR
State DOT QPL
Meet requirements of AASHTO Design X.Y.1?
Y
N
Obtain Loads
Design per other resource such as ACI 318 D
Choose materials & resistance factors AASHTO LRFD Design X.Y.2
Calculate Factored Loads (γQ) AASHTO LRFD Design
Construction, page 4
Design for Tension AASHTO LRFD Design X.Y
Steel Strength AASHTO LRFD Design 6.13.2.10
Bond Failure AASHTO LRFD Design X.Y.3
Concrete Breakout AASHTO LRFD Design X.Y.4
Design for Sustained Load if applicable AASHTO LRFD Design X.Y.2
Determine Limiting Tensile Mode AASHTO LRFD Design X.Y.2
Design
N
$\phi N > \gamma N_u$?
Y
Construction, page 4


NCHRP 04-37
AASHTO ADHESIVE ANCHOR FLOWCHART – CONSTRUCTION & INSPECTION
PAGE 4/4
Construction
Prequalification/ Materials
AASHTO LRFD Construction 29.2&3
ACI 355.4 approved product?
N
Choose new product
Y
Installed in special conditions?
Y
ACI 355.4 Approved Product for special installation conditions
N
Construction Methods
AASHTO LRFD Construction 29.4
Concrete age > 21 days?
N
Y
f’c > 2500 psi
N
Y
Inspection
Inspection and Testing
AASHTO LRFD Construction 29.5
Continuous Inspection
Horizontal or Upward Install
Y
N
Special Inspection
Install per MPII by ACI/CRSI Adhesive Anchor Certified Installer
MPII
Install per MPII
Proof Loading (some)
Finish

APPENDIX O

AASHTO Test Method

Standard Method of Test for

Adhesive Anchors in Concrete

AASHTO Designation: T XXXX-XX

Prior to possible addition of SvTTF:

Refer to ACI 355.4-11 for testing of adhesive anchors in concrete with the following exceptions:

- ACI 355.4 §8.5.2.3 shall read as follows:

  Qualify anchors for one or both of the temperature categories given in Table 8.1. The minimum long-term temperature for which anchors shall be qualified is 110°F. The minimum short-term temperature for which anchors shall be qualified is 176°F. Install and test a minimum of five anchors at each temperature data point. For Temperature Category A, perform tests at standard temperature and at the short- and long-term temperatures. For Temperature Category B, perform tests on anchors at standard temperature, at the long-term and short-term test temperatures and a minimum of two intermediate temperatures between the long-term and short-term temperatures with a maximum increment of 35°F. If the zdifference between the long- and short-term test temperatures is less than 35°F, then testing at intermediate temperatures is not required.

- In ACI 355.4 §10.4.5.1 the definition of α_{setup} shall be:
  - α_{setup} = 1.0 if service condition tests are performed as unconfined tests, or determined from a series of five unconfined (per Table 3.2 test 11b) and five confined tests (per table 3.2 test 1c) if tests are performed as confined tests.

- ACI 355.4 §7.9 shall read as follows:

7.9—Sensitivity to mixing effort (Table 3.1, Test 2e; Table 3.2, Test 2e; and Table 3.3, Test 2e)

R7.9 *For adhesive anchor systems that do not use automatic metering and mixing systems, and for automatic mixing systems that do not provide information in the MPII regarding delays in the automatic mixing process it is necessary to check the sensitivity of the system to sub-optimal mixing of the adhesive components.*

7.9.1 *Purpose*—These reliability tests are used to assess the sensitivity of the adhesive material to mixing effort. These tests are required only for those anchor systems where the mixing of the adhesive material is substantially controlled by the installer or where MCII instructions are not provided to address delays in the automatic mixing process. Such cases include systems that require:

a) Components to be mixed until a color change is effected throughout the adhesive material;
b) The adhesive materials to be mixed with recommended equipment for a specific duration;
c) That the adhesive materials be mixed with a repetitive mixing operation a specific number of times; and

d) Continuous mixing in a nozzle but do not provide information in the MPII that addresses delays in the automatic mixing process that might occur during anchor installation (e.g., setting the injection system aside while an anchor is installed and then reinitiating adhesive injection some minutes later).

7.9.1.1 These tests are not required for capsule anchor systems or cartridge or bulk systems that employ automatic metering and mixing through a manifold and disposable mixing nozzle unless the MPII does not provide instructions regarding delays in the automatic mixing process.
7.9.2 *General test conditions*—Perform confined tension tests in uncracked concrete.
7.9.3 Conduct tests as required to establish the required time for full mixing using standard mixing equipment. Reduced mixing effort shall be achieved by decreasing the mixing time required for full mixing by 25%. For automatic mixing systems that do not provide MPII instructions on delays in the automatic mixing process, discard adhesive from the nozzle then pause the injection of the adhesive for 3/4 of the recommended working time of the adhesive and then inject into the hole. Repeat this process for all replicates. Load the anchors to failure with continuous measurement of load and displacement.

With addition of SvTTF:

Conduct sustained load testing in accordance with AASHTO TP 84-10 with the following exceptions:

- Modify section 9.4.2 as follows:
    - 9.4.2 Test Series – Conduct a minimum of three series of sustained load (creep) tests at three stress levels (PL1, PL2, and PL3) based on the mean static load from the static load test.
    - 9.4.2.1 Percent load level range 1 (PL1) is suggested to be at 70 percent of mean static load.
    - 9.4.2.2 Percent load level range 2 (PL2) is suggested to be at 60 percent of mean static load.
    - 9.4.2.3 Percent load level range 3 (PL3) is suggested to be at 50 percent of mean static load.
- Modify section 10 as follows:
    - 10.6 Plot the normalized values from the sustained load (creep) tests on a Stress versus Time-to-Failure graph.
    - 10.7 Extend a trendline through the nine points plotted.
- If a long-term (creep) test has not failed within 1000 hours, the following options are permitted:
    - Continue the test until failure or
    - Terminate at a test duration specified by the manufacturer
- If the test is terminated, denote test as terminated and plot the sample on the SvTTF curve at the larger of the following:
    - Current test duration
    - Projected time to reach the average displacement of the short-term tests

APPENDIX P

AASHTO Material Specification

Standard Specification for

Adhesive Anchors in Concrete

AASHTO Designation: M XXXX-XX

Prior to possible addition of SvTTF:

Refer to ACI 355.4-11 for material specifications of adhesive anchors in concrete.

With addition of SvTTF:

Refer to ACI 355.4-11 for material specifications of adhesive anchors in concrete.

Ψ_{sus} for use in AASHTO 2010 LRFD Bridge Design Specifications is determined from the Stress versus Time to Failure curve generated in AASHTO TP 84-10 evaluated at 876,000 hours (100 years).

The percent stress level at 876,000 hours (100 years) on the Stress versus Time to Failure curve generated in AASHTO TP 84-10 must be greater than 50%. If not, the product is not acceptable for sustained load applications.

APPENDIX Q

AASHTO Design Specification

AASHTO 2010 LRFD BRIDGE DESIGN SPECIFICATIONS
SECTION XXXX

ADHESIVE ANCHORS

X.Y-ADHESIVE ANCHORS

X.Y.1-Definitions

Adhesive - Chemical components formulated from organic polymers, or a combination of organic polymers and inorganic materials that cure when blended together.

Adhesive anchor - A post-installed anchor, inserted into hardened concrete with an anchor hole diameter not greater than 1.5 times the anchor diameter, that transfers loads to the concrete by bond between the anchor and the adhesive, and bond between the adhesive and the concrete.

Anchor - A steel element post-installed into a hardened concrete member and used to transmit applied loads to the concrete. Steel elements for adhesive anchors include threaded rods, deformed reinforcing bars, or internally threaded steel sleeves with external deformations.

Anchor group - A number of similar anchors having approximately equal effective embedment depths with spacing ***s*** between adjacent anchors such that the protected areas overlap.

Edge distance - The distance from the edge of the concrete surface to the center of the nearest anchor.

Effective depth of embedment - The overall depth through which the anchor transfers force to or from the surrounding concrete. The effective embedment depth will normally be the depth of the concrete failure surface in tension applications.

Manufacturer Printed Installation Instructions (MPII) - Published instructions for the correct installation of the anchor under all covered installation conditions as supplied in the product packaging.

X.Y.2-Notations

A_{Na} = projected influence area of a single adhesive anchor or group of adhesive anchors based on actual edge distances and anchor spacing (in.^{2}) (X.Y.5.1)

A_{Nao} = projected influence area of a single adhesive anchor or group of adhesive anchors with an edge distance greater than or equal to c_{Na} (in.^{2}) (X.Y.5.1)

A_{Nc} = projected influence area of a single adhesive anchor or group of adhesive anchors based on actual edge distances and anchor spacing (X.Y.6.1)

A_{Naco} = projected influence area of a single adhesive anchor or group of adhesive anchors with an edge distance greater than or equal to c_{Nc} (X.Y.6.1)

c = edge distance from the center of the anchor to the nearest edge of concrete (X.Y.3)

$c_{a,max}$ = largest of the edge distances that are less than $1.5h_{ef}$ (in.) (X.Y.6.2)

c_{min} = distance from the center of an anchor to the closest edge of the concrete (in.) (X.Y.5.4)

c_{Na} = projected distance from the center of an anchor required to develop the full bond strength (in.) (X.Y.5.4)

c_{Nc} = projected distance from the center of an anchor for a concrete failure prism with an assumed angle of 35° (X.Y.6.4)

d_a = outside diameter of anchor (in.) (X.Y.5.2)

h_{ef} = effective embedment depth of anchor (in.) (X.Y.5.2)

N_a = basic bond strength of a single adhesive anchor in tension in cracked concrete (X.Y.5.1)

N_c = basic concrete breakout strength of a single adhesive anchor in tension in cracked concrete (X.Y.6.1)

N_n = nominal resistance of an adhesive anchor bolt or group of anchors (X.Y.4)

N_r = factored resistance of an adhesive anchor bolt or group of anchors (X.Y.4)

s_{max} = maximum spacing between anchors within a group (in.) (X.Y.6.2)

τ_{cr} = characteristic bond stress of adhesive anchor in cracked concrete (ksi) (X.Y.5.2)

$\tau_{cr,min}$ = minimum characteristic bond stress (ksi) (X.Y.5.2)

φ = resistance factor for anchor bolts (X.Y.4)

φ_a = resistance factor for anchor bolts for adhesive bond and concrete breakout (X.Y.4)

φ_t = resistance factor for anchor bolts for tensile failure (X.Y.4)

$\Psi_{ed,Na}$ = modification factor for edges effects beyond what is accounted for by the ratio $\frac{A_{Na}}{A_{Na0}}$ (X.Y.5.1)

$\Psi_{ed,Nc}$ = modification factor for edges effects beyond what is accounted for by the ratio $\frac{A_{Nc}}{A_{Nc0}}$ (X.Y.6.1)

ψ_{sus} = resistance factor for sustained load (X.Y.4)

X.Y.3-General Conditions

Adhesive anchors designed under this specification shall meet the following criteria:

- Products shall be qualified for use in cracked concrete in accordance with ACI 355.4.
- The effective depth of embedment, h_{ef}, must not be less than $4d_a$, 1-5/8”, or the minimum stated in the Manufacturer’s Printed Installation Instructions (MPII).
- The effective depth of embedment, h_{ef}, must be less than or equal to $20d_a$ or the maximum stated in the MPII, whichever is less.
- Edge distance, c, from the center of the anchor to the nearest edge of concrete must not be less than the larger of $6d_a$ or the minimum stated in the MPII.
- Anchors must be installed in holes drilled with a manufacturer’s approved rotary impact drill or rock drill unless otherwise permitted by MPII.
- Concrete must be normal weight concrete as defined in Article 5.2.
- The concrete member is considered cracked with normal temperature and shrinkage cracks and with minimum reinforcement.
- The concrete at time of installation shall have a minimum temperature of 50°F or that stated in the

CX.Y.3

ACI 355.4 contains the testing and evaluation requirements for adhesive anchor systems for use in concrete. ACI 355.4 was created from the product approval standards originally contained within ICC-ES AC58 and later in ICC-ES AC308.

The limitation on the minimum and maximum effective embedment depth is included due to the limitation of the uniform bond stress model.

Adhesive anchors gain their bond strength in part due to mechanical interlock with the sides of the hole. Rotary impact drills or rock drills create relatively rough sided holes as opposed to holes created with diamond core drills. NCHRP Project 04-37 report indicates that bond strengths of adhesive anchors installed in holes created by diamond cored drills can be 74% of anchors installed in holes created by rotary impact drills or rock drills. Several manufacturers prohibit the installation of adhesive anchors installed in diamond cored holes.

Adhesive anchor systems can have reduced strengths in lightweight concrete which is not considered in this design provision.

This design provision assumes that the concrete is cracked during the service life of the anchor system and that minimum reinforcement is present. If the designer can ensure that the concrete will remain uncracked during the service

MPII, whichever is greater.

- Concrete at time of installation shall have a minimum age of 21 days and a minimum compressive strength of 2500 psi.
- The tensile loading on the group of anchors must be applied centrically to the anchor group.
- Anchor group effects shall be considered wherever two or more anchors have spacing less than less than $3h_{ef}$ for evaluation of concrete breakout failure or $2c_{Na}$ for evaluation of adhesive bond failure. Only those anchors susceptible to the particular failure mode under investigation shall be included in the group.
- The tension loading on the anchor group must be applied concentrically to the anchor group.
- Anchors must not be subjected to seismic loads.

The contract documents shall also specify all parameters associated with the characteristic bond stress used for the design according to D.5.5 including minimum age of concrete; concrete temperature range; moisture condition of concrete at time of installation; type of lightweight concrete, if applicable; and requirements for hole drilling and preparation.

life of the anchor, higher bond stress values can be used and the designer is referred to ACI 318-11 Appendix D for design in uncracked concrete.

Adhesive anchor systems cannot fully cure at low temperatures. The MPII state the minimum permissible installation temperature which varies per product.

The provision for installation in concrete that is at least 21 days old is due to lower bond strengths for adhesive anchor systems in early-age concrete. NCHRP Project 04-37 Report showed that adhesive anchor systems had reduced bond strengths in concrete specimens less than 14 days old.

The provision for a minimum compressive strength of 2500 psi is due to adverse effects on adhesive anchor bond strength due to very low strength concrete.

For adhesive anchor situations that fall outside of these limitations, the designer is encouraged to develop case-specific design criteria using other design resources such as those found within ACI 318-11 Appendix D.

For adhesive anchors, the contract documents must also provide all parameters relevant to the characteristic bond stress used in the design. These parameters may include, but are not limited to:

1. Acceptable anchor installation environment (dry or saturated concrete; concrete temperature range);
2. Acceptable drilling methods;
3. Required hole cleaning procedures; and
4. Anchor type and size range (threaded rod or reinforcing bar).

Hole cleaning is intended to ensure that drilling debris and dust do not impair bond. Depending on the on-site conditions, hole cleaning may involve operations to remove drilling debris from the hole with vacuum or compressed air, mechanical brushing of the hole wall to remove surface dust, and a final step to evacuate any remaining dust or debris, usually with compressed air. Where wet core drilling is used, holes may be flushed with water and then dried with compressed air. If anchors are installed in locations where the concrete is saturated (for example, outdoor locations exposed to rainfall), the resulting drilling mud must be removed by other means. In all cases, the procedures used should be clearly described by the manufacturer in printed installation instructions accompanying the product. These printed installation instructions, which also describe the limits on concrete temperature and the presence of water during installation as well as the procedures necessary for void-free adhesive injection and adhesive cure requirements, constitute an integral part of the adhesive anchor system and are part of the assessment performed in accordance with ACI 355.4.

X.Y.4-Factored Resistance

For adhesive anchors subjected to tensile loading, the factored resistance, N_r, of an adhesive anchor bolt or group of anchors at Service II Load Combinations shall be taken as:

$$N_r = N_n \qquad \text{(X.Y.4-1)}$$

CX.Y.3.2

This design specification only addresses tensile loading. For other loading applications (e.g., shear, combined tension and shear), the designer is encouraged to use other design resources such as those found within ACI 318-11 Appendix D.

The ACI 355.4 product evaluation report classifies adhesive anchor systems into three categories based on their where:

N_n = nominal resistance of an adhesive anchor bolt or group of anchors as specified in Article X.Y.4.

The factored resistance, N_r, of an adhesive anchor bolt or group of anchors at the strength limit state shall be taken as:

$$N_r = \varphi \, \psi_{sus} N_n \qquad \text{(X.Y.4-2)}$$

where:

N_n = nominal resistance of an adhesive anchor bolt or group of anchors shall be taken as the smallest of:

- Adhesive bond strength, N_n, as specified in Article X.Y.5.1.
- Concrete breakout strength, N_n, as specified in Article X.Y.6.1.
- Steel strength, N_n, as specified in Article 6.13.2.10.

φ = resistance factor for anchor bolts shall be taken as:

- $\varphi_a = 0.65$ for adhesive bond and concrete breakout for category 1
- $\varphi_a = 0.55$ for adhesive bond and concrete breakout for category 2
- $\varphi_a = 0.45$ for adhesive bond and concrete breakout for category 3
- $\varphi_t = 0.75$ for tensile steel failure

ψ_{sus} = resistance factor for sustained load:

- $\psi_{sus} = 1.0$ in the absence of sustained load or for concrete breakout failure or for steel failure
- $\psi_{sus} = 0.55$ for the presence of sustained load for a lifetime of 50 years at 70°F and 10 years at 110°F
- $\psi_{sus} = 0.50$ for the presence of sustained load for a lifetime of 100 years at 70°F and 20 years at 110°F

sensitivity to installation procedures. ACI 318 then assigns different resistance factors based on anchor category. The three categories are described as follows:

- Category 1 is for adhesive anchor systems with a low sensitivity to installation procedures and a high reliability
- Category 2 is for adhesive anchor systems with a medium sensitivity to installation procedures and a medium reliability
- Category 3 is for adhesive anchor systems with a high sensitivity to installation procedures and a low reliability

ACI 318-11 uses a 0.55 factor for sustained load calculations which is in agreement with the ACI 355.4 sustained load testing program. The ACI 355.4 sustained testing program subjects an anchor to 55% of its mean short-term load strength at 70°F and 110°F for 1000 hours. Displacements from both tests are projected to 10 years at 110°F and 50 years at 70°F and anchors are qualified for sustained load if the projected displacements are less than a prescribed displacement limit.

The ψ factor for sustained load used by AASHTO has been correlated with the displacement limitations found in the ACI 355.4 testing program and provides reduction factors for structure lifetimes of 50 and 100 years at 70°F and 10 and 20 years at 110°F.

X.Y.5-Adhesive Bond Failure

X.Y.5.1-Nominal Resistance due to Adhesive Bond

The nominal resistance of an adhesive anchor bolt or group of anchors due to adhesive bond failure shall be taken as:

$$N_n = \frac{A_{Na}}{A_{Nao}} \psi_{ed,Na} N_a \qquad \text{(X.Y.5.1-1)}$$

where:

N_a = basic bond strength of a single adhesive anchor in tension in cracked concrete as defined in Article X.Y.5.2.

A_{Na} = projected influence area of a single adhesive anchor or group of adhesive anchors based on actual edge distances and anchor spacing as defined in Article X.Y.5.3 (in^2).

A_{Nao} = projected influence area of a single adhesive anchor or group of adhesive anchors with an edge distance greater than or equal to c_{Na} as defined in Article X.Y.5.3 (in^2).

$\psi_{ed,Na}$ = modification factor for edges effects beyond what is accounted for by the ratio $\frac{A_{Na}}{A_{Na0}}$ as defined in Article X.Y.5.4.

CX.Y.5.1

Adhesive anchors are susceptible to anchor spacing and distance to an edge. If located too close to each other or to an edge, adhesive anchors will not be able to fully develop their design strength. Two different modification factors for anchor spacing and edge distance are included, $\frac{A_{Na}}{A_{Nao}}$ and $\psi_{ed,Na}$.

X.Y.5.2-Basic Bond Strength

The basic bond strength of an adhesive anchor due to adhesive bond failure shall be taken as:

$$N_a = \tau_{cr}\, \pi\, d_a\, h_{ef} \qquad \text{(X.Y.5.2-1)}$$

where:

d_a = outside diameter of anchor (in.)

h_{ef} = effective embedment depth of anchor (in.)

τ_{cr} = characteristic bond stress of adhesive anchor in cracked concrete (ksi). Shall be taken as the 5% fractile of tests performed in accordance with ACI 355.4. It shall be permitted to use the minimum characteristic bond stress, $\tau_{cr,min}$, as defined below.

$\tau_{cr,min}$ = minimum characteristic bond stress:

- $\tau_{cr,min} = 0.200$ ksi
- $\tau_{cr,min} = 0.080$ ksi for sustained tension load applications

CX.Y.5.2

The equation for the nominal resistance of an adhesive anchor to adhesive bond is based on a uniform bond stress model developed by Cook et al. (1998) based on numerical studies and an international database of experimental tests. Due to the relatively thin bond line in adhesive anchors, the model is valid for the interface between the adhesive and the anchor as well as the adhesive and the concrete.

The characteristic bond stress is determined from a battery of tests in ACI 355.4 for various combinations of installation and service conditions. In the absence of product-specific information, the minimum characteristic bond stress provided may be used. The minimum characteristic bond stress is the minimum allowed for qualification by ACI 355.4 for the given conditions. These are very conservative values and the designer is encouraged to specify approved product and use properties of these products in the design.

ACI 318-11 Table D.5.5.2 classifies two installation and service conditions of “indoor” and “outdoor”. Indoor conditions are for anchors installed in dry concrete with a rotary impact drill or rock drill and subjected to minimal temperature variations over the service life. Outdoor conditions are for anchors installed in concrete exposed to weather and could be wet during installation or the service life. Outdoor conditions also provide for larger temperature variations during the service life. This standard assumes an “outdoor” installation and the values for the minimum characteristic bond stress, $\tau_{cr,min}$, are based on this

X.Y.5.3-Projected Influence Areas

The projected influence are of a single adhesive anchor without the influence of edge or spacing effects used to determine bond strength, A_{Na0}, shall be computed as:

$$A_{Nao} = \ 2c_{Na}{}^{2} \qquad \text{(X.Y.5.3-1)}$$

where:

$$c_{Na} = 16d_a \qquad \text{(X.Y.5.3-2)}$$

The parameter A_{Na} is the projected influence area of a single adhesive anchor or group of anchors.

For a single adhesive anchor, A_{Na} is the projected rectangular area that projects outward from the center of the anchor in all four principle directions a distance c_{Na} but shall not exceed the distance, *c*, to the edge.

For a group of anchors, A_{Na} is the projected rectangular area that projects outward from the outer rows of a group of adhesive anchors in all four principle directions a distance c_{Na} but shall not exceed the distance, *c*, to the edge. The value of A_{Na} shall not exceed nA_{Na0} where *n* is the number of anchors in the group.

"outdoor" condition.

CX.Y.5.3

The parameter A_{Nao} is the projected influence area of a single anchor without any influence of edge effects as illustrated in Figure 1.

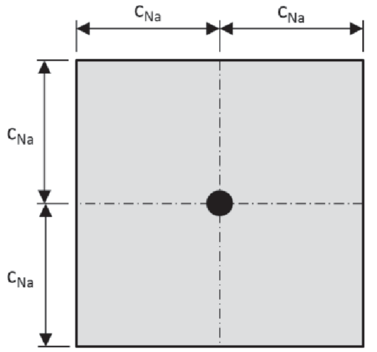


Figure 1: Projected influence area A_{Na0}

The parameter, c_{Na}, is the critical radial distance from the centerline of an anchor to where stresses in the concrete due to the adhesive bond stress are negligible. This is a function of anchor diameter and bond strength. This parameter has been calibrated from ACI 318-11 equation (D-21) by inserting the value of τ_{uncr} slightly larger than the maximum characteristic bond stress in uncracked concrete from a sampling of seventeen ICC-ES AC308 approved adhesive anchor products.

The parameter A_{Na} is the projected influence area of a single adhesive anchor or group of anchors as illustrated in Figure 2 for a single anchor and Figure 3 for a group of anchors.

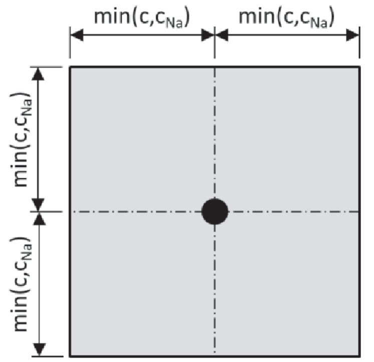


Figure 2: Projected influence area A_{Na} for a single anchor

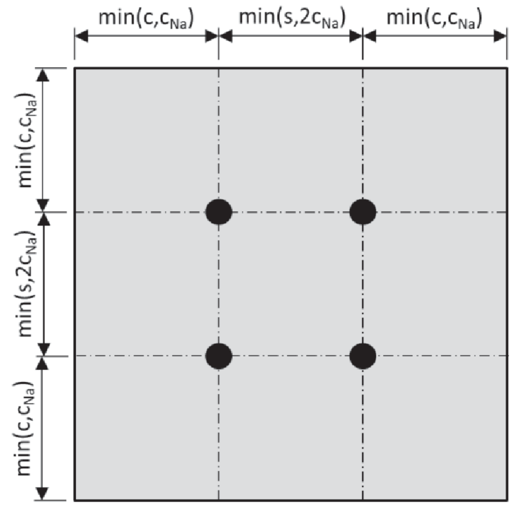


Figure 3: Projected influence area A_{Na} for a group of anchors

X.Y.5.4-Modification Factor for Edge Effects

The modification factor, $\psi_{ed,Na}$, for anchors located close to an edge beyond what is accounted for in Article X.Y.5.3, shall be computed as:

If $c_{min} \geq c_{Na}$

then $\psi_{ed,Na} = 1.0$ (X.Y.5.4-1)

If $c_{min} < c_{Na}$

then $\psi_{ed,Na} = 0.7 + 0.3\frac{c_{min}}{c_{Na}}$ (X.Y.5.4-2)

where:

c_{min} = distance from the center of an anchor to the closest edge of the concrete (in.)

c_{Na} = projected distance from the center of an anchor required to develop the full bond strength as defined in Article X.Y.5.3 (in.).

X.Y.6-Concrete Breakout Failure

X.Y.6.1-Nominal Resistance due to Concrete Breakout Failure

The nominal resistance of an adhesive anchor bolt or group of anchors due to concrete breakout failure shall be taken as:

$$N_n = \frac{A_{Nc}}{A_{Nco}} \psi_{ed,Nc} N_c \qquad \text{(X.Y.6.1-1)}$$

where:

N_c = basic concrete breakout strength of a single adhesive anchor in tension in cracked concrete as defined in Article X.Y.6.2.

A_{Nc} = projected influence area of a single adhesive anchor or group of adhesive anchors based on actual edge distances and anchor spacing as defined in Article X.Y.6.3 (in^2).

A_{Nco} = projected influence area of a single adhesive anchor or group of adhesive anchors with an edge distance greater than or equal to c_{Nc} as defined in Article X.Y.6.3 (in^2).

$\psi_{ed,Nc}$ = modification factor for edges effects beyond what is accounted for by the ratio $\frac{A_{Nc}}{A_{Nc0}}$ as defined in Article X.Y.6.4.

CX.Y.6.1

Adhesive anchors are susceptible to anchor spacing and distance to an edge. If located too close to each other or to an edge, adhesive anchors will not be able to fully develop their design strength. Two different modification factors for anchor spacing and edge distance are included, $\frac{A_{Nc}}{A_{Nc0}}$ and $\psi_{ed,Nc}$.

X.Y.6.2-Basic Concrete Breakout Strength

The basic concrete breakout strength of an adhesive anchor shall be taken as:

$$N_c = 0.54 \sqrt{f'_c}\, h_{ef}^{\,1.5} \qquad \text{(X.Y.6.2-1)}$$

where:

f'_c = specified compressive strength of concrete for use in design (ksi)

h_{ef} = effective embedment depth of anchor (in.)

If an anchor is located closer than $1.5h_{ef}$ to three or more edges, h_{ef} used in the calculation of equations X.Y.6.2-1 and X.Y.6.3-2 shall be taken as:

$$h_{ef} = max\begin{cases} \frac{c_{a,max}}{1.5} \\ \frac{s_{max}}{3} \end{cases} \qquad \text{(X.Y.6.2-2)}$$

where:

$c_{a,max}$ = largest of the edge distances that are less than $1.5h_{ef}$ (in.)

s_{max} = maximum spacing between anchors within a group (in.)

CX.Y.6.2

The equation for the nominal resistance of an adhesive anchor due to concrete breakout failure assumes a 35° concrete failure prism based on fracture mechanics (Fuchs et al. (1995), Eligehausen and Balogh (1995), Eligehausen & Fuchs (1988), CEB (1994)).

Note that equation (X.Y.6.2-1) has been calibrated from ACI 31-11 equation (D-6) by a factor of 0.0316 ($\sqrt{1000}/1000$) for the conversion of f'_c from psi in ACI to ksi in AASHTO.

The 0.54 coefficient incorporates both the conversion factor described above and the k_c value from ACI 318 determined from a database of tests in uncracked concrete evaluated at the 5% fractile (Fuchs et al. (1995) and adjusted for cracked concrete (Eligehausen and Balogh (1995), Goto (1971)).

The adjustment on h_{ef} in cases where anchors are located very close to three or more edges is correct the approximation of the factor $\frac{A_{Nc}}{A_{Nc0}}$ which produces overly conservative results.

X.Y.6.3-Projected Influence Areas

The projected influence area of a single adhesive anchor without the influence of edge or spacing effects used to determine concrete breakout strength, A_{Nco}, shall be computed as:

$$A_{Nco} = 2c_{Nc}{}^{2} \qquad \text{(X.Y.6.3-1)}$$

where:

$$c_{Nc} = 1.5h_{ef} \qquad \text{(X.Y.6.3-2)}$$

The parameter A_{Nc} is the projected influence area of a single adhesive anchor or group of anchors.

For a single adhesive anchor, A_{Nc} is the projected rectangular area that projects outward from the center of the anchor in all four principle directions a distance c_{Nc} but shall not exceed the distance, c, to the edge.

For a group of anchors, A_{Nc} is the projected rectangular area that projects outward from the outer rows of a group of adhesive anchors in all four principle directions a distance c_{Nc} but shall not exceed the distance, c, to the edge. The value of A_{Nc} shall not exceed nA_{Nco} where n is the number of anchors in the group.

CX.Y.6.3

The parameter A_{Nc0} is the projected influence area of a single anchor without any influence of edge effects as illustrated in Figure 4.

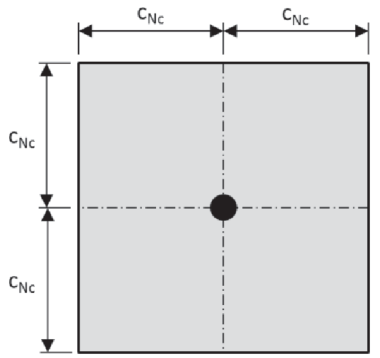


Figure 4: Projected influence area A_{Nc0}

The value c_{Nc} is the distance from the center to the edge of the assumed failure prism with a 35 angle. This is simplified from a 35° angle as illustrated in Figure 5.

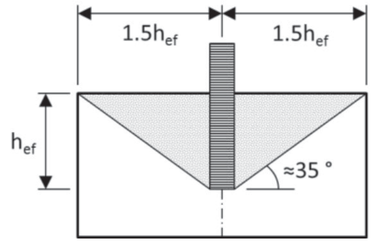


Figure 5: Assumed failure prism

The parameter A_{Nc} is the projected influence area of a single adhesive anchor or group of anchors as illustrated in Figure 6 for a single anchor and Figure 7 for a group of anchors.

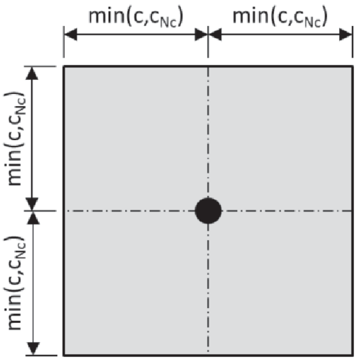


Figure 6: Projected influence area A_{Na} for a single anchor

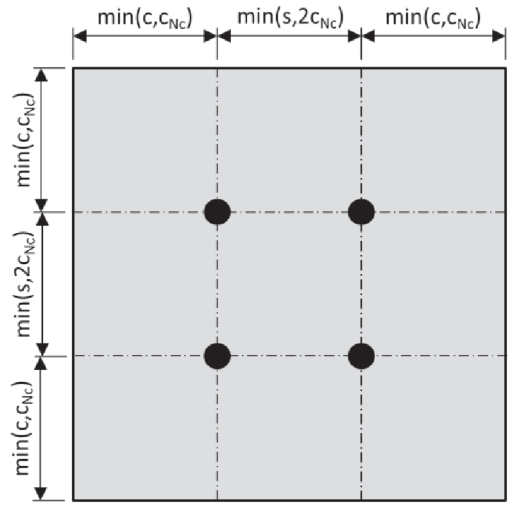


Figure 7: Projected influence area A_{Na} for a group of anchors

X.Y.6.4-Modification Factor for Edge Effects

The modification factor anchors located close to an edge beyond what is accounted for in Article X.Y.6.3, shall be computed as:

If $c_{min} \geq c_{Nc}$

then $\psi_{ed,Nc} = 1.0$ (X.Y.6.4-1)

If $c_{min} < c_{Nc}$

then $\psi_{ed,Nc} = 0.7 + 0.3\frac{c_{min}}{c_{Nc}}$ (X.Y.6.4-2)

where:

c_{min} = distance from the center of an anchor to the closest edge of the concrete (in.)

c_{Nc} = projected distance from the center of an anchor for a concrete failure prism with an assumed angle of 35° as defined in Article X.Y.6.3 (in.).

X.Y.5-References

ACI 2011. Building Code Requirements for Structural Concrete, ACI 318-11, American Concrete Institute, Farmington Hills, MI.

ACI 2011. Qualification of Post-Installed Adhesive Anchors in Concrete, ACI 355.4-11, American Concrete Institute, Farmington Hills, MI.

Cook, R.A., Kunz, J., Fuchs, W., and Konz, R.C. (1998), “Behavior and Design of Single Adhesive Anchors Under Tensile Load in Uncracked Concrete,” ACI Structural Journal, Vol. 95, No. 1, pp. 9-26.

Eligehausen, R. and Balogh, T. (1995), “Behavior of Fasteners Loaded in Tension in Cracked Reinforced Concrete,” ACI Structural Journal, Vol. 92, No. 3, pp. 365-379.

Eligehausen, R., and Fuchs, W., “Load Bearing Behavior of Anchor Fastenings under Shear, Combined Tension and Shear or Flexural Loadings,” Betonwerk + Fertigteiltechnik, 2/1988, pp. 48-56.

"Fastenings to Concrete and Masonry Structures, State of the Art Report," Comité Euro-International du Béton (CEB), Bulletin No. 216, Thomas Telford Services Ltd., London, 1994.

Fuchs, W., Eligehausen, R., and Breen, J.E. (1995), "Concrete Capacity Design (CCD) Approach for Fastening to Concrete," ACI Structural Journal, Vol. 92, No. 1, pp. 73-94.

Goto, Y., "Cracked Formed in Concrete around Deformed Tension Bars in Concrete," ACI JOURNAL, Proceedings V. 68, No. 4, Apr. 1971, pp. 244-251.

ICC-ES AC58 (2005), Acceptance Criteria for Adhesive Anchors in Concrete and Masonry Elements, ICC Evaluation Services, Inc., Whittier, CA.

ICC-ES AC308 (2008), Acceptance Criteria for Post Installed Adhesive Anchors in Concrete, ICC Evaluation Services, Inc., Whittier, CA.

APPENDIX R

AASHTO Design Guideline

AASHTO DESIGN GUIDELINES FOR ADHESIVE ANCHOR SYSTEMS

This guideline addresses the design of adhesive anchor systems in transportation applications.

ADHESIVE ANCHOR SYSTEMS

Adhesive anchor systems are used to connect new construction to existing concrete using an adhesive and a threaded rod or reinforcing bar in holes with diameters no larger than 1.5 times the anchor diameter. Adhesives for adhesive anchor systems can be an epoxy, polyester, vinyl ester, acrylate, or hybrid mortar and consist of two parts (a resin and a hardener) and come in either cartridge or capsule format. The term “adhesive anchor system” includes all the materials and equipment necessary for proper installation. This includes not only the adhesive, but also the anchor, the mixing and delivery systems (dispenser gun, mixing nozzle), equipment for hole cleaning (air nozzles, air pumps, brushes), and the manufacturer’s printed installation instructions (MPII).

The MPII provided with the adhesive anchor system includes the instructions for the correct installation procedure. The approval and acceptance of adhesive anchor systems is based on strict adherence to the MPII. This includes but is not limited to drilling procedures (drill type, drill bit type, and diameter), hole cleaning procedures (blowing, vacuuming, brushing), installation conditions (dry, moist, or submerged hole, adhesive temperature, and concrete temperature), adhesive dispensing procedure (discarding initial adhesive, maintaining nozzle tip submerged during dispensing), and adherence to gel/working and curing times.

APPROVED ADHESIVE ANCHOR SYSTEMS

ACI 355.4 contains the testing and evaluation requirements for adhesive anchor systems for use in concrete. ACI 355.4 was created from the product approval standards originally contained within ICC-ES AC58 and later in ICC-ES AC308. Products for use in AASHTO transportation structures must be ACI 355.4 approved. Individual DOTs might have additional testing requirements beyond what is required in ACI 355.4 for adhesive anchors.

Consult your DOT’s QPL for approved adhesive anchor systems. In specifying an adhesive anchor system, attention must be taken to ensure that the adhesive anchor system is appropriate for the installation and in-service conditions (especially in-service temperature) experienced by the anchor. If an anchor is exposed to service temperatures greater than or equal to 120°F for significant portions of its service life, the anchor should be evaluated for temperature category B (ACI 355.4 §8.5) at a temperature equal to or greater than the highest service temperature.

DESIGN OF ADHESIVE ANCHOR SYSTEMS

AASHTO Section X.Y. contains design provisions for single adhesive anchors and groups of adhesive anchors in tension. There are three tension failure modes (adhesive bond failure, concrete breakout failure, and steel rupture) as illustrated in Figure 1 that must be considered.

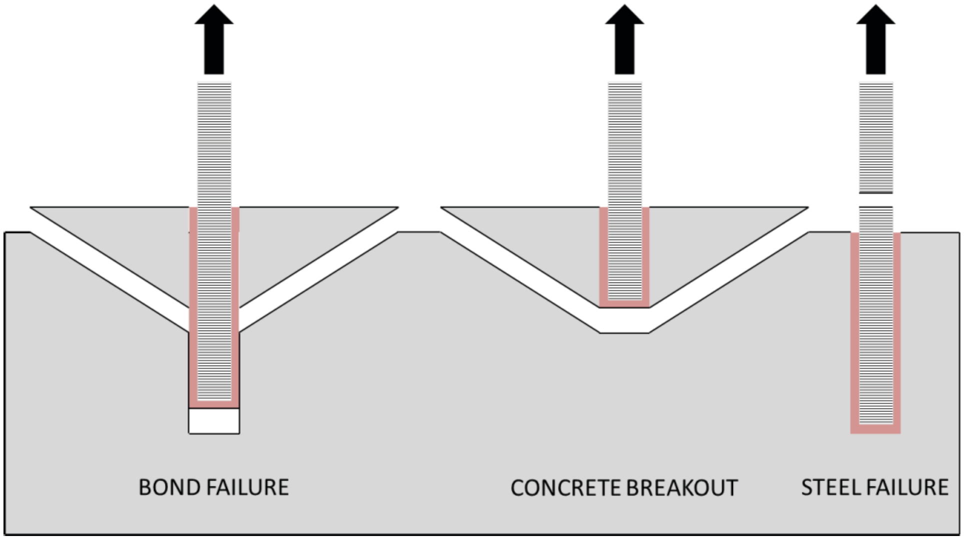


Figure 1: Three adhesive anchor tension failure modes.

Bond Strength

The basic adhesive bond strength is based on a uniform bond stress model evaluated at the anchor diameter. Due to the thin bond line (~1/16”), this model works well for the stress at the anchor diameter and the hole diameter. The characteristic bond stress for each adhesive can be obtained from the Evaluation Service Report (ESR) created from the ACI355.4 testing program. If an adhesive anchor system is not chosen prior to design, AASHTO X.Y.3.2 contains minimum values for the characteristic bond stress that can be used in design. Separate values are given for sustained tension load applications, applications subject to earthquake loads, and for the combination of the two.

Adhesive anchors are susceptible to anchor spacing and distance to an edge. If located too close to each other or to an edge, adhesive anchors will not be able to fully develop their design strength. Two different modification factors for anchor spacing and edge distance are included, $\frac{A_{Na}}{A_{Nao}}$ and $\psi_{ed,Na}$.

Due to the creep deformation of polymers, adhesive anchor systems are particularly sensitive to sustained tension load. In cases of sustained tension load, the bond strength is adjusted by a sustained load resistance factor (ψ_{sus}). The sustained load resistance factor is 0.55 for structures with a lifetime of 50 years and 0.50 for structures with a lifetime up to 100 years.

Concrete Breakout Strength

Concrete breakout strength assumes the creation of a 35° failure prism of concrete. As for adhesive bond strength, concrete breakout strength is susceptible to anchor spacing and distance to an edge. Two different modification factors for anchor spacing and edge distance are included, $\frac{A_{Nc}}{A_{Nco}}$ and $\psi_{ed,Nc}$.

Steel Strength

Adhesive anchors must also be designed for steel strength per the provisions provided in AASHTO *LRFD Bridge Design Specifications* Article 6.13.2.10.

AASHTO Tension Design Provisions Limitations

The AASHTO adhesive anchor tension design provisions place various limitations as listed in AASHTO *LRFD Bridge Design Specifications* Article X.Y.1 and discussed in the commentary. For adhesive anchor situations that fall outside of these limitations, the designer is encouraged to develop case-specific design criteria using other design resources such as those found within ACI 318-11 Appendix D.

Shear and Tension-Shear Interaction

Adhesive anchors are susceptible to three shear failure modes (steel, concrete breakout, and concrete pryout). Refer to ACI 318-11 Appendix D for the design for these failure modes. Additionally, consult ACI 318-11 Appendix D in situations of combined tension and shear.

SAMPLE CALCULATIONS

Included in this design guideline are two examples of sample calculations using the AASHTO design specifications for adhesive anchors found in AASHTO 2010 *LFRD Bridge Design Specifications* Section X.Y. The first example is for a single anchor in tension and the second example is for a group of anchors in tension.

Single Adhesive Anchor Sample Calculations

Given:

5/8” ASTM A193 grade B7 threaded rod

$A_b = 0.307\ in^2$

$F_{ub} = 125\ ksi$

Effective embedment depth = 5”

$h_{ef} = 5"$

Anchor is located 7” from the nearest edge

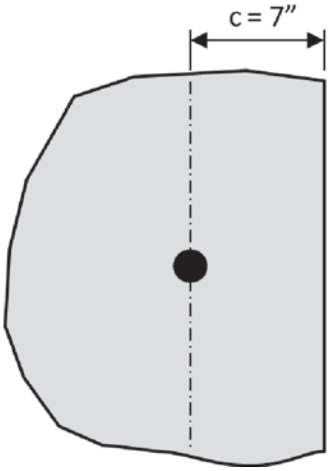
$c = 7"$

Conditions of X.Y.1 are satisfied

Adhesive anchor system is not chosen

Anchor is subjected to sustained load

$f'_c = 4000$ psi



Find:

Find the factored resistance N_r

Calculation in accordance with the proposed AASHTO Design Specifications for Adhesive Anchors	**Code Reference**

DETERMINE RESISTANCE FACTORS

Assume category 3

$\varphi_a = 0.45$ X.Y.2

ASTM A193 B7 is considered a ductile steel element

$\varphi_t = 0.75$ X.Y.2

Assume a structure lifetime of 75 years

$\psi_{sus} = 0.50$ X.Y.2

CALCULATE THE FACTORED RESISTANCE DUE TO ADHESIVE BOND FAILURE

Calculate Projected Influence Areas

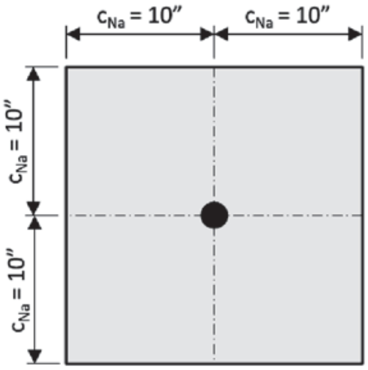


Figure 2: Schematic of A_{Nao}.

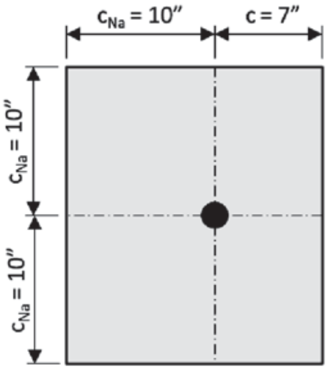


Figure 3: Schematic of A_{Na}.

Determine the critical radial distance from the centerline of the anchor to where the stresses in the concrete are negligible

$c_{Na} = 16d_a$ (X.Y.3.3-2)

$c_{Na} = 16(0.625") = 10"$

Determine the projected influence area without the influence of edge effects

$A_{Nao} = (2c_{Na})^2$ (X.Y.3.3-1)

$A_{Nao} = (2(10"))^2 = 400in^2$

Determine the projected influence area of a single anchor

$A_{Na} = (c_{Na} + c_{Na})(c_{Na} + c)$ X.Y.3.3

$A_{Na} = (10" + 10")(10" + 7") = 340\ in^2$

Calculate the Modification Factor for Edge Effects

Determine c_{min}

$c_{min} = min(c, c_{Na})$

$c_{min} = min(7", 10") = 7"$

Since $c_{min} < c_{Na}$

$\psi_{ed,Na} = 0.7 + 0.3\frac{c_{min}}{c_{Na}}$ (X.Y.3.4-2)

$\psi_{ed,Na} = 0.7 + 0.3\frac{7"}{10"} = 0.91$

Calculate the Basic Bond Strength

Determine characteristic bond stress
Since product is not chosen, use the minimum values specified in X.Y.3.2 for sustained load applications
$\tau_{cr} = \tau_{cr,min} = 0.080\ ksi$ X.Y.3.2

Calculate the basic bond strength
$N_a = \tau_{cr}\ \pi\ d_a\ h_{ef}$ (X.Y.3.2-1)
$N_a = (0.080\ ksi)\ \pi\ (0.625")\ (5")= 0.785\ kips$

Calculate the Nominal Resistance Due to Adhesive Bond

$$N_n = \frac{A_{Na}}{A_{Nao}} \psi_{ed,Na} N_a \qquad \text{(X.Y.3.1-1)}$$

$$N_n = \frac{(340)}{(400)}(0.91)(0.785\ kips) = 0.607\ kips$$

Calculate the Factored Resistance Due to Adhesive Bond

$N_r = \varphi_a\ \psi_{sus}\ N_n$ (X.Y.2-2)
$N_r = (0.45)(0.50)(0.607\ kips) = 0.137\ kips$

CALCULATE THE FACTORED RESISTANCE DUE TO CONCRETE BREAKOUT FAILURE

Determine if a reduced embedment depth is necessary

Anchor is not located closer than $1.5h_{ef}$ to three or more edges, therefore no reduction in h_{ef} is necessary X.Y.2.4

Calculate Projected Influence Areas

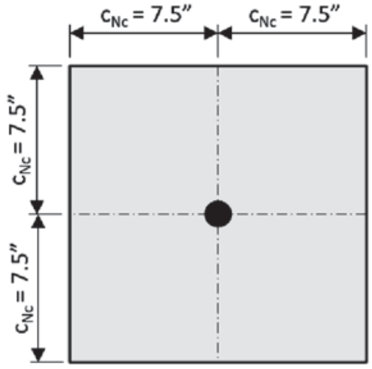


Figure 4: Schematic of A_{Nco}.

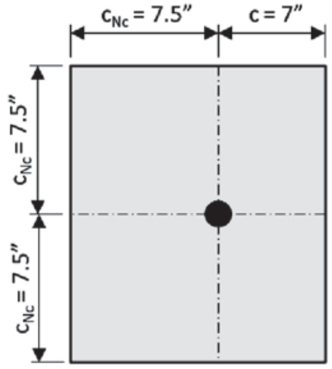


Figure 5: Schematic of A_{Nc}.

Determine the center to the edge of an assumed failure prism with a 35° angle

$c_{Nc} = 1.5h_{ef}$ (X.Y.4.3-2)

$c_{Nc} = 1.5(5") = 7.5"$

Determine the projected influence area without the influence of edge effects

$A_{Nco} = (2c_{Nc})^2$ (X.Y.4.3-1)

$A_{Nco} = (2(7.5"))^2 = 225\ in^2$

Determine the projected influence area of a single anchor

$A_{Nc} = (c_{Nc} + c_{Nc})(c_{Nc} + c)$ X.Y.4.3

$A_{Nc} = (7.5" + 7.5")(7.5" + 7") = 217.5\ in^2$

Calculate the Modification Factor for Edge Effects

Determine c_{min}

$c_{min} = min(c, c_{Nc})$

$c_{min} = min(7", 7.5") = 7"$

Since $c_{min} < c_{Nc}$

$\psi_{ed,Nc} = 0.7 + 0.3\frac{c_{min}}{c_{Nc}}$ (X.Y.4.4-2)

$\psi_{ed,Nc} = 0.7 + 0.3\frac{7"}{7.5"} = 0.98$

Calculate the Basic Concrete Breakout Strength

Calculate the basic concrete breakout strength

$N_c = 0.54\sqrt{f'_c}{h_{ef}}^{1.5}$ (X.Y.4.2-1)

$N_c = 0.54\sqrt{4\ ksi}(5")^{1.5} = 12.1\ kips$

Calculate the Nominal Resistance Due to Concrete Breakout Failure

$N_n = \frac{A_{Nc}}{A_{Nco}}\psi_{ed,Nc}N_c$ (X.Y.4.1-1)

$N_n = \frac{(217.5)}{(225)}(0.98)(12.1\ kips) = 11.5\ kips$

Calculate the Factored Resistance Due to Concrete Breakout Failure

$N_r = \varphi_a N_n$ (X.Y.2-2)

$N_r = (0.45)(11.5\ kips) = 5.2\ kips$

CALCULATE THE FACTORED RESISTANCE DUE TO STEEL FAILURE

Calculate the Nominal Resistance Due to Steel Failure

$N_n = T_n = 0.76 A_b F_{ub}$ (6.13.2.10.2-1)
$N_n = 0.76\,(0.307)(125) = 29.2\ kips$

Calculate the Factored Resistance Due to Steel Failure

$N_r = \varphi_t N_n$ (X.Y.2-2)
$N_r = (0.75)(29.2\ kips) = 21.9\ kips$

DETERMINE THE LIMITING RESISTANCE

Summary of Factored Resistances

Bond Failure	$N_r = 0.137\ kips$
Concrete Breakout Failure	$N_r = 5.2\ kips$
Steel Failure	$N_r = 21.9\ kips$

Limiting Resistance

$N_r = 0.137\ kips$

Note:
If an ACI 355.4 approved product was chosen prior to design a higher characteristic bond stress could have been used. For example:

$\tau_{cr} = 1.045\ ksi$

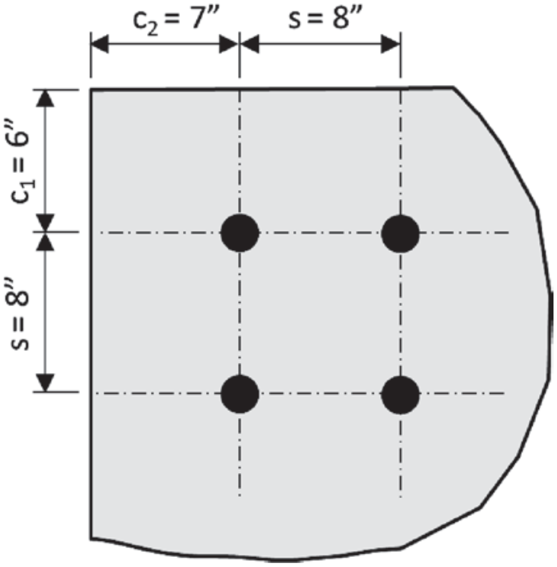
$N_a = \tau_{cr}\ \pi\ d_a\ h_{ef}$ (X.Y.3.2-1)
$N_a = (1.045\ ksi)\ \pi\ (0.625")\ (5”) = 10.2\ kips$

$N_n = \frac{A_{Na}}{A_{Nao}} \psi_{ed,Na} N_a$ (X.Y.3.1-1)

$N_n = \frac{(340)}{(400)}(0.91)(10.2\ kips) = 7.9\ kips$

$N_r = \varphi_a\ \psi_{sus}\ N_n$ (X.Y.2-2)
$N_r = (0.45)(0.50)(7.9\ kips) = 1.8\ kips$

Adhesive Anchor Group Sample Calculations



Given:

4 5/8" ASTM A193 grade B7 threaded rod

$A_b = 0.307\ in^2$

$F_{ub} = 125\ ksi$

Effective embedment depth = 5"

$h_{ef} = 5"$

Centerlines of anchor group are located 6" from the one edge and 7" from another edge

$c_1 = 6"$

$c_2 = 7"$

Anchors are spaced 8" apart

$s = 8"$

Conditions of X.Y.1 are satisfied

Adhesive anchor system is chosen

Category 1

Temperature range A

(maximum short term = 110°F)

(maximum long-term = 80°F)

$\tau_{cr} = 1.045\ ksi$

Anchors are subjected to sustained load

$f'_c = 4000$ psi

Find:

Find the factored resistance N_r

Calculation in accordance with the proposed AASHTO Design Specifications for Adhesive Anchors	**Code Reference**

DETERMINE RESISTANCE FACTORS

Given category 1

$\varphi_a = 0.65$ X.Y.2

ASTM A193 B7 is considered a ductile steel element

$\varphi_t = 0.75$ X.Y.2

Assume a structure lifetime of 75 years

$\psi_{sus} = 0.50$ X.Y.2

CALCULATE THE FACTORED RESISTANCE DUE TO ADHESIVE BOND FAILURE

Calculate Projected Influence Areas

Determine the critical radial distance from the centerline of the anchor to where the stresses in the concrete are negligible (X.Y.3.3-2)

$c_{Na} = 16d_a$

$c_{Na} = 16(0.625") = 10"$

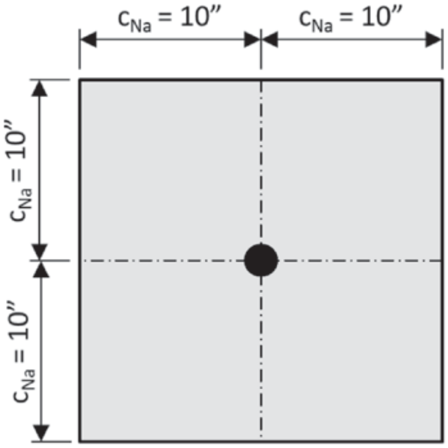


Figure 6: Schematic of A_{Nao}.

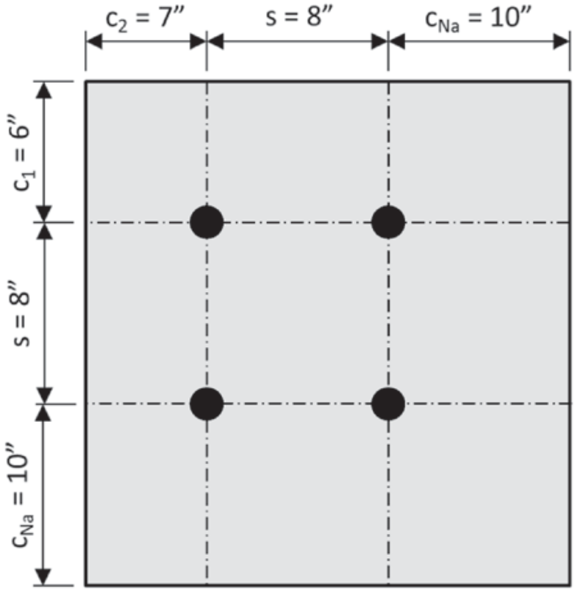


Figure 7: Schematic of A_{Na}.

Determine the projected influence area without the influence of edge effects

$A_{Nao} = (2c_{Na})^2$ (X.Y.3.3-1)

$A_{Nao} = (2(10"))^2 = 400\ in^2$

Determine the projected influence area of a single anchor

$A_{Na} = (c_1 + s + c_{Na})(c_2 + s + c_{Na})$ X.Y.3.3

$A_{Na} = (6" + 8" + 10")(7"+ 8" + 10") = 600\ in^2$

Check maximum limit of A_{Na}

$$A_{Na} = min\begin{cases} A_{Na} \\ n\ A_{Nao} \end{cases} = min\begin{cases} 600\ in^2 \\ 4\ (400\ in^2) \end{cases} = min\begin{cases} 600\ in^2 \\ 1600\ in^2 \end{cases} = 600\ in^2$$ X.Y.3.3

Calculate the Modification Factor for Edge Effects

Determine c_{min}
$c_{min} = min(c_1, c_2, c_{Na})$
$c_{min} = min(6", 7", 10") = 6"$

Since $c_{min} < c_{Na}$
$$\psi_{ed,Na} = 0.7 + 0.3\frac{c_{min}}{c_{Na}} \qquad \text{(X.Y.3.4-2)}$$

$$\psi_{ed,Na} = 0.7 + 0.3\frac{6"}{10"} = 0.88$$

Calculate the Basic Bond Strength

Obtain characteristic bond stress from ICC-ES AC308 ESR
$\tau_{cr} = 1.045\ ksi$ ICC-ES AC308 ESR

Calculate the basic bond strength
$N_a = \tau_{cr}\ \pi\ d_a\ h_{ef}$
$N_a = (1.045\ ksi)\ \pi\ (0.625")\ (5") = 10.2\ kips$ (X.Y.3.2-1)

Calculate the Nominal Resistance Due to Adhesive Bond

$$N_n = \frac{A_{Na}}{A_{Na0}}\psi_{ed,Na}N_a \qquad \text{(X.Y.3.1-1)}$$

$$N_n = \frac{(600)}{(400)}(0.88)(10.2\ kips) = 13.5\ kips$$

Calculate the Factored Resistance Due to Adhesive Bond

$N_r = \varphi_a\ \psi_{sus}\ N_n$ (X.Y.2-2)
$N_r = (0.65)(0.50)(13.5\ kips) = 4.4\ kips$

CALCULATE THE FACTORED RESISTANCE DUE TO CONCRETE BREAKOUT FAILURE

Determine if a reduced embedment depth is necessary

Anchor is not located closer than $1.5h_{ef}$ to three or more edges, therefore no reduction in h_{ef} is necessary X.Y.2.4

Calculate Projected Influence Areas

Determine the center to the edge of an assumed failure prism with a 35° angle (X.Y.4.3-2)

$c_{Nc} = 1.5h_{ef}$

$c_{Nc} = 1.5(5") = 7.5"$

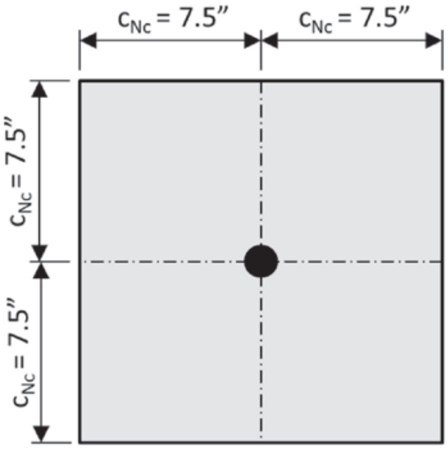


Figure 8: Schematic of A_{Nco}.

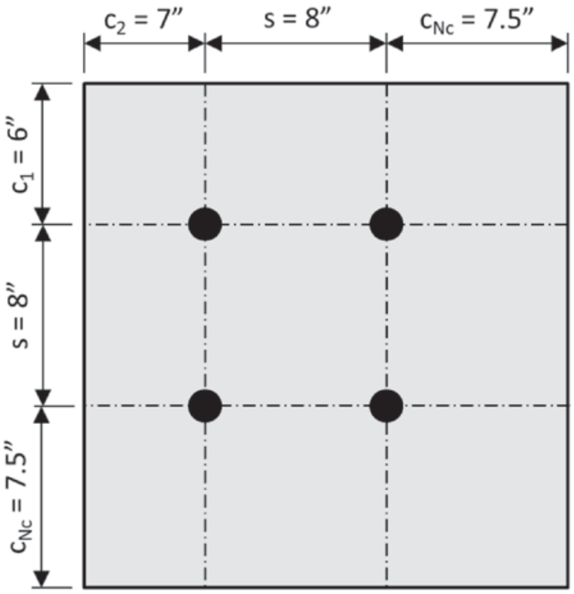


Figure 9: Schematic of A_{Nc}.

Determine the projected influence area without the influence of edge effects

$A_{Nc0} = (2c_{Nc})^2$ (X.Y.4.3-1)

$A_{Nc0} = (2(7.5"))^2 = 225\ in^2$

Determine the projected influence area of a single anchor

$A_{Nc} = (c_1 + s + c_{Nc})(c_2 + s + c_{Nc})$ X.Y.4.3

$A_{Nc} = (6" + 8" + 7.5")(7" + 8" + 7.5") = 484\ in^2$

Check maximum limit of A_{Nc}

$$A_{Nc} = min\begin{cases} A_{Nc} \\ n\ A_{Nco} \end{cases} = min\begin{cases} 484\ in^2 \\ 4\ (225\ in^2) \end{cases} = min\begin{cases} 484\ in^2 \\ 900\ in^2 \end{cases} = 484\ in^2 \qquad \text{X.Y.4.3}$$

Calculate the Modification Factor for Edge Effects

Determine c_{min}

$c_{min} = min(c_1, c_2, c_{Nc})$

$c_{min} = min(6", 7", 7.5") = 6"$

Since $c_{min} < c_{Nc}$

$$\psi_{ed,Nc} = 0.7 + 0.3\frac{c_{min}}{c_{Nc}} \qquad \text{(X.Y.4.4-2)}$$

$$\psi_{ed,Nc} = 0.7 + 0.3\frac{6"}{7.5"} = 0.94$$

Calculate the Basic Concrete Breakout Strength

Calculate the basic concrete breakout strength

$$N_c = 0.54\sqrt{f'_c}{h_{ef}}^{1.5} \qquad \text{(X.Y.4.2-1)}$$

$$N_c = 0.54\sqrt{4\ ksi}(5")^{1.5} = 12.1\ kips$$

Calculate the Nominal Resistance Due to Concrete Breakout Failure

$$N_n = \frac{A_{Nc}}{A_{Nco}}\psi_{ed,Nc}N_c \qquad \text{(X.Y.4.1-1)}$$

$$N_n = \frac{(484)}{(225)}(0.94)(12.1\ kips) = 24.5\ kips$$

Calculate the Factored Resistance Due to Concrete Breakout Failure

$$N_r = \varphi_a N_n \qquad \text{(X.Y.2-2)}$$

$$N_r = (0.65)(24.5\ kips) = 15.9\ kips$$

CALCULATE THE FACTORED RESISTANCE DUE TO STEEL FAILURE

Calculate the Nominal Resistance Due to Steel Failure

$$N_n = T_n = n\ 0.76A_bF_{ub} \qquad \text{(6.13.2.10.2-1)}$$

$$N_n = (4)0.76\ (0.307)(125) = 117\ kips$$

Calculate the Factored Resistance Due to Steel Failure

$$N_r = \varphi_t N_n \qquad \text{(X.Y.2-2)}$$

$$N_r = (0.75)(117kips) = 87.8\ kips$$

DETERMINE THE LIMITING RESISTANCE

Summary of Factored Resistances

Bond Failure	$N_r = 4.4\ kips$
Concrete Breakout Failure	$N_r = 15.9\ kips$
Steel Failure	$N_r = 87.8\ kips$

Limiting Resistance

$N_r = 4.4\ kips$

APPENDIX S

AASHTO Quality Assurance Guideline

AASHTO QUALITY ASSURANCE GUIDELINES FOR MATERIALS AND INSTALLATION OF EPOXY ANCHOR SYSTEMS IN TRANSPORTATION APPLICATIONS

ADHESIVE ANCHOR SYSTEMS

This guideline addresses the material and installation of adhesive anchor systems in transportation applications.

Material

Adhesive for adhesive anchor systems can be an epoxy, polyester, vinyl ester, acrylate, or hybrid mortar and consist of two parts (a resin and a hardener) and come in either cartridge or capsule format. Cartridge systems are commonly packaged in two tube cartridges with a dispensing gun and mixing nozzle. Capsule systems have glass or foil packages that are placed directly in the hole and the two parts are mixed during insertion of the anchor. Bulk systems must be approved by ACI 355.4 and have automatically controlled metering and mixing of components.

The term “adhesive anchor system” includes all the materials and equipment necessary for proper installation. This includes not only the adhesive, but also the anchor, the mixing and delivery systems (dispenser gun, mixing nozzle), equipment for hole cleaning (air nozzles, air pumps, brushes), and the Manufacturer’s Printed Installation Instructions (MPII).

Adhesive anchor systems have a shelf life and the expiration date should be checked prior to use and all expired product should be discarded and not used. As most adhesives are sensitive to temperature, the MPII should be consulted for the proper environmental conditions and temperature ranges during storage and installation.

INSTALLATION

Adhesive anchor systems are approved for use for specific installation conditions and procedures as specified in the Manufacturer’s Printed Installation Instructions (MPII). This quality assurance guideline discusses and explains the common installation conditions and procedures encountered in most MPIIs but should not be viewed as an instruction for installation of adhesive anchor systems. Each adhesive anchor system must be installed in accordance with its specific MPII.

Per ACI 355.4, adhesive anchors can only be installed in holes drilled in concrete that is at least 21 days old and with a minimum compressive strength of 2500 psi. The concrete should be structurally sound and free of surface cracks. Some products require installation only in dry concrete while others permit damp, saturated, or even submerged installation conditions and the MPII should be consulted for the approved installation conditions.

Drilling

Most adhesive anchor systems require drilling with a rotary impact drill with carbide bit. Diamond core drilling is not allowed for approved products unless covered in the MPII. Adhesive anchor systems develop their strength partly due to interlock with the roughness of the side of the drilled holes. Due to their violent nature, rotary impact drills create a relatively rough hole while diamond core drills produce a relatively smooth hole – especially in high strength concrete.

Holes should be drilled perpendicular to the surface of the concrete. Holes should be drilled to the proper embedment depth as stated in the drawings making sure to observe the minimum and maximum hole depths as stated in the MPII. If reinforcement is encountered during drilling the anchor should be relocated, or, if approved by the Engineer, a diamond core drill can be used to cut the reinforcing steel. Once the reinforcing steel is cut, the drilling should resume with the rotary impact drill.

Hole diameters shall be in accordance with the MPII, but typically range from 1.15 to 1.50 times the anchor diameter as this is the range of the adhesive anchor design model found in AASHTO 2010 *LRFD Bridge Design Specifications* and ACI 318-11. As some adhesive anchor systems are sensitive to the width of the annular gap between the anchor and the side of the hole, manufacturers specify in the MPII the required bit diameter for each anchor type and size which is usually around a 1/8” larger than the anchor.

Hole Cleaning

One of the most important aspects to ensure adhesive anchor performance is the cleanliness of the hole. Hole cleaning procedures vary by manufacturer and the steps in the MPII should be strictly followed. Most hole cleaning procedures will include a series of blowing, brushing, and blowing cycles.

Blowing can be accomplished by compressed air or a hand pump with a nozzle that extends to the base of the hole. Manufacturers will typically require several blows of air.

The blowing cycle is usually followed by a series of brushing cycles. Brushes can be either metallic or nylon and can be attached to a drill or a hand tool. The type and size of the brush as well as the brushing procedure is specified in the MPII and most manufacturers only allow their proprietary brushes to be used. Brushes should periodically be checked to make sure the diameter is still within the tolerances specified in the MPII. It is common that the brushing cycle be followed by another blowing cycle.

If the installation is in a damp, saturated, or submerged condition, the MPII might specify additional hole cleaning and preparation steps, which might include flushing the hole with clean water and vacuuming the water out of the hole.

Once the hole has been cleaned per the MPII it is good practice to protect the hole from contamination until the adhesive and anchor are inserted. This can be accomplished by covering the hole with tape.

Adhesive Insertion

For all adhesive anchor systems, the two parts of the adhesive must be thoroughly mixed at the correct proportions.

For cartridge systems, the dispenser gun ensures the proper proportions and the adhesive is thoroughly mixed within the special mixing nozzle. However, most manufacturers require that the first few (typically three) full strokes be discarded until the adhesive is of a consistent color in order to ensure that the adhesive is properly mixed. The adhesive is typically dispensed from the bottom or back of the hole while the nozzle is slowly retracted. The tip of the nozzle should remain submerged in the adhesive to prevent the formation of air pockets which can result in voids that reduce the bond strength of the adhesive anchor system. The hole is filled to roughly 60–75% of the depth of the hole.

For capsule systems, the glass or foil capsules are placed directly in the hole and are broken and mixed during the insertion of the anchor.

For horizontally or upwardly inclined holes, some manufacturers provide retaining caps to prevent the adhesive from running out of the hole during installation.

Anchor Installation

Each manufacturer will specify approved anchor types for use with their system. Anchors should be free of oil, rust, or other residue that might reduce the adhesive bond. The required embedment depth should be marked on the anchor in order to confirm when the anchor is fully embedded.

For cartridge systems, the anchor is inserted by hand and some manufacturers require that the anchor be rotated and jiggled while inserting in the hole to better distribute the adhesive and reduce the chance of voids.

For capsule systems, the anchor is most commonly inserted into the hole with a drill but some are also hammered into the hole. The anchor will typically have a chiseled end and will break the capsules and mix the adhesive during the insertion of the anchor.

Once inserted to the proper depth, the anchor should be centered in the hole and adjusted for perpendicularity. It is important that this happen immediately upon insertion and within the stated working (or gel) time as specified in the MPII. The working time varies by product and temperature and should be listed in the MPII, but usually is on the order of a few minutes.

Anchors installed in overhead and horizontal installations must be installed by ACI/CRSI certified installers and continuously inspected by a qualified inspector.

Curing

Once the working time has expired, the anchor cannot be disturbed until the cure time has elapsed. As with the working time, the cure time varies by product and temperature and can range from a few minutes to several hours. Information on cure time is provided in the MPII.

Torquing

Once the adhesive has fully cured, objects can be fixed to the anchor. It is important that the maximum permissible torque for pretension clamping as stated in the MPII not be exceeded. For adhesive anchors used in sustained load applications, the anchor cannot be loaded or torqued until after the manufacturer's minimum cure time as listed in the MPII plus an additional 24 hours.

CONCLUSION

Correct storage, preparation, installation, and torquing procedures are necessary in order to ensure proper performance of adhesive anchor systems. As these procedures vary by manufacturer and product, it is imperative that the procedures specified in the MPII be strictly followed.

APPENDIX T

AASHTO Construction Specification

SECTION 29

EMBEDMENT ANCHORS

29.1-DESCRIPTION

This work shall cover installation and field testing of cast-in-place, grouted, adhesive-bonded, expansion, and undercut steel anchors.

C29.1

The use of embedment anchors is prevalent but standardized installation and field testing is not. Therefore, a new section was created.

29.2-PREQUALIFICATION

Concrete anchors, including cast-in-place; all bonded anchor systems, including grout, chemical compound and adhesives; and undercut steel anchors shall be prequalified by universal test standards designed to allow approved anchor systems to be employed for any construction attachment use.

Only adhesive anchor systems that meet the assessment criteria of ACI 355.4 “Qualification of Post-Installed Adhesive Anchors in Concrete” are approved for use with the AASHTO design provisions. Adhesive anchors to be installed under special conditions that require optional tests in ACI 355.4 (i.e., water-filled holes, submerged concrete, installation temperature less than 50°F, and in horizontal or upwardly inclined holes), must be specifically approved by ACI 355.4 for these conditions.

Expansion anchors shall be tested in accordance with ASTM E488, Standard Test Methods for Strength of Anchors in Concrete and Masonry Elements.

Embedment anchor details shall comply with ACI 349, *Code Requirements for Nuclear Safety Related Concrete Structures,* "Appendix B, Steel Embedments."

For anchor systems other than mechanical expansion anchors, the Contractor shall provide the Engineer with certified test reports prepared by an independent laboratory documenting that the system is capable of achieving the minimum tensile strength of the embedment steel.

C29.2

ACI 355.4 provides the testing and acceptance criteria for adhesive anchors in concrete. ACI 355.4 was originally developed by ICC-ES as AC-308. ACI 355.4 utilizes test methods established in ASTM E488 and ASTM E1512.

29.3-MATERIALS

Mill test reports shall be provided to the Engineer to certify physical properties, chemistry, and strengths used to manufacture the anchors.

Adhesive anchor systems are qualified for different anchor element types and coatings and only those anchor types and coatings specifically mentioned in the Manufacturer’s Printed Installation Instructions (MPII) shall be used.

~~Either an epoxy, vinylester, or polyester chemical compound shall be acceptable for adhesive anchors.~~ Adhesive anchor systems acceptable for use include, but are not limited to, epoxies, polyurethanes, polyesters, methyl methacrylates, and vinyl esters. –Moisture-insensitive, high-modulus, low shrinkage, and high-strength adhesives shall be used. —Only adhesive anchor products that meet the assessment criteria of ACI 355.4 shall be used. Adhesive

C29.3

Due to the sensitivity of bond strength to installation, on-site quality control is important for adhesive anchors. Where appropriate, a proof loading program should be specified in the contract documents. For adhesive anchors, the contract documents must also provide all parameters relevant to the characteristic bond stress used in the design. These parameters may include, but are not limited to:

1. Acceptable anchor installation environment (dry or saturated concrete; concrete temperature range);
2. Acceptable drilling methods;
3. Required hole cleaning procedures; and
4. Anchor type and size range (threaded rod or reinforcing bar).

Hole cleaning is intended to ensure that drilling debris and dust do not impair bond. Depending on the on-site conditions, hole cleaning may involve operations to remove anchor systems may include not only the adhesive material but the anchor, all the equipment provided by the manufacturer for proper installation and cleaning of the hole, and the MPII. Bulk adhesives mixed in open containers without automatically controlled metering and mixing of components are not permitted. Materials should be stored in unopened containers and according to the storage conditions specified in the MPII. Materials should be discarded once the expiration date has expired.

For adhesive anchors, the contract documents shall specify proof loading where required. The contract documents shall also specify all parameters associated with the characteristic bond stress used for the design including minimum age of concrete; concrete temperature range; moisture condition of concrete at time of installation; type of lightweight concrete, if applicable; and requirements for hole drilling and preparation.

The use of additives to grout and bonding materials that are corrosive to steel or zinc/cadmium coatings shall be prohibited.

drilling debris from the hole with vacuum or compressed air, mechanical brushing of the hole wall to remove surface dust, and a final step to evacuate any remaining dust or debris, usually with compressed air. Where wet core drilling is used, holes may be flushed with water and then dried with compressed air. If anchors are installed in locations where the concrete is saturated (for example, outdoor locations exposed to rainfall), the resulting drilling mud must be removed by other means. In all cases, the procedures used should be clearly described by the manufacturer in printed installation instructions (MPII) accompanying the product. These printed installation instructions, which also describe the limits on concrete temperature and the presence of water during installation as well as the procedures necessary for void-free adhesive injection and adhesive cure requirements, constitute an integral part of the adhesive anchor system and are part of the assessment program.

29.4-CONSTRUCTION METHODS

Adequate edge distance, embedment depth, and spacing to develop the required strength of the embedment anchors and to ensure ductility of the connection shall be provided. The correct drill-hole diameter shall be used as specified ~~by the Manufacturer~~in the MPII. Rotary impact drilling with carbide-tipped hammer bits conforming to ANSI B212.15 shall be used unless diamond core drilling is permitted by the MPII and has been ~~specified~~ approved by the Engineer~~or tested~~. If a reinforcing bar is encountered during drilling, the hole shall be moved to a different location or the reinforcing steel shall be drilled through using a diamond core bit as directed by the Engineer. Once the reinforcing steel is cut, the drilling should resume with a rotary impact drill. Abandoned holes shall be patched with an approved bonding material. Holes shall be thoroughly cleaned as ~~recommended by the Manufacturer~~specified in the MPII.

Adhesive anchors shall only be installed in concrete that is at least 21 days old and has a minimum compressive strength of 2500 psi at the time of installation. Adhesive anchors that are installed in the horizontal or upwardly inclined direction shall be installed by personnel certified by the ACI/CRSI Adhesive Anchor Installer Certification program, or its equivalent.

The Contractor shall remove all loose dust and concrete particles from the hole and protect the hole from contamination until the anchor is installed. The Contractor shall prepare bonding material and install anchors according to the ~~Manufacturer's instructions~~ MPII.~~or as approved by the Engineer.~~ Unless otherwise indicated, anchors shall be installed perpendicular to the concrete surface. Adhesive anchors that displace prior to full adhesive cure shall be replaced at the Contractor's expense. Adhesive Anchors cannot be adjusted by bending with a pipe or by hammering unless approved by the Engineer.

Improperly installed embedded anchors or anchors not

C29.4

The MPII provided with the adhesive anchor system includes the instructions for the correct installation procedure. The approval and acceptance of adhesive anchor systems is based on strict adherence to the MPII. This includes but is not limited to drilling procedures (drill type, drill bit type and diameter), hole cleaning procedures (blowing, vacuuming, brushing), installation conditions (dry, moist, or submerged hole, adhesive temperature, and concrete temperature), adhesive dispensing procedure (discarding initial adhesive, maintaining nozzle tip submerged during dispensing), and adherence to gel/working and curing times.

While adhesive anchors are not particularly sensitive to concrete compressive strength, ACI 318 adopts the 21 day limit on adhesive anchor installation due to adhesive anchor sensitivity to various early-age concrete properties such as moisture content and tensile strength.

The installation of adhesive anchors in horizontal or upwardly inclined holes presents unique difficulties and careful installation and monitoring is required. Therefore ACI 318 requires personnel certified by the ACI/CRSI Adhesive Anchor Installer Certification program or its equivalent for these installations.

It is suggested that a drilling rig similar to that shown below be used to help ensure that the hole is drilled perpendicular to the surface. It is also suggested that an adaptor similar to that shown below be used to protect the operator while blowing with compressed air and vacuuming the loose dust and concrete particles from the hole.

having the required strength shall be removed and replaced to the satisfaction of the Engineer at the Contractor's expense.

29.5-INSPECTION AND TESTING

Adhesive anchors installed in horizontal or upwardly inclined holes shall be continuously inspected by a qualified inspector.

Adhesive anchors subjected to in-service temperatures of 120°F shall be qualified under temperature category B of ACI 2355.4 §8.5 at a temperature equal to or greater than the highest in-service temperature.

Each type and size of adhesive anchor shall be proof tested in accordance with ACI 355.4. Proof loading for adhesive anchors shall be conducted only after the minimum curing time as specified in the MPII has elapsed.

Where specified, sacrificial tests of the anchor system shall be done at the job site to ultimate loads to document the capability of the system to achieve pullout loads equaling the full minimum tensile value of the anchor employed. Anchor testing shall be done on fully cured concrete samples. At least three anchors shall be tested by ASTM E488 methods, unless otherwise specified. The Contractor may use any prequalified anchor systems meeting the above requirements.

Provision shall be made for use of an alternative system that will reach the designated pullout requirement, without delay in progress, if the job site proof loading proves incapable of achieving minimum tensile values, or the load required by the Engineer if too little concrete exists in which to develop full ductile loads.

After installation and cure of the bonding material, each anchor system shall be torqued to specified values per the MPII as a result of ACI 355.4 qualification testing using approved torque methods only. If torque values are not specified, the Manufacturer's recommendation or values provided by the Engineer shall be used. For adhesive anchors used in sustained load applications, the anchor shall not be permitted to be loaded or torqued until after the manufacturer’s minimum cure time as listed in the MPII plus an additional 24 hours.

29.6-MEASUREMENT

Measurement of embedment anchors incorporated into the project shall be the number of each anchor size and orientation shown in the contract documents or authorized for use on the project. Each embedment anchor type satisfactorily installed shall be counted and summarized in the contract documents according to anchor system; orientation, i.e., vertical, horizontal, and diagonal; and size taken as the diameter.

29.7-PAYMENT

Payment shall be based upon the quantity of embedment anchors determined under measurement for each embedment anchor type and shall include full compensation for furnishing all labor, materials, tools, equipment, testing, and incidentals necessary to place each anchor type.

29.8-REFERENCES

ACI. 2001. *Code Requirements for Nuclear Safety Related Concrete Structures,* ACI 349-01, American Concrete Institute, Farmington Hills, MI, Appendix B: Steel Embedments.

ACI 2011. *Building Code Requirements for Structural Concrete*, ACI 318-11, American Concrete Institute, Farmington Hills, MI.

ACI 2011. *Qualification of Post-Installed Adhesive Anchors in Concrete*, ACI 355.4-11, American Concrete Institute, Farmington Hills, MI.

Abbreviations and acronyms used without definitions in TRB publications:

A4A	Airlines for America
AAAE	American Association of Airport Executives
AASHO	American Association of State Highway Officials
AASHTO	American Association of State Highway and Transportation Officials
ACI–NA	Airports Council International–North America
ACRP	Airport Cooperative Research Program
ADA	Americans with Disabilities Act
APTA	American Public Transportation Association
ASCE	American Society of Civil Engineers
ASME	American Society of Mechanical Engineers
ASTM	American Society for Testing and Materials
ATA	American Trucking Associations
CTAA	Community Transportation Association of America
CTBSSP	Commercial Truck and Bus Safety Synthesis Program
DHS	Department of Homeland Security
DOE	Department of Energy
EPA	Environmental Protection Agency
FAA	Federal Aviation Administration
FHWA	Federal Highway Administration
FMCSA	Federal Motor Carrier Safety Administration
FRA	Federal Railroad Administration
FTA	Federal Transit Administration
HMCRP	Hazardous Materials Cooperative Research Program
IEEE	Institute of Electrical and Electronics Engineers
ISTEA	Intermodal Surface Transportation Efficiency Act of 1991
ITE	Institute of Transportation Engineers
MAP-21	Moving Ahead for Progress in the 21st Century Act (2012)
NASA	National Aeronautics and Space Administration
NASAO	National Association of State Aviation Officials
NCFRP	National Cooperative Freight Research Program
NCHRP	National Cooperative Highway Research Program
NHTSA	National Highway Traffic Safety Administration
NTSB	National Transportation Safety Board
PHMSA	Pipeline and Hazardous Materials Safety Administration
RITA	Research and Innovative Technology Administration
SAE	Society of Automotive Engineers
SAFETEA-LU	Safe, Accountable, Flexible, Efficient Transportation Equity Act: A Legacy for Users (2005)
TCRP	Transit Cooperative Research Program
TEA-21	Transportation Equity Act for the 21st Century (1998)
TRB	Transportation Research Board
TSA	Transportation Security Administration
U.S.DOT	United States Department of Transportation