Using Existing Pavement in Place and Achieving Long Life

DETAILS

122 pages | 8.5 x 11 | PAPERBACK
ISBN 978-0-309-12962-6 | DOI 10.17226/22684

AUTHORS

Jackson, Newton; Mahoney, Joe; and Puccinelli, Jason

The Second
STRATEGIC HIGHWAY RESEARCH PROGRAM

SHRP 2 REPORT S2-R23-RR-1

Using Existing Pavement in Place and Achieving Long Life

NEWTON JACKSON AND JASON PUCCINELLI
Nichols Consulting Engineers, Chtd.

JOE MAHONEY
University of Washington, Seattle, Washington

TRANSPORTATION RESEARCH BOARD
WASHINGTON, D.C.
2014
www.TRB.org

Subscriber Categories

Construction
Highways
Maintenance and Preservation
Pavements

The Second Strategic Highway Research Program

America's highway system is critical to meeting the mobility and economic needs of local communities, regions, and the nation. Developments in research and technology—such as advanced materials, communications technology, new data collection technologies, and human factors science—offer a new opportunity to improve the safety and reliability of this important national resource. Breakthrough resolution of significant transportation problems, however, requires concentrated resources over a short time frame. Reflecting this need, the second Strategic Highway Research Program (SHRP 2) has an intense, large-scale focus, integrates multiple fields of research and technology, and is fundamentally different from the broad, mission-oriented, discipline-based research programs that have been the mainstay of the highway research industry for half a century.

The need for SHRP 2 was identified in *TRB Special Report 260: Strategic Highway Research: Saving Lives, Reducing Congestion, Improving Quality of Life,* published in 2001 and based on a study sponsored by Congress through the Transportation Equity Act for the 21st Century (TEA-21). SHRP 2, modeled after the first Strategic Highway Research Program, is a focused, time-constrained, management-driven program designed to complement existing highway research programs. SHRP 2 focuses on applied research in four areas: Safety, to prevent or reduce the severity of highway crashes by understanding driver behavior; Renewal, to address the aging infrastructure through rapid design and construction methods that cause minimal disruptions and produce lasting facilities; Reliability, to reduce congestion through incident reduction, management, response, and mitigation; and Capacity, to integrate mobility, economic, environmental, and community needs in the planning and designing of new transportation capacity.

SHRP 2 was authorized in August 2005 as part of the Safe, Accountable, Flexible, Efficient Transportation Equity Act: A Legacy for Users (SAFETEA-LU). The program is managed by the Transportation Research Board (TRB) on behalf of the National Research Council (NRC). SHRP 2 is conducted under a memorandum of understanding among the American Association of State Highway and Transportation Officials (AASHTO), the Federal Highway Administration (FHWA), and the National Academy of Sciences, parent organization of TRB and NRC. The program provides for competitive, merit-based selection of research contractors; independent research project oversight; and dissemination of research results.

SHRP 2 Report S2-R23-RR-1

ISBN: 978-0-309-12962-6

Library of Congress Control Number: 2014933826

Copyright Information

Note: SHRP 2 report numbers convey the program, focus area, project number, and publication format. Report numbers ending in "w" are published as web documents only.

Notice

The project that is the subject of this report was a part of the second Strategic 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 committee 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 committee 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 second Strategic 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.

SHRP 2 Reports

Available by subscription and through the TRB online bookstore:
www.TRB.org/bookstore

Contact the TRB Business Office:
202-334-3213

More information about SHRP 2:
www.TRB.org/SHRP2

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 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. (Dan) 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. Victor J. Dzau 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. (Dan) 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

SHRP 2 STAFF

ACKNOWLEDGMENTS

This work was sponsored by the Federal Highway Administration in cooperation with the American Association of State Highway and Transportation Officials. It was conducted in the second Strategic Highway Research Program (SHRP 2), which is administered by the Transportation Research Board of the National Academies. The project was managed by James Bryant, Senior Program Officer for SHRP 2 Renewal.

The research team comprised Newton Jackson and Jason Puccinelli, Nichols Consulting Engineers, Chtd.; Dr. Joe Mahoney and Dr. Steve Muench, University of Washington; Dr. Karim Chatti and Dr. Neeraj Buch, Michigan State University; Dr. Dan Zollinger and Dr. Tom Scullion, Texas A&M; George White, Pavia; Dr. Julie Vandenbossche, University of Pittsburgh; Dr. E. B. Lee, University of California, Berkeley; and Dr. Katie Hall, ARA.

Of particular importance to the outcome of this project were the contributions from a number of individuals who helped coordinate meetings and who provided comments and recommendations throughout the project: Gregory Stukel, Illinois Tollway Authority; Mike Eacker, Michigan Department of Transportation; Dr. Shongtao Dai, Minnesota Department of Transportation; John Donahue and Bill Stone, Missouri Department of Transportation; Dr. Magdy Mikhail, Texas Department of Transportation; Trenton Clark and Alex Teklu, Virginia Department of Transportation; Jeff Uhlmeyer, Washington State Department of Transportation; Larry Scofield, American Concrete Paving Association; and Dr. Dave Newcomb, National Asphalt Paving Association.

FOREWORD

James W. Bryant, Jr., PhD, PE, *SHRP 2 Senior Program Officer, Renewal*

On roadways that have acceptable geometric features, renewal can be greatly accelerated and costs reduced if the existing pavement can be incorporated into the new pavement structure. Transportation agencies need reliable procedures that allow them to identify when an existing pavement can successfully be used in place and how to incorporate it into the new pavement structure to achieve long life. This report and the accompanying guide and web tool provide guidance for selecting, designing, and constructing long-life pavements by using existing pavement structure.

The goal of this project was to develop reliable procedures and guidelines for identifying when existing pavements can be used in place and the methods necessary to incorporate the original material into the new pavement structure while achieving long life. "Long life" was defined as 50 years or longer from the time the pavement was renewed or rehabilitated until the next major rehabilitation. (This report does not provide guidance on the use of routine overlays designed for maintenance and preservation, which is included in the report and guide for SHRP 2 Renewal Project R26, Preservation Approaches for High-Traffic-Volume Roadways.)

The report and guide encourage longer-lasting renewed pavement designs; provide realistic, easy-to-use pavement thickness scoping assessments; and guide users through the data-gathering process needed for input into designing and constructing a long-life pavement by using the existing pavement structure. The guide includes the following: project assessment manual; best practices for rehabilitation of flexible pavements and rigid pavements; guide specifications; life-cycle cost analysis; and emerging pavement technology. All the guidance has been incorporated into the web-based pavement design scoping tool, which is meant to complement, not replace, a transportation agency's normal processes for design and pavement-type selection. The guide and web tool were developed with the support of several transportation agencies, including the Illinois Tollway Authority, Michigan DOT, Minnesota DOT, Missouri DOT, Texas DOT, Virginia DOT, and Washington DOT.

As a result of outreach to transportation agencies, a set of enhancements is currently under way and will be included as a future addendum to the report and guide. Those enhancements will include providing guidance on pavement thickness for 30 to 50 years of rehabilitated design life and updating the guidance and design table to incorporate precast concrete pavements and composite pavement as options for the rehabilitation strategy.

CONTENTS

Executive Summary

This report documents the findings from the second Strategic Highway Research Program (SHRP 2) R23 project, Using Existing Pavement in Place and Achieving Long Life. This project falls within the SHRP 2 Renewal area, which focuses on improving the ability of highway agencies to design and construct long-lasting highway projects with minimal disruption to the traveling public. The project found that construction costs and time can be greatly reduced if the existing pavement can be used in place for part of the rehabilitation solution.

The goal of this project was to develop reliable procedures that identify when existing pavements can be used in place and what methods are necessary for incorporating the original material into the new pavement structure while achieving long life. SHRP 2 has defined "long-life pavements" as those lasting in service for 50 years or longer without needing major rehabilitation. This project concentrated on understanding the state of the art of rapid renewal approaches currently used either nationally or internationally to construct long-lived pavement for high-volume roadways.

Through literature reviews, industry interviews, international surveys, and extensive interactions with numerous state highway agencies (SHAs), this project developed a list of renewal alternatives that use the existing pavement in place. The list of alternatives included not only composite pavement sections but also both flexible and rigid pavements. Project and performance records from the SHAs and numerous site visits were used to gather valuable information about each renewal alternative. Data on pavement performance captured in the Long-Term Pavement Performance (LTPP) database and detailed analyses of those data using the *Mechanistic-Empirical Pavement Design Guide* (MEPDG), PerRoad, and other analytical tools were used to evaluate the advantages and disadvantages of each approach under different site conditions and the features critical to achieving long life. From these analyses, criteria on when an existing pavement could be used in place were established. The project team also considered situations where modification of the existing pavement structure would be needed before renewal activities to ensure long life. Figure ES.1 shows an unbounded portland cement concrete (PCC) overlay in the state of Washington that is providing excellent performance after 35 years of service.

Project Development Guidelines

The project team developed a set of decision matrices, organized as tables, to aid highway agencies in the identification of renewal strategies. Separate matrices, with associated decision paths, were developed for selecting renewal options for the various, existing pavement types. The decision matrices account for types of deterioration or surface distress in existing pavement, as well as structural response (i.e., deflections), subgrade conditions, and other site-specific constraints. The intent of the decision matrices is to provide a set of feasible long-life alternatives and to include both flexible and rigid pavement renewal options as outputs.

Figure ES.1. Photo of 35-year-old unbonded PCC overlay on I-90.

Additionally, a series of flexible and rigid pavement renewal thickness design tables was established to supplement the decision matrices. These thicknesses provide approximate ranges (or scoping) for long-life pavement designs and are intended as a starting point for project-level design. The design thicknesses were developed based on newer design approaches including the MEPDG, PerRoad, and other analytical tools.

Selecting, designing, and constructing an optimal renewal alternative that will achieve long-life performance require attention to detail. While fragments of these details have been addressed in documentation available before the study, a comprehensive set of resources specifically devoted to addressing long-life renewal did not exist. Therefore, this project developed a set of resource documentation that addresses details critical to achieving long life. The documentation addresses long-life concepts at every stage of a project, starting at the assessment stage and continuing through feasible approach selection, design, traffic staging considerations, life-cycle cost analysis, and construction specifications. The following six documents, whose development was part of the study, address each stage of a project.

Project Assessment Manual

The Project Assessment Manual was prepared to provide a systematic collection of relevant pavement-related data. The manual is meant to complement the design tools developed by the study. The types of data critical for making pavement-related decisions are described along with methods (analysis tools) for organizing the information for decision making.

Best Practices for Flexible Pavements and Best Practices for Rigid Pavements

The best practices documents for both flexible and rigid pavements provide a collection of best practices for the design and construction of long-life flexible pavement alternatives using existing pavements. Standard practices for added lanes and transitions to adjacent structures are also discussed.

Guide Specifications

The Guide Specifications document was developed in a format that would allow SHAs to easily make additions or modifications to their existing specifications. The specifications recommendations for long life are organized into three sections, which are (1) guide specifications for pavement components that are not contained within the American Association of State Highway and Transportation Officials (AASHTO; 2008) Guide Specifications, (2) elements that can be added to or otherwise modify existing AASHTO Guide Specifications, and (3) summaries for relevant SHAs and AASHTO specifications that were used to produce the “elements” in item 2.

Life-Cycle Cost Analysis

Most public agencies have specific procedures in place for life-cycle cost analyses, and it is expected that those agencies will follow those procedures. For any agency that does not have a specific procedure in place, the team provided a general discussion of life-cycle cost analysis in the Life-Cycle Cost Analysis document.

Emerging Technology

The document on emerging technology discusses rigid and flexible pavement technologies that are not yet considered to be long life renewal options but that may become so in the future as field performance is accrued.

Interactive Software

To provide a user-friendly means of navigating the large amount of information, and to automate the use of the decision matrices and thickness design tables, a computer-based application that guides the users through the process was established. A screenshot of the opening screen is shown in Figure ES.2.

Product Validations

All of the products and tools described above were developed in close consultation with several SHAs. Specifically, extensive interaction took place with seven agencies: Illinois Tollway Authority, Michigan Department of Transportation (DOT), Minnesota DOT, Missouri DOT, Texas DOT, Virginia DOT, and Washington DOT. A series of visits were made to each agency over the

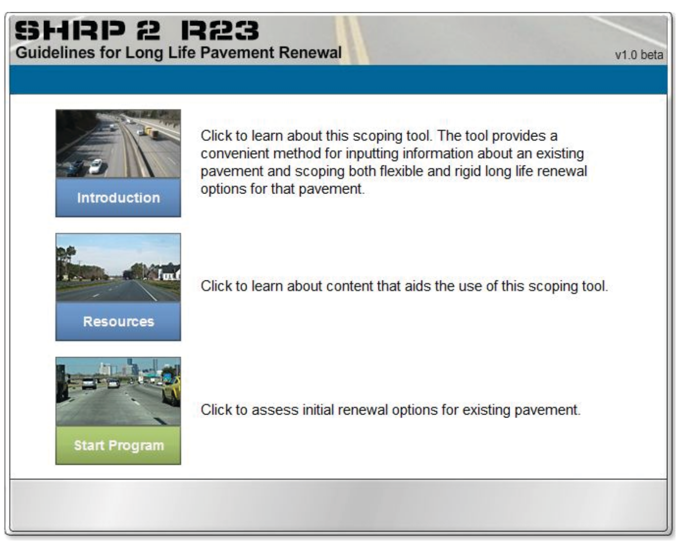


Figure ES.2. Opening screen from the interactive software.

course of the project to obtain information and solicit feedback on the products. These visits were typically structured as follows:

- *Kick-off meetings.* The objectives and preliminary findings of the project were discussed. Additionally, field visits were made to multiple renewal projects throughout each agency. Relevant project information was obtained from agency records.
- *Test case meetings.* These meetings focused on soliciting feedback regarding the decision matrices and thickness design tables, as well as the resource documentation. Access to the beta version of the interactive software was provided along with presentations explaining the development and use of the software. Coordination with each agency took place to identify and obtain information for one project to be used as a test case. This test case was used to compare the agency's standard design approach for pavement renewal with the recommendations provided by the new guidelines. In many cases, a field visit to the project was made to conduct a visual assessment of the site and capture photographs of the pavement and drainage features. A design report using the guidelines and interactive software was developed for the test case, which included feasible flexible and rigid pavement renewal strategies. The results were compared to the agencies' standard design approach for the project. The Virginia and Washington test cases both included analyses of construction productivity, lane closure alternatives, and traffic impacts using the CA4PRS software. The test-case comparisons generated valuable feedback from the agencies.
- *Workshops.* The team organized and facilitated one pilot workshop in Washington and two regional workshops in Virginia and Missouri. The workshops were attended by representative departments within the agency, as well as local contractors and industry representatives. Adjacent state agency personnel were invited to attend the regional workshops. Near the end of each workshop, each participant was asked to complete a questionnaire. Overall, the participants viewed the guidelines as valuable and useful. In particular, the resource documentation was viewed by attendees as providing excellent content for pavement designers. All of the comments received were reviewed and addressed in the final guidelines.

Through these visits, meetings, workshops, and interactions, the community vetted the products developed under this study, and they form a practical set of tools for pavement engineers and designers.

Implementation and Recommended Research

The guidelines that this project developed provide a single source of current information on a comprehensive list of approaches that an agency can reasonably apply to design and build pavements that use existing pavements in place and achieve long life. The products were placed in an interactive program to facilitate use and implementation. The guidelines are unique in that they not only address the design approaches but also provide guide specifications that are congruent with those approaches. To enhance implementation, this product should be housed on the web to ensure accessibility to the pavement community. Recommended future enhancements include modifying the guidelines and resource documents to include design lives of less than 50 years and enhancing the interactive software. Such enhancements would include the addition of a self-directed tutorial and conversion of static documents like the Project Assessment Manual, Guide Specifications, and best practices into a content management system with cross-linked pages to aid in accessibility and to improve search capabilities of the documentation.

CHAPTER 1

Background

This report documents the findings from SHRP 2 Renewal Project R23, Using Existing Pavement in Place and Achieving Long Life. The SHRP 2 Renewal area focuses on improving the ability to design and construct long-lasting highway projects quickly with minimal disruption to the traveling public. Key components to achieving these objectives include the application of innovative methods and materials for preserving, rehabilitating, and reconstructing the nation's transportation infrastructure. Specific to the R23 project, construction costs and time can be greatly reduced if the existing pavement can be used in place as part of the rehabilitation solution.

During the past 20 years, there have been numerous projects where the existing pavement was either modified in place or used as is and a new structural pavement was placed on top. Both asphalt and concrete pavement solutions have shown promise, but there is limited in-service performance on heavy-duty pavements. Techniques include rubblizing and crack and seat technique for asphalt-over-concrete pavements and concrete-over-concrete or concrete-over-asphalt pavements.

There is a need for reliable procedures that allow agencies to identify when an existing pavement can successfully be used in place and how to incorporate it into the new structural pavement to achieve long life. The guidelines, resource documentation, specifications, manuals, and software developed as part of the SHRP 2 R23 effort focused on addressing these needs.

This effort concentrated on understanding the state of the art of rapid renewal approaches currently used both nationally and internationally to construct long-lived pavement for high-volume roadways. The project also identified promising alternatives to renewal approaches currently in use (but without substantive performance history) or imminently on the horizon. SHRP 2 has defined long-life pavements as those lasting in service for 50 years or longer (details on the long-life definition can be found in subsequent sections of this report).

State highway agency (SHA) participation and contribution to this project were critical in developing a practical and useable set of guidelines and tools. The project team recognizes the critical and substantial information and feedback provided by the following agencies:

- Illinois Tollway Authority (ITA);
- Michigan Department of Transportation (MDOT);
- Minnesota Department of Transportation (MnDOT);
- Missouri Department of Transportation (MoDOT);
- Texas Department of Transportation (TxDOT);
- Virginia Department of Transportation (VDOT); and
- Washington State Department of Transportation (WSDOT).

Project Objectives

The goal of this project was to develop reliable procedures that identify when existing pavements can be used in place and the methods necessary to incorporate the original material into the new pavement structure while achieving long life. To that end, the project had the following objectives:

- Identification of alternatives for using existing pavements in place for rapid renewal;
- Analysis of advantages and disadvantages of each approach under different conditions;
- Development of detailed criteria on when an existing pavement can be used in place, with or without significant modification;
- Identification of practices and techniques available to construct pavements with the above characteristics; and
- Determination of the optimal methods to integrate the renewed pavement with adjacent pavements and structures.

Scope of Work

Project R23 was structured in two phases. Phase 1 consisted of five tasks:

1. Document current renewal approaches in use by SHAs.
2. Analyze renewal approaches to determine which factors are critical for success.
3. Develop criteria for when existing pavement can be used, with or without modification.
4. Present advantages and disadvantages of each approach under different project conditions.
5. Develop an interim report and Phase 2 work plan.

Phase 1 focused on documenting the existing practices, analyzing each approach to determine which factors are critical for success, establishing criteria on when the existing structure requires modification (i.e., pulverization, rubblization, crack and seat) as part of the renewal, and evaluating the advantages or disadvantages of renewal approaches. These findings served as the basis for developing practical design guides in consultation with seven SHAs during Phase 2. This was accomplished by working with the states to develop draft guidelines, using the guidelines on a test project in each state, and then facilitating two regional workshops with the agencies where agency personnel, industry, and contractors were able to provide input on the process. The workshops were also used to compare designs between the existing agency practice and the new procedure developed from this study.

Phase 2 consisted of the following tasks:

1. Work with seven SHAs to develop practical design guides.
2. Verify usability of design guides by designing actual projects with each SHA.
3. Compare the results from new design guides and existing SHA procedures and solicit feedback through regional workshops.
4. Revise guidelines based on comments from SHAs.
5. Develop final report and final design guidelines.

Report Organization

The research approach used for the study is described in Chapter 2. The methodology associated with the two major phases is described along with the agency interactions.

A summary of the Phase 1 and Phase 2 activities performed for this study is provided in Chapter 3. Details on the national and international literature review and survey can be found in Appendix A. The analysis conducted using test sections from the Long-Term Pavement Performance program can be found in Appendix B. The development of the decision matrices for both flexible and rigid pavement renewal can be found in Appendix C. Appendix D shows how the flexible and rigid pavement renewal thickness design tables were developed.

Chapter 3 provides an overview of the products developed from the project including the interactive software that directs the user through the guidelines and contains the primary resource documentation. The following resource documentation can also be found in this project's guide:

- Guide, Chapter 1—Project Assessment Manual;
- Guide, Chapter 2—Flexible Pavement Best Practices;
- Guide, Chapter 3—Rigid Pavement Best Practices;
- Guide, Chapter 4—Guide Specifications;
- Guide, Chapter 5—Life-Cycle Cost Analysis; and
- Guide, Chapter 6—Emerging Pavement Technology.

A summary including conclusions, implementation, and suggested additional research are provided in this report's Chapter 4.

CHAPTER 2

Research Approach

Introduction

This chapter describes the study's research approach. The primary research was to confirm that long-life pavements could be designed and constructed using the existing pavements as part of the structure. To do this, two major phases were conducted. Phase 1 began the study with a thorough literature review documenting the potential long-life approaches using existing pavements. This included a comprehensive evaluation of state highway agency (SHA) project records and international documentation. Detailed analyses of pavement performance, including information from the Long-Term Pavement Performance (LTPP) database, were used to confirm the approaches that could provide 50 years of service life. During Phase 2, additional information became available and it was used to refine the findings from Phase 1, as well as to develop the guidelines and tools delivered as part of the project.

SHRP 2 defined long-lived pavements as those that last 50 years or longer without requiring major structural rehabilitation or reconstruction. This definition was the primary criterion that resulted in the findings and products associated with this study.

Phased Research Approach

This project's research started with an extensive discovery process in Phase 1, consisting of agency surveys, literature reviews, and specific queries of individuals throughout the world. The information gained in Phase 1 was used to develop the long-life guidance in Phase 2. Additionally, more detailed information was collected during site visits with several agencies in Phase 2. Information gathered in both Phase 1 and Phase 2 was used to produce the research findings and products described in Chapter 3.

Phase 1 Structure

The Phase 1 discovery process consisted of the following individual tasks:

- Literature review;
- National and international survey of practice;
- Review of practices in 15 states;
- Analysis of LTPP data to confirm long-life performance of different approaches; and
- Mechanistic-Empirical Pavement Design Guide (MEPDG) and PerRoad runs to predict long-life performance.

A literature search for information on highway renewal using existing pavements in place was conducted. The findings from the literature review are discussed in Chapter 3 with details in Appendix A.

Literature Review

The literature review served three purposes. First, it allowed the team to refine the definition of long-life pavements, as well as typical criteria that are currently used by the industry to differentiate between conventional and long-life pavements. Second, it provided a means to develop a complete list of viable approaches that have been used by SHAs and show promise for meeting the established long-life criteria. Third, the data from the literature provided insight into the design, features, and configurations of each alternative.

The following list shows the strategies that were obtained from the literature review:

- Asphalt concrete (AC) over AC renewal methods:
  - AC over existing AC pavement,
  - AC over rubblized AC pavement,
  - AC over reclaimed AC (recycling), and
  - Lane additions.

- AC over portland cement concrete (PCC) renewal methods:
  - AC over existing continuously reinforced concrete pavements,
  - AC over crack and seat jointed plain concrete pavements (JPCPs),
  - AC over rubblized JPCP, and
  - Lane replacement (inlay) and lane additions.
- PCC over PCC-renewal methods:
  - Unbonded PCC overlay of PCC pavement,
  - Bonded PCC overlay of PCC pavement, and
  - Lane replacement (inlay) and lane additions.
- PCC over AC renewal methods:
  - Unbonded PCC overlay of AC pavements,
  - Bonded PCC overlay of AC pavements, and
  - Lane replacement (inlay) and lane addition.

These approaches were analyzed as part of Phase 1, and the findings are described in Chapter 3.

Survey of Practice

A survey of national and international practices was part of the Phase 1 effort. Questionnaires were sent to each of the SHAs, the Federal Highway Administration (FHWA), and industry. These were followed by a series of e-mails and phone calls to learn more about individual projects. In some cases, the team visited SHAs to obtain project-level information. The agencies surveyed are listed below (those that responded are in bold):

- **National Asphalt Pavement Association;**
- **American Concrete Pavement Association;**
- SHAs and FHWA division offices of Alabama, **Alaska, Arizona,** Arkansas, California, **Colorado, Connecticut,** Delaware, District of Columbia, **Florida, Georgia,** Hawaii, Idaho, **Illinois, Indiana, Iowa, Kansas,** Kentucky, **Louisiana, Maine, Maryland,** Massachusetts, **Michigan,** Minnesota, Mississippi, Missouri, Montana, **Nebraska,** Nevada, **New Hampshire, New Jersey, New Mexico, New York, North Carolina,** North Dakota, **Ohio,** Oklahoma, **Oregon,** Pennsylvania, Puerto Rico, Rhode Island, **South Carolina,** South Dakota, Tennessee, **Texas, Utah, Vermont, Virginia, Washington,** West Virginia, Wisconsin, and Wyoming;
- **Antigo Construction, Carlo Construction, Duit Construction;** and
- Government and industry contacts in **Argentina, Australia, Belgium, Canada (British Columbia, Ontario, and Québec),** Chile, Colombia, **Germany, Italy,** Japan, **the Netherlands, South Africa, Sweden, Taiwan,** and the **United Kingdom.**

To obtain more detailed information, several agencies and individuals were contacted. The following individuals provided information on the approaches that had been used by their agency and how they were performing:

- Colorado (Steve Olson);
- Florida (Bruce Dietrich);
- Georgia (Georgene Geary);
- Indiana (Dave Kumar);
- Iowa (Chris Brake);
- Michigan (Michael Eacker);
- New York (Wes Yang);
- North Carolina (Judith Corley-Lay);
- Ohio (Roger Green);
- Oklahoma (Jeff Dean);
- Ontario (Tom Kazmierowski);
- Oregon (John Coplantz);
- South Carolina (Andrew Johnson);
- Texas (Magdy Mikhail); and
- Washington (Jeff Uhlmeyer).

These contacts provided access to the available documentation. In several cases, they provided project-specific information including design documents, copies of plan sheets, date of construction, and current condition. A sample of this information is illustrated in the plan section (Figure 2.1) provided by the Oregon DOT.

LTPP Data and MEPDG Analysis

Neither the literature review nor the survey of current practices confirmed the long-life performance of the approaches being considered. Although there was information on the long-life aspects of new pavements, there was none on the approaches for using existing pavements in place. To provide more information on service life, both the specific pavement study (SPS) and the general pavement study (GPS) sections in the LTPP database were investigated. There were several SPS and GPS experiments that specifically included some of the approaches being considered.

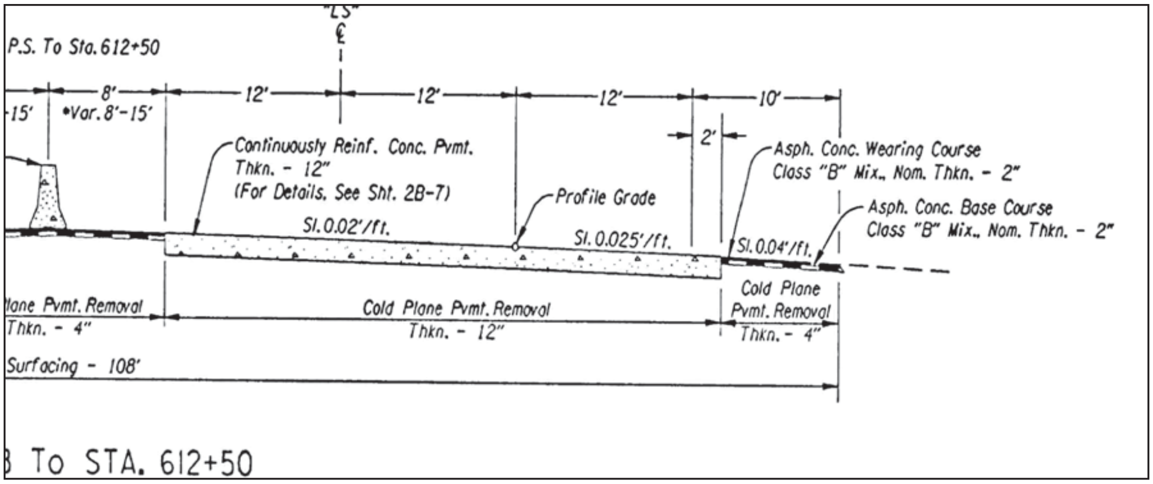
For the flexible pavements sections, the following LTPP experiments were considered:

- GPS-6A and GPS-6B (AC overlay over AC pavement);
- GPS-7A and GPS-7B (AC overlay over PCC);
- SPS-5 (AC overlay of AC pavement); and
- SPS-6 (rehabilitation of jointed PCC pavement).

For rigid pavement sections, they were the following:

- GPS-9 (unbonded PCC overlays of PCC pavement); and
- SPS-7 (bonded PCC overlays on PCC pavements).

In most cases, the LTPP data indicated general trends but the performance periods were not long enough to show which approaches would provide the long-life service required for



Courtesy of John Coplantz.

Figure 2.1. Example of plan section provided by the Oregon DOT.

the study. To provide additional insight, specific test sites for both flexible and rigid pavements were analyzed using the MEPDG. At the time of the analysis, the MEPDG did not include limiting strain criteria, so PerRoad was also used (which does provide for selection of limiting strain criteria). Features that would produce long-life performance and those that might limit long-life performance were considered. The findings are described in Chapter 3, and the detailed analysis of both the LTPP data and the MEPDG is included in Appendix B.

Phase 2 Structure

Phase 2 had several activities that were continuations from Phase 1. The critical activities were the following:

- Develop guidelines based on findings from Phase 1.
- Work with seven agencies to develop and test the guidelines, using
  - Agency visits; and
  - Test cases.
- Develop an interactive program to facilitate the use of the guidelines and provide a platform for the information needed to produce long-life pavements.
- Develop the information needed to produce long-life pavements, which is contained in the following documents:
  - Guide, Chapter 1—Project Assessment Manual;
  - Guide, Chapter 2—Flexible Pavement Best Practices;
  - Guide, Chapter 3—Rigid Pavement Best Practices;
  - Guide, Chapter 4—Guide Specifications;
  - Guide, Chapter 5—Life-Cycle Cost Analysis; and
  - Guide, Chapter 6—Emerging Pavement Technology.
- Conduct two regional workshops to get additional feedback on the guidelines.

Guidelines were developed initially in outline form and then converted to decision tables, which made them easier to use. The development of the guidelines and their refinements based on agency reviews and comments is described in this report's Chapter 3.

Agency Visits

Seven agencies were visited during the development of guidelines. Those agencies and the primary contacts were the following:

- Illinois Tollway Authority (Steven Gullien);
- Michigan DOT (Michael Eacker);
- Minnesota DOT (Shongtao Dai);
- Missouri DOT (John Donahue, William Stone);
- Texas DOT (Magdy Mikhail);
- Virginia DOT (Trenton Clark, Alex Teklu); and
- Washington State DOT (Jeff Uhlmeyer).

In the initial set of meetings, the team met with the agency to introduce the project and obtain appropriate details. The team asked the agencies to identify specific projects where they had used the previously identified approaches and to provide the following information, where available:

- Design procedure;
- Typical thicknesses;
- Construction considerations;
- Specifications;
- Performance;
- Construction risks and issues;
- Reason for any changes or modifications over time; and
- Reasons for abandoning approaches, if applicable.

The team also made field visits to projects constructed by the agency using renewal alternatives considered for inclusion in the guidelines. Details on these field visits can be found in Chapter 3.

Test Cases

In part of agency visits, the team and agency personnel identified potential projects that could be used as test cases for comparing what the agency had done to application of the guidelines. Those projects were the following:

- Michigan: I-75 in Cheboygan County;
- Minnesota: I-35 in Chisago County;
- Missouri: I-55 in Perry County;
- Texas: US-75 Loy Lake Road to Exit 64;
- Virginia: I-95 in Caroline County; and
- Washington: I-5 in Skagit County (at Bow Hill).

The data collected from each agency were used to develop a design report using the guidelines and interactive software. For each test case, feasible flexible and rigid pavement renewal strategies were developed and documented. The results were compared to the agencies' standard design approach for the project. Only two of the test cases dealt with long-life designs by the individual agency. For the other four cases, the guidelines were compared to current practice, which were 20-, 30-, or 40-year designs.

Resource Development

Considerable effort was taken to develop the resource documents that go with the guidelines. There are approximately 400 pages of documents that were prepared to be used with the decision tables. Designing and building long-life pavements typically require more attention to detail than simple treatment selection and thickness design. Those details that should be considered in designing and building long-life pavements include the following:

- Pavement assessment;
- Best practices for flexible pavements;
- Best practices for rigid pavements;
- Guide specifications;
- Life-cycle cost analysis;
- Emerging technology;
- Traffic considerations; and
- Life-cycle assessment.

A set of six resource documents were developed to address these details and are described in more detail in Chapter 3.

Workshops

Two regional workshops and a local pilot workshop were conducted to assess the guidelines. The team organized and facilitated one pilot workshop in Washington and two regional workshops in Virginia and Missouri. The pilot workshop was held with Washington State Department of Transportation employees from design, materials, construction, and traffic divisions. Additionally, local contractors and industry representatives participated. Similarly, the two regional workshops were attended by representative departments within the agency, as well as local contractors and industry representatives. Adjacent state agency personnel were invited to attend and public advertisement of the workshop was conducted in accordance with the agency's protocols. Attendance by adjacent state representatives generally was not possible because of travel restrictions. However, these representatives received access to all of the material and were asked to provide comments.

The agendas distributed before each workshop contained information on the purpose and objective of the workshop. A link was also provided to the interactive guideline software and resource documentation so that attendees could complete some advanced reading and review of the material.

During each workshop, presentations were provided on the resource documentation developed as part of the study, as well as results from the test cases. Several scenarios were demonstrated using the software. The group was asked for their comments and feedback based on the material presented at the workshop. All dialogue was documented and utilized to modify the deliverables of the project.

Near the end of the workshop, each participant was asked to complete a questionnaire. Overall, the participants viewed the guidelines as valuable and useful. In particular, the resource documentation was viewed by attendees as a solid tool for pavement designers. All of the comments received were reviewed and addressed in the final guidelines.

CHAPTER 3

Findings and Applications

Introduction

The major findings from the project were assembled into one application with several resource documents, which collectively serve as guidelines for roadway renewal using existing pavements. Implementation and use of the guidelines will be largely dependent on the ease of use and practicality of the products. To this end, an interactive software program was developed to package the major components of the guidelines. The software and associated resource documents are described following an overview of the study development findings.

Phase 2 activities built upon and refined the findings from Phase 1 to develop a comprehensive set of decision matrices, design tables, and resource documentation that, collectively, comprise the renewal guidelines. In developing these guidelines, significant coordination took place with the agency partners as identified in Chapter 2.

Long-Life Definitions

Rigid Pavements

Long-life concrete pavements exist in the United States, as evidenced by the number of high-age pavements that remain in service. Fortunately, at this time, advances in design, construction, and materials provide the knowledge and technology needed to consistently achieve a long life.

Some distress development over a concrete pavement's service life is expected. However, the rate of distress development is managed by incorporating sound designs, durable paving materials, and quality construction practices. Generally recognized threshold values in the United States for distresses at the end of the pavement's service life are listed in Table 3.1 for jointed plain concrete pavements (JPCPs) and continuously reinforced concrete pavements (CRCPs).

Flexible Pavements

The purpose of long-life flexible pavements is to significantly extend current pavement design life by restricting distress, such as cracking and rutting, to the pavement surface. Common distress mechanisms such as bottom-up fatigue cracking and rutting in the unbound layers should, in principle, be eliminated for long life. However, surface-initiated (top-down) cracking will still be possible in hot-mix asphalt (HMA). This type of cracking is caused by a combination of pavement structure, load, and environmental and material characteristics. Although its causes are still not fully resolved, this deterioration mechanism involves a fatigue-like response in the upper layers of the pavement. In addition to fatigue cracking and rutting, in cold climates, low-temperature cracking and frost heave must be eliminated or significantly reduced. Another deterioration mechanism is aging. Aging mainly affects the top asphalt layers and is manifested by increased stiffness and decreased flexibility over time.

A common denominator of the distress mechanisms is that they are difficult to model using current mechanistic-empirical methods. Some of the distresses require advanced response and/or performance models. In the case of top-down cracking and permanent deformations in the asphalt-bound layers, new and improved design methods may address this in the future.

For asphalt concrete pavements, achieving long life requires the combination of a rut- or wear-resistant surface layer with a rut-resistant intermediate layer and a fatigue-resistant base layer. As illustrated in Figure 3.1 (Newcomb, Buncher, and Huddleston 2001), this requires a high-quality HMA wearing surface or an open graded friction course, a thick stiff dense graded intermediate layer, and possibly a flexible (asphalt-rich) bottom layer. In addition, the pavement foundation must be strong enough to satisfy the limiting strain criteria.

When using existing pavements in the renewal process, the inhibition of reflective cracking is crucial. Reflective cracking is caused by repetitive shearing—for example, when a new

Table 3.1. Threshold Values for Long-Life Concrete Pavement Distresses

Distress	Threshold Value
Cracked slabs, % of total slabs (JPCP)	10–15
Faulting, mm (in.) (JPCP)	6–7 (0.25)
Smoothness (IRI), m/km (in./mi) (JPCP and CRCP)	2.5–3.0 (150–180)
Spalling (length and severity) (JPCP and CRCP)	Minimal
Materials-related distress (JPCP and CRCP)	None
Punchouts, no./km (no./mi) (CRCP)	10–12 (12–16)

Source: Tayabji and Lim 2007.

asphalt layer is laid upon an already cracked layer. With time, the crack will propagate through the new layer. This is true regardless of the existing pavement type [i.e., distressed HMA or portland cement concrete (PCC)], although experience shows that reflective cracking can be more predominant when the existing pavement is a rigid pavement.

Background on Existing Renewal Approaches

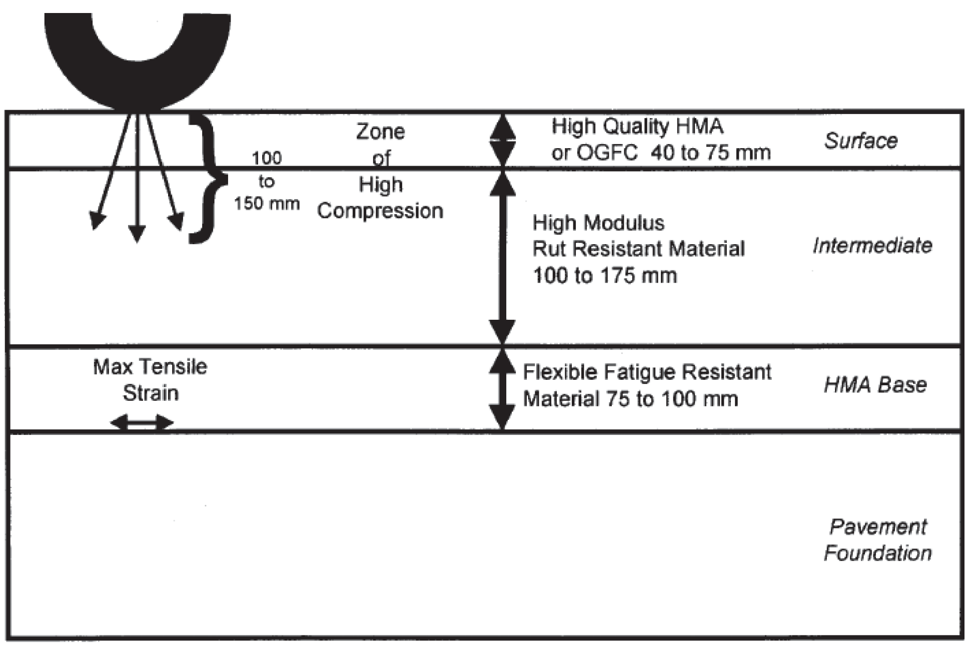
The project team sought information on highway renewal using existing pavements for both flexible and rigid pavement renewal types. In addition, questionnaires were distributed to state highway agencies (SHAs) and international representatives to solicit input on experience with the various renewal approaches. The following sections provide an overview of both relevant literature and practitioners' experience. Details on the literature review can be found in Appendix A.

Rigid Pavement Renewal

Long-life rigid pavement renewal strategies involve concrete overlays. Smith, Yu, and Peshkin (2002) state that the success of long-life renewal alternatives using existing pavements hinges on two critical parameters: (1) the timing of the renewal and (2) the selection of the appropriate renewal strategy. The selection and timing are dependent on factors such as the condition of the existing pavement, the rate of deterioration of the distress, the desired performance, lane closures and traffic control considerations, and user costs.

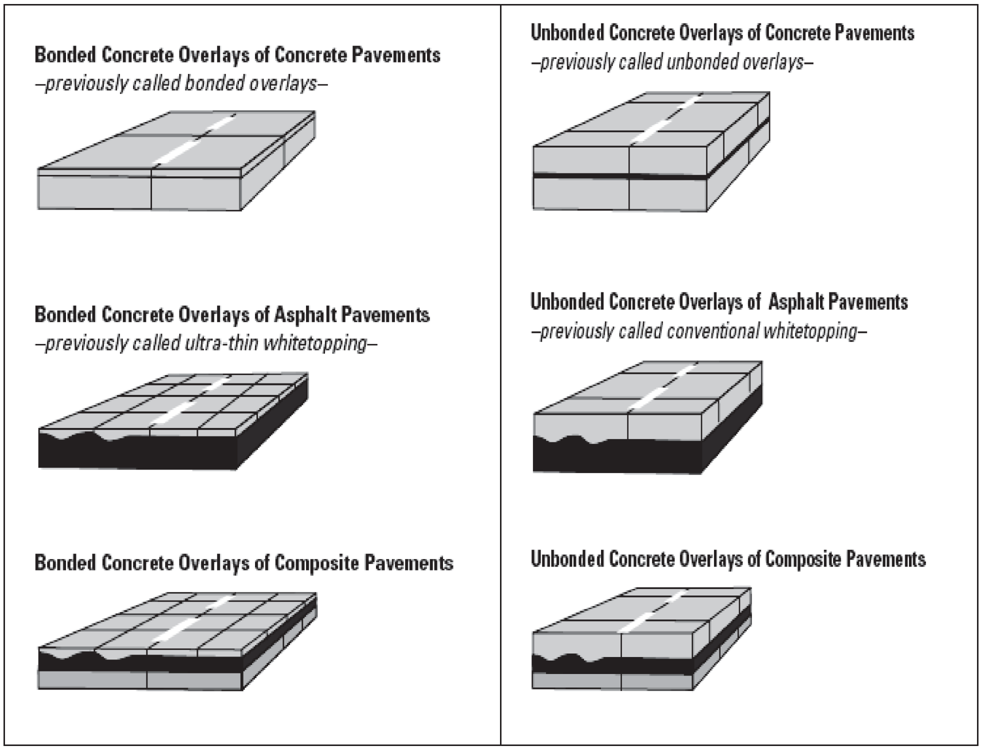
Recent concrete overlay terminology was described by Harrington (2008). These definitions provide a straightforward description of concrete overlays as shown in Figure 3.2. Two categories are shown: (1) unbonded concrete overlays and (2) bonded concrete overlays. Subcategories are defined based on the underlying pavement, which can be (1) concrete, (2) asphalt, or (3) composite pavements.

Detained performance observations of bonded concrete overlays were obtained from the Texas Department of Transportation (TxDOT), Washington State Department of Transportation (WSDOT), and Minnesota Department of Transportation (MnDOT). Observed performance of 4- to 8-in. bonded overlays by TxDOT personnel indicated that their thicker bonded CRCP overlays can be expected to perform up to 25 years; however, TxDOT only recommends a



Source: Newcomb et al. 2001.

Figure 3.1. Long-life flexible pavement design concept.



Source: Harrington 2008.

Figure 3.2. Types of concrete overlays.

design life of 5 to 10 years for 4- to 7-in. bonded concrete overlays of asphalt pavements (TxDOT 2011).

The literature and documented SHA experience with bonded concrete overlays is supported by the data within the Long-Term Pavement Performance (LTPP) database (discussed in a subsequent section). These experience and performance data for slabs up to about 6 in. thick suggest that a 50-year life is unlikely for bonded concrete overlays.

Harrington (2008) found that bonded overlays are used to "add structural capacity and/or eliminate surface distress when the existing pavement is in good structural condition. Bonding is essential, so thorough surface preparation is necessary before resurfacing." Harrington also noted that unbonded overlays are used to "rehabilitate pavements with some structural deterioration. They are basically new pavements constructed on an existing, stable platform (the existing pavement)." This concept of unbonded concrete overlays being similar to new pavement construction is expanded below.

A best practices document by Tayabji and Lim (2007) overviewed a selection of design, materials, and construction features for new concrete pavements for four SHAs (Illinois, Minnesota, Texas, and Washington). These practices were updated based on recent information and are summarized in Table 3.2 and Table 3.3. Minnesota and Washington were grouped together in Table 3.2 since their practices are for JPCP. Illinois and Texas are summarized in Table 3.3 to reflect their CRCP practices. Although these practices were developed with new pavement construction in mind, they are applicable to long-life concrete overlay systems. This type of information illustrates the following:

- For JPCP
  - Design lives range from 50 to 60 years.
  - Slab thicknesses range between 11.5 and 13.0 in.
  - Joint spacings are 15 ft long, doweled, and corrosion resistant.
  - Maximum water/cementitious ratios range between 0.40 and 0.44.
- For CRCP
  - Design lives range from 30 to 40 years.
  - Slab thicknesses range between 13.0 and 15.0 in.

A more specific example of a long-lasting concrete overlay over preexisting PCC comes from Washington State. WSDOT constructed an unbonded concrete overlay on I-90 over 35 years ago. Figure 3.3 is a photograph of this overlay taken in 2010. The overlay is still performing well as of 2011 with no observable distress.

Belgium is the only country outside the United States identified in this review as having reported appreciable experience with unbonded concrete overlays (Hall et al. 2007). Belgium constructed its first concrete overlay in 1960, over a concrete

Table 3.2. Examples of Long-Life JPCP Standards for MnDOT and WSDOT

Item	Minnesota DOT	Washington DOT
Design life	• 60 years	• 50 years
Typical structure	• Slab thicknesses = 11.5–13.5 in. • 3- to 8-in. dense-graded granular base • Subbase 12–48 in. select granular (frost resistant)	• Slab thickness = 12–13 in. (typical) • 4-in. HMA base • 4-in. crushed stone subbase
Joint design	• Spacing = 15 ft with dowels • All transverse joints are doweled	• Spacing = 15 ft with dowels • Joints saw cut with single pass • Hot poured sealant
Dowel bars	• Diameter = 1.5 in. (typical) • Length = 15 in. (typical) • Spacing = 12 in. • Bars must be corrosion resistant	• Diameter = 1.5 in. • Length = 18 in. • Spacing = 12 in. • Bars must be corrosion resistant. Epoxy coatings not acceptable.
Outside lane and shoulder		• 14-ft lane with tied PCC or HMA • 12-ft lane with tied and dowel PCC
Surface texture	• Astroturf or broom drag • Longitudinal direction • Requires 1-mm average depth in sand patch test (ASTM E965)	• Longitudinal texturing
Alkali-silica reactivity (ASR)	• Fine aggregate must meet ASTM C1260 (ASR Mortar-Bar Method) • Expansion ≤ 0.15% is OK. If ≥ 0.30%, reject. • Mitigation required by use of ground granulated blast furnace slag (GGBFS) or fly ash when expansion is between 0.15% and 0.30%.	• Allow various combinations of Class F fly ash and GGBFS.
Aggregate gradation	• Use a combined gradation	• Use a combined gradation.
Concrete permeability	• Use GGBFS or fly ash to lower permeability of concrete • Apply ASTM C1202 for rapid chloride ion permeability test.	
Air content	• 7.0% ± 1.5%	• 5.0% ± 2.0%
Water/cementitious ratio	• ≤ 0.40	• ≤ 0.44 • Minimum cementitious content = 564 lb/CY of PCC mix
Curing	• No construction or other traffic for 7 days or flexural strength ≥ 350 psi.	• Traffic opening compressive strength ≥ 2,500 psi by cylinder tests or maturity method
Construction quality	• Monitor vibration during paving	

Sources: Tayabji and Lim 2007, MnDOT 2005, WSDOT 2010.

pavement originally constructed in 1934. The jointed reinforced concrete pavement (JRCP) overlay is 7 in. thick. Figure 3.4 shows the overlay still in service nearly 45 years later.

The study review found that design thicknesses of unbonded PCC overlays are typically greater than or equal to 9 in. for Interstate applications. This is supported by data from LTPP. In a study by Smith et al. (2002), a large number of unbonded overlay projects were identified and the highway agencies asked to rate their performance from good to poor. They found a strong correlation between thickness and performance, as shown in Figure 3.5. This figure was generated based on expert opinion from the study perform by Smith et al. (2002). It is evident that, for long-life pavements in high-traffic-volume applications, the unbonded overlay thickness should be 9 in. or greater.

A recurring theme emerges in examining the literature and practices discussed above: (1) thick unbonded PCC slabs are used, (2) design lives are greater than or equal to 30 years ranging up to 60 years, and (3) PCC mix and materials requirements are important. Thus, long-life PCC renewal options are not just about slab thickness but also about materials and construction, as expected. Key considerations include the following:

- Foundation support (uniformity, volumetric stability—including stabilizing treatments);
- Drainage design (moisture collection and removal and design for minimal maintenance);
- Concrete mixture proportioning and components (selected, e.g., to minimize shrinkage and potential for chemical attack,

Table 3.3. Examples of Long-Life CRCP Standards for the Illinois and Texas DOTs

Item	Illinois DOT	Texas DOT
Design life	• 30–40 years	• 30 years
Typical structure	• Up to 14-in. CRCP slab • 4- to 6-in. HMA base • 12-in. aggregate subbase	• Up to 13 in. CRCP slab with one layer of reinforcing steel • 14- to 15-in. CRCP slab with two layers of reinforcing steel • Uses stabilized base either 6-in. CTB with 1-in. HMA bond breaker on top or 4-in. HMA • Recommends tied PCC shoulders
Tie bars	• Use at centerline and lane-to-shoulder joints • Use 1-in. by 30-in. bars spaced at 24 in.	
CRCP reinforcement	• Reinforcement ratio = 0.8% • Steel depth 4.5 in. for 14-in. slabs • All reinforcement in CRCP epoxy coated	• Increased amount of longitudinal steel • Design details for staggering splices
Aggregate requirements	• Illinois DOT applies tests to assess aggregate freeze-thaw and alkali-silica reactivity (ASR) susceptibilities	
PCC mix		• Limits the coefficient of thermal expansion of concrete to ≤ 6 microstrains per degree Fahrenheit.
Construction requirements	• Limits on concrete mix temperature = 50–90°F • Slipform pavers must be equipped with internal vibration and vibration monitoring • Curing compound must be applied within 10 min of concrete finishing and tining • Curing ≥ 7 days before opening to traffic	• Revised construction joint details

Sources: Tayabji and Lim 2007; TxDOT.

for low coefficient of thermal expansion, and to provide adequate strength);
- Dowels and reinforcing (corrosion resistance, sized and located for good load transfer);
- Construction parameters (including paving operations, surface texture, initial smoothness, etc.); and
- Quality assurance/quality control (e.g., certification, prequalification, inspection).

Flexible Pavement Renewal

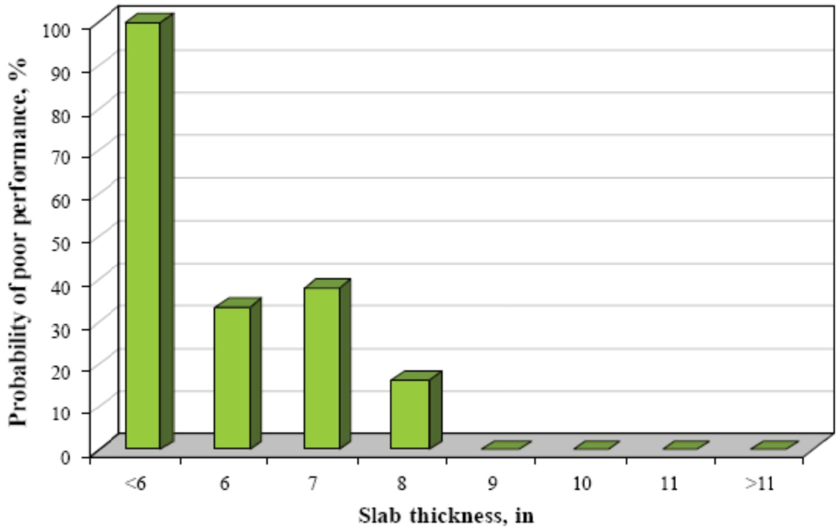
The review of flexible pavement renewal included the following seven approaches, each of which is briefly described below:

- HMA over HMA renewal methods
  - HMA over existing HMA pavement and
  - HMA over reclaimed HMA (recycling).

Figure 3.3. Photo of 35-year-old unbonded PCC overlay on I-90 MP 74.

Source: Hall et al. 2007.

Figure 3.4. Belgium's first concrete overlay after 45 years in service.



Source: Smith et al. 2002.

Figure 3.5. Probability of poor performance for unbonded JPCP overlays.

- HMA over PCC renewal methods
  - HMA over crack and seat JPCPs,
  - HMA over saw, crack, and seat JRCPs,
  - HMA over rubblized JPC pavements,
  - HMA over composite pavements, and
  - HMA over existing CRCPs.

HMA Overlay and Existing HMA Pavement

If there is no visible distress in the existing HMA pavement other than that in isolated areas, the existing pavement can be directly overlaid as long as it is determined to be structurally sound, level, clean, and capable of bonding to the overlay. However, when visible surface distress is present and it is determined (through coring) to be near the surface, milling is required prior to the overlay.

HMA Overlay and Reclaimed HMA

In cases where the surface of the existing HMA layer is in poor condition, and the depth of the distress (cracking) is deeper in the pavement section, reclaiming the existing HMA pavement before the placement of new layers is required. To enable use of the existing pavement, this solution entails the pulverization of the existing HMA layer. However, by definition, once this solution is adopted, the reclaimed HMA material is considered a base layer and its thickness should not be included in the total HMA thickness that is used to calculate the limiting tensile strain at the bottom of that layer.

The main limitation of this renewal solution is that the performance of partial- and full-depth reclamation with cement or asphalt emulsion has not been substantiated for long life. Records on performance are highly variable because there has not been a common definition applied to judge the comparative performance levels. Causes commonly noted for poor performance using cold in-place recycling include (Hall et al. 2001) (1) use of an excessive amount of recycling agent; (2) premature application of a surface seal; (3) recycling only to the depth of an asphalt layer, resulting in delamination from the underlying layer; and/or (4) allowing a project to remain open for too long into the winter season. Also, excessive processing can result in higher fines content, leading to rutting because of low stability.

HMA Overlay and Crack and Seat JPCP

HMA over crack and seat JPCP is suitable for plain (unreinforced) concrete pavements. The performance of this renewal option has been variable in the United States. This could be tied to the quality of the cracking operation. The rationale behind the crack and seat technique is to shorten the effective slab length between the transverse joints or cracks in the existing concrete pavement before placing the HMA overlay. This will distribute the horizontal strains resulting from thermal movements of the concrete more evenly over the existing pavement, thus reducing the risk of reflective transverse cracks in the HMA overlay. If construction guidelines ensure closely spaced, tight, full-depth vertical cracks, then potential for long life should be achievable.

Experience in the United Kingdom has been excellent with crack and seat projects, but with a strict quality control process and a minimum HMA overlay thickness in excess of 6 in. (Jordan et al. 2008). Thinner overlays like those commonly used in the United States were not found to perform as well in test sections in the United Kingdom (Coley and Carswell 2006). In addition, Caltrans (2004) has extensive experience with crack and seat processing of PCC slabs followed by an HMA overlay. The agency applies this treatment wherever the PCC pavement has an unacceptable ride and extensive slab cracking. The typical crack spacing is about 4 ft by 6 ft, followed by seating with five passes of a pneumatic-tired roller of at least 15 tons (Caltrans 2008). For several years, the overlay thickness associated with the crack and seat process ranged from a minimum of 4 in. up to about 6 in. Service-life expectation was a minimum of 10 years with these thicknesses [or about 10 to 20 million equivalent single axle loads (ESALs)]. Starting in 2003 with the I-710 rehabilitation of existing 8-in.-thick PCC slabs near Long Beach (Monismith et al. 2009), the crack and seat process is followed by HMA overlays that are 9 in. thick. The design ESAL levels for these sections of I-710 have ranged between 200 and 300 million. This renewal strategy adopted by Caltrans implies a long life of at least 40 years.

HMA Overlay and Saw, Crack, and Seat JRCP

The crack and seat technique of fracturing reinforced concrete pavements (JRCPs) has generally not performed well because of its inability to shear the steel reinforcement or break the bond between the reinforcing steel and concrete. The bonded and unsheared reinforcing steel results in thermal contraction concentrated at the existing transverse joints, thus leading to reflective cracks through the HMA layer.

An alternative solution used primarily in the United Kingdom is the saw, crack, and seat approach, which involves sawing narrow transverse cuts into the concrete deep enough to cut through the longitudinal steel reinforcement, and then cracking the pavement at the locations of the sawed cuts, using the same crack and seat procedure described above (Merrill 2005). Verification coring should follow to ensure that fine, full-depth, vertical cracks are achieved. The U.K. Department of Transport Road Note 41 (Jordan et al. 2008) recommends a saw and crack spacing of 3 to 6 ft. Under these conditions, the critical features and limitations are the same as for the crack and seat approach. Similar to crack and seat process, thicker overlays were found to perform substantially better than thinner overlays in test sections in the United Kingdom (Coley and Carswell 2006).

HMA Overlay and Rubblized JRCP and JPCP

The rubblization approach effectively eliminates the problem of reflection cracking, because the technique is supposed to completely disintegrate the existing concrete slab and debond the concrete from the reinforcing steel. However, this also reduces the strength of the existing concrete pavement substantially because it renders the concrete into broken fragments resembling an unbound base course, although with "aggregate" sizes much larger than a regular crushed aggregate base layer. Thus, it is the only approach that uses the existing concrete pavement and fully addresses slab movement responsible for reflective cracking, particularly for JRCP.

Von Quintus et al. (2007) reviewed the performance of HMA overlays of PCC pavements from the 2005 LTPP database. Those findings suggest that sections without edge drains or those with rubblized pieces less than 2 in. in size exhibit higher levels of distress.

SHA experience indicates construction difficulties with rubblization if the foundation underneath the existing concrete is not sufficiently strong. The rubblization process can damage the base or subbase and/or the existing subgrade and produce an unstable condition. Sebesta and Scullion (2007) refined a risk assessment methodology for rubblization first developed in Illinois (Heckel 2002) based on dynamic cone penetrometer testing. This process is fully described in this project's guide, Chapter 2 (Flexible Pavement Best Practices).

HMA Overlay and Existing Composite Pavement

HMA overlay of existing HMA-surfaced composite pavement is also a viable long-life HMA renewal solution. Sebesta and Scullion (2007) recommend milling the old HMA overlay completely off to expose the existing PCC pavement. The PCC pavement should be modified using either the crack and seat approach; the saw, crack, and seat approach; or the rubblization approach described above.

HMA Overlay and Existing CRCP

HMA over existing CRCP has significant potential to provide long life. This is because a CRCP eliminates moving joints within the concrete slab as it develops narrow transverse cracks at a regular spacing. If these cracks remain tight, then no reflection cracking should appear in the HMA overlay as long as the surface of the existing CRCP is in good condition and a good bond between the HMA overlay and the CRCP is achieved. This solution should lead to thinner HMA overlays compared to HMA over existing jointed concrete pavements. The main limitation of this renewal strategy is that any untreated or improperly treated defect in the existing CRCP can develop into a major repair. Studies have shown that the placement of HMA overlays can accelerate D-cracking, resulting in poor performance of HMA overlays (Liu et al. 2003). Therefore, this approach would only apply to CRCP in good condition. Also, if bonding is not properly ensured, water caught between the HMA overlay and the existing CRCP can lead to stripping and HMA deterioration. Finally, the performance of HMA overlays on CRCPs has been variable in the United States. Therefore, the performance of HMA overlays using this solution has not been substantiated for a long life

(>50 years), and their use in the context of long-life pavements, while possible, is still unproven.

Regardless of the flexible pavement renewal approaches reviewed, the following principles are required to achieve well-performing long-life pavements:

- The quality of construction is essential in achieving long-life pavements.
- Pavements are supposed to act as one layer; therefore, the bond between layers should never be compromised, and a few thick layers are better than multiple thin layers.
- All joints are weaknesses; therefore, they need to be treated as such.
- Good, continuous, and sustainable drainage is essential to long-life pavement; therefore, no matter how thick the renewal solution is, it can fail if drainage is not sufficient.
- Foundation uniformity is essential to reduce or eliminate stress concentrations, which can cause future cracking.
- A solid foundation allows good compaction; unsupported edges can never be properly compacted.
- Thermal movements of the existing pavement are the underlying cause for much reflective cracking; therefore, they must be eliminated (by fracturing the existing pavement).
- Well-performing asphalt mixtures should have high binder content and low air voids (to have high durability) and smaller nominal size (to avoid segregation).

LTPP Analyses

The research team reviewed the LTPP database to provide insight into performance of various renewal approaches. A detailed analysis was made of the available, appropriate data. The analyses for both flexible and rigid pavement experiments are shown in Appendix B. In addition, selected projects from the LTPP database were examined by mechanistic-empirical design programs (MEPDG and PerRoad) to determine whether the basic roadway sections were likely to provide long-life pavements and to define critical features and limitations. The following is a summary of both the LTPP and related MEPDG analyses.

Rigid Pavements

The General Pavement Study 9 (GPS-9) (Unbonded PCC Overlay on PCC Pavement) and Specific Pavement Study 7 (SPS-7) (Bonded PCC Overlay on PCC Pavement) experiments were reviewed. The information for both experiments was extracted from the LTPP DataPave Online database (Release 21). The pavement performance criteria selected for the summary included transverse cracking, international roughness index (IRI), joint and crack faulting (JPCP), and punchouts (CRCP only).

The original construction (preoverlay) date for the unbonded PCC overlay sections ranged from the early 1950s to the mid-1970s. The actual overlays included both JPCP and CRCP. The average age of overlays until the test sections were taken out of service was about 17 years. The overlay thicknesses of the various test sections ranged from 5.8 to 10.5 in. with an average joint spacing of 16 ft. The load transfer mechanisms were either aggregate interlock or dowel bars. While a significant fraction of these unbonded PCC overlay GPS-9 test sections have potential for long-life performance, all were monitored for less than 20 years. Figure 3.6 provides a summary of transverse cracking as a function of overlay thickness for JPCP overlay sections. As can be seen, there is a clear difference in performance when overlay thicknesses are greater than 8 in. It should be noted that this finding is very similar to that from Smith et al. (2002) and shown in Figure 3.5.

The LTPP SPS-7 experiment included bonded PCC overlays on PCC pavement. Data from 18 CRCP, 9 JPCP, and

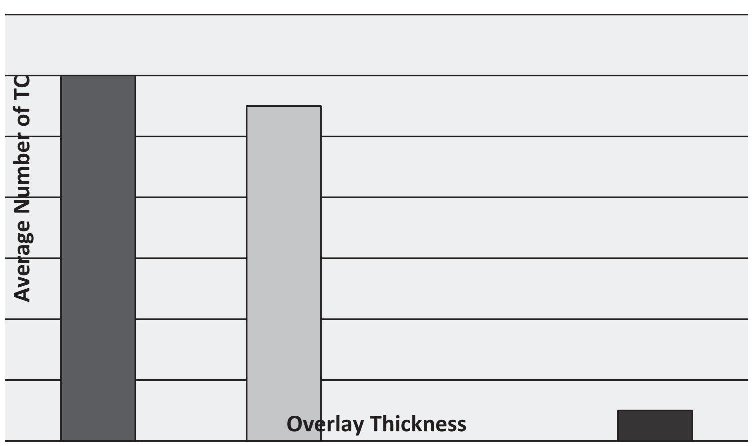


Figure 3.6. JPCP overlay thickness versus average number of transverse cracks.

8 PCC (unreinforced PCC overlays of CRCP) test sections were analyzed. However, these 35 test sections only represent pavements in four locations since multiple SPS-7 test sections were constructed at each project. This is a limited data set given the grouping of test sections.

The average age of overlays at the time the test sections were taken out of the LTPP study (and no longer monitored) was about 15 years. The overlay thicknesses of the various test sections ranged from 3.1 to 6.5 in. The bonded overlays exhibited significant transverse cracking after 15 years of service and are unlikely candidates for long-life renewal.

Because of the limited nature of this experiment, it is difficult to assess the likelihood that bonded concrete overlays will provide a long-life service. This was confirmed with numerous discussions and project evaluations with TxDOT and other SHAs during Phase 2. Observed performance along with mechanistic-empirical analyses implies performance lives of up to 35 years, but 50-year service lives are unlikely.

Flexible Pavements

The following LTPP experiments were reviewed to determine the pavement life achieved for HMA-surfaced pavements where the existing pavement remained in place:

- GPS-6A (Existing AC Overlay of AC Pavement);
- GPS-6B (AC Overlay with Conventional Binder of AC Pavement);
- GPS-7A (Existing AC Overlay of PCC Pavement);
- GPS-7B (AC Overlay with Conventional Binder of PCC Pavement);
- SPS-5 (Rehabilitation Strategies for AC Pavement); and
- SPS-6 (Rehabilitation Strategies for PCC Pavement).

Performance data including longitudinal cracking, fatigue cracking, transverse cracking, rut depth, and IRI were plotted against pavement age. Sections with the longest overlay ages were selected and traffic data (ESALs) corresponding to pavement age were extracted. The next step was to examine the better-performing sections to determine potential long-life pavement candidates. The majority of the test sections evaluated had overlays with ages of 16 years or less. Data from the GPS test sections with overlay ages of up to 34 years were available from the database.

Although none of the test sections had overlays with 50 years of service, a selection of test sections exhibited performance that had the potential to meet the long-life criteria. These test sections were analyzed using the MEPDG and PerRoad software to model each of the test sections for performance.

Limitations in the reflective cracking models, questionable predicted performance curves, and inability of the MEPDG to produce results using HMA over CRCP all limited findings that could be applied to the long-life renewal objectives of the project. Because of this, the sections were analyzed using the PerRoad software, which is based on the mechanistic-empirical approach of calculating pavement response mechanistically and estimating damage using empirical transfer functions and Miner's rule. It uses the concept of limiting strain criteria. PerRoad estimates the time (i.e., pavement life) at which damage accumulation reaches 0.1 according to Miner's rule.

PerRoad results indicated that actual traffic loadings produced horizontal and vertical strains well below reasonable thresholds. Although the field performance observations only captured about 16 years of actual performance, there is virtually no fatigue damage observed for the sites. These findings support the notion that structural designs of flexible pavement renewal alternatives satisfying the limiting strain criteria for fatigue and subgrade rutting have the potential to achieve long-life service, assuming all other critical features are satisfied. PerRoad does not account for reflective cracking in its analysis, which must be considered when selecting the appropriate level of modification to the existing pavement structure.

Assessment of Renewal Approaches

The results of the prior work were used to develop the features and describe the limits of each renewal alternative, which follow.

Rigid Pavements

Table 3.4 provides an overview of critical features and limitations of the rigid pavement renewal approaches.

Flexible Pavements

Table 3.5 provides a summary of critical features and limitations of each of the flexible pavement renewal approaches.

Advantages and Disadvantages of Renewal Approaches

In terms of advantages and disadvantages, Table 3.6 provides an overview of the rigid pavement renewal approaches, and Table 3.7 provides an overview of the flexible pavement renewal approaches. Rigid pavement renewal options require less modification to the existing pavement. As such, there are fewer approaches listed for the rigid pavement renewal as compared to the flexible pavement alternatives.

Based on the preceding findings, decision matrices were developed with the intent of establishing a list of feasible alternatives for a project based on existing conditions. These matrices were submitted in draft form for review and comment by

Table 3.4. Summary of Rigid Pavement Renewal Features and Limitations

Approach	Critical Features	Limitations
Unbonded PCC overlay over existing PCC	• Overlay thickness is critical to performance • Repair locally failed areas • Stable subbase • 1.5-in. diameter rust-resistant dowels • 15-ft maximum joint spacing • Interlayer should not trap water • Thicker HMA interlayer performed better • Adequate drainage	• Significant surface elevation increase • Consistent foundation support when widening • Consistent drainage when widening
Unbonded PCC overlay over existing HMA	• Overlay thickness is critical to performance • Locally failed areas must be repaired • Stable subbase • 1.5-in. diameter rust resistant dowels • 15-ft maximum joint spacing • Adequate drainage	• Significant surface elevation increase • Consistent foundation support when widening • Consistent drainage when widening
Bonded PCC overlay over existing PCC	• Adequate surface preparation • Bonding is a critical feature • Locally failed areas must be repaired • Match joint location, width, type of existing PCC • Adequate drainage	• Existing pavements with materials-related distress are not good candidates • Existing pavements with voids are not good candidates • Working cracks can cause debonding of overlay • Service life up to 35 years

Table 3.5. Summary of Flexible Pavement Renewal Features and Limitations

Approach	Critical Features	Limitations
HMA over existing HMA	• Absence or removal of full-depth cracking • Good foundation support • No stripping • Adequate drainage	• Reconstruction required if base or subgrade is poor • Milling required to remove surface cracking
HMA over reclaimed HMA	• Good foundation support • Adequate drainage • Proper surface prep and tack coat	• Cement and/or emulsion have not yet been proven in field for long life • Reclaimed layer considered as base material
HMA over existing CRCP	• Good foundation support • Adequate drainage • No evidence of pumping • Existing pavement is structurally adequate • Absence or repair of major defects • Good bond of CRCP and HMA	• CRCP has to be in good condition with few major defects (which must be repaired) • Inadequate bonding can lead to poor performance • Unproven for 50-year life
HMA over crack and seat JPCP	• Good foundation support • Adequate drainage • No evidence of pumping	• Inability to break and seat JRCP has been documented • Crack and seat is not viable for reinforced PCC
HMA over saw, crack, and seat JRCP	• Good foundation support • Adequate drainage • No evidence of pumping	• Saw cuts must extend below reinforcement
HMA over rubblized	• Good foundation support • Adequate drainage • No evidence of pumping	• Pavement needs to be adequately drained before rubblization • Performance tied to quality of rubblization process • When subgrade conditions are inadequate, significant damage to base or subgrade has created construction problems

Table 3.6. Advantages and Disadvantages of Rigid Pavement Renewal Approaches

Rigid Pavement Renewal Approach	Advantages	Disadvantages
Unbonded concrete overlay over PCC	• Very good long-term performance with minimal maintenance or rehabilitation • Insensitive to existing pavement condition • Best documented record of projects in place that have achieved long life	• Significant surface elevation gain • Placement or cure time may make work-zone management difficult
Bonded concrete overlay	• Smallest vertical elevation gain	• Unlikely to be viable for service lives longer than 35 years
Unbonded concrete overlay over HMA	• Requires little preparation for existing pavement • Easily accommodates lane addition	• Significant surface elevation gain • Placement or cure time may make work-zone management difficult

the study review panel. Details are discussed in the following section.

Design Guides

The development of design guides started with development of a draft decision process based on the initial study results. The following strategies were included:

- HMA over existing HMA;
- HMA over reclaimed or milled existing HMA pavement;
- HMA over existing CRCP;
- HMA over crack and seat existing JPCP;
- HMA over saw, crack, and seat existing JRCP;
- HMA over rubblized existing JPCP or JRCP;
- Unbonded concrete overlay over existing JPCP, JRCP, or CRCP; and
- Unbonded concrete overlay over existing HMA.

Development of Decision Matrices

A set of decision matrices, organized as tables, were developed to aid in the scoping of renewal strategies. Separate matrices, with associated decision paths, were developed for selecting renewal options for the various, existing pavement types. The existing pavement types include flexible, rigid

Table 3.7. Advantages and Disadvantages of Flexible Pavement Renewal Strategies

Flexible Pavement Renewal Approach	Advantages	Disadvantages
HMA over reclaimed/milled HMA pavement	• Elimination of all existing deterioration that could lead to reflective cracking	• Existing pavement is considered base material in renewal structural design • Significant thickness of new HMA required over modified existing structure
HMA over CRCP	• Utilizes CRCP in place as part of renewal	• HMA wearing surface will need to be removed or replaced at 10- to 20-year cycles
HMA over crack and seat	• Does not diminish the structural competency as much as rubblization	• Reflection cracking risk • Performance dependent on quality of crack and seat • HMA wearing surface will need to be removed/replaced at 10- to 20-year cycles
HMA over saw, crack, and seat	• Does not diminish the structural competency as much as rubblization	• Reflection cracking risk • Performance dependent on quality of crack and seat • HMA wearing surface will need to be removed or replaced at 10- to 20-year cycles • Costs associated with sawing
HMA over rubblized	• Elimination of features in existing pavement that cause reflective cracking • Stiffness of rubblized material greater than granular base • Total HMA thickness is less than that over granular base	• Construction risk with weak or wet subgrade • Performance dependent on quality of rubblization process • Poorly rubblized material cannot be improved through additional rubblization • Raises surface elevations • HMA wearing surface will need to be removed or replaced at 10- to 20-year cycles

(JPCP, JRCP, and CRCP), and composite pavements. Specific decision tables, regardless of existing pavement type, use three levels of decision making, as illustrated in Table 3.8. The surface condition of the existing pavement is the primary information required for starting the renewal decision-making process.

The guidelines were developed to help designers in selecting either a rigid or flexible reconstruction approach that can reasonably be expected to provide long-life pavement performance. For this project, long-life performance was defined as providing 50 years of service without major structural deterioration. It is anticipated that any approach selected will require some form of rehabilitation or resurfacing during the service life of the pavement. The final selection of the most appropriate design should be based on a life-cycle cost analysis of the various approaches, including all rehabilitation or resurfacing costs over the life of the pavements.

The development of the decision matrices followed a process where team members laid out an outline of the decision process. The outline had the basic form seen on the tables with pavement type, distress present, and potential renewal approaches for those conditions. The outline was circulated to the full team and modified as additional considerations were added. The outline was presented at the kickoff meetings and then circulated among the participating agencies for comment, and again adjustments were made. To make the process clearer the decision matrix was put in a set of tables. The tables were then circulated again to the full R23 team and the participating agencies, who provided more comments (most likely because the tables were easier to follow than the outlines). The tables were then used to build an interactive Flash-based program that would simplify using the decision matrix. In building the logic for the interactive program, a few more decision points were added based on the more rigorous nature of that process. After the program was developed, it was evaluated through a series of trials that included a wide range of potential applications. The decision tables were adjusted again based on errors or omissions found in that process. The interactive program and the decision tables were again presented to the participating agencies for review and comment and final adjustments were made to the program and the tables presented in this report.

The decision matrices account for deterioration and surface distress types present in existing pavement, as well as structural response (i.e., deflections) and subgrade conditions. They provide a feasible set of alternatives based on in situ conditions of the existing pavement. For example, if full-depth cracking is present and the quantity is large enough to make full-depth patching cost prohibitive, the decision matrix eliminates the alternative to mill existing HMA and overlay with new HMA.

Table 3.8. Organization and Decision Levels for Renewal Selection

Decision Levels	First Level		Second Level	Third Level	
Basis for Decision	**Identify Distress Category**	**Identify Specific Distress Type within a Distress Category**	**Select Renewal Pavement Type**	**Renewal Action**	**Design Resources**
Details associated with each decision. Decision tables a function of the existing pavement type.	*Existing flexible* • Environmental cracking • Materials caused distress • Full-depth fatigue cracking • Top-down cracking	• Transverse or block cracking • Stripping • Longitudinal or alligator cracking	Either a flexible or rigid option can be selected for each specific distress or category.	Describes what is to be done to the existing pavement and the type of renewal strategy.	Describes the design resources to be used to complete the scoping process.
	Existing JPCP or JRCP • Materials caused distress • Pavement cracking • Joint faulting and movement • Pumping	• D-cracking • Alkali-silica reactivity (ASR) • Fault depth • Joint deflection			
	Existing CRCP • Punchouts	—			
	Existing composite • Surface course condition	—			

Instead, for the flexible alternative, full-depth pulverization or reclamation is recommended along with HMA overlay. The decision process would also recommend an unbonded concrete overlay as a rigid renewal alternative.

The intent of the decision matrices is to provide a set of feasible long-life alternatives. Both flexible and rigid renewal options are included as outputs. The decision matrices are shown in Table 3.9 (renewal of existing flexible pavement), Table 3.10 (renewal of existing JPCP and JRCP), Table 3.11 (renewal of existing CRCP), and Table 3.12 (renewal of composite pavements). Three rules are commonly referenced in Tables 3.9 through 3.12 under the Design Resources column.

Rule 1

Rubblization of existing PCC and then application of AC overlay are detailed in this project's guide. Rubblization guidelines include the following:

- If the subgrade M_R < 6,000 psi or CBR < 4%, do not rubblize, thus defaulting to crack and seat only.
- If the subgrade $M_R \geq$ 6,000 psi but M_R < 10,000 psi, consult the TTI rubblization guidelines as to whether rubblization is viable (Sebesta and Scullion 2007).
- If the subgrade $M_R \geq$ 10,000 psi, then rubblization is a viable option.

The selection of the AC thickness is based on a drop-down menu of subgrade moduli of 5,000 psi, 10,000 psi, or 20,000 psi. The existing pavement shall be characterized by one of four possible moduli: 30,000 psi, 50,000 psi, 75,000 psi, or 100,000 psi. It is recommended that an existing pavement modulus equal to 50,000 psi be used to reflect rubblized PCC.

Rule 2

Regarding crack and seat existing PCC followed by application of AC overlay, see Tables 3.13 through 3.15. The selection of the AC thickness is based on a drop-down menu of subgrade moduli of 5,000 psi, 10,000 psi, or 20,000 psi. The existing pavement shall be characterized by one of four possible moduli: 30,000 psi, 50,000 psi, 75,000 psi, or 100,000 psi. It is recommended that an existing pavement modulus of 75,000 psi be used for crack and seat PCC to produce thickness in line with those recommended in TRL Road Note 41 (Jordan et al. 2008).

Rule 3

Use Table 3.16 for thickness determination of an unbonded PCC overlay and place on a 2-in.-thick AC bond breaker. The unbonded PCC overlay thickness is independent of subgrade support conditions.

Development of Renewal Thickness Designs

In part of its study, the project developed the thickness design tables that the decision matrices reference. These thicknesses provide approximate ranges for scoping purposes. They can also be used as a starting point for project-level design, but the agency-specific design methodologies should be used to develop the final thickness design.

The flexible pavement renewal thickness design tables were developed using the limiting strain approach via the PerRoad, Version 3.5 software. Numerous scenarios were analyzed using PerRoad, including combinations to account for the following factors:

- Traffic levels;
- Subgrade stiffness;
- Base stiffness;
- Base thickness;
- Seasonal temperatures (from climatic data) for five locations;
- Standard PG binder specifications for five locations;
- Tensile strains at the bottom of the HMA layer; and
- Damage ratio scenarios (0.1 at 10 years and 0.1 at 50 years).

For each combination of factors, PerRoad was run iteratively to find the HMA thickness that would provide a damage ratio less than or equal to 0.1 at 10 years and 50 years of service life. Details about the analyses can be found in this project's guide. The final design thicknesses used in the guidelines are shown in Tables 3.13 through 3.15. These thicknesses are representative of analyses from five U.S. locations. It is expected that any agency using the guidelines will refine the design thickness using their standard design procedure.

The rigid pavement renewal thickness design tables were developed in a similar fashion as the flexible pavement renewal alternatives. AASHTO 93 and MEPDG Version 1.1 were used in the development of the rigid pavement thickness design tables. AASHTO 93 was used during a preliminary investigation on thickness requirements. Numerous iterations were conducted using MEPDG to account for the following factors:

- Traffic levels;
- Performance criteria thresholds;
- Mixture properties;
- Shoulder support; and
- Geographic location.

(continued on page 30)

Table 3.9. Feasible Renewal Alternatives for Existing Flexible Pavements

Distress Category	Specific Distress Description	Distress Present?	Renewal Pavement Type Option	Action	Design Resources
Environmental cracking	Transverse or block cracking	Yes	Flexible	Pulverize pavement structure full depth followed by a thick AC overlay.	Pulverize and use residual material as untreated base (50 ksi). Apply AC thickness from Tables 3.13–3.15.
					Pulverize and treat residual material with emulsion or foamed asphalt resulting in a treated base (100 ksi). Apply AC thickness from Tables 3.13–3.15.
			Rigid	No mitigation required; place an unbonded PCC overlay.	Use Table 3.16 for thickness determination of an unbonded PCC overlay.
		No	—	Continue to “materials-caused distress.”	—
Materials-caused distress	Stripping	Yes	Flexible	If stripping is found through all layers, pulverize pavement structure full-depth followed by a thick AC overlay.	Pulverize and use residual material as untreated base (50 ksi). Apply AC thickness from Tables 3.13–3.15.
					Pulverize and treat residual material with emulsion or foamed asphalt resulting in a treated base (100 ksi). Apply AC thickness from Tables 3.13–3.15.
				If stripping is found in specific layers, remove AC to maximum depth of stripping followed by a thick AC overlay.	Use Tables 3.13–3.15 with 30-ksi base and the subgrade M_R to determine total depth of AC thickness, then subtract remaining AC thickness to determine overlay thickness.
			Rigid	Place unbonded PCC overlay. If grade limits require, mill existing pavement. AC overlay over stripped pavement may be required to stabilize HMA.	Use Table 3.16 for thickness determination of an unbonded PCC overlay.
		No	—	Continue to “full-depth fatigue cracking.”	—

(continued on next page)

Table 3.9. Feasible Renewal Alternatives for Existing Flexible Pavements (continued)

Distress Category	Specific Distress Description	Distress Present?	Renewal Pavement Type Option	Action	Design Resources
Full-depth fatigue cracking	Longitudinal or alligator cracking in wheelpaths	Yes	Flexible	<15% fatigue cracking: patch and repair, moderate thickness AC overlay.	Use Tables 3.13–3.15 with 30-ksi base for AC overlay thickness, then subtract existing AC thickness to determine overlay thickness.
				>15% fatigue cracking: pulverize pavement structure full-depth followed by a thick AC overlay.	Pulverize and use residual material as untreated base. Apply AC thickness from Tables 3.13–3.15 with 50-ksi base.
					Pulverize and treat residual material with emulsion or foamed asphalt resulting in a treated base. Apply AC thickness from Tables 3.13–3.15 with 100-ksi base.
			Rigid	Patch severely cracked areas, place an unbonded PCC overlay. Profile elevation may require milling existing AC pavement.	Use Table 3.16 for thickness determination of an unbonded PCC overlay.
		No	—	Continue to "top-down cracking."	—
Top-down cracking	Longitudinal or alligator cracking in wheelpaths	Yes	Flexible	<15% patch and overlay.	Use Tables 3.13–3.15 with 30-ksi base and the subgrade M_R to determine total depth of AC thickness, then subtract the thickness milled out to eliminate the top-down cracking (unless indicated the assumed depth is 2 in.). Where patching only, subtract existing depth to calculate overlay.
				>15% mill down to bottom of cracking followed by a moderate thickness AC overlay.	
			Rigid	Place an unbonded PCC overlay.	Use Table 3.16 for thickness determination of an unbonded PCC overlay.

Table 3.10. Feasible Renewal Alternatives for Existing JPCP and JRCP Pavements

Distress Category	Specific Distress Description	Distress Present?	Renewal Pavement Type Option	Action	Design Resources
Materials-caused distress	D-cracking with light severity	Yes	Flexible option for JPCP	Rubblization or crack and seat JPCP followed by a thick AC overlay. For rubblization, apply TTI guidelines (Sebesta and Scullion 2007).	Apply Rule 1.
					Apply Rule 2.
			Flexible option for JRCP	Rubblization or saw, crack and seat JRCP with a thick overlay. For rubblization, apply TTI guidelines (Sebesta and Scullion 2007).	Apply Rule 1.
					Saw, crack, and seat existing PCC followed by application of AC overlay from Tables 3.13–3.15; otherwise, Rule 2 applies.
			Rigid option	Apply 2-in. AC overlay bond breaker followed by an unbonded PCC overlay.	Apply Rule 3.
		No	—	Continue to next level of "D-cracking."	—
	D-cracking with moderate to high severity	Yes	Flexible option with rubblization if subgrade meets TTI guidelines	Rubblize followed by a thick AC overlay. For rubblization, apply TTI guidelines.	Apply Rule 1.
			Flexible option if does not meet TTI guidelines for rubblization	Do not use the existing pavement; requires all new pavement.	—
			Rigid option	Full-depth patch and apply 2-in. AC overlay bond breaker followed by an unbonded overlay.	Apply Rule 3.
		No	—	Continue to "ASR."	—
	Alkali-silica reactivity (ASR)	Yes	Flexible option	Rubblize followed by thick AC overlay. For rubblization, apply TTI guidelines.	Apply Rule 1.
			Rigid option	Patch plus 2-in. AC bond breaker followed by unbonded PCC overlay.	Apply Rule 3.
		No	—	Continue to "pavement cracking."	—
Pavement cracking	% multiple cracked panels	Yes	Flexible option for low to moderate multiple cracked panels (1 to 10% of panels)	Rubblization or crack and seat JPCP with a thick AC overlay. For rubblization, apply TTI guidelines (Sebesta and Scullion 2007).	Apply Rule 1.
			Rigid option for low to moderate multiple cracked panels (1% to 10% of panels)	Place a 2-in. AC bond breaker followed by an unbonded PCC overlay.	Apple Rule 3.
			Flexible option for moderate to high multiple cracked panels (>10% of panels)	If subgrade meets or exceeds TTI criteria, apply rubblization followed by a thick AC overlay.	Apply Rule 1.
				If subgrade does not meet TTI criteria, options include crack and seat or do not use existing pavement.	Apply Rule 2.
			Rigid option for moderate to high multiple cracked panels (>10% of panels)	Replace rocking or shattered slabs followed by a 2-in. AC overlay bond breaker followed by an unbonded PCC overlay.	Apply Rule 3.
		No	—	Continue to "joint faulting."	—

(continued on next page)

Table 3.10. Feasible Renewal Alternatives for Existing JPCP and JRCP Pavements (continued)

Distress Category	Specific Distress Description	Distress Present?	Renewal Pavement Type Option	Action	Design Resources
Joint faulting	—	Yes	Flexible option for low faulting (<0.25 in.)	Rubblization or crack and seat JPCP with a thick AC overlay. For rubblization, apply TTI guidelines (Sebesta and Scullion 2007).	Apply Rule 1.
				Rubblization or saw, break and seat JRCP with a thick AC overlay. For rubblization, apply TTI guidelines (Sebesta and Scullion 2007).	Apply Rule 2.
					Apply Rule 1.
					Saw, crack, and seat existing PCC followed by application of AC overlay from Tables 3.13–3.15; otherwise, Rule 2 applies.
			Rigid option for low faulting (<0.25 in.)	Place a 2 in. AC overly followed by an unbonded PCC overlay.	Apply Rule 3.
		Yes	Flexible option for high faulting (>0.25 in.)	Rubblization or crack and seat JPCP with a thick AC overlay. For rubblization, apply TTI guidelines (Sebesta and Scullion 2007).	Apply Rule 1.
					Apply Rule 2.
				Rubblization or saw, break, and seat JRCP with a thick AC overlay. For rubblization, apply TTI guidelines (Sebesta and Scullion 2007).	Apply Rule 1.
					Saw, crack, and seat existing PCC followed by application of AC overlay from Tables 3.13–3.15; otherwise, Rule 2 applies.
			Rigid option for high faulting (>0.25 in.)	Place a 2-in. AC overlay followed by an unbonded PCC overlay. If joint deflections >40 mils (0.040 in.), then consider crack and seat JPCP or saw, break, and seat JRCP to stabilize slabs.	Apply Rule 3.
		No	—	Continue to “pumping.”	—
Pumping	—	Yes	Flexible	Crack and seat JPCP with a thick AC overlay if the drainage can be improved.	Apply Rule 2.
				Saw, crack, and seat JRCP with a thick AC overlay if the drainage can be improved.	Saw, crack, and seat existing PCC followed by application of AC overlay from Tables 3.13–3.15; otherwise, Rule 2 applies.
				If drainage cannot be improved, then AC based renewal should not be used.	—
			Rigid	If joint deflections >40 mils (0.040 in.), consider crack and seat followed by a 2-in. AC bond breaker followed by an unbonded PCC overlay. Drainage must be improved.	Apply Rule 3.
		No	—	—	—

Table 3.11. Feasible Renewal Alternatives for Existing CRCP Pavements

Distress Category	Specific Distress Description	Distress Present?	Renewal Pavement Type Option	Action	Design Resources
Punchouts	—	Yes	Flexible option with ≤5 punchouts per mile	Repair all punchouts; place thick AC overlay to achieve a longer service life.	Apply AC overlay from Tables 3.13–3.15. The selection of the AC thickness is based on a drop-down menu of subgrade moduli = 5,000 psi, 10,000 psi, or 20,000 psi. The existing pavement shall be characterized by one of four possible moduli to select from: 30,000 psi, 50,000 psi, 75,000 psi, or 100,000 psi.
			Rigid option with ≤5 punchouts per mile	Repair major punchouts if slab load support in question. Follow repairs with a 2-in. AC bond breaker followed by an unbonded PCC overlay.	Apply Rule 3.
			Flexible option with >5 punchouts per mile	Rubblization of CRCP with a thick AC overlay. For rubblization, apply TTI guidelines (Sebesta and Scullion 2007).	Apply Rule 1.
			Rigid option with >5 punchouts per mile	Repair major punchouts if slab load support in question. Follow repairs with a 2-in. AC bond breaker followed by an unbonded PCC overlay.	Apply Rule 3.
		No	—	—	—

Table 3.12. Feasible Renewal Alternatives for Existing Composite Pavements

Distress Category	Specific Distress Description	Distress Present?	Renewal Pavement Type Option	Action	Design Resources
Surface course in fair to poor condition	Can be a range of distress types. For the underlying PCC, these are mostly cracking related.	Yes	Flexible option	Remove existing AC surface(s). Apply rubblization if meets TTI criteria.	Apply Rule 1.
				Remove existing AC surface(s). Use crack and seat or saw, crack, and seat.	Following crack and seat or saw, crack, and seat of existing PCC pavement. Apply Rule 2.
			Rigid option	Place unbonded PCC overlay. If grade limits require, mill existing AC pavement.	Apply Rule 3.
Surface course in very poor condition	Can be a range of distress types. For the underlying PCC, these can include severe D-cracking and ASR.	Yes	Flexible option	Remove and replace existing pavement structure.	—
			Rigid option	Place unbonded PCC overlay. If grade limits require, mill existing AC pavement.	Apply Rule 3.

Table 3.13. Flexible Pavement Renewal Designs

ESALs (millions)	Existing Pavement or Base Modulus			
	30,000 psi	50,000 psi	75,000 psi	100,000 psi
≤10	10.0	9.0	8.0	6.0
10–25	11.0	10.0	8.5	6.5
25–50	12.0	11.0	9.0	7.0
50–100	13.0	11.5	9.5	7.5
100–200	14.0	12.0	10.0	7.5

Note: Subgrade M_R = 5,000 psi.

Table 3.14. Flexible Pavement Renewal Designs

ESALs (millions)	Existing Pavement or Base Modulus			
	30,000 psi	50,000 psi	75,000 psi	100,000 psi
≤10	10.0	8.0	7.0	6.0
10–25	11.0	9.0	8.0	6.5
25–50	12.0	9.5	8.5	7.0
50–100	12.0	10.0	8.5	7.0
100–200	13.0	11.0	9.0	7.0

Note: Subgrade M_R = 10,000 psi.

Table 3.15. Flexible Pavement Renewal Designs

ESALs (millions)	Existing Pavement or Base Modulus			
	30,000 psi	50,000 psi	75,000 psi	100,000 psi
≤10	9.5	7.5	6.5	5.5
10–25	10.0	8.5	7.0	6.0
25–50	11.0	9.0	7.5	6.5
50–100	11.5	9.5	8.0	6.5
100–200	12.0	10.0	8.5	7.0

Note: Subgrade M_R = 20,000 psi.

(continued from page 23)

Initial evaluations indicated that for purposes of thickness tables for the guidelines, Baltimore, Maryland, would provide results that were representative of the range of climates found in the United States. The default calibration coefficients in MEPDG were used in the analysis and yielded results that were similar to those of other geographic locations. The results were also compared to the thickness catalog recently developed by WSDOT for long-life concrete pavement projects based on MEPDG runs calibrated to actual pavement performance in Washington State.

The final design thicknesses selected for use in the guidelines are provided in Table 3.16. Results from the assessment of the LTPP test sections along with findings from prior studies suggest that unbonded concrete overlay thicknesses greater than 8.5 in. exhibit long-life potential. Complete details on the analysis conducted in developing the rigid pavement design thickness table can be found in Appendix D.

Validation

Throughout this project, the team made several visits to the participating agencies to solicit feedback on the guidelines.

During the first set of visits, the findings from Phase 1 along with objectives of the project were discussed. Additionally, field visits were made to multiple renewal projects throughout each agency.

A second round of visits with the agencies focused on soliciting feedback on the decision matrices and thickness design tables, as well as the resource documentation. The interactive software was in beta version for many of these meetings. The team provided access to the beta version along with presentations explaining the development and use of the software. Through this process, valuable comments were received from the agencies.

The team also worked with each agency to identify one project to be used as a test case—as noted in Chapter 2. This test case would be used to compare the agency's standard design

Table 3.16. Rigid Pavement Renewal Designs (AASHTO 93, MEPDG, and WSDOT Results)

ESALs (millions)	AASHTO 93 for k = 500 pci	Design Thicknesses from WSDOT Pavement Policy	Thickness Range for MEPDG for M_R = 5–10 ksi	PCC Slab Thickness for R23 Study (in.)
≤10	10.0	9.0	7.75–8.25	8.5
10–25	11.5	10.0	8.75–9.0	9.5
25–50	12.5	11.0	9.25	10.5
50–100	14.0	12.0	11.5–12.25	11.5
100–200	15.5	13.0	11.25–15.5	13.0

approach for pavement renewal with the recommendations provided by the new guidelines. During the visit, the team acquired detailed design information on the project from each agency to be used as a test case. This included design traffic levels, existing pavement structure, subgrade conditions, falling weight deflectometer (FWD) data (if available), materials test results, and any project constraints (e.g., maintenance of traffic, vertical clearances). In many cases, the team made a field visit to the project to conduct a visual assessment of the site and capture photographs of the pavement and drainage features. The following projects were used as test cases for this study:

- Michigan: I-75 in Cheboygan County;
- Minnesota: I-35 in Chisago County;
- Missouri: I-55 in Perry County;
- Texas: US-75 Loy Lake Road to Exit 64;
- Virginia: I-95 in Caroline County; and
- Washington: I-5 in Skagit County at Bow Hill.

The data collected from each agency were used to develop a design report using the guidelines and interactive software. For each test case, feasible flexible and rigid renewal strategies were developed and documented. The results were compared to the agencies' standard design approach for each project.

As an example, the test case for the Virginia DOT was on I-95, a major traffic corridor for that state. Maintenance of traffic was a major concern and a primary limiting constraint of the renewal strategy selected. For this particular test case, the analysis was expanded to include construction productivity, lane closure alternatives, and traffic impacts. Each of the scenarios was analyzed using CA4PRS and the results were summarized in a report.

In most cases, the recommendations differed between the guidelines and agency standard practice. This was mostly due to differences in thickness design methodologies and design life. The guidelines provide recommendations for 50-year service life, whereas many of the agencies were designing for 20 to 30 years. In other cases, the agency adopted the recommendations that came out of the guidelines. Table 3.17 provides a summary of the renewal strategies for each test case.

For the Washington test case, WSDOT estimated that using the existing pavement in the renewal process reduced the costs by over 25% compared to removing and replacing the existing pavement. There was also a comparable reduction in the time required for construction.

The team organized and facilitated one pilot workshop in Washington and two regional workshops in Virginia and Missouri.

Near the end of each workshop, every participant was asked to complete a questionnaire. Overall, the participants viewed the guidelines as valuable and useful. In particular, the resource documentation (see next section) was viewed by attendees as excellent content for pavement designers. All comments received were reviewed and addressed in the final guidelines.

Resource Knowledge Base

The knowledge base assembled as part of the guidelines includes six documents developed specifically for this project, all of which are provided in this project's guide:

- Guide, Chapter 1—Project Assessment Manual;
- Guide, Chapter 2—Flexible Pavement Best Practices;
- Guide, Chapter 3—Rigid Pavement Best Practices;
- Guide, Chapter 4—Guide Specifications;
- Guide, Chapter 5—Life-Cycle Cost Analysis; and
- Guide, Chapter 6—Emerging Pavement Technology.

A synopsis of each document developed as part of this study is provided below.

In addition, several other resources developed under separate research efforts have been referenced in the knowledge base.

Table 3.17. Comparison of Study and Agency Renewal Approaches

Agency	R23 Recommendation (Flexible)	R23 Recommendation (Rigid)	Agency Renewal Approach
MDOT	9-in. HMA over rubblized or 8-in. HMA over saw, crack, and seat	9.5-in. unbonded concrete overlay (UBCOL) with 2-in. HMA bond breaker	8.5-in. HMA over rubblized PCC pavement
MnDOT	9-in. HMA over pulverized AC pavement	10.5-in. UBCOL	6-in. bonded PCC OL (20-year design)
MoDOT	9.5-in. HMA over rubblized or 8.5-in. HMA over saw, crack, and seat	10.5-in. UBCOL with 2-in. HMA bond breaker	8-in. UBCOL with 1-in. HMA bond breaker or 12-in. HMA over rubblized PCC
TxDOT	9.5-in. HMA over crack and seated PCC pavement	11.5-in. UBCOL with 2-in. HMA bond breaker	6-in. bonded PCC OL (special test case)
VDOT	Mill 6-in. stripped HMA then place 9-in. new HMA	13-in. UBCOL	Mill all 10-in. HMA and replace with 12-in. HMA
WSDOT	Remove existing HMA over PCC, crack and seat PCC, and place 7.5-in. HMA	10.5-in. UBCOL	Remove existing HMA over PCC, crack and seat PCC, and place 8.5-in. HMA

Project Assessment Manual

The Project Assessment Manual was prepared to offer agencies a systematic collection of relevant pavement-related data. Furthermore, such data need to be organized to maximize the usefulness in the pavement decision-making process. To that end, this manual provides an overall assessment scheme (Figure 3.7).

The types of data collection in the manual range from basic information such as a distress survey to insights on construction-related traffic impacts. The last section in the Project Assessment Manual provides information on life-cycle assessments (environmental accounting). This type of assessment is receiving increasing use and is likely to be more widely applied in the future. The complete manual can be found in this project's guide, Chapter 1.

The use of the manual is to complement the design tools developed by the study. The types of data critical for making pavement-related decisions are described along with methods (analysis tools) for organizing the information for decision making. It is not assumed that all data categories will be collected or assessed for a specific renewal project.

The following 10 data types are contained in the Project Assessment Manual:

- Pavement distress surveys;
- Pavement rut depths and roughness;
- Nondestructive testing—FWD;
- Ground-penetrating radar;
- Pavement cores;
- Dynamic cone penetrometer;
- Subgrade soil sampling and tests;
- Traffic loads for design;
- Construction productivity and traffic impacts; and
- Life-cycle assessment (environmental accounting).

Flexible Pavement Best Practices

The Flexible Pavement Best Practices document can be found in this project's guide, Chapter 2. This document provides a collection of best practices for the design and construction of long-life flexible pavement alternatives using existing pavements. The intent is to restrict distress such as cracking and rutting to the pavement surface. The document provides an overview of the renewal strategies and the reasoning behind their selection, as well as the critical features associated with each strategy, including construction issues.

The document also provides a discussion of HMA construction quality control and ties that discussion to the Guide Specifications also provided in the guidelines. Design issues associated with transitions beneath structures are included as illustrated in Figure 3.8.

Rigid Pavement Best Practices

The Rigid Pavement Best Practices document can be found in this project's guide, Chapter 3. This document provides recommendations for the design and construction of long-life rigid pavement alternatives using existing pavements.

The goal of achieving long-life concrete pavements requires an understanding of design and construction factors that affect both short-term and long-term concrete pavement performance. This requires an understanding of how concrete pavements deteriorate and fail, as well as what is required to provide long life both from the structural design and from construction details.

The rigid pavement approaches using existing pavements, as well as the supporting information for their selection, are described. Material considerations common to all approaches

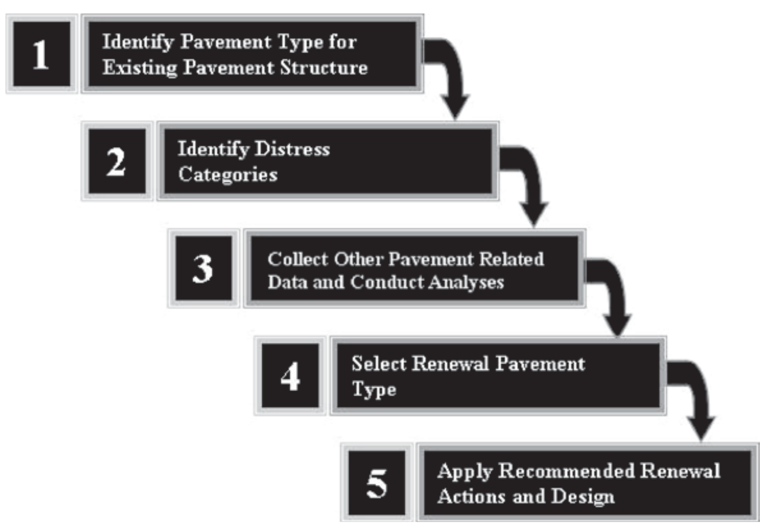


Figure 3.7. Outline of Project Assessment Manual scheme.

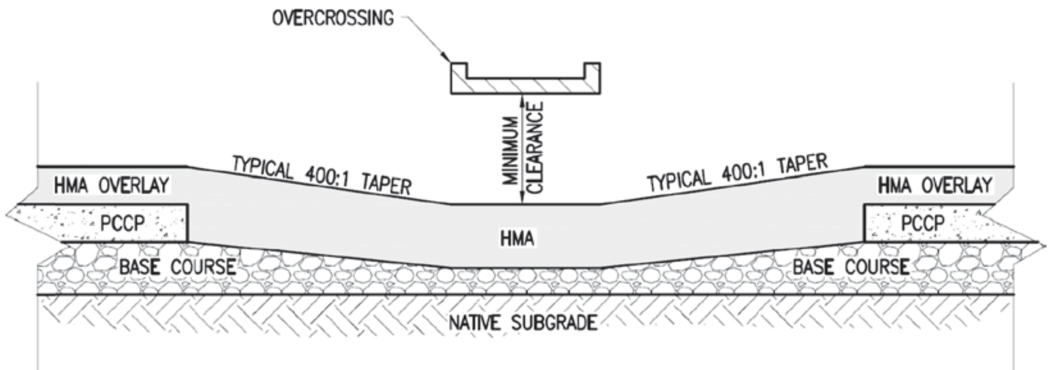


Figure 3.8. Illustration of flexible pavement transitions to overcrossings.

are discussed. The design and construction for the different long-life approaches are presented in some detail along with quality control and assurance needs. Standard practices for added lanes and transitions to adjacent structures are also discussed as illustrated in Figure 3.9.

Guide Specifications

The project team used AASHTO Guide Specifications (2008) as a starting point in specification development. This was done, in part, because there are a wide variety of pavement-oriented specifications developed and maintained by AASHTO committees. Furthermore, the AASHTO specifications provide a common set of terms and structure on which to add components from state specifications. The approach was to review existing state agency and AASHTO guide specifications, select sensible components (or elements), and place those in lists.

The guide specifications are organized into three sections: (1) guide specifications for pavement components that are not contained within the AASHTO Guide Specifications, (2) elements that can be added to or can otherwise modify existing AASHTO Guide Specifications, and (3) summaries for relevant state SHA and AASHTO specifications that were used to produce the elements in item 2. An illustration of specification elements is shown in Table 3.18 for tack coats—a basic paving process spanning several renewal options. The complete specification documentation can be found in this project's guide, Chapter 4.

Four guide specifications are not contained in the AASHTO Guide Specifications, but the R23 team felt them necessary for this study: Stone Matrix Asphalt (SMA); Open Graded Friction Course (OGFC); Rubblization of PCC; and Saw, Crack, and Seat.

Life-Cycle Cost Analysis

These guidelines provide a range of approaches for the design of long-life pavements using existing pavements. The determination as to which approach should be selected will depend on how well they meet the engineering requirements of the project and which is the most cost effective. Determining the cost effectiveness of the various approaches requires a life-cycle cost analysis. Most public agencies have specific procedures in place and it is expected that those agencies will follow those procedures. Where an agency does not have a specific procedure in place, a general discussion of life-cycle cost analysis is included.

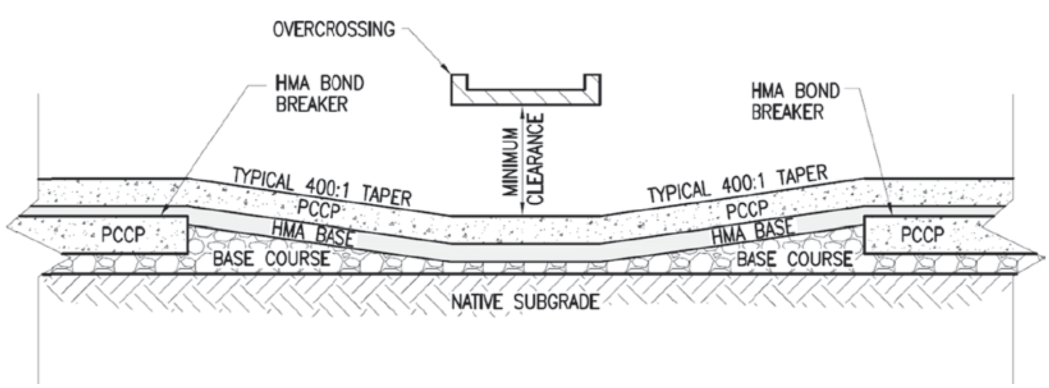


Figure 3.9. Illustration of rigid pavement transitions to overcrossings.

Table 3.18. Specification Elements Developed from Multiple Sources for Tack Coats

AASHTO Paragraph	R23 Recommendations		Source
404.02 Materials	Binder	Use either an asphalt cement (AASHTO M320) or emulsified asphalt (AASHTO M140 or M208) in accordance with local practice.	AASHTO 404 Texas 340 Virginia 310
404.03 Construction	Weather limitations	Apply tack coat during dry weather only.	AASHTO 404 Michigan 501
	Surface preparation	Patch, clean, and remove irregularities from all surfaces to receive tack coat. Remove loose materials.	AASHTO 404 Minnesota 2357 Missouri 407
	Application surfaces	1. Apply the bond coat to each layer of HMA and to the vertical edge of the adjacent pavement before placing subsequent layers. 2. Apply a thin, uniform tack coat to all contact surfaces of curbs, structures, and all joints.	Michigan 501 Texas 340
	Application rate	1. Apply undiluted tack at a rate ranging from 0.05 to 0.10 gal/SY. 2. Many SHAs allow dilution with water up to 50%.	Range generally falls within most state limits
	Application temperatures	Use manufacturer recommendations.	Study team

Sources: AASHTO 2008; MDOT 2003; MnDOT 2005; MoDOT 2004; TxDOT 2004; VDOT 2007.

The complete Life-Cycle Cost Analysis manual can be found in this project's guide, Chapter 5.

Emerging Pavement Technologies

Some PCC and flexible pavement technologies are not yet considered to be long-life renewal options but may become so in the future. One technology that was reviewed, precast concrete pavement, is likely a long-lasting renewal option at this time. The limitation is that there are too few projects under traffic to make that type of assessment. Thus, the term "emerging pavement technologies" does not necessarily imply that the concept is "new." Several of these promising technologies were selected for a brief overview and include the following:

- Rigid pavements
  - Ultrathin CRCP overlays and
  - Precast concrete pavement.
- Flexible or composite pavements
  - Resin-modified pavement (illustrated in Figure 3.10).

Without doubt, there are other technologies that could be featured; however, featuring them is not the primary purpose

(a) (b)

Courtesy of Joe Mahoney.

Figure 3.10. Resin-modified pavement in South Africa. (a) Resin-modified pavement at a truck weigh station on the N-3 near Johannesburg, South Africa. (b) A close-up of the resin-modified cement that was placed in open-graded HMA.

of this study. This short treatment simply suggests that technologies exist which should be monitored as they continue to evolve and which may be or become viable components for long-lasting pavement renewal.

The complete Emerging Pavement Technology document can be found in this project's guide, Chapter 6.

Interactive Application

The project resulted in the development of several documents and reference tools that provide guidance on scoping and estimating long-life renewal strategies for pavements. The following goals and objectives were identified during the study in order to foster broad implementation of the research results:

- Provide a user-friendly means of navigating the large amount of design and best practice information contained within the work product.
- Provide guidance and a method for selecting an appropriate rehabilitation strategy based on information specific to a given project.
- Provide a transparent view of the decision-making process as users are selecting the appropriate rehabilitation strategy, design, and best practices given their local practices.

To meet these objectives and facilitate accelerated adoption of the research results, a computer-based application to guide users to the applicable research findings—in essence a "scoping tool" for users—was developed to aid implementation. The following sections outline the requirements, approach, and results of the application development portion of the study.

User Requirements

To best serve the intended audience of the application (scoping tool), the project team determined that the following end-user requirements must be met:

- The application must run on any computer (PC/Mac) with commonly installed libraries.
- The application must be distributable on CD-ROM, with option for web distribution in the future.
- No third-party licenses or controls to be required by end users to install or distribute.
- Provide capabilities to periodically update renewal strategies and guidance.
- Provide printable report available to users.
- Minimize application support and maintenance needs.

These requirements were then assessed against several different implementation technologies to determine the best approach to the application design.

Application Design

To meet the preceding user requirements, the project team performed an initial assessment of available technologies regarding whether they best meet the preceding goals. Several technologies were considered, although, ultimately, the Adobe Flash platform and Flex Builder toolkit were selected.

Adobe's Flash Player is currently the world's most pervasive software, reaching 99% of Internet-enabled desktops in markets such as the United States and Western Europe, and providing a medium for both connected (web) and nonconnected (CD-ROM) distribution. The platform also provides users the option of running applications directly via the web, or directly from CD-ROM without need for installation files or impact on the user's computer.

Other technologies considered for implementation included Java, .NET, HTML 5, and Microsoft Office (Excel). Although each of these technologies could perform the required function of the scoping tool application, each was unable to meet the user requirements at the same level as Adobe Flash.

Data Structure

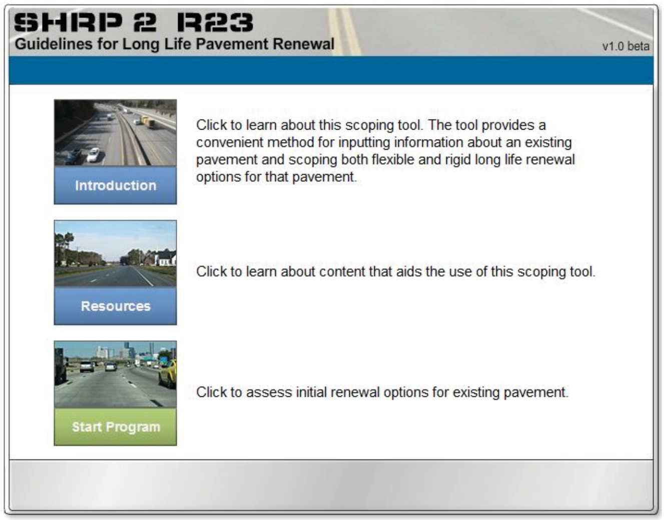
The scoping tool was designed to allow subject-matter experts the ability to modify the renewal strategy language and recommendations that result from ongoing feedback without having to recompile the application. To do so, an Extensible Markup Language (XML) data structure was devised to store all of the application logic and workflow information. Screen shots of the major pages in the application follow in Figure 3.11.

Interactive Software Steps

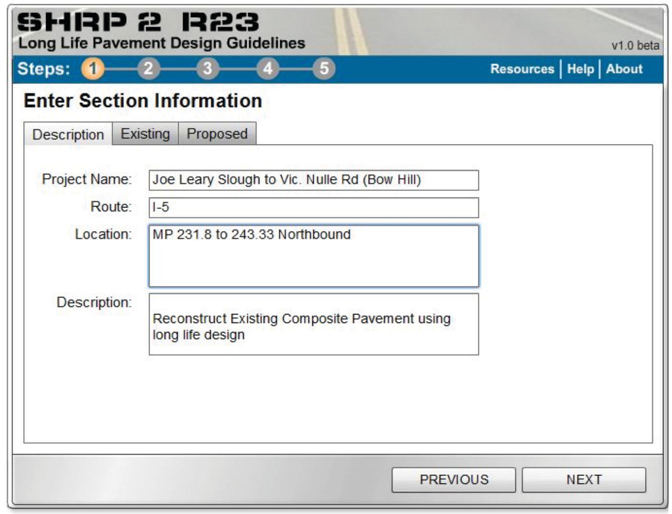
The interactive software developed for this project guides users through the following five steps:

1. Specify existing and proposed section information.
2. Specify existing pavement condition.
3. Confirm section design parameters.
4. Select renewal strategy.
5. Receive recommended section design.

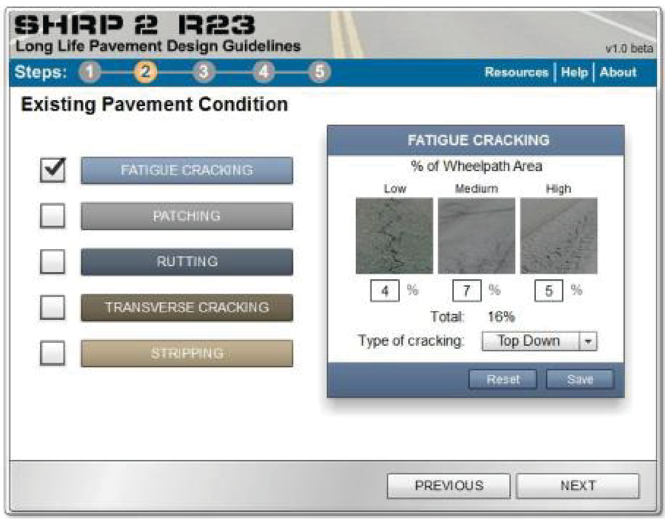
These five steps allow the user to input the parameters needed to obtain feasible renewal options from the decision matrices and thickness design tables discussed previously. In Step 1, the user inputs the existing pavement structure and the design information for the proposed renewal project (i.e., traffic levels, subgrade conditions, geometric constraints). The software uses this information to determine the type of existing pavement being evaluated and selects the appropriate decision matrix from Tables 3.9 through 3.12. Design information for the proposed renewal is stored for later use



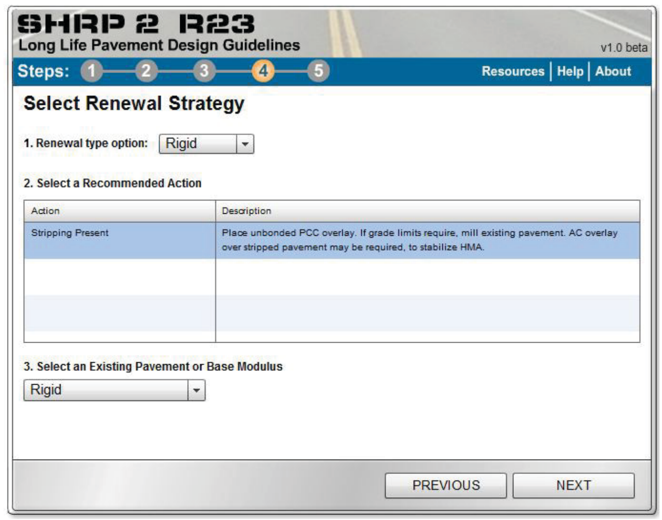
(a) Opening screen



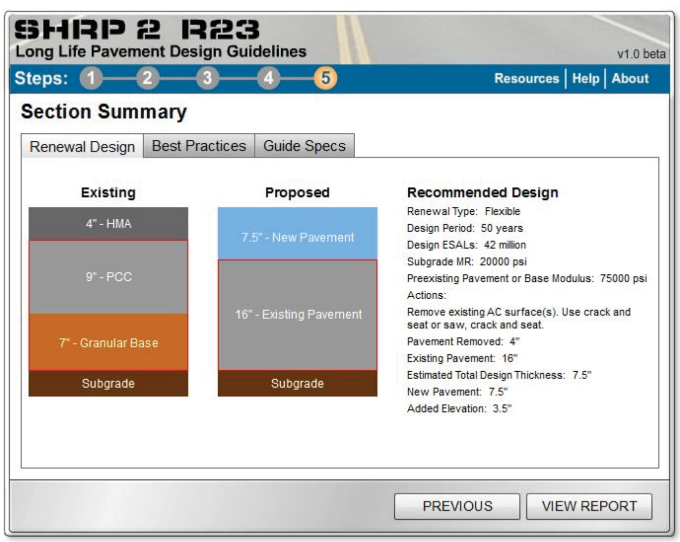
(b) Section information



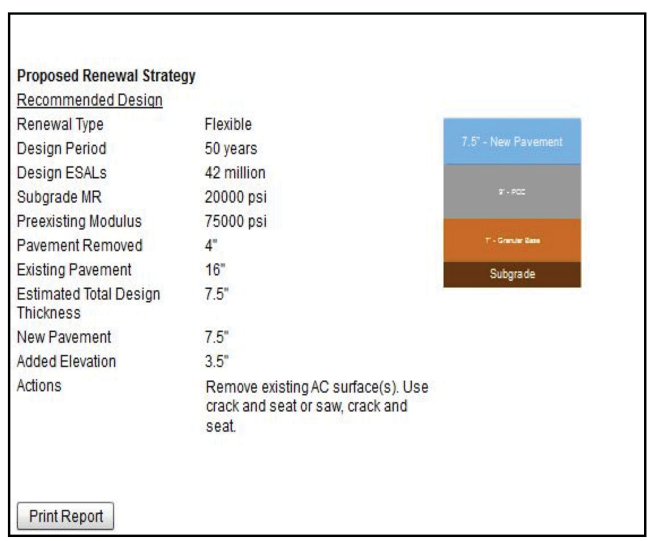
(c) Pavement condition



(d) Selection of renewal strategy



(e) Section summary



(f) Proposed renewal strategy

Figure 3.11. Screen shots from the interactive software.

in determining the renewal-layer design thickness (described in Step 5).

In Step 2, users input the condition of the existing pavement in terms of key distress types. These distress types are used in the decision matrices to determine feasible renewal alternatives. The presence of certain types of distress (or distress in high quantities and/or severities) precludes some of the renewal strategies from achieving long life. These alternatives are eliminated by the program during Step 2.

Step 3 provides the user with an overall summary of the existing pavement type and layering, existing condition, and proposed design parameters.

With the existing pavement and proposed design elements confirmed, the user can select the type of renewal (i.e., flexible or rigid) in Step 4. The program utilizes the selection, along with the existing conditions stored in Step 2, to determine a list of feasible renewal options, recommended actions and considerations, and a description of the approach. This information is pulled from the decision matrices listed in Tables 3.9 through 3.12. The user can choose from the list of feasible options and select the existing pavement or base modulus. (This information will be used in Step 5.)

In Step 5, the software uses the thickness design tables listed previously in Tables 3.15 and 3.16. The software uses the proposed design parameters entered in Step 1 along with the renewal strategy and modulus selected in Step 4 to determine a proposed renewal thickness. In addition, the software provides an overview of the existing pavement, the recommended design, and all of the pertinent design parameters. Links to the specific resource documentation for the renewal strategy are also listed.

CHAPTER 4

Conclusions and Suggested Research

There are obvious benefits to using existing pavements in the construction of long-life pavements. A more rapid construction process can be achieved because it eliminates the need for removal of material from the project and reduces or eliminates the importation of base aggregates. This type of construction can also facilitate traffic staging through the project. This results in reduced construction duration, as well as costs and impact on the traveling public.

The guidelines developed in this project provide a range of approaches for the design and construction of long-life pavements using existing pavements. Most agencies used one or more of the approaches identified, but none were found to use all of the approaches identified in this project. A large number of agencies were contacted both nationally and internationally in the development of the guidelines. Some of the agencies that were contacted had tried one or more of the approaches identified and had experienced construction problems, which caused them to not consider that approach in future work. In working with the different agencies, it became clear that the details related to the success or failure of these processes must be provided in some form of knowledge base. The old adage that "the devil is in the details" applies fully to the use of existing pavements to construct long-life pavements. As such, much of the effort in Phase 2 of this project was devoted to the development of that knowledge base.

The decision matrices that were developed (and refined through the help of the industry and various agencies' review) are quite detailed. To facilitate the flow and simplify the use of the matrices, an Adobe Flash–based program was developed. The program also provides the platform on which to place the knowledge base that supports the decision-making process. That knowledge base was separated into six specific documents:

- Guide, Chapter 1—Project Assessment Manual;
- Guide, Chapter 2—Flexible Pavement Best Practices;
- Guide, Chapter 3—Rigid Pavement Best Practices;
- Guide, Chapter 4—Guide Specifications;
- Guide, Chapter 5—Life-Cycle Cost Analysis; and
- Guide, Chapter 6—Emerging Pavement Technology.

The Project Assessment Manual contains two unique sections. The Construction Productivity and Traffic Impact section will be extremely useful because most of the projects considered in these guidelines have a significant traffic-staging component to them. Additionally, the Life-Cycle Assessment section discusses the current approaches to environmental accounting, which is becoming an added consideration in today's highway program.

The guidelines developed under this project provide a single source of current information on all approaches that an agency can reasonably use to design and build long-life pavements utilizing existing pavements. The products from this project offer all of the resources in one location. The guidelines are also unique in that they not only address the design approaches but also provide guide specifications that are congruent with those approaches. The material presented will become dated; thus, the guidelines should be reviewed in about 5 years and updated as needed given advances in the industry.

Suggested Research

The guidelines were produced under a contract that defined "long life" as referring to pavements that provide 50 years of service. Although this is an admirable goal, most agencies that the project team interviewed do not design pavements for 50 years of service. The more typical design life was for about 30 years. In Europe and the United Kingdom, long-life pavement designs are for 30 to 40 years. The one comment that the team heard often was "If we designed for 50 years of service this would be a very good resource," implying that the guidelines had limited use. All agencies also had funding issues, so the full application of the guidelines was also limited because of the current funding levels.

The design process in the guidelines is not restricted to 50 years. The program allows the user to compute traffic loading ranging from 30 to 50 years. The decision matrix, however, *does not* include some approaches that could provide 30 to 40 years of service. The team clearly felt that if the guidelines were shown as providing guidance for long-life pavements (with long-life pavements defined as those that provide 30 to 50 years of service), more agencies would use them.

It is recommended that the guidelines be modified to provide design guidance for 30- to 50-year service lives. The bulk of the information contained in the guidelines would not change. The major change would be in the decision matrix to include several applications that were eliminated because they would likely provide only 30 to 40 years of service. These would include bonded portland cement concrete (PCC) overlays, as well as hot-mix asphalt overlays of continuously reinforced concrete pavement (CRCP). There would also be additional material placed in the best practices documents to describe the design and construction of those approaches. The Guide Specifications would be updated to include guide specifications unique to the construction of those added approaches. There would be little actual change in the guidelines, but it is felt that there would be a perception by many agencies that the guidelines were developed for their use, not just for those few agencies that designed for 50 years.

To account for the 30- to 40-year design lives, the following actions are proposed:

- Revise decision tables to include bonded PCC overlays and asphalt concrete overlays of CRCP and add design thickness estimate tables to match added approaches.
- Circulate revised decision tables to agencies and industry for review.
- Finalize decision tables based on review comments.
- Revise best practices documents and guide specifications to account for added options.
- Circulate revised documents to agencies and industry for review comments.
- Finalize documents based on review comments.
- Revise program based on changes.
- Conduct a beta test of the revised program with participating agencies.
- Prepare addendum to final report to document revisions.

Those agencies that participated in Phase 2 would also be asked to work on the revisions to the guidelines. Those agencies would be asked to comment on the revisions and then on the revised program. A workshop or two may be required to help focus the process.

Implementation

Fully Web-Enable the Guidelines

The R23 program application was originally designed for self-contained delivery via CD to minimize the up-front cost and promote rapid development, but ultimately this design has limited its functionality as to the broader use, support, and maintenance of the program:

- User inputs and results are not stored, meaning users do not have the ability to “load” or “save” user input and application outputs to reproduce guidance, compare results between scenarios, or share with colleagues. Once the application is closed, all inputs and results are lost.
- Documentation is not cross-linked, limiting the full effectiveness of the information provided. For example, cross-linking would allow the reader to move easily from sections in the best practices to appropriate sections in either the Project Assessment Manual or the Guide Specifications. This will significantly improve access to the information and the utility of the program.
- Application and documentation are not indexed or searchable, limiting search engine recognition and ultimately exposure to potential users.
- Increased long-term maintenance and support cost would be reduced because the current program has a disconnected distribution environment and dependency on Adobe AIR and Flash framework compilation for any development updates.

To promote the implementation of the application and research results, it is recommended that further work be done to improve the functionality of the guidelines. Because of funding and time limitations during this project, the documents that reside on the current program were prepared in MS Word and housed on a host server in PDF format for access by the users. They were developed, however, with the view that the content could be reformatted so that there would be cross connections between the various sections within the documents to increase their utility. Based on feedback from the pilot group of users and the experience of the R23 team, it is recommended that the R23 application be moved into a web-based application with the following elements:

- Develop database and security elements to provide users the ability to load, save, and compare various individual application results within their organization.
- Convert static documents such as the Project Assessment Manual, guide specifications, and best practices into a content management system with cross-linked pages to aid in accessibility, reduce maintenance costs, and improve search capabilities of the documentation.

References

American Association of State Highway and Transportation Officials (AASHTO). 2008. *Guide Specifications for Highway Construction,* 9th ed. American Association of State Highway and Transportation Officials, Washington, D.C.

Caltrans. 2004. "Interim PCC Pavement Rehabilitation Guidelines," Pavement Tech Notes, July 28.

Caltrans. 2008. *Crack Existing Concrete Pavement.* Standard Special Provision 41-250.

Coley, C. C., and I. Carswell. 2006. *Improved Design of Overlay Treatments to Concrete Pavements: Final Report on the Monitoring of Trials and Schemes.* Report TRL657. U.K. Transport Research Laboratory, Wokingham, United Kingdom.

Hall, K. T., C. E. Correa, S. H. Carpenter, and R. P. Elliott. 2001. *NCHRP Web Document 35 (Project C1-38): Rehabilitation Strategies for Highway Pavements.* TRB, National Research Council, Washington, D.C.

Hall, K. T., D. Dawood, S. Vanikar, R. Tally, Jr., T. Cackler, A. Correa, P. Deem, J. Duit, G. M. Geary, A. J. Gisi, A. N. Hanna, S. Kosmatka, R. O. Rasmussen, S. Tayabji, and G. Voigt. 2007. *Long-Life Concrete Pavements in Europe and Canada.* Report FHWA-PL-07-027. FHWA, U.S. Department of Transportation.

Harrington, D. 2008. *Guide to Concrete Overlays: Sustainable Solution for Resurfacing and Rehabilitating Existing Pavements,* 2nd ed. National Concrete Pavement Technology Center, Ames, Iowa.

Heckel, L. 2002. *Rubblizing with Bituminous Concrete Overlay: 10 Years' Experience in Illinois.* Physical Research Report 137. Illinois Department of Transportation, Springfield.

Jordan, R. W., C. Coley, H. M. Harding, I. Carswell, and K. E. Hassan. 2008. *Best Practice Guide for Overlaying Concrete.* TRL Road Note RN41. U.K. Transport Research Laboratory, Wokingham, United Kingdom.

Liu, J., D. G. Zollinger, S. D. Tayabji, and K. D. Smith. 2003. *Repair and Rehabilitation of Concrete Pavements: Volume IV: Strategic Analysis of Pavement Evaluation and Repair (SAPER).* Draft Final Report. FHWA, U.S. Department of Transportation.

Merrill, D. 2005. *Guidance on the Development, Assessment and Maintenance of Long-life Flexible Pavements.* Report TRL639. Highways Agency, Quarry Products Association, and Refined Bitumen Association, U.K. Transport Research Laboratory, Wokingham, United Kingdom.

Michigan Department of Transportation. 2003. *Standard Specifications for Construction.* Michigan Department of Transportation Publications Office, Lansing.

Minnesota Department of Transportation. 2005. *Standard Specifications for Construction,* 2005 ed. Minnesota Department of Transportation, St. Paul.

Missouri Department of Transportation. 2004. *Missouri Standard Specifications for Highway Construction,* 2004 ed. Missouri Department of Transportation, Jefferson City.

Monismith, C., J. Harvey, B. Tsai, F. Long, and J. Signore. 2009. *Summary Report: The Phase One I-710 Freeway Rehabilitation Project—Initial Design (1999) to Performance after Five-Plus Years of Traffic (2009).* Report UCPRC-SR-2008-04. Pavement Research Center, University of California, Davis and Berkeley.

Newcomb, D. E., M. Buncher, and I. J. Huddleston. 2001. *Transportation Research Circular 503: Concepts of Perpetual Pavements.* TRB, National Research Council, Washington, D.C.

Sebesta, S., and T. Scullion. 2007. *Field Evaluations and Guidelines for Rubblization in Texas.* Report FHWA/TX-08/0-4687-2. Texas Transportation Institute.

Smith, K. D., H. T. Yu, and D. G. Peshkin. 2002. *Portland Cement Concrete Overlays: State of the Technology Synthesis.* Report DTFH61-00-P-00507. FHWA, U.S. Department of Transportation.

Tayabji, S., and S. Lim. 2007. *Long Life Concrete Pavements: Best Practices and Directions from the States.* Concrete Pavement Technology Program, Technical Brief FHWA-HIF-07-030. FHWA, U.S. Department of Transportation.

Texas Department of Transportation. 2004. *Standard Specifications for Construction and Maintenance of Highways, Streets, and Bridges.* Texas Department of Transportation, Austin.

Texas Department of Transportation. 2009a. "Continuously Reinforced Concrete Pavement—One Layer Steel Bar Placement," Design Division Standard, Texas Department of Transportation, Austin.

Texas Department of Transportation. 2009b. "Continuously Reinforced Concrete Pavement—Two Layer Steel Bar Placement," Design Division Standard, Texas Department of Transportation, Austin.

Texas Department of Transportation. 2011. Section 5: Determining Concrete Pavement Thickness, "Pavement Design Guide," Texas Department of Transportation, Austin.

Virginia Department of Transportation. 2007. *Road and Bridge Specifications.* Virginia Department of Transportation, Richmond.

Von Quintus, H. L., C. Rao, J. Mallela, B. Aho, Applied Research Associates, Incorporated, and Wisconsin DOT. 2007. *Guidance, Parameters, and Recommendations for Rubblized Pavements: Final Report.* Project WHRP 06-13, Project 16730. National Technical Information Service, Alexandria, Va.

Washington State Department of Transportation. 2010. "Standard Specifications for Road, Bridge, and Municipal Construction," M41-10, Washington State Department of Transportation, Olympia.

APPENDIX A

Literature Review

The R23 team conducted a thorough literature search for information on highway renewal using existing pavements. The resources utilized for this task include the following:

- The Transportation Research Information Service (TRIS) database,
- The International Transportation Research Documentation (ITRD) database,
- The Transportation Libraries Catalog (TLCat),
- The National Technical Information Service (NTIS) database,
- The Transportation Research in Progress (RiP) database,
- The Online Library Catalog of the University of Illinois at Urbana-Champaign,
- ProQuest's ABI/INFORM Complete database of periodicals, professional journals, and trade publications,
- The Federal Highway Administration's (FHWA's) National Highway Specifications website,
- The Bureau of Transportation Statistics' National Transportation Library (which searches some of the above databases and others, as well as the websites of the departments of transportation of all 50 states and the District of Columbia),
- The Virtual Library of publications of the World Road Association (PIARC),
- The United Kingdom's Transport Research Laboratory (TRL) publication database,
- The Netherlands' Foundation Center for Research and Contract Standardization in Civil and Traffic Engineering (CROW) publication database,
- The publication databases of the American Concrete Pavement Association (ACPA), Asphalt Institute (AI), and National Asphalt Paving Association (NAPA), and
- The publication databases of the roadway authorities of Austria, Germany, France, Belgium, the Netherlands, the United Kingdom, Canada, Australia, South Africa, and other countries facing demands of heavy traffic on high-volume roads and the need for in-place renewal of existing pavement structures.

In addition, questionnaires were sent to each of the state highway agencies. These surveys were followed by a series of phone calls to learn more about state-sponsored reports. The state survey portion of the project is described in more detail in Chapter 2. A number of definitions for long-life pavements exist, depending on the location, pavement type, and roadway facility. For purposes of this study, long-life pavement is defined as pavement sections designed and built to last 50 years or longer without requiring major structural rehabilitation or reconstructions and needing only periodic surface renewal in response to distresses confined to the top of the pavement. Table A.1 shows typical ranges of service life for reconstruction and various major rehabilitation techniques for each pavement type (Thompson 1989). These ranges are general estimates only and represent the "conventional wisdom" about the service lives that may reasonably be expected of the different rehabilitation techniques. Based on these estimates, the most promising renewal strategies for long life using existing pavements are the following:

- Thick AC overlay over existing AC pavement,
- PCC overlay over existing AC pavements,
- Thick AC overlay over fractured PCC pavement,
- Bonded PCC overlay over existing PCC pavement,
- Unbonded PCC overlay over existing PCC pavement,
- Thick AC or PCC overlay over fractured PCC of AC/PCC composite pavement, and
- Unbonded PCC overlay over existing AC/PCC composite pavement.

The following sections provide details on each rapid renewal strategy along with considerations for long-life pavement based on relevant literature and agency information.

Table A.1. Typical Ranges of Service Lives for Rehabilitation Treatments

Treatment	Typical Range of Service Life (years)
Reconstruction	
Reconstruction in asphalt	15–20
Reconstruction in concrete	20–30
Asphalt pavement rehabilitation	
Structural asphalt overlay of asphalt pavement	18–15
Structural concrete overlay of asphalt pavement	20–30
Surface recycling without overlay	4–8
Nonstructural asphalt overlay of asphalt pavement	4–8
Nonstructural (ultrathin) concrete overlay of asphalt pavement	5–15
Asphalt patching without overlay	4–8
Concrete pavement rehabilitation	
Structural asphalt overlay of concrete pavement	8–15
Asphalt or concrete overlay of fractured concrete slab	15–25
Unbonded concrete overlay of concrete pavement	20–30
Nonstructural asphalt overlay of concrete pavement	4–8
Bonded concrete overlay of concrete pavement	15–25
Restoration without overlay	5–15
Asphalt-overlaid concrete pavement rehabilitation	
Structural asphalt overlay of asphalt concrete (AC)/portland cement concrete (PCC) pavement	8–15
Asphalt or concrete overlay of fractured concrete slab	15–25
Unbonded concrete overlay of AC/PCC pavement	20–30
Surface recycling without overlay	4–8
Nonstructural asphalt overlay of AC/PCC pavement	4–8
Nonstructural (ultrathin) concrete overlay of AC/PCC pavement	5–15

Source: Hall et al. 2001.

Asphalt Concrete (AC) Renewal Approaches

AC over AC Methods

The team sought information on the following potential flexible pavement renewal methods:

- AC over existing AC,
- AC over crushed and shaped AC, and
- AC over reclaimed AC.

The three overlay methods listed above have been used by many states and other countries, for conventional rehabilitation purposes—that is, for rehabilitation design lives typically not exceeding 15 years. Nonetheless, it seems entirely feasible from a conceptual standpoint that a new AC surface of sufficient thickness and durable mix design could be placed on an existing AC-surfaced pavement as a long-life renewal approach. However, to determine the structural and material requirements needed to achieve a true long-life renewal of the existing pavement, it may be necessary to think of the new AC surface as new construction on a high-quality base rather than as a conventional overlay.

AC over Existing AC Pavement

The hot-mix asphalt (HMA)-over-existing-HMA strategy ranges from “milling and filling” for the lower levels of traffic to “milling and strengthening” for the higher levels of traffic. Figure A.1 shows the example design cross sections for long-life performance of HMA pavements developed by Von Quintus for the Michigan Asphalt Pavement Association (Asphalt Pavement Alliance 2002). It includes suggested types of HMA mixtures to be placed within the pavement structure. Von Quintus recommends that the asphalt mixture for the HMA base layer be designed to have 3% air voids to mitigate bottom-up fatigue cracking. The surface course mixture is a dense graded Superpave in the case of 3 and 10 million equivalent single axle load (ESAL) levels, and an SMA in the case of 20 and 30 million ESAL levels (20-year life). The strategies presented in the figure are for planning purposes only.

AC over Crushed and Shaped AC Pavement

The technique involving HMA over crushed and shaped HMA consists of crushing the existing HMA layer and shaping it into a base layer before overlaying it with a new HMA layer (Figure A.2). This strategy is suitable for severely cracked HMA pavements. Marginal base material can be upgraded with admixtures to provide high-quality support. To avoid reflection cracking, crack-relieving separator layers or membranes can be used, including (1) geotextile or fabrics and (2) stress-relieving or stress-absorbing membrane interlayers. Crushing is usually more economical than hot mix recycling, unless the asphalt surface is quite thick. When the existing mat is quite thick (greater than 6 in.), a common procedure is to mill off part of the HMA then crush the remainder.

AC over Reclaimed AC Pavement

An alternative to crushing and shaping is to recycle the HMA layer using hot mix or cold mix in-place recycling techniques. The product is a renewed HMA base layer that is overlaid with new HMA. Recycling can involve cold mix for the lowest

Design Catalog of Michigan Perpetual Pavement Sections (Von Quintus, 2001)								
20-Year Traffic Level, ESAL X 10		3		10		20		30
Total HMA Thickness, mm		290		345		370		405
SMA Thickness, mm		—		—		65		65
Superpave Thickness, mm		50		50		—		—
Binder Course, mm		115	90	140	11	140	125	150
Base Course, mm		125	150	155	180	165	180	190
Aggregate Subbase, mm		—		—		330		430
Non-Frost Susceptible Soils, mm		345		315		220		200
Rehabilitation 1	Year	20		15		15		15
	Mill-Overlay, mm	50-50		50-100		65-115		65-115
Rehabilitation 2	Year	32		30		30		30
	Mill-Overlay, mm	50-50		50-50		50-50		50-75

Source: Asphalt Pavement Alliance 2002.

Figure A.1. Michigan design catalog for long-life HMA pavements.

layers or hot mix for the upper base layer. The categories of pavement recycling options are shown in Figure A.3 (National Highway Institute 2003). Only the categories applicable to using existing pavement in place are discussed next.

Cold In-Place Recycling (CIPR)

CIPR involves the reuse of an asphalt concrete pavement that is processed in place with the addition of asphalt emulsions, cutbacks, portland cement, lime, and/or other materials as required to achieve desired mix quality, followed by placement and compaction. CIPR is accomplished by a special machine that scarifies the existing surface to a given depth, crushes it in a pug mill, adds asphalt cement, and lays the resultant mix back down, almost in its original location. The Asphalt Recycling and Reclaiming Association (ARRA) differentiates two different CIPR procedures as full depth and partial depth. Partial-depth CIPR involves the recycling of the asphalt-bound layers to a depth of 3 to 4 in. Full-depth CIPR, also termed full-depth reclamation, involves the recycling of the asphalt-bound layers and the unbound granular layers in the flexible pavement. The finished product is considered a base only, and a hot mix surface course is necessary. CIPR has been performed on all types of roadways, with the concentration being on lower-volume roadways. However, full-depth reclamation has successfully been conducted on high-volume Interstate pavements. This process can directly address structural problems through the production of an improved stabilized layer when full-depth reclamation is used. Partial-depth reclamation is limited to correcting only those distresses that are surface problems in the asphalt layer (Hall et al. 2001).

Records on performance are highly variable because a common definition has not been applied to judge the comparative performance levels. Causes commonly noted for poor performance using CIPR include (1) use of an excessive amount of recycling agent; (2) application of a surface seal prematurely; (3) recycling only to the depth of an asphalt layer, resulting in delamination from the underlying layer; and/or (4) allowing a project to remain open for too long into the winter season (Hall et al. 2001).

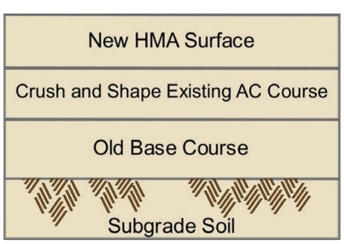
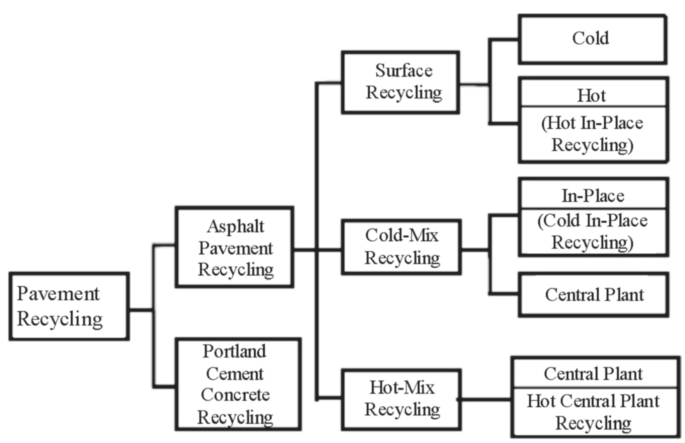


Figure A.2. Schematic of HMA over crushed and shaped HMA pavement.



Source: National Highway Institute 2003.

Figure A.3. Categories of pavement recycling options.

Hot In-Place Recycling (HIPR)

ARRA defines three types of HIPR operations: heater scarification, repaving, and remixing. Each is described below (Hall et al. 2001).

Heater scarification involves the following steps: (1) heating the existing pavement surface to about 110°C to 150°C, using one or more propane-fired radiant heaters; (2) scarifying the softened surface to a depth of about one-half to three-quarters of an inch; (3) applying a liquid rejuvenating agent (if needed); (4) mixing and leveling the loose mixture with an auger and/or lay-down machine; and (5) compacting with rollers.

Repaving is heater scarification combined with placement of a new asphalt concrete overlay. The process involves the following steps: (1) heating the existing pavement surface to about 190°C, using infrared heaters; (2) scarifying the softened surface to a depth about one-half to three-quarters of an inch; (3) applying a liquid rejuvenating agent (if needed); (4) mixing the loose mixture with an auger; (5) spreading and screeding the recycled mixture; (6) placing a new asphalt concrete layer over the recycled mixture; and (7) compacting with rollers.

Remixing is similar to repaving but involves mixing mineral aggregate or new asphalt concrete hot mix into the scarified, rejuvenating material rather than placing a layer of new asphalt concrete on top. Remixing not only increases the structural capacity of the pavement, as does repaving, but also permits improvement of the gradation or binder properties of the existing asphalt concrete layer. Remixing involves heating and reworking material to a greater depth than in heater scarification and repaving. The steps in the remixing process are the following: (1) heating the existing pavement surface to about 85°C to 105°C, using one or more propane-fired radiant heaters; (2) milling the softened surface to a depth of about 1 to 2 in.; (3) mixing the hot milled material, rejuvenating agent, and new asphalt concrete material in a pug mill; (4) placing the mixture; and (5) compacting with rollers.

HIPR without an accompanying overlay or addition of new asphalt concrete material is estimated to have a service life of about 4 to 8 years. How much HIPR in conjunction with an overlay or additional asphalt concrete thickness benefits overlay performance has not yet been quantified (Hall et al. 2001), although remixing with a thick HMA overlay provides the best potential of achieving long life.

AC-over-PCC Methods

When in-place renewal of an existing PCC pavement is considered, the structural design considerations that must be taken into account to ensure good long-term performance are the adequacy of the subgrade, protection of the subgrade from excessive deformation, limiting strain in the existing PCC, limiting stress and strain in the new AC or PCC surface, and minimizing reflection cracking in the new surface.

Although AC overlay is undoubtedly the most common major rehabilitation method for jointed PCC pavements, the service life of this technique is limited by the rate at which reflection cracks develop and deteriorate to unacceptably rough levels. Thus, an AC overlay of a jointed PCC pavement is typically considered a conventional rather than a long-life rehabilitation approach, with an expected service life of about 10 to 15 years.

However, exceptions exist: Iowa, for example, has experience with jointed PCC pavements built in the 1930s and 1940s, widened with PCC or AC from 18, 20, or 22 ft to 24 ft in the 1970s, and then overlaid over time with a total of 5 or more inches of AC. Now, some 30 years later, these old AC/PCC pavements are being widened again, to 28 or 32 ft, and are being overlaid with PCC (J. K. Cable, personal communication, 2008).

The most promising long-life rigid pavement methods, however, appear to be the following:

- AC over continuously reinforced concrete pavement (CRCP),
- AC over cracked and seated jointed plain concrete pavement (JPCP), and
- AC over rubblized PCC.

AC over Existing CRCP

AC overlays of CRCPs can reasonably be expected to perform much longer than AC overlays of jointed concrete pavements, especially when (a) working cracks and punchouts in the existing CRCP are repaired with continuously reinforced full-depth concrete and (b) the existing CRCP does not have D-cracking. Permanent patching of punchouts and working cracks will delay for many years the occurrence and deterioration of reflection cracks in asphalt overlays of continuously reinforced concrete pavements. Reflection crack control treatments are not necessary for asphalt overlays of continuously reinforced concrete pavements, as long as continuously reinforced concrete repairs are used for deteriorated areas and cracks (Barnett, Darter, and Laybourne 1981; Darter, Barnett, and Morrill 1982; Hall and Darter 1989).

It has often been suggested that an adequate thickness of AC over a sound CRCP may be the perfect application for long-life design, which would require nothing more than periodic renewal of the AC surface. However, such rehabilitation projects are not currently typically designed for lives in excess of about 20 years.

The most commonly used approach to structural design of asphalt overlays of concrete pavements and asphalt-overlaid concrete pavements is the structural deficiency approach, exemplified by the 1993 AASHTO Guide procedure. The required AC overlay thickness is determined by multiplying the structural deficiency (D_f, the required concrete thickness for future traffic, minus D_{eff}, the effective thickness of the existing concrete slab) by an adjustment factor, A, that converts the thickness deficiency from inches of concrete to inches of asphalt.

A value of 2.5 has traditionally been used for the adjustment factor A. This value was based on the results of accelerated traffic tests conducted by the Corps of Engineers in the 1950s. The value 2.5 does not represent the best fit of the relationship of concrete thickness deficiency to asphalt overlay thickness in those field tests, but rather a conservative value suggested by the Corps for use in design. However, an A value of 2.5 can lead to excessive overlay thickness for larger concrete thickness deficiencies. A formula for the A factor as a function of the magnitude of the concrete thickness deficiency was developed by Hall (1991) using elastic layer analysis and is recommended in the 1993 AASHTO Guide in place of a constant A factor.

The NCHRP 1-37A Mechanistic-Empirical Pavement Design Guide (MEPDG) procedure's software for design of AC over CRCP allows the user to select some or all of the following performance criteria by which the adequacy of a trial overlay design is judged:

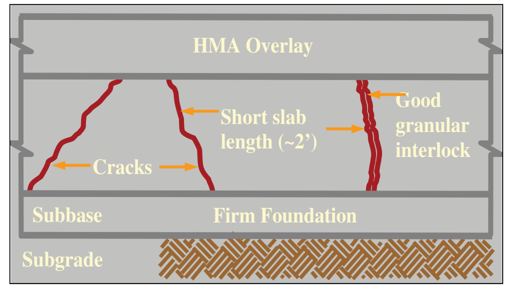
- Longitudinal cracking of the AC overlay,
- Thermal cracking of the AC overlay,
- Rutting of the AC overlay, and
- Punchout damage in the existing CRCP.

New pavement models for rutting in AC layers, longitudinal (top-down) cracking in AC, thermal cracking in AC, and punchouts in CRCP are adapted for use in the prediction of AC overlays of CRCP in the MEPDG methodology. The smoothness parameter used for AC overlays of PCC pavements in the MEPDG methodology is the international roughness index (IRI), predicted from an empirical model as a function of the existing pavement's IRI at the time of overlay placement, the time elapsed since placement of the overlay, the average rut depth, and the average spacing of medium- and high-severity transverse cracks.

The viability of the AC-over-CRCP method as an in-place renewal option, and the AC overlay thickness and CRCP condition requirements necessary to make it viable, need to be explored in this study in coordination with the work done on composite pavements in SHRP 2 Renewal Project R21.

AC over Cracked and Seated Pavement

Cracking and seating a plain jointed concrete pavement before overlaying it with AC has been done in the United States as far back as the 1940s. The technique attracted renewed interest beginning in the 1980s as an approach to reflection crack control (J. K. Cable, personal communication, 2008; Barnett et al. 1981; Darter et al. 1982). A great number of crack and seat projects have been built on highways in the United States, including test sections in the Long-Term Pavement Performance (LTPP) specific pavement study (SPS)-6 (Rigid Pavement Rehabilitation) experiment.



Source: National Highway Institute 2003.

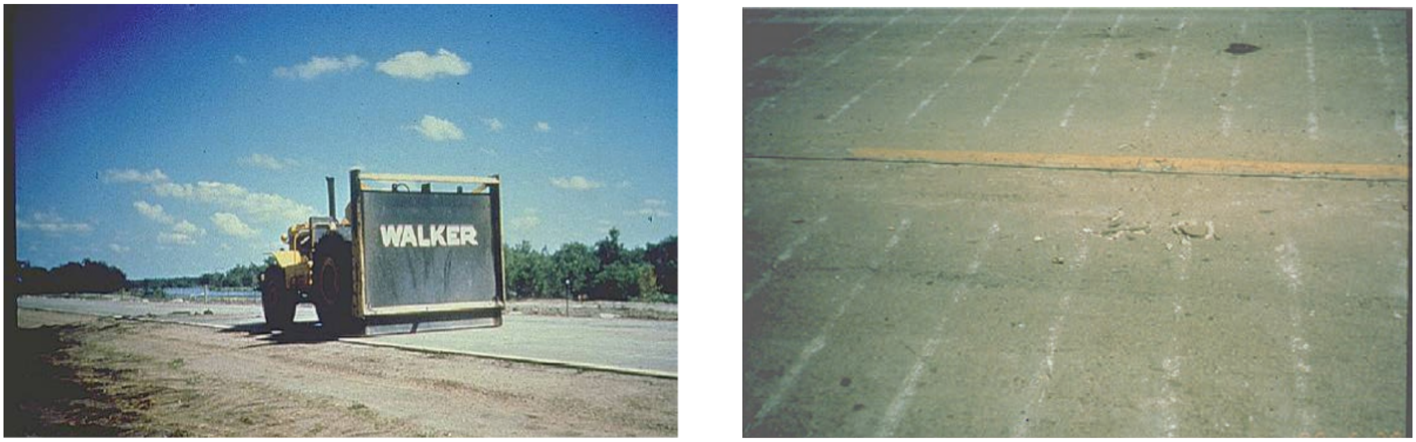
Figure A.4. Schematic of HMA over cracked and seated pavement.

This technique is suitable for JPCPs. It involves breaking the existing concrete into pieces about 12 to 48 in. (305 to 1,220 mm), as shown in Figure A.4. In principle, the smaller the cracked piece, the larger the potential for reduction in reflection cracking, and the larger the reduction in the structural strength of the concrete pavement. Cracking and seating is done in four major steps: (1) cracking the concrete slab, (2) seating the cracked slab, (3) special treatments, and (4) HMA overlay.

Cracking of the pavements can be accomplished with drop hammers, guillotine hammers (Figure A.5), modified pile drivers, or whip hammers, with the most commonly used equipment being the drop hammer. These are self-propelled units that raise a heavy mass several feet above the pavement and then release the weight, which then falls and strikes the surface of the slabs. Some agencies require cracking in both transverse and longitudinal directions. The resulting pieces should be large enough to retain interlock between aggregates, but also small enough to minimize the joint movement of the unreinforced PCC pavement. Excessive cracking can be detrimental to the PCC pavement.

After cracking, the slab is seated using 66- to 110-kip-capacity (30- to 50-ton-capacity) rubber-tired rollers (Figure A.6). Seating of the concrete is done to (1) ensure reestablishment of the support between the subbase and the slab by reducing the existing voids, (2) create a relatively uniform grade for supporting paving operations, and (3) locate soft zones in the underlying layers that may need to be removed and/or replaced with more stable material. Excessive rolling may be harmful to the slab.

The main concern with break or crack and seat is the reduction in the structural capacity of the pavement. To compensate for the reduction in structural capacity, thickness of the overlay should be increased. Pavement rehabilitated with



(a) (b)

Source: National Highway Institute 2003.

Figure A.5. Crack of pavement with guillotine hammer. (a) Guillotine hammer. (b) Fractured slab with guillotine hammer.

the crack and seat technique can perform well when the subgrade support is uniform and the subgrade modulus is more than 15,000 psi after cracking. Nondestructive testing (NDT) should be used to analyze and design the cracked and seated pavements.

Some studies have suggested that cracking and seating only succeeds in delaying the onset of reflection cracking by a few years (e.g., five or fewer), and that once reflection cracking appears, it tends to progress at much the same rate as it does in an AC overlay of an intact PCC pavement (e.g., about a year per inch of overlay thickness in reaching the surface) (Carpenter and Darter 1989). Improvements in slab cracking techniques and the use of greater overlay thicknesses have resulted in better performance from crack and seat on later projects.

Source: National Highway Institute 2003.

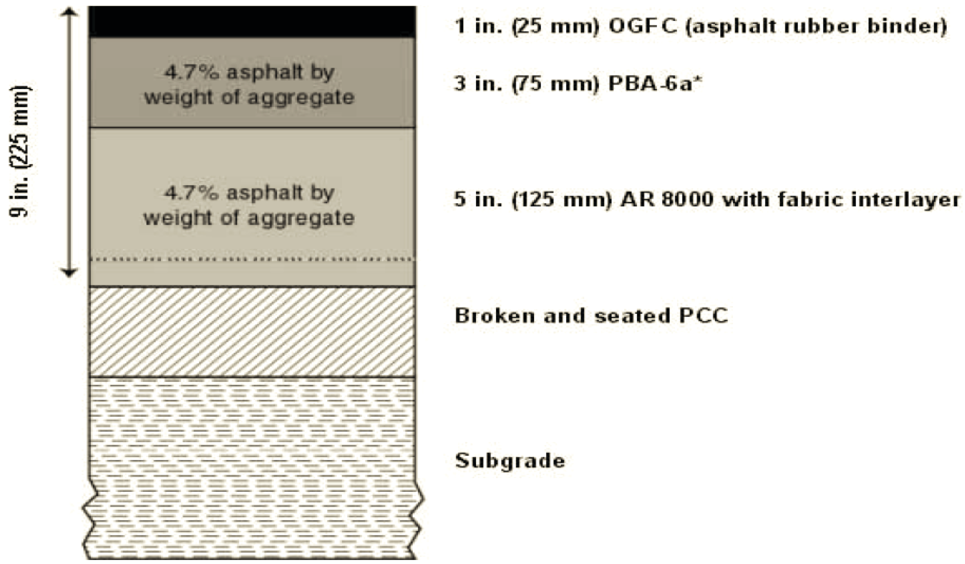
Figure A.6. Heavy roller used to seat the cracked pavement.

The term “breaking and seating,” rather than cracking and seating, is applied to the technique of fracturing a jointed reinforced concrete pavement prior to placement of an AC overlay. In general, breaking and seating has been found to be less effective at reflection crack control than cracking and seating because of the difficulty of ensuring that the reinforcing steel in the concrete is completely ruptured in the process of breaking the slab.

An example of a successful application of this technique as a long-life HMA pavement is the California Interstate 710 (Figure A.7) in Los Angeles County, known as the Long Beach Freeway, with a design lane traffic of 100 million to 200 million ESALs for a 40-year period.

AC over Rubblized Concrete Pavement

Rubblization originally developed as an improvement in reflection crack control over cracking and seating. The LTPP SPS-6 experiment includes several rubblized sections built as supplements to the main experimental test sections. At AC overlay thicknesses comparable to those built on crack and seat projects, rubblizing projects typically are expected to provide about 5 to 10 years of additional service life. However, in recent years the two U.S. manufacturers of concrete pavement rubblizing equipment (Antigo and PB4) have both been involved in rubblizing projects in which a much more substantial thickness of AC, e.g., 15 in. or more, has been placed. Such structures are in essence full-depth AC pavements on high-strength granular bases, and thus it appears reasonable to expect that they are viable candidates for long-life in-place renewal projects.



Source: TRB 2001.

Figure A.7. Cross-sectional design for the I-710 Freeway.

Rubblizing involves breaking the existing concrete pavement into pieces, and thereby destroying any slab action, and overlaying with HMA. The sizes of the broken pieces usually range from 2 to 6 in. (51 to 152 mm) (Asphalt Pavement Alliance 2002). The technique is suitable for both JPCPs and jointed reinforced concrete pavements (JRCPs). It has also been used on severely deteriorated CRCPs, although the heavy reinforcement in the CRCP presents some challenges and requires extra care in quality control/quality assurance (QC/QA) procedures.

A rubblized PCC pavement behaves like a high-quality granular base layer. This loss of structure must be accounted for in the HMA overlay design thickness. A study by NAPA indicated that strength of the rubblized layer is one and a half to three times greater than a high-quality dense graded crushed stone base (National Asphalt Pavement Association 1994).

Rubblization is considered a viable, rapid, and cost-effective rehabilitation option for deteriorated PCC pavements. Good performance of rubblized pavements requires a high-quality process of rubblization, effective rubblizing equipment, and maintaining a strong base and/or subgrade soil. Also, poor performance can occur when the underlying soils are saturated. Installation of edge drains prior to rubblization has proven to be successful for this type of condition. If the existing concrete pavement is deteriorated due to poor subgrade support, then rubblization may not be a viable option. Two types of equipment are used in the rubblization process: (1) a resonant breaker and (2) a multiple-head breaker.

The *resonant rubblizer* (Figure A.8) is composed of a sonic shoe (hammer) located at the end of a pedestal, which is attached to a beam whose dimensions vary from one machine to another, and a counterweight situated on top of the beam. The principle on which the resonant breaker operates is that a low-amplitude (about 0.5-in.) high-frequency resonant energy is delivered to the concrete slab, which causes high tension at the top. This causes the slab to fracture on a shear plane inclined at about 35° from the pavement surface. Several equipment variables affect the quality of the rubblization process, including shoe size, beam width, operating frequency, loading pressure, velocity of the rubblizer, and the degree of overlapping of the various passes. The rate of production depends on the type of base or subbase material and is approximately 1.0 to 1.5 lane miles per day.

During its operation, a resonant rubblizer encounters difficulty in the vicinity of pavement discontinuities such as joints or cracks. At a discontinuity, the microprocessor controller increases the rubblizer speed, causing a decrease in the energy delivered to the concrete, or it causes a shutdown. Bituminous patches or unmilled overlays can also be problematic, because the shoe penetrates the asphalt, causing a large loss in the energy delivered to the concrete. Last, the type of base or subbase material, the roadbed or subgrade soil, and the condition of the concrete pavement being rubblized all affect the quality of the rubblized product. For example, if the base or subbase materials are softer than the roadbed soil, shear failure may result.

The *multihead breaker* operation includes multiple drop hammers arranged in two rows on a self-propelled unit and a vibratory grid roller (Figure A.9). The hammers strike the pavement approximately every 4.5 in. The bottom of the hammer is shaped as to strike the pavement on 1.5-in.-wide and 8-in.-long loading strips. The hammers in the first row

(a) (b)

Sources: (a) Karim Chatti; (b) National Highway Institute 2003.

Figure A.8. Resonant frequency pavement breaker. (a) Resonant breaker machine. (b) Close-up of the sonic shoe.

strike the pavement at an angle of 30° from the transverse direction. The hammers in the second row strike the pavement parallel to the transverse direction. The sequence of hammer drops is irregular because each cylinder is set on its own timer or frequency system. By disabling some cylinders, the width of the rubblized area can be varied from 2.5 to 12.67 ft. Typically, a 10-ton vibratory grid roller follows the multihead breaker to reduce the size of the broken concrete. The rate of production of the multihead breaker depends on the type of base or subbase material and is about 0.75 to 1 lane mile per day. Several variables affect the rubblization process, including speed, height, weight, and frequency of the drop hammers. The multihead breaker encounters difficulties on weak or saturated subbase and/or roadbed soil, which fail in shear, causing large concrete pieces to rotate and/or penetrate the underlying material. Such failure would result in poor pavement performance.

Examples of successful application of the rubblization technique as a long-life HMA pavement include (1) I-440, Raleigh Beltway, North Carolina (average daily traffic (ADT) > 100,000); (2) I-65, Alabama; and (3) I-496 near Lansing, Michigan. Figure A.10 shows example design cross sections for long-life performance of HMA over rubblized concrete pavements developed by Von Quintus for the Michigan APA (Asphalt Pavement Alliance 2002).

Thompson has demonstrated that a mechanistic-empirical approach to evaluation of the structural capacity of in-service asphalt pavement can be used to determine the required overlay

(a) (b)

Figure A.9. (a) Multihead breaker. (b) Grid roller.

Design Catalog of Michigan Perpetual Pavement Sections Over Rubblized Concrete (Von Quintus, 2001b)

Design Period, Years	*20-Year Traffic Level, ESAL X 10^6*	*3*	*10*	*20*	*30*
20	Total HMA Thickness, mm	150	215	270	290
	SMA Thickness, mm	—	—	65	65
	Superpave Thickness, mm	50	50	—	—
	Binder Course, mm	100	50	75	75
	Base Course, mm	—	115	130	150
	Rehab. Year 20, Mill/Replace, mm	65/130	65/130	65/130	65/130
	Rehab. Year 32, Mill/Replace, mm	50/75	50/90	40/75	40/75
30	Total HMA Thickness, mm	175	255	305	330
	SMA Thickness, mm	—	—	65	65
	Superpave Thickness, mm	50	50	—	—
	Binder Course, mm	50	75	75	75
	Base Course, mm	75	130	165	190
	Rehab. Year 20, Mill/Replace, mm	65/115	65/115	65/115	65/115
	Rehab. Year 32, Mill/Replace, mm	50/50	50/50	50/50	50/50
40	Total HMA Thickness, mm	215	290	330	370
	SMA Thickness, mm	—	—	65	65
	Superpave Thickness, mm	50	50	—	—
	Binder Course, mm	65	100	100	100
	Base Course, mm	100	140	165	205
	Rehab. Year 20, Mill/Replace, mm	50/50	50/50	65/65	65/65
	Rehab. Year 32, Mill/Replace, mm	50/50	50/50	65/65	65/65

Source: Asphalt Pavement Alliance 2002.

Figure A.10. Michigan design catalog for long-life HMA pavements over rubblized concrete.

thickness for rubblized concrete pavements (Thompson 1999). An algorithm to predict the tensile strain at the bottom of the asphalt overlay as a function of a deflection basin parameter, called the area under the pavement profile (AUPP), has been validated with measurements from instrumented full-depth and conventional flexible pavements. Falling weight deflectometer (FWD) data from rubblized concrete pavements with asphalt concrete overlays were used to develop a relationship between AUPP and an overlay stiffness parameter (Eh^3, where E is the asphalt concrete modulus and h is the asphalt overlay thickness). The estimated strain is an input to an asphalt concrete fatigue model. The asphalt overlay thickness is selected to limit the asphalt concrete tensile strain to an acceptable level.

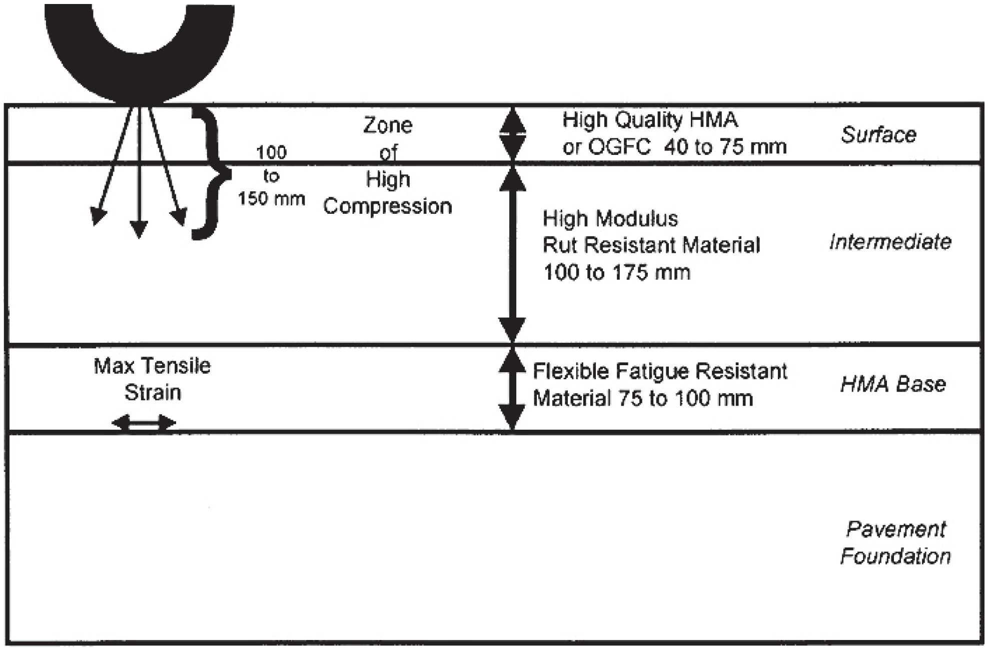
The NCHRP 1-37A MEPDG procedure's software for design of AC overlay of rubblized PCC allows the user to select some or all of the following performance criteria by which the adequacy of a trial overlay design is judged:

- Rutting,
- Alligator cracking,
- Longitudinal cracking,
- Transverse cracking, and
- Smoothness.

In the MEPDG software, the elastic modulus of the rubblized PCC is assigned a modulus of 150 ksi for Level 3 design (the simplest approach, requiring the fewest and simplest user inputs). For Level 1 design (the most sophisticated approach, requiring the most numerous and precise user inputs), however, the rubblized PCC modulus may be assigned a value from 300 to 600 ksi, depending on the expected level of control on the breaking process, and the anticipated coefficient of variation of the fractured slab modulus.

Criteria for Long-Life AC Renewal Approaches

For asphalt concrete pavements, achieving long life requires the combination of a rut- or wear-resistant top layer with a rut-resistant intermediate layer and a fatigue-resistant base



Source: Newcomb et al. 2001.

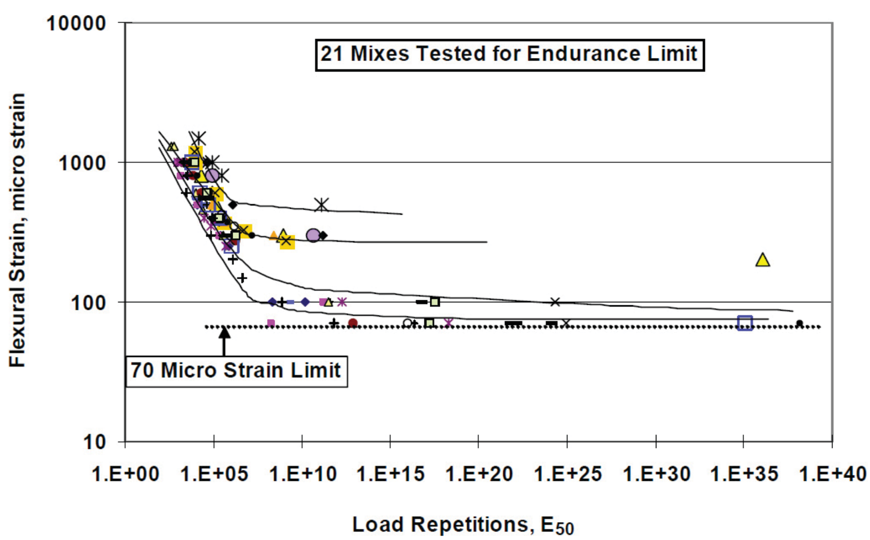
Figure A.11. Long-life HMA pavement design concept.

layer, as illustrated in Figure A.11 (Newcomb, Buncher, and Huddleston 2001).

This requires a high-quality HMA wearing surface or an open graded friction course, a thick, stiff dense graded intermediate layer, and a flexible (asphalt-rich) bottom layer. In addition, the pavement foundation must be strong enough to satisfy the limiting strain criteria. Suggested values for the horizontal tensile strain at the bottom of the AC layer and vertical subgrade strain are 65 and 200 microstrains, respectively.

The value for the endurance limit of the tensile strain at the bottom of the AC layer is still debated. Original work by Monismith and others suggests a value of 65 microstrains (Figure A.12). Others believe that this value is too conservative, and that a higher value (100 to 120 microstrains) should be used to ensure that the AC renewal solution is economical.

When applied to existing pavements, a fourth condition is added: the inhibition of reflective cracking. This is true regardless of the existing pavement type (i.e., distressed HMA



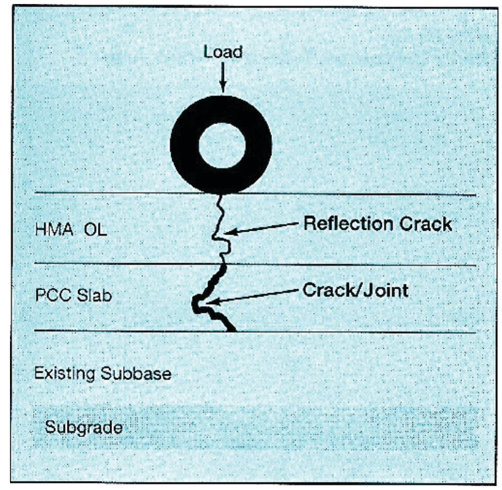
Source: Thompson and Carpenter 2006.

Figure A.12. Endurance fatigue limit for long-life AC pavements.

or PCC), although experience shows that reflective cracking can be more predominant when the existing pavement is a PCC pavement. Reflection cracking can occur in an HMA overlay over any joint or crack in the PCC pavement. The current state of the art does not provide accurate methods to predict the occurrence and growth of the reflection crack. Figure A.13 schematically illustrates reflection crack distress in an HMA overlay placed over a joint or crack of an existing PCC slab. Figure A.14 illustrates the mechanism through which the crack develops and propagates in the HMA layer (National Asphalt Pavement Association 1994).

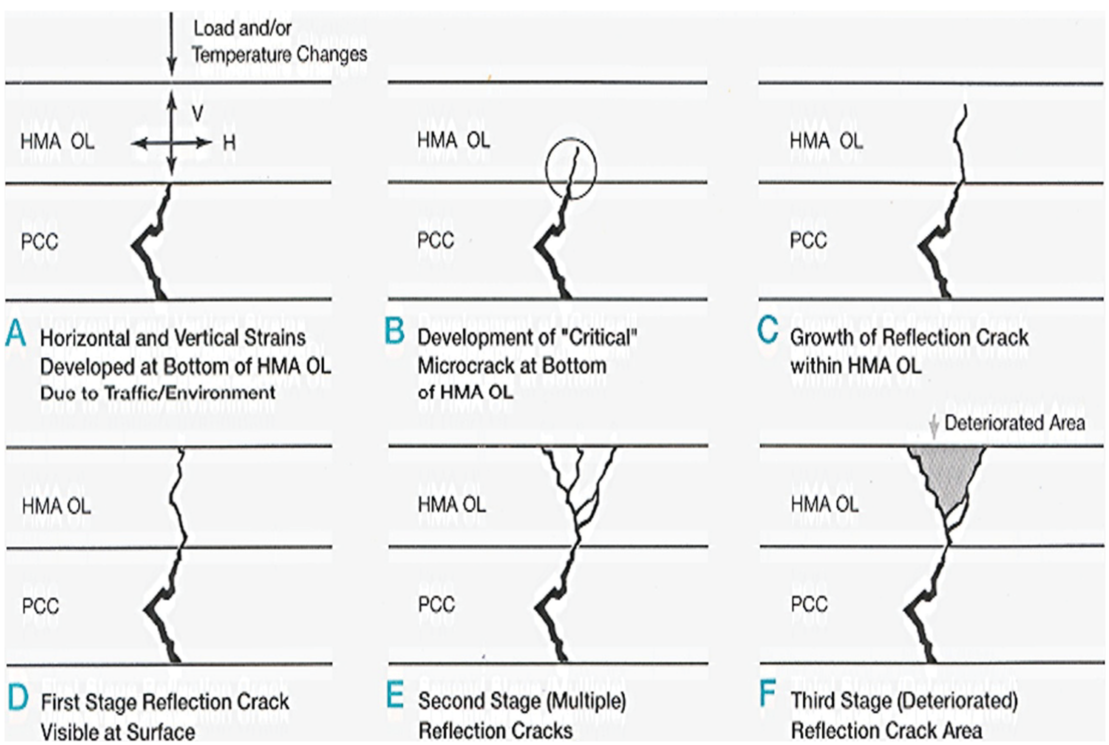
PCC slabs expand and contract with seasonal changes in temperature. This movement causes the development of forces at the bottom of the HMA layer as shown in Figure A.14, part A. The combination of forces at the bottom of the HMA overlay will eventually cause the development of a microcrack at the bottom of the HMA overlay, as shown in B. With time, this microcrack will grow and eventually reflect upward to the surface of the HMA overlay, as shown in C and D. As temperature and loading cycles continue, multiple cracks will form and eventually result in significant deterioration of the HMA surface, as shown in E and F. Figure A.15 illustrates a distressed reflection crack area in an HMA overlay over an existing PCC pavement.

Existing CRCP is an excellent foundation for a new long-life HMA pavement since reflection cracking is not a problem as long as cracks are of low severity and failed areas (punchouts and deteriorated cracks) are repaired prior to overlaying. Pavements with D-cracking are not good candidates for HMA overlays without slab fracturing. Studies have shown that the placement of HMA overlay can accelerate D-cracking, and field data showed poor performance of HMA overlays of concrete pavement with D-cracking (Liu et al. 2003).



Source: National Asphalt Pavement Association 1994.

Figure A.13. Schematic representation of a reflection crack.



Source: National Asphalt Pavement Association 1994.

Figure A.14. Growth of a reflection crack.

Source: Martin 1973.

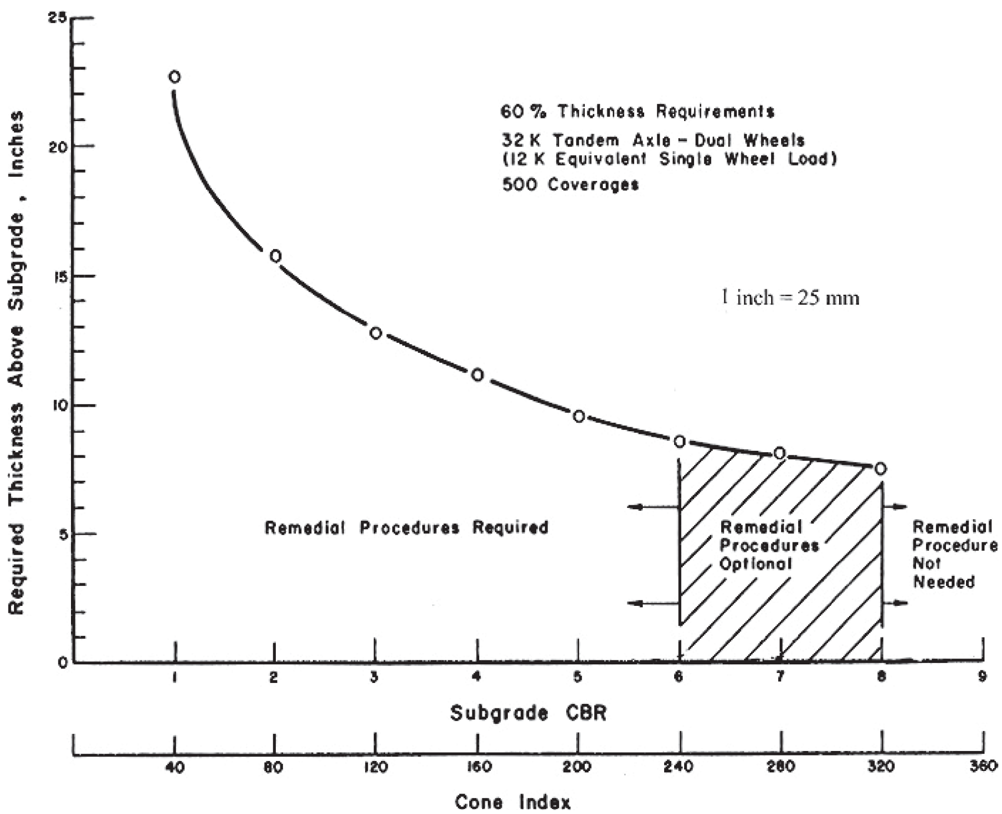
Figure A.15. Reflection cracking in HMA overlay over PCC pavement.

Because the pavement foundation is critical to the construction and performance of a long-life HMA pavement, the question of whether an existing pavement can be used in place largely depends on the quality of the existing foundation. A careful consideration of the existing condition of the pavement foundation must therefore be made. This is in light of the fact that there will be cases where the condition of the existing subgrade does not warrant using the existing pavement in place (e.g., drainage problems or soft layer underneath existing pavement structure). Several end-result specifications for the foundation layers have been used in Europe (United Kingdom, France, and Germany), requiring a minimum modulus under FWD loading or imposing a maximum tolerable surface deflection (Newcomb et al. 2001). The state of Illinois requires a minimum CBR- or DCP-based cone index value below which the subgrade soil must be modified (using lime treatment), as shown in Figure A.16.

Overlay Design Approaches for AC Surfaced Pavements

The two most commonly used approaches to structural design of asphalt overlays of asphalt pavements are (1) the structural deficiency approach, exemplified by the 1993 AASHTO procedure (AASHTO 1993) and (2) the deflection-based approach, exemplified by the Asphalt Institute procedure (Asphalt Institute 1999). Much less common is the mechanistic approach, in which fatigue and rutting performance are predicted using mechanistic-empirical models (Hall et al. 2001).

In a mechanistic-empirical approach to design of asphalt overlays of asphalt pavements, performance of the overlay is



Source: Illinois Department of Transportation 1982.

Figure A.16. Illinois granular thickness requirement for foundations.

predicted using mechanistic-empirical distress models. The distresses considered should include at least fatigue cracking, and ideally rutting and thermal cracking as well. The existing pavement layers and foundation are characterized using non-destructive deflection testing and backcalculation of their elastic moduli. Material properties for the overlay are assumed. The overlay thickness that will yield acceptable performance in terms of the distresses considered is determined by iteration. A conceptual overview of the mechanistic-empirical approach to design of asphalt overlays of asphalt pavements is given by Monismith (1992).

The individual tools used in mechanistic-empirical design of asphalt pavements (e.g., fatigue models, rutting models, seasonal adjustment) can be adapted to some extent to design of asphalt overlays. However, there are additional aspects of the problem that need to be considered to develop a full design procedure for asphalt overlays of asphalt pavements. Among these are consideration of the extent, type, and quality of preoverlay repairs, prediction of reflection crack propagation and deterioration (a problem for asphalt overlays of both asphalt and concrete pavements), and calibration of asphalt overlay performance prediction models to the observed performance of asphalt overlays.

Several examples of mechanistic-empirical procedures for design of asphalt pavements exist, such as the Shell procedure (Shell International Petroleum Company 1978), the Asphalt Institute procedure (1981; Shook et al. 1982), the NCHRP 1-26 procedure (Thompson 1989), and the MEPDG procedure developed under NCHRP 1-37A (Applied Research Associates 2004). Fewer examples exist, however, of mechanistic-empirical procedures for design of asphalt overlays of asphalt pavements.

The NCHRP 1-37A MEPDG procedure's software for design of AC overlay of AC allows the user to select some or all of the following performance criteria by which the adequacy of a trial overlay design is judged:

- Rutting,
- Alligator cracking,
- Longitudinal cracking,
- Transverse cracking, and
- Smoothness.

According to the MEPDG, "the models used for the prediction of structural distresses (i.e., excluding smoothness prediction) in the overlaid pavement are basically the same as those described in Part 3, Chapter 3 [for design of new AC pavements] with some modifications to the rates of distress accumulation in the existing layers."

The smoothness parameter used for AC overlays of AC pavements in the MEPDG methodology is the IRI, predicted from an empirical model as a function of the existing pavement's IRI at the time of overlay placement, the time elapsed since placement of the overlay, the percent of the wheelpath area with fatigue cracking, the average spacing of medium- and high-severity transverse cracks, the length of medium- and high-severity sealed longitudinal cracks in the wheelpath, the percent of the total lane area with medium- and high-severity patches, and the percent of the total lane area with potholes.

Among the few state departments of transportation (DOTs) that have developed a mechanistic-empirical design procedure for asphalt overlays of asphalt pavements are Washington (Mahoney et al. 1989), Idaho, and Nevada (Nevada Department of Transportation 1996; Sebaaly et al. 1996). The Washington State DOT procedure uses a model to predict fatigue as a function of horizontal tensile stress at the bottom of the asphalt overlay and at the bottom of the original asphalt layer, as well as a model to predict rutting as a function of vertical compressive stress at the top of the subgrade. The critical stress locations considered are illustrated in Figure A.17. A flowchart of the Washington State procedure is illustrated in Figure A.18. The overlay thickness required to keep fatigue and rutting below critical levels is determined through a process of iteration.

Figure A.19 compares traditional mechanistic-empirical (M-E) design to long-life pavement design. The basic concept in designing long-life AC pavements is to use limiting strain criteria (see Figure A.19b).

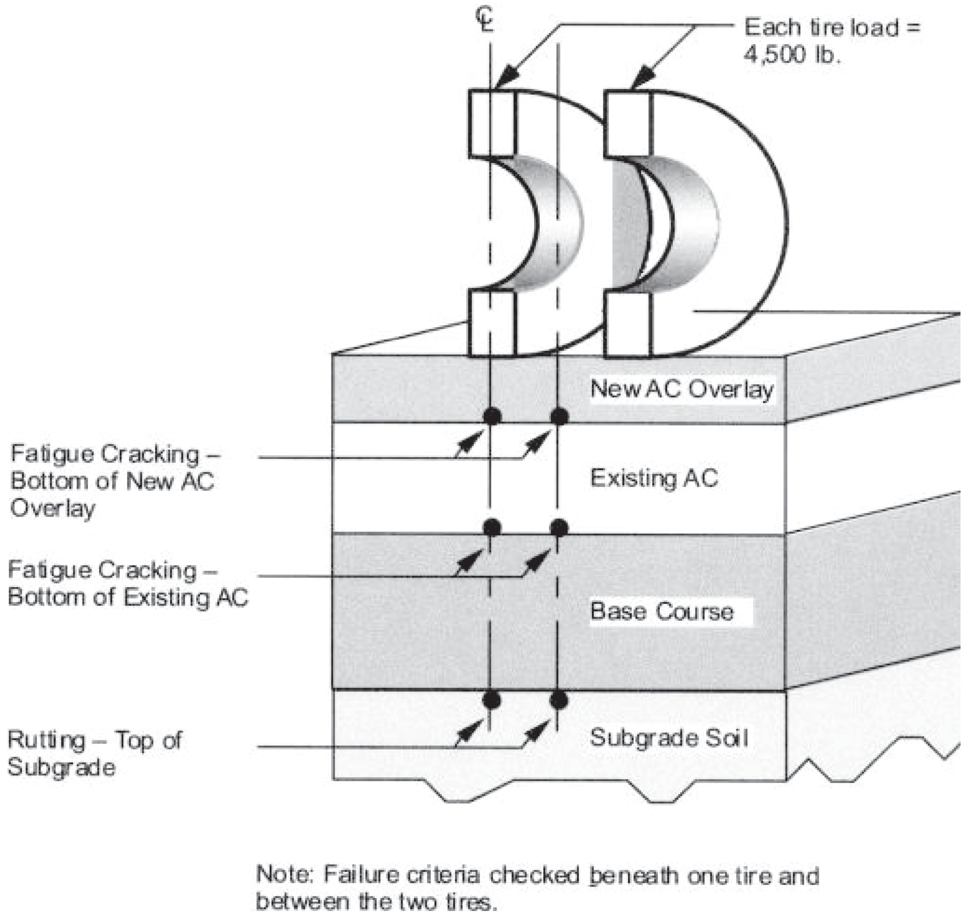
Structural Design of AC Overlay over Fractured Slab

The approach taken in the 1993 AASHTO Guide to design of asphalt overlays of fractured slabs (both crack and seat and rubblizing) is a structural deficiency approach. The overlay must satisfy the deficiency between the structural number (SN_f) required to support traffic over some future design period, and the effective structural number (SN_{eff}) of the existing pavement (after fracturing).

Perhaps the most contentious aspect of overlay design for fractured slabs by the structural deficiency approach is what structural coefficient should be assigned to the fractured slab. The 1993 AASHTO Guide recommends the following ranges for structural coefficients for different types of slab fracturing:

- Rubblized: 0.14–0.30,
- Crack and seat: 0.20–0.35, and
- Break and seat: 0.20–0.35.

Other recommendations for overlay design for fractured slabs, including recommended ranges of structural coefficients and overlay thickness design tables, have been developed by NAPA. A study done for the ACPA recommended a range of 0.15 to 0.25 for the structural coefficient of all three types of fractured slabs (Hall 1999).



Source: Washington State Department of Transportation 2005.

Figure A.17. Critical stress locations considered in Washington State DOT overlay design procedure.

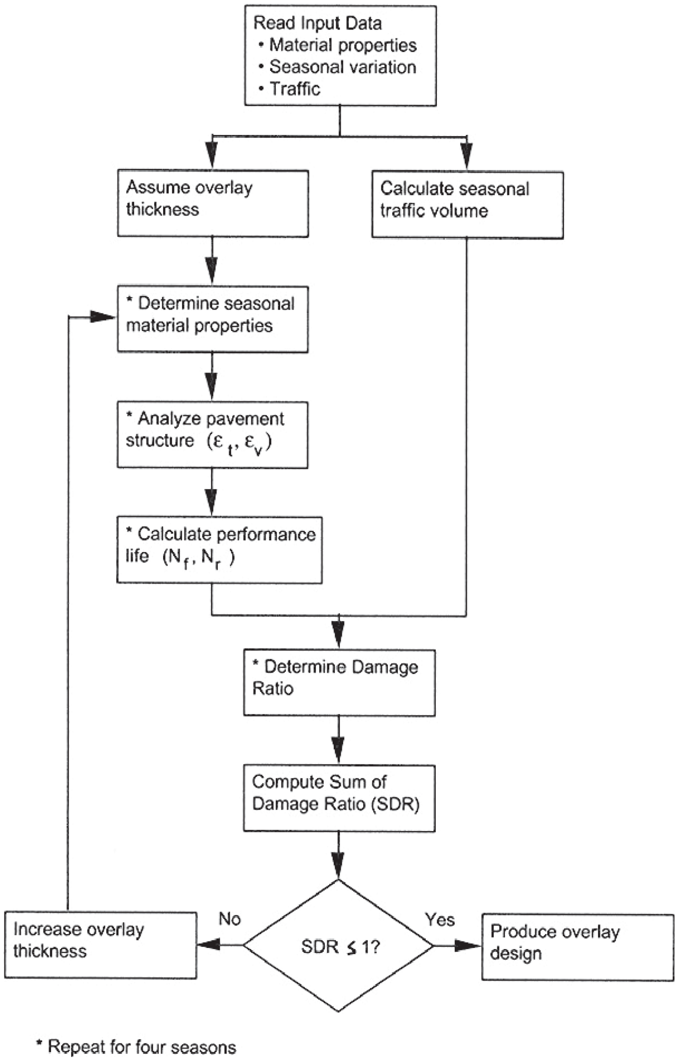
A mechanistic procedure for design of AC overlays of cracked and seated concrete pavements was developed by Thompson at the University of Illinois as part of the FHWA/Illinois DOT study Mechanistic Evaluation of Illinois Flexible Pavement Design Procedures. For a given overlay thickness, the required inputs are the design AC elastic modulus, the subgrade resilient modulus, and the "equivalent modulus" of the cracked and seated concrete.

In the development of the design procedure, the finite element program ILLI-PAVE was used to estimate the asphalt concrete bending strain for a range of overlay thicknesses. Transfer functions for the number of repetitions to failure for a given bending strain were developed for typical Illinois DOT Class I asphalt concrete mixtures (Schutzbach 1988, 1989). Additional guidance on the use, design, and construction of AC overlays of cracked and seated PCC pavements is given by Thompson in NCHRP Synthesis No. 144 (Thompson 1989).

Ahlrich has documented the use of FWD testing on intact PCC slabs and testing after cracking and seating and overlaying with AC to determine the "effective modulus" of the cracked and seated PCC layer (Ahlrich, 1989). In field studies conducted by the U.S. Army Corps of Engineers Waterways Experiment Station, at the Rock Island Arsenal in Illinois and Fort Wainwright in Alaska, concrete slabs with an elastic modulus of about 6 million psi were reduced by cracking and seating to a fractured concrete layer with an effective elastic modulus of about 1 to 1.5 million psi. Similar results from analysis of FWD deflections measured on test sections at the LTPP SPS-6 test site on I-57 in Illinois have been reported by Hall (1991).

The NCHRP 1-37A MEPDG procedure's software for design of AC overlay of cracked and seated PCC allows the user to select some or all of the following performance criteria by which the adequacy of a trial overlay design is judged:

- Rutting,
- Alligator cracking,
- Longitudinal cracking,
- Transverse cracking, and
- Smoothness.



Source: Washington State Department of Transportation 2005.

Figure A.18. Washington State Department of Transportation overlay design procedure flowchart.

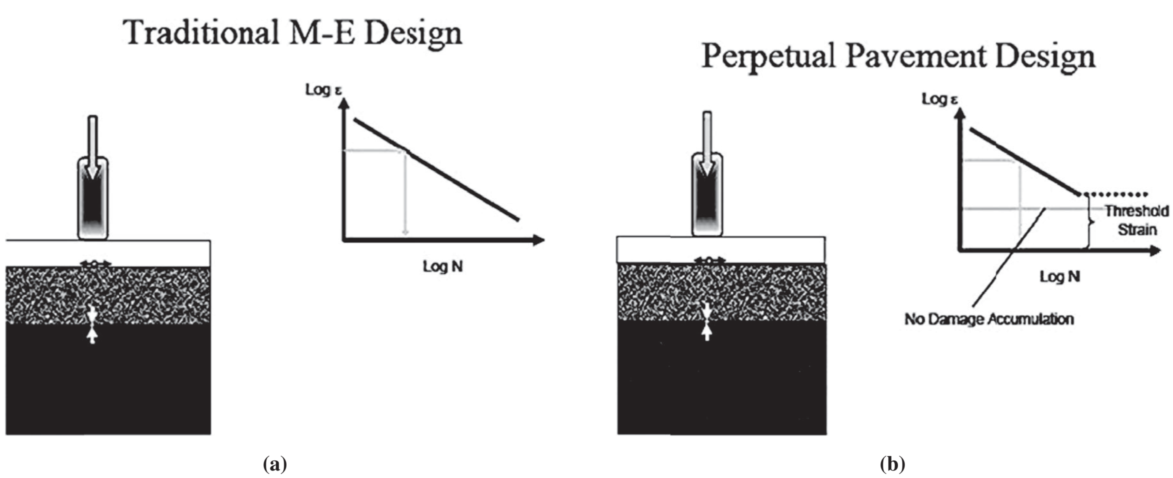
In the MEPDG software, the elastic modulus of the cracked and seated PCC is assigned as a function of the crack spacing (i.e., 200 ksi for 12-in. spacing, 250 ksi for 24-in. spacing, and 300 ksi for 36-in. spacing) for Level 3 design (the simplest approach, requiring the fewest and simplest user inputs). For Level 1 design (the most sophisticated approach, requiring the most numerous and precise user inputs), however, the rubblized PCC modulus may be assigned a value from 300 to 600 ksi, depending on the expected level of control on the breaking process and the anticipated coefficient of variation of the fractured slab modulus.

Renewal of Rigid Pavements

When in-place renewal of an existing PCC pavement is considered, the structural design considerations that must be taken into account to ensure good long-term performance are the adequacy of the subgrade, protection of the subgrade from excessive deformation, limiting strain in the existing PCC, limiting stress and strain in the new AC or PCC surface, and minimizing reflection cracking in the new surface.

While AC overlay is undoubtedly the most common major rehabilitation method for jointed PCC pavements, the service life of this technique is limited by the rate at which reflection cracks develop and deteriorate to unacceptably rough levels. Thus, an AC overlay of a jointed PCC pavement is typically considered a conventional rather than a long-life rehabilitation approach, with an expected service life of about 10 to 15 years.

However, exceptions exist: Iowa, for example, has experience with jointed PCC pavements built in the 1930s and 1940s, widened with PCC or AC from 18, 20, or 22 ft to 24 ft the 1970s, and then overlaid over time with a total of five or more inches of AC. Now, some 30 years later, these old AC/PCC pavements are being widened again, to 28 or 32 ft, and



Source: Timm 2005.

Figure A.19. Traditional versus long-life AC pavement design.

are being overlaid with PCC (J. K. Cable, personal communication, 2008).

The most promising long-life rigid pavement methods, however, appear to be the following:

- AC over CRCP,
- AC over cracked and seated JPCP,
- AC over rubblized PCC,
- Unbonded PCC over PCC, and
- Bonded PCC over PCC.

Definition of Long-Life Concrete Pavements

Long-life concrete pavements (LLCPs) have been quite attainable for a long time in the United States, as evidenced by the number of very old pavements that remain in service; however, recent advances in design, construction, and concrete materials technology give engineers the knowledge and technology needed to consistently achieve what they know to be attainable. A working definition of long-life concrete pavement in the United States is summarized as follows (Tayabji and Lim 2007):

- Original concrete service life is 40+ years.
- Pavement will not exhibit premature construction and materials-related distress.
- Pavement will have reduced potential for cracking, faulting, and spalling.
- Pavement will maintain desirable ride and surface texture characteristics with minimal intervention activities, if warranted, for ride and texture, joint resealing, and minor repairs.

The quest for long-life concrete pavements necessitates a much better understanding of design and construction factors that affect both short-term and long-term concrete pavement performance. Essentially, this requires a better understanding of how concrete pavements deteriorate or fail. Concrete pavements deteriorate over a period of time as a result of distresses that develop due to a combination of traffic and environmental loading. Typical distresses that can develop include the following:

1. *Cracking:* Typically transverse cracking occurs, but longitudinal, random, and corner cracking may also develop due to poor design and construction practices. Cracking is typically referred to as a stress-based distress.
2. *Joint faulting:* Joint faulting may develop with or without outward signs of pumping. Faulting is typically referred to as a deflection-based response. Joint faulting is significantly affected by the type of load transfer provided at transverse joints.
3. *Spalling:* Spalling may develop along joints or cracks and may be caused by poor joint-sawing practices, incompressible materials in joints or cracks, winter snow removal operations, or poor-quality concrete.
4. *Materials-related distress:* The more significant materials-related distresses may include alkali-silica reactivity and D-cracking in freezing environments.
5. *Roughness:* The lack of pavement smoothness, or roughness, is affected by the development of various distresses in the concrete pavement, as listed in items 1 through 4 above. The effect of each distress type is additive and results in pavement roughness over a period of time. Some pavement roughness is also built in during construction. Initial pavement smoothness is needed so that the pavement does not become prematurely rough. Construction specifications typically utilize incentives and disincentives to control new pavement smoothness.
6. *Texture loss:* Although not conventionally considered a distress, texture loss is a significant distress for pavements in high-volume, high-speed applications.

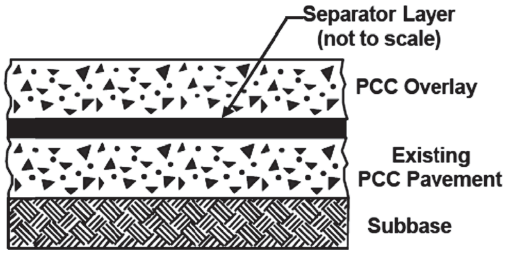
It is realized that it would be impossible or impractical to design and construct concrete pavements that exhibit very little or no distress. Distress development over the pavement's service life is expected. However, the rate of distress development is managed by incorporating sound designs, durable paving materials, and quality construction practices. Generally recognized threshold values in the United States for distresses at the end of the pavement's service life are listed in Table A.2 for JPCPs and CRCPs.

Unbonded PCC over PCC

An unbonded PCC overlay (sometimes called a separated overlay) contains an interlayer between the existing PCC pavement and the new PCC overlay (Figure A.20). Unbonded overlays of all types (jointed plain, jointed reinforced, and continuously reinforced) can be placed on all types of concrete

Table A.2. Threshold Values for Long-Life Concrete Pavement Distresses

Distress	Threshold Value
Cracked slabs, % of total slabs (JPCP)	10–15
Faulting, mm (in.) (JPCP)	6–7 (0.25)
Smoothness (IRI), m/km (in./mi) (JPCP and CRCP)	2.5–3.0 (150–180)
Spalling (length and severity) (JPCP and CRCP)	Minimal
Materials-related distress (JPCP and CRCP)	None
Punchouts, no./km (no./mi) (CRCP)	10–12 (12–16)



Source: McGhee 1994.

Figure A.20. Typical cross section of an unbonded PCC overlay.

pavements, including those with existing asphalt overlays. Unbonded concrete pavements are appropriate for pavements with little or no remaining structural life and/or extensive and severe durability distress. Unbonded concrete overlays require little or no preoverlay repair and are thus well suited to badly deteriorated concrete and asphalt-overlaid concrete pavements. An unbonded concrete overlay is an attractive alternative to reconstruction when construction duration is a pressing issue (e.g., for high traffic volumes and/or very poor subgrade conditions).

Jointed unbonded PCC overlays of PCC highway pavements have been built in the United States since the 1920s. The first unbonded continuously reinforced concrete (CRC) overlay of an existing jointed PCC highway pavement in the United States was constructed in Texas in 1959 (Martin 1973). In subsequent years CRC overlays were placed on hundreds of miles of both asphalt and jointed concrete pavements. Illinois built its first experimental test sections of CRC overlay on jointed reinforced PCC pavement in 1967 (Dhamrait and Schwartz 1978). Georgia built its first CRC overlay of a jointed plain PCC pavement in 1973 (Tyner, Gulden, and Brown 1981). The first unbonded CRC overlay of an existing CRC highway pavement in the United States was constructed on I-59 in Mississippi in 1982 (Crawley 1982).

There is little doubt that unbonded concrete overlays, be they jointed or CRC, are substantial pavement structures with expected performance characteristics as good as or better than new concrete pavement construction. They are essentially new concrete pavements on high-quality foundations, and the consensus from past field studies is that, as long as an adequate separation layer is used, their performance is fairly insensitive to the condition of the overlaid pavement. Thus, they are certainly viable candidates for long-life in-place renewal projects. To date, unbonded overlays have typically been designed for service lives in the range of 20 to 30 years. The PCC overlay thickness design approaches, slab thicknesses, and other design details required to achieve service lives of 40 or 50 years needs to be studied (Hall, Darter, and Seiler 1993).

Traditionally, unbonded concrete overlays have been designed using some form of the familiar "square root" equation shown below:

$$h_{ol} = \sqrt{h_f^2 - h_{eff}^2}$$

where
h_{ol} = unbonded overlay thickness,
h_f = required slab thickness for future traffic, and
h_{eff} = effective thickness of the existing slab.

The square root equation dates back to the Bates Road Test in the 1920s, and its use in unbonded overlay design procedures started in the 1940s (Older 1924). Full-scale field tests of concrete overlays conducted by the Corps of Engineers in the 1940s and 1950s indicated that the square root equation yielded conservative results (Mellinger 1963).

Although many engineers have the impression that the square root equation (also called the Corps of Engineers equation) for unbonded overlay design is completely empirical, it has a theoretical basis. Several researchers have demonstrated that an overlay slab and a base slab can be represented by an equivalent single slab in a variety of ways—for example, equivalent surface deflection, equivalent tensile stress in the overlay slab, and equivalent tensile stress in the base slab.

There are, however, some important limitations to the characterization of an unbonded overlay and base slab as an equivalent single slab. The Corps of Engineers square root equation is a simplified form of the equations for stress in either the base slab or the overlay slab equivalent to stress in the equivalent single slab. This simplified equation is only valid when the two slabs are equal in thickness and equal in elastic modulus.

Another important limitation to characterizing an unbonded overlay slab and base slab in terms of an equivalent single slab is that it assumes full contact between the overlay and base slabs. They may bend independently, but they must have the same radius of curvature. To whatever extent the overlay slab curls and/or warps to a different shape than the underlying slab, it will experience different, and in some cases much greater, stresses under combined load and curling than the equivalent thickness concept implies.

The third major limitation of the Corps of Engineers equation is the structural deficiency concept itself, namely, the assumption that an overlay satisfies a structural deficiency between a required single slab thickness and an existing slab's effective (i.e., damage-adjusted) thickness. As can be seen by examining the square root equation, the structural deficiency concept implies that for a given required slab thickness for future traffic, a thicker existing pavement will require a thinner unbonded overlay than a thinner existing pavement in the same condition. Conversely, it implies that a given thickness of unbonded overlay will perform better on a thicker existing pavement than on a thinner existing pavement in the same condition.

Field observations do not support the implication that unbonded overlay performance is as sensitive to existing pavement thickness as the structural deficiency concept suggests.

One alternative to the Corps of Engineers equation for design of an unbonded overlay is to design the overlay as if it were a new pavement, with the existing pavement structure characterized as a foundation for the new slab. The elastic modulus, modulus of rupture, and load transfer coefficient inputs to the design model are typically the anticipated values for the overlay slab. Two key differences exist between this approach and the Corps of Engineers approach. The first difference is that the existing pavement is not considered to contribute any structural capacity to the total structural capacity of the overlaid pavement. The existing pavement is instead considered a foundation for the new slab. This leads to the second major difference between the two methods. The *k* value of the foundation beneath the existing pavement is used to determine the required future slab thickness in the Corps of Engineers method, whereas the new pavement design method requires a *k* value beneath the overlay. The major difficulty in application of the new design approach thus lies in selection of an appropriate design *k* value (Barenberg 1981).

Conventional practice in concrete pavement design for many years has been to assign a *k* value to a granular or stabilized base that is considerably higher than the *k* value of the subgrade and which was a function of the thickness and stiffness of the base layer. This convention is still employed for new concrete pavements in the 1993 AASHTO Guide and Portland Cement Association design procedures. Following this logic, an existing concrete pavement with an asphalt concrete surfacing for a separation layer would be assigned a very high *k* value, such as 500 psi/in. or more for unbonded overlay design. However, backcalculation results indicate that when an unbonded overlay is designed as a new pavement with the existing pavement as its foundation, it is neither necessary nor appropriate to use an extremely high *k* value such as 500 psi/in. or more. A design static *k* value in the range of 200 to 400 psi/in. is probably appropriate in most cases. Whenever possible, deflections should be measured on the existing pavement prior to overlay to backcalculate a dynamic *k* value for the existing foundation and to estimate from this a reasonable static *k* value for design.

Another issue that should be considered is the effect of curling on performance. If a jointed overlay slab is designed as a new pavement with the existing pavement serving as its foundation, it will experience much higher curling stresses than a conventional concrete pavement on a weaker foundation (Voigt, Darter, and Carpenter 1989). These higher curling stresses may be computed using finite element analysis or available equations. However, if the performance model used to determine the required slab thickness was developed for concrete pavements on weak foundations, the detrimental effect of high curling stress will not be adequately reflected in the predicted performance of the overlay. This would be the case if, for example, the 1993 AASHTO design procedure was used to determine the required slab thickness rather than a fatigue analysis that directly considered the combined effects of load and curling. Either increased slab thickness or reduced joint spacing may be necessary to achieve the performance from the unbonded overlay that is predicted by the model.

Other alternatives to unbonded overlay design involve modeling the overlay and existing slab as either two elastic layers or two plates on a foundation. This is arguably the most realistic of the three design approaches described here, but also the most difficult. The basic approach is the same as for design of the overlay as a new pavement, except that the existing pavement structure is characterized more realistically, not as a uniform foundation but as a multilayered system. Among the difficulties associated with this approach are the following:

- Characterization of the existing slab, including deciding how (if at all) to account for existing deterioration;
- Identifying the important structural responses (e.g., overlay stress, overlay deflection, original slab stress); and
- Identifying the important performance criteria (e.g., cracking in the original slab and/or cracking in the overlay slab).

In jointed unbonded concrete overlays, the joints should be spaced more closely than they would be in a new pavement on a granular base, and the overlay's transverse joints and the old pavement's transverse joints should be mismatched to improve load transfer across the overlay joints. Mismatching the joints by at least 1 ft is advisable; several agencies specify a mismatch of 3 ft.

According to the ACPA, dowels are not considered necessary for jointed unbonded overlays less than 8 in. thick. For overlays 8 to 9 in. thick, 1.25-in.-diameter dowels are recommended, and for overlays greater than 9 in. thick, 1.5-in.-diameter dowels are recommended. The ACPA also provides guidelines for constructing transitions between unbonded concrete overlays and existing or reconstructed pavement sections.

Additional information on the design and performance of unbonded concrete overlays is provided in NCHRP Synthesis 99, *Resurfacing with Portland Cement Concrete* (Hutchinson 1982); NCHRP Synthesis 204, *Portland Cement Concrete Resurfacing* (McGhee 1994); the ACPA's *Guidelines for Unbonded Concrete Overlays* (1990); the Portland Cement Association's *Guide to Concrete Resurfacing Designs and Selection Criteria* (1981); and NCHRP Report 415, *Evaluation of Unbonded Portland Cement Concrete Overlays* (ERES Consultants 1999).

The performance of unbonded PCC overlays of existing PCC pavements depends significantly upon obtaining effective *separation* between the two layers. Since the unbonded PCC overlays are placed on PCC pavements in a more advanced state of deterioration, distresses from the underlying pavement can potentially reflect through the new overlay and compromise its performance. Typically, a fine-graded asphalt surface mixture is used for the separator layer. The thickness of the separator layer is a function of (1) the condition of the existing pavement and (2) the type of preoverlay repairs. Based on the review of the literature a minimum thickness of 1 in. is recommended for HMA separator layers. Thinner layers erode easily near joints and do not provide adequate isolation of the overlay from underlying PCC pavement. The separator layer is not intended to provide structural enhancement; therefore, the placement of an excessively thick layer should be avoided. Some state DOTs have modified the asphalt mixture because their surface mixes were not stable and were prone to scouring, particularly under heavy truck traffic. In an effort to reduce the scour pore pressure and increase stability, the sand content was reduced and the volume of 3/8-in. (9.5-mm) chip aggregate was increased (National Concrete Pavement Technology Center 2007). This modified mixture has a reduced unit weight and lower asphalt content.

Other bituminous surface treatments such as slurry seals, cutbacks, and emulsions have been used for low-volume roads. In Germany, lean concrete is used as an interlayer. This is done in conjunction with breaking or fracturing the existing pavement before overlaying the lean concrete interlayer. In addition to this process the interlayer is jointed to match the joints of the overlay.

Belgium is the only country outside the United States identified in this review as having reported appreciable experience with unbonded concrete overlays (Hall et al. 2007). Belgium constructed its first concrete overlay in 1960, over a concrete pavement originally constructed in 1934. The jointed concrete overlay was constructed of 7-in.-thick reinforced concrete slabs. Figure A.21 shows the overlay still in service nearly 45 years later.

Source: Hall et al. 2007.

Figure A.21. Belgium's first concrete overlay after 45 years in service.

Source: Hall et al. 2007.

Figure A.22. CRC overlay construction on E40/A10 in Belgium.

Construction of a concrete overlay on the E40/A10 road from Brussels to Ostende in Belgium is shown in Figure A.22. Two mobile concrete plants were used to produce the 2,600 cubic yards of concrete a day required for this project. The average paving rate was 3,900 ft per day, 24 ft wide. A closer view of the paver is shown in Figure A.23. Due to the very tight schedule for this project, concrete was placed without interruption, 24 hours a day, 7 days a week. As a result, the CRC overlay has no construction joints. A slipform paver was also used to construct the safety barriers on this job, as shown in Figure A.24.

Source: Hall et al. 2007.

Figure A.23. CRC overlay paving on E40/A10 in Belgium.

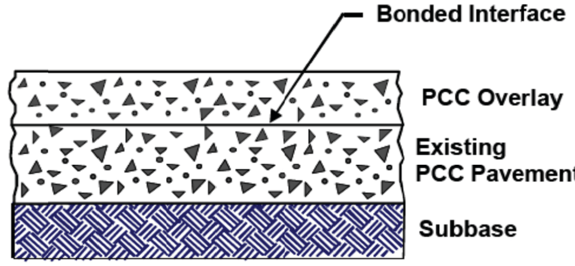
Source: Hall et al. 2007.

Figure A.24. Slipform paving of the safety barriers on the E40/A10 CRC overlay project.

Bonded PCC over PCC

Bonded PCC overlays of PCC are generally not considered very long-life pavement rehabilitation techniques because of their sensitivity to the condition of the underlying pavement and the difficulty of achieving the long-lasting bond necessary for composite bending action. Bonded concrete overlays are not often used, because they perform best on pavements in good to fair condition, that is, pavements that are not in urgent need of rehabilitation.

The *bonded concrete surface* is bonded to the existing concrete pavement to form a monolithic section. This renewal strategy has the potential to increase the structural capacity of an existing concrete pavement or to improve the overall ride quality. The bonded concrete surface is typically 2 to 5 in. thick. The bonded concrete surface works best when the existing pavement is free of structural distress and in relatively good condition. This rapid renewal strategy is typically attractive when vertical clearances must be met, or in mill and inlay sections, or in conjunction with widening projects. The achievement of an effective bond between the existing pavement and the new surface is critical in ensuring satisfactory performance of the bonded concrete surface. The use of "bonding agents" and "direct placement" are two methods that are practiced for this type of rehabilitation. Figure A.25 shows a cross section of a typical bonded PCC overlay.



Source: McGhee 1994.

Figure A.25. Typical cross section of a bonded PCC overlay.

The service life of a bonded PCC overlay of a PCC highway pavement is typically estimated at about 15 to 25 years at best. However, in the course of the work done for Task 1 of this study, a bonded PCC overlay recently constructed in Oklahoma was identified as one that is expected by some to be very capable of providing 40 years of service or more. The design and construction details of this project warrant study to gain insight into whether, and under what conditions, bonded PCC overlays might be viable candidates for long-life in-place renewal projects. Bonded PCC overlays have also been constructed in many different states, including California, Illinois, Iowa, Louisiana, New York, Pennsylvania, South Dakota, Texas, and Virginia, as well as in the countries of Belgium, Canada, Japan, and Sweden. By far the most common bonded PCC overlay type is JPCP, and these overlays have been placed on existing JPCP, JRCP, and CRCP designs (Sebaaly et al. 1996). Some bonded JRCP overlays have been used on existing JPCP and JRCP, although presently they are rarely used. Texas and Virginia have both constructed several bonded overlays on existing CRCP.

For bonded PCC overlays of existing PCC pavements, achieving the bond between the two layers is critical monolithic slab behavior. To help achieve this, many state highway agencies place either a cement grout or an epoxy resin on the existing PCC pavement just ahead of the paver. Cement grouts are generally produced in a mobile mixer from a mixture of portland cement and water; the grout should have a maximum *w/c* of 0.62 (American Concrete Pavement Association 1990). Epoxy bonding agents should be applied in accordance with the manufacturer's instructions. Prior to the placement of either type of bonding agent, the pavement surface should have already been prepared and should be dry (American Concrete Pavement Association 1990).

Renewal by Lane Replacement (Inlay) or Lane Addition

When a lane replacement or lane addition is contemplated as an approach to in-place renewal of an existing AC or PCC pavement, the design considerations that must be taken into account to ensure good long-term performance include the adequacy of the foundation, the required thickness and any constraints on it, the method of connection to the adjacent lane, the design of transitions, and, in the case of widening, geometric considerations such as the availability of horizontal and vertical space for relocating shoulders, slopes, ditches, and/or drainage systems, interchanges, and bridges.

Lane Replacement

The evident viability of this technique as a long-life in-place renewal method seems at odds with the relatively little use that it has seen to date in the United States. When a portion of the thickness of an AC lane is milled out and replaced with PCC, it can be considered, and designed and constructed as, a conventional white-topping overlay. One caution, however, is that in some such applications of concrete inlays with undoweled joints, premature joint faulting has occurred and has been attributed to the "bathtub effect" of water collecting under the PCC overlay slab. The ACPA recommends that either doweled jointed PCC or CRC be used when constructing an inlay to replace a portion of the thickness of an AC traffic lane subjected to heavy traffic in one direction and wet climatic conditions. An *inlay* is a renewal option that involves the replacement of all or part of an existing pavement travel lane (or lanes) without significantly raising the surface elevation. Inlays are practical for deteriorated concrete pavements. Single-lane and multilane inlays are common for concrete reconstruction. When a lane replacement or lane addition is contemplated as an approach to in-place renewal of an existing PCC pavement, the design considerations that must be taken into account to ensure good long-term performance include the adequacy of the foundation, the required thickness and any constraints on it, the method of connection to the adjacent lane, the design of transitions, and, in the case of widening, geometric considerations such as the availability of horizontal and vertical space for relocating shoulders, slopes, ditches, and/or drainage systems, interchanges, and bridges.

More information on design and construction of concrete inlays in existing AC or PCC pavements is provided in the ACPA publication *Reconstruction Optimization Through Concrete Inlays* (American Concrete Pavement Association 1993).

Belgium's experience with concrete inlays dates back to 1933 (ERES Consultants 1999). Concrete inlays in Belgium are constructed with either JPCP or CRCP. Figure A.26 is a photo of a CRC inlay being placed on the A10 freeway in Belgium (Caestecker and Lonneux 2004). The roadway had three lanes in each direction, and the existing pavement was AC over JPCP. Rutting, reflection cracking, and roughness over AC patches in the PCC layer, particularly in the outer lanes, were resulting in steadily increasing annual maintenance costs.

Source: Hall et al. 2007.

Figure A.26. CRC inlay construction in Belgium.

Lane Addition

Although adding new lanes to an existing pavement structure is also clearly a viable option for in-place long-life pavement renewal, it is costly and thus usually is only done when it is essential to increase the capacity of an existing roadway. In the course of the Task 1 work done for this study, several examples of lane addition projects on major highways in the eastern north-south corridor of the United States, including some that are currently under construction, were identified. Both the structural design aspects and the construction logistics aspects of such projects need to be studied to identify the requirements for achieving good performance over an extended service life.

Caestecker described an example of this type of work: the replacement of an outer AC shoulder with a fourth traffic lane on a heavily trafficked section of a six-lane highway on the A3 motorway toward Brussels, Belgium (Caestecker 1993). An important reason that the lane addition option was chosen was that highway noise is a significant environmental concern in Belgium, and designers were confident that a concrete-surfaced lane addition could achieve the capacity increase desired while minimizing the traffic noise generated by the roadway. The new lane was placed with a GOMACO slip form paver, operating at its capacity of 300 to 500 m per day.

Immediately after paving, the surface was sprayed with a retarding agent and covered with plastic sheeting, to be brushed later to achieve the kind of exposed aggregate surface that has become popular in some European countries for both noise control and friction. The bituminous surface material salvaged from the old pavement shoulder was used in the cement-bound base layer of the new shoulder constructed alongside the new traffic lane.

Concrete Overlay Materials Needed for Long Life

Much of the emphasis in defining the characteristics of in-place pavement renewal options with the potential for service lives in the range of 50 years is necessarily on the structural design of the new material. Decisions regarding PCC mix materials are affected by the type of mixture—conventional or fast track (accelerated)—desired for a specific project. For the purpose of this report, only conventional PCC mixtures are discussed.

Conventional PCC Mixtures for Overlay Construction

Conventional concrete paving mixtures are typically used in the construction of concrete overlays. As with conventional concrete pavements, an effective mixture design is essential to the performance of a concrete overlay. Each component of the concrete mixture should be carefully selected so that the resulting mixture is dense, relatively impermeable, and resistant to both environmental effects and material-related chemical reactions over its service life. As Shilstone points out, thickness is only one of two key components of long-life pavement materials; the other is durability (Shilstone 1993). For example, in portland cement concrete, Shilstone identifies the following characteristics as key to long-term durability:

- *Low permeability* is achieved with low total water, well-graded aggregate, good mixture rheology, and high in-place relative density.
- *Freeze-thaw resistance* is achieved with closely spaced small air voids, ultimate compressive strength of 40 MPa (6,000 psi) or higher, well-graded aggregate, low permeability, and good curing.
- *Low shrinkage* is achieved with low total water, low cement factor, low water-cement ratio, and minimal use of sharp and elongated particles.
- *Low reactivity* is achieved with proper selection of cement type and aggregates, low permeability to reduce the potential for water penetration, low water-cement ratio, and use of a properly selected pozzolanic material in the mix.
- *Abrasion resistance* is achieved with compressive strength of 40 MPa (6,000 psi) or higher, well-graded aggregate, low water content, hard and dense aggregate, and air content appropriate for the exposure conditions.

Most agencies specify a minimum concrete strength requirement for their pavements. Typical values include a 28-day compressive strength of 4,000 psi or a 28-day, third-point flexural strength of 650 psi (these specifications vary among state highway agencies).

Cementitious Materials

In general, Type I and Type II cements are commonly used in concrete mixtures for concrete overlay construction. The standard specification for portland cements used in the United States is presented in AASHTO M85 (ASTM C150). There are many references available that provide detailed descriptions of the physical and chemical characteristics of cements [e.g., *Design and Control of Concrete Mixtures* (Kosmatka et al. 2002)], which are not discussed further in this section. Depending on the mix design and strength requirements, cement content is typically in the range of 500 to 700 lb/yd^3 (226.8 to 317.5 kg/m^3), although higher content is sometimes used. The American Concrete Institute and Portland Cement Association provide guidelines for the selection of the appropriate w/cm ratio. A maximum w/cm ratio value of 0.45 is common for pavements in a moist environment that will be subjected to freeze-thaw cycles. However, lower w/cm ratio values are used for concrete resurfacing to minimize drying shrinkage. As with conventional paving, supplementary cementitious materials (SCMs) normally improve durability and can improve construction.

Aggregates

To ensure long life of the overlay, these aggregates should possess adequate strength and physical and chemical stability within the concrete mixture. All aggregates used in the production of PCC mixtures should conform to ASTM C33. Extensive laboratory testing or demonstrated field performance is often required to ensure the selection of a durable aggregate. For concrete resurfacing of concrete pavements, the types of aggregates in both the original pavement and the overlay should be similar so that the thermal expansion is similar. The coefficient of thermal expansion of concrete significantly influences joint design. It is therefore recommended that the coefficient of thermal expansion of concrete be measured in accordance with AASHTO TP60. The maximum coarse aggregate size used in concrete mixtures is a function of the pavement thickness or the amount of reinforcing steel. It is recommended that the largest practical maximum coarse aggregate size be used to minimize paste requirements, reduce shrinkage, minimize costs, and improve mechanical interlock properties at joints and cracks. Typically, maximum coarse aggregate sizes of ¾ to 1 in. (1.9 to 2.5 cm) have been common in the past two decades; however, smaller maximum coarse aggregate sizes may be required for concrete (thin) resurfacing. The use of well-graded aggregates reduces shrinkage.

Admixtures

Typical admixtures and additives that are commonly used in concrete mixtures include air entrainment (6% to 7%) water reducers, and supplementary cementitious materials (SCMs) such as fly ash and ground granulated blast furnace slag (GGBFS) may also be added to concrete mixtures.

Summary

In this appendix, various renewal approaches that are applicable to using existing pavements in place and achieving long life were described. These include (1) AC overlay over existing AC pavements, (2) AC over crushed and shaped AC, (3) AC over reclaimed AC, (4) AC over CRCP, (5) AC over cracked and seated JPCP, and (6) AC over rubblized PCC. An overview of the criteria required for achieving long life was also presented, and various overlay design approaches for AC surfaced pavements were outlined.

References

Ahlrich, R. C. 1989. Performance and Structural Evaluation of Cracked and Seated Concrete. *Transportation Research Record 1215,* TRB, National Research Council, Washington, D.C.

American Association of State Highway and Transportation Officials (AASHTO). 1993. *Guide for Design of Pavement Structures.* American Association of State Highway and Transportation Officials, Washington, D.C.

American Concrete Pavement Association. 1990. *Guidelines for Unbonded Concrete Overlays.* Technical Bulletin TB-005P. American Concrete Pavement Association, Skokie, Ill.

American Concrete Pavement Association. 1993. *Reconstruction Optimization Through Concrete Inlays.* Technical Bulletin TB013P. American Concrete Pavement Association, Skokie, Ill.

Applied Research Associates. 2004. *Guide for Mechanistic–Empirical Design of New and Rehabilitated Pavement Structures.* NCHRP Project 1-37A. TRB, National Research Council, Washington, D.C.

Asphalt Institute. 1981. *Thickness Design Manual (MS-1),* 9th ed. College Park, Md.

Asphalt Institute. 1999. *Asphalt Overlays for Highway and Street Rehabilitation.* Manual Series MS-17. Lexington, Ky.

Asphalt Pavement Alliance. 2002. *Perpetual Pavements: A Synthesis.* APA 101. Lanham, Md.

Asphalt Recycling and Reclaiming Association. 2001. *Basic Asphalt Recycling Manual.* Publication NHI01-022. FHWA, U.S. Department of Transportation.

Barenberg, E. J. 1981. Rehabilitation of Concrete Pavements by Using Portland Cement Concrete Overlays. *Transportation Research Record 814,* TRB, National Research Council, Washington, D.C.

Barnett, T. L., M. I. Darter, and N. R. Laybourne. 1981. *Evaluation of Maintenance/Rehabilitation Alternatives for CRCP.* Report FHWA/IL/UI-185. Illinois Cooperative Highway Research Program, University of Illinois, Urbana.

Caestecker, C. 1993. Widening Works on the Motorway E40 at Leuven and Bertem (Belgium). *Proc., Fifth International Conference on Concrete Pavement Design and Rehabilitation,* Purdue University, West Lafayette, Ind.

Caestecker, C., and T. Lonneux. 2004. Inlay in Continuous Reinforced Concrete on the A10 Brussels–Oostende at Ternat. Presented at 9th International Symposium on Concrete Roads, Istanbul, April 4–7, 2004.

Carpenter, S. H., and M. I. Darter. 1989. Field Performance of Crack and Seat Projects. *Transportation Research Record 1215,* TRB, National Research Council, Washington, D.C.

Chou, Y. T. 1984. Asphalt Overlay Design for Airfield Pavements. *Proceedings of the Association of Asphalt Paving Technologists,* Vol. 53, Association of Asphalt Paving Technologists, Minneapolis, Minn.

Crawford, C. 1985. *Cracking and Seating of PCC Pavements Prior to Overlaying with Hot Mix Asphalt—State of the Art.* Information Series 91. National Asphalt Pavement Association, Riverdale, Md.

Crawley, A. B. 1982. *CRC Overlay of Existing CRCP.* Report MSHD-RD-82-074-I. Mississippi State Highway Department, Jackson.

Darter, M. I., T. L. Barnett, and D. J. Morrill. 1982. *Repair and Preventative Maintenance Procedures for Continuously Reinforced Concrete Pavement.* Report FHWA/IL/UI-191. Illinois Cooperative Highway Research Program, University of Illinois, Urbana.

Dhamrait, J. S., and D. R. Schwartz. 1978. *Continuously Reinforced Concrete Overlays on Existing Portland Cement Concrete Pavement.* Report FHWA-IL-PR-80. Illinois Department of Transportation, Springfield.

Eckrose, R. A., and W. E. Poston, Jr. 1982. *Asphalt Overlays on Cracked and Seated Concrete Pavements.* Information Series 83. National Asphalt Pavement Association, Riverdale, Md.

ERES Consultants, Incorporated. 1999. *NCHRP Report 415: Evaluation of Unbonded Portland Cement Concrete Overlays.* TRB, National Research Council, Washington, D.C.

Fitts, G. L. 2006. *Transportation Research Circular E-C087: Rubblization Using Resonant Frequency Equipment.* Transportation Research Board of the National Academies, Washington, D.C.

Hall, K. T. 1991. *Performance, Evaluation, and Rehabilitation of Asphalt-Overlaid Concrete Pavements.* PhD thesis, University of Illinois at Urbana-Champaign.

Hall, K. T. 1999. *Structural Coefficients for Fractured Concrete Slabs.* American Concrete Pavement Association, Skokie, Ill.

Hall, K. T., and M. I. Darter. 1989. Rehabilitation Performance and Cost-Effectiveness: 10-Year Case Study. *Transportation Research Record 1215,* TRB, National Research Council, Washington, D.C.

Hall, K. T., M. I. Darter, and W. J. Seiler. 1993. Improved Design of Unbonded Concrete Overlays. *Proc., 5th International Conference on Concrete Pavement Design and Rehabilitation,* Purdue University, West Lafayette, Ind.

Hall, K. T., C. E. Correa, S. H. Carpenter, and R. P. Elliott. 2001. *Guide for Selection of Pavement Rehabilitation Strategies.* NCHRP Project 1-38. TRB, National Research Council, Washington, D.C.

Hall, K. T., D. Dawood, S. Vanikar, R. Tally, Jr., T. Cackler, A. Correa, P. Deem, J. Duit, G. M. Geary, A. J. Gisi, A. N. Hanna, S. Kosmatka, R. O. Rasmussen, S. Tayabji, and G. Voigt. 2007. *Long-Life Concrete Pavements in Europe and Canada.* Report FHWA-PL-07-027. FHWA, U.S. Department of Transportation.

Harrington, D. 2008. *Guide to Concrete Overlays: Sustainable Solutions for Resurfacing and Rehabilitating Existing Pavements,* 2nd ed. National Concrete Pavement Technology Center, Iowa State University, Ames.

Hutchinson, R. L. 1982. *NCHRP Synthesis of Highway Practice 99: Resurfacing with Portland Cement Concrete.* TRB, National Research Council, Washington, D.C.

Illinois DOT. 1982. "Subgrade Stability Manual," Policy Mat-10, Illinois Department of Transportation.

Kosmatka, S. H., B. Kerkhoff, W. C. Panarese. 2002. *Design and Control of Concrete Mixtures.* Portland Cement Association, Skokie, Ill.

Liu, J., D. G. Zollinger, S. D. Tayabji, and K. D. Smith. 2003. *Repair and Rehabilitation of Concrete Pavements: Volume IV: Strategic Analysis* *of Pavement Evaluation and Repair (SAPER).* Draft Final Report. FHWA, U.S. Department of Transportation.

Mahoney, J., S. W. Lee, N. Jackson, and D. Newcomb. 1989. *Mechanistic-Based Overlay Design Procedures for Washington State Flexible Pavements.* Report WA-RD-170.1. Washington State Department of Transportation.

Martin, R. 1973. Design Considerations for Resurfacing Pavement with Concrete. *Highway Research Record 434,* HRB, Washington, D.C.

McGhee, K. H. 1994. *NCHRP Synthesis of Highway Practice 204: Portland Cement Concrete Resurfacing.* TRB, National Research Council, Washington, D.C.

Mellinger, F. M. 1963. Structural Design of Concrete Overlays. *Journal of the American Concrete Institute,* Vol. 60, No. 2, pp. 225–238.

Mellinger, F. M., and J. P. Sale. 1956. The Design of Non-Rigid Overlays for Concrete Airfield Pavements. *Journal of the Air Transport Division,* Vol. 82, No. AT 2, American Society of Civil Engineers.

Monismith, C. L. 1992. Analytically Based Asphalt Pavement Design and Rehabilitation: Theory to Practice, 1962–1992. *Transportation Research Record 1354,* TRB, National Research Council, Washington, D.C.

National Asphalt Pavement Association. 1994. *Guidelines for the Use of HMA Overlays to Rehabilitate PCC Pavements.* Information Series 117, National Asphalt Pavement Association, Lanham, Md.

National Concrete Pavement Technology Center. 2007. *Guide to Concrete Overlay Solutions.* Iowa State University, Ames.

National Highway Institute. 2003. Course 131083: Pavement Evaluations and Rehabilitation, Reference Manual. Publication FHWA-NHI 02-002.

Nevada Department of Transportation. 1996. *Pavement Structural Design and Policy Manual.* Nevada Department of Transportation, Carson City.

Newcomb, D. E., M. Buncher, and I. J. Huddleston. 2001. *Transportation Research Circular 503: Concepts of Perpetual Pavements.* TRB, National Research Council, Washington, D.C.

Older, C. 1924. Highway Research in Illinois. *Transactions of the American Society of Civil Engineers,* Vol. 87.

Portland Cement Association. 1981. *Guide to Concrete Resurfacing Designs and Selection Criteria.* Engineering Bulletin EB087.01P. Portland Cement Association, Skokie, Ill.

Schutzbach, A. M. 1988. *The Crack and Seat Method of Pavement Rehabilitation.* Physical Research Project 104. Bureau of Materials and Physical Research, Illinois Department of Transportation, Springfield.

Schutzbach, A. M. 1989. Crack and Seat Method of Pavement Rehabilitation. *Transportation Research Record 1215,* TRB, National Research Council, Washington, D.C.

Scullion, T. 2006. Nondestructive Testing Results from the Rubblized Concrete Pavement on Interstate 10 in Louisiana. *Transportation Research Circular E-C087: Rubblization of Portland Cement Concrete Pavements.* Transportation Research Board of the National Academies, Washington, D.C.

Sebaaly, P. E., A. Hand, J. Epps, and C. Bosch. 1996. Nevada's Approach to Pavement Management. *Transportation Research Record 1524,* TRB, National Research Council, Washington, D.C.

Shell Pavement Design Manual. 1978. Shell International Petroleum Company, London.

Shilstone, J. M. 1993. The Concrete Mixture: The Key to Pavement Durability. *Proc., 5th International Conference on Concrete Pavement Design and Rehabilitation,* Purdue University, West Lafayette, Ind.

Shook, J. F., F. N. Finn, M. W. Witczak, and C. L. Monismith. 1982. Thickness Design of Asphalt Pavements: The Asphalt Institute Method. *Proc., 5th International Conference on the Structural Design of Asphalt Pavements,* University of Michigan and Delft University of Technology.

Smith, K. D., H. T. Yu, and D. G. Peshkin. 2002. *Portland Cement Concrete Overlays: State of the Technology Synthesis.* Report DTFH61-00-P-00507. FHWA, U.S. Department of Transportation.

Tayabji, S., and S. Lim. 2007. *Long Life Concrete Pavements: Best Practices and Directions from the States.* Concrete Pavement Technology Program, Technical Brief FHWA-HIF-07-030. FHWA, U.S. Department of Transportation.

Thompson, M. R. 1989. *NCHRP Synthesis of Highway Practice 144: Breaking/Cracking and Seating Concrete Pavements.* TRB, National Research Council, Washington, D.C.

Thompson, M. R. 1999. Hot-Mix Asphalt Overlay Design Concepts for Rubblized Portland Cement Concrete Pavements. *Transportation Research Record 1684,* TRB, National Research Council, Washington, D.C.

Thompson, M. R., and E. J. Barenberg. 1989. *Calibrated Mechanistic Structural Analysis Procedures for Pavements.* Phase I final report, NCHRP Project 1-26. TRB, National Research Council, Washington, D.C.

Thompson, M. R. and S. H. Carpenter. 2006. Considering Hot-Mix-Asphalt Fatigue Endurance Limit in Full-Depth Mechanistic-Empirical Pavement Design. Presented at 2006 International Conference on Perpetual Pavement, Columbus, Ohio, September 2006.

Timm, D. 2005. Perpetual Pavement Design. Presented to the Asphalt Pavement Alliance in Perpetual Pavement Open House, Ashton, Iowa, October 5, 2005.

TRB Committee on General Issues in Asphalt Technology (A2D05). 2001. *Transportation Research Circular 503: Perpetual Bituminous Pavement.* TRB, National Research Council, Washington, D.C.

Tyner, H. L., W. Gulden, and D. Brown. 1981. Resurfacing of Plain Jointed Concrete Pavement. *Transportation Research Record 814,* TRB, National Research Council, Washington, D.C.

Voigt, G. F., M. I. Darter, and S. H. Carpenter. 1989. Field Performance Review of Unbonded Jointed Concrete Overlays. *Transportation Research Record 1227,* TRB, National Research Council, Washington, D.C.

Von Quintus, H. L., C. Rao, J. Mallela, B. Aho, Applied Research Associates, Incorporated, and Wisconsin Department of Transportation. 2007. *Guidance, Parameters, and Recommendations for Rubblized Pavements.* Project WHRP 06-13, Project 16730. National Technical Information Service, Alexandria, Va.

Washington State Department of Transportation. 2005. *Pavement Design Manual.* Washington State Department of Transportation, Olympia.

APPENDIX B

Synthesis of Data on Long-Term Pavement Performance

Data available from the Long-Term Pavement Performance (LTPP) experiment provide valuable information on the materials, climate, and traffic of test sections with measured performance data. This information was an integral part of the project because it provides an indication of pavement life under various conditions.

AC Renewal Projects

The following LTPP experiments were reviewed to determine the pavement life achieved for hot-mix asphalt (HMA)-surfaced pavements:

- General Pavement Study (GPS)-6A: Existing AC Overlay on AC Pavement;
- GPS-6B: AC Overlay with Conventional Asphalt Cement on AC Pavement;
- GPS-7A: Existing AC Overlay on PCC Pavement;
- GPS-7B: AC Overlay with Conventional Asphalt Cement on PCC Pavement;
- Specific Pavement Study (SPS)-5: AC Overlay of AC Pavement; and
- SPS-6: Rehabilitation of Jointed PCC Pavement.

The LTPP DataPave Online database (Release 21, January 2007) was used as the primary data source. Layer Inventory information was extracted from the table TST_L05B in IMS module TST (Testing) and has been summarized by

- Layer number,
- Layer type,
- Layer description,
- Representative thickness,
- Material type, and
- Construction number.

"Pavement Age" was calculated at different construction events for each section in a given state as follows: (1) age since initial construction, (2) age at the time of overlay, and (3) age since overlay construction. The initial date was taken as the "Traffic Opening Date" for GPS sections and the "Assigned Date" for SPS sections. Age at the time of overlay was calculated as the difference between "CN Change Date" for SPS-5, SPS-6, GPS-6B and GPS-7B sections, or "Major Improvement Date" for GPS-6A and GPS-7A sections (these sections have been fixed before their "Assign Date") and the initial date, or the date of any previous fix. The latest "Survey Date" was taken as the end date.

Performance data, including "Longitudinal Cracking," "Alligator (Fatigue) Cracking," "Transverse Cracking," "Rut Depth," and international roughness index ("IRI"), were plotted against pavement age. Sections with the longest overlay ages were selected within the experiment, and "Traffic Data" [equivalent single axle loads (ESALs)] corresponding to pavement age were extracted from "TRF_MON_EST_HIST." In some cases, due to missing "Traffic Monitoring" data, ESAL counts were estimated for the latest reported "Survey Date" by fitting the recorded data and extrapolating.

The following summarizes the main statistics obtained from each experiment, focusing only on (1) age at last survey, (2) original pavement type, and (3) overlay thickness. Note that the lower overlay ages do not necessarily imply poor performance, since these are ages at the latest survey and are not tied to any performance criterion. Older overlays merit further investigation.

The next step is to look into the better-performing sections to determine potential long-life pavement candidates, if any. To do so, different criteria were considered for selecting sections. Initially, pavements with "Longer Lasting Overlay" were selected within each experiment. Tables B.1, B.4, B.7, B.10, B.13, and B.14 summarize the sections that met this criterion. Except for Asphalt Overlay over CRCP, the outcome of this exercise was not conclusive since overlay age is determined up to the latest survey date and not to the end of its life based on some performance threshold. Therefore, younger overlay structures may potentially live longer. Also, performance of a given pavement structure depends on traffic volume. Therefore, a relatively thick pavement structure that was exposed to low ESALs may not necessarily represent a good-performing pavement.

Next, we selected sections within each experiment that have been subjected to "Heavy Volume of Traffic"; that is, cumulative ESAL counts within an experiment were extrapolated up to the latest survey date. Then, projected ESAL was normalized to pavement age. Within each experiment, sections of higher ESAL count per year were selected, and their performance was evaluated. Tables B.2, B.5, B.8, and B.11 represent such sections. Some sections have shown an acceptable level of performance after rehabilitation while serving higher traffic volume. Such cross sections can be candidates for perpetual pavement analysis.

The third approach was to select "Good Performing" sections using "Fatigue Cracking" and "Rutting" performance as the critical distresses. Good-performing cross sections within each experiment were selected and the number of ESALs was projected up to the latest survey date. These sections were categorized as "Thin," "Medium," and "Thick" structures as follows:

- "Thin Structure" refers to any thickness of less than 5 in. for asphalt concrete layers and 9 in. for portland cement concrete layers.
- "Medium Structure" refers to any thickness for asphalt concrete layers that is greater than 5 in. but less than 9 in. For portland cement concrete layers, these limits change to 9 and 12 in., respectively.
- "Thick Structure" refers to any asphalt concrete layer and portland cement concrete layers with a thickness greater than 9 in. and 12 in., respectively.

Tables B.3, B.6, B.9, and B.12 present such cross sections within the different experiments. Not all the sections were useful since either overlays were not old enough to represent a reasonable trend of performance, or sections were exposed to lower traffic volume.

GPS-6A: Existing AC Overlay on AC Pavement

There are a total of 51 sections in 25 states within this experiment. Figure B.1 summarizes the frequency of overlay age within the experiment. Tables B.1, B.2, and B.3 summarize the relevant inventory and performance information on sections with the longest overlay ages, those with high traffic loading, and those with the best performance in cracking and rutting.

Summary Interpretation

At first glance, no real trends can be observed in Table B.1. It shows that HMA overlays on existing HMA pavements can perform at an acceptable level for up to 30 or more years. However, the required overlay thickness (obviously) depends on the traffic loading: Section 19-6150 has received only a surface treatment and its cumulative ESAL is only 236,000, clearly indicating that it is a low-volume road. Also, it has extensive transverse cracking (at about 5 ft spacing). Section 48-1046 (Texas) has a 10-in. HMA overlay, which is expected for a cumulative traffic of 14.8 million ESALs. It has clearly reached its fatigue end life since it has more than 50% cracking. Section 48-6179 has a 4-in. HMA overlay with 1.8 million ESALs. Section 47-6015 was selected for mechanistic analysis. It is 30 years old with an original 8.8-in. HMA layer and a

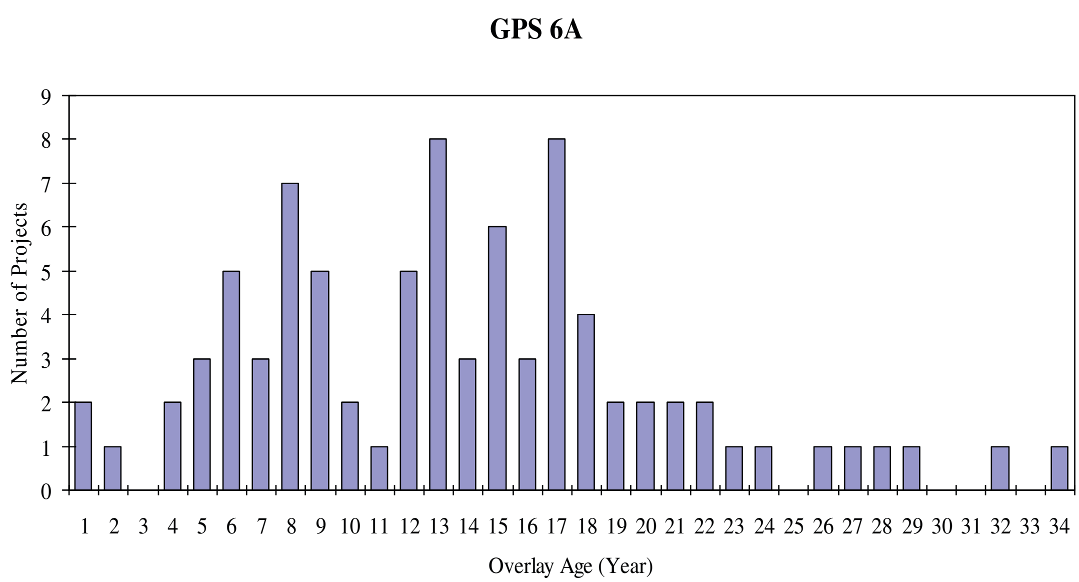


Figure B.1. Frequency of overlay age within experiment GPS-6A.

Table B.1. Summary of Sections with the Longest Overlay Age within GPS-6A

State	SHRP ID	Traffic Open Date	Overlay Construction Date	Overlay Thickness (in.)	Overlay Age (years)	Traffic (KESAL)	Longitudinal Cracking (m)	Fatigue Cracking (%)	No. of Transverse Cracking	Rut Depth (mm)	IRI (m/km)
19	6150	8/1/1952	1965	0.4	34	236	0	3.95	102	10	1.830
48	1046	7/1/1956	1971	10.1	32	14798	0	52.83	35	8	2.782
48	6179	6/1/1965	1975	4.1	29	1806	1.20	0	18	11	1.702

Table B.2. Summary of Sections Subjected to High-Volume Traffic within GPS-6A

Experiment	State	SHRP ID	Initial Structure Thickness (in.)	Overlay Thickness (in.)	Overlay Age (years)	Traffic (KESAL) per Year	Longitudinal Cracking (m)	Fatigue Cracking (%)	No. of Transverse Cracking	Rut Depth (mm)	IRI (m/km)
GPS-6A	4	6053	3.2	4.2	16	1690	No data	No data	No data	13	1.604
	4	6054	7.0	1.4	15	1085	14.3	20.6	23.0	9	1.316
	4	6055	1.8	3.8	No data	814	No data	No data	No data	5	0.765
	4	6060	3.9	3.4	13	943	0.0	0.0	0.0	55	0.502
	18	6012	14.8	4.0	15	2137	0.0	0.0	0.0	11	2.957
	19	6049	20.4	2.8	26	785	1.0	18.55	25.0	9	2.125
	41	6011	6.1	6.8	22	1547	0.0	0.0	0.0	4	1.183
	47	6015	8.8	5.5	19	986	0.0	0.0	0.0	3	0.588

Table B.3. Summary of Good-Performing Sections within GPS-6A

Experiment	State	SHRP ID	Age (years)	Traffic (KESAL)	Original Thickness (in.)		Overlay Thickness (in.)		Overlay Age (years)
GPS-6A	30	7075	40	16618	3.40	Thin	3.70[a]	3.00	19
								3.50	4
	48	6179	38	2084	1.40	Thin	4.10		29
	56	6029	29	892	1.90	Thin	2.70[a]	1.60	21
								1.10	8
	1	6019	20	6874	8.30	Medium	5.00[a]	2.80	13
								2.40	8
	47	6015	30	23647	8.80	Medium	5.50		19
	48	6086	29	2771	8.50	Medium	1.50		16
	49	1006	31	5556	9.20	Thick	1.30		15
	56	6031	26	521	11.10	Thick	4.60[a]	2.30	14
								2.30	7
	56	6032	28	874	11.70	Thick	4.20[a]	2.30	12
								1.00	9
								1.00	0

[a] Mill and fill.

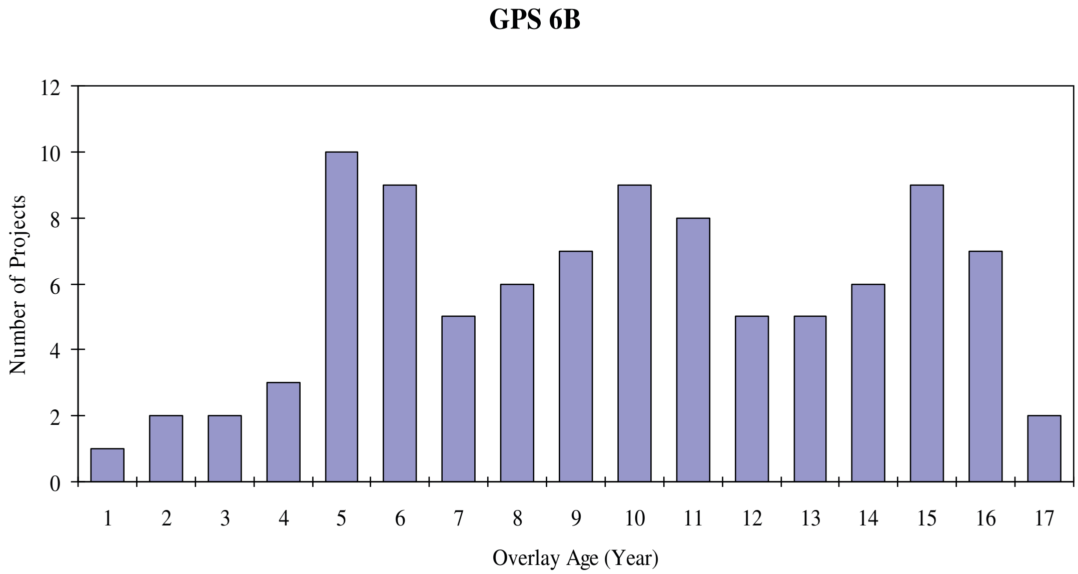


Figure B.2. Frequency of overlay age within experiment GPS-6B.

5.5-in. overlay. It has been subjected to 23.6 million ESALs and the overlay age is 19 years at the latest survey date. It has no fatigue, no longitudinal or transverse cracking, only 3 mm of rutting, and an international roughness index (IRI) of 0.6 m/km.

GPS-6B: AC Overlay with Conventional Asphalt Cement on AC Pavement

There are a total of 87 sections in 32 states within this experiment. Figure B.2 summarizes frequency of overlay age within the experiment. Tables B.4, B.5, and B.6 summarize the relevant inventory and performance information on sections with the longest overlay ages, those with high ESAL, and those with the best performance in cracking and rutting.

Summary Interpretation

Neither of the sections with the longest overlay age is promising because they both have fatigue and transverse cracking after 17 years. Two sections subjected to heavy traffic are promising: 18-2008 and 47-3108. They have very little to no cracking, low rutting and IRI values after 11 and 16 years, with 1.275 and 0.861 million ESAL/year, respectively. Two good-performing sections are promising: 6-8535 and 47-3108. They have very

Table B.4. Inventory Information of Sections with the Longest Overlay Age within GPS-6B

State	SHRP ID	Traffic Open Date	Overlay Construction Date	Overlay Thickness (in.)	Overlay Age (years)	Traffic (KESAL)	Longitudinal Cracking (m)	Fatigue Cracking (%)	No. of Transverse Cracking	Rut Depth (mm)	IRI (m/km)
47	3109	11/1/1978	6/25/1989	1.70	17	1808	0	2.30	14	6	1.203
47	3110	8/1/1981	6/15/1989	1.40	17	2251	0	5.79	71	4	0.758

Table B.5. Inventory Information of Sections Subjected to High-Volume Traffic within GPS-6B

Experiment	State	SHRP ID	Initial Structure Thickness (in.)	Overlay Thickness (in.)	Overlay Age (years)	Traffic (KESAL) per Year	Longitudinal Cracking (m)	Fatigue Cracking (%)	No. of Transverse Cracking	Rut Depth (mm)	IRI (m/km)
GPS-6B	18	2008	12.9	2.5	11	1275	0.0	0.0	0.0	1	0.541
	36	1643	2.2	2.9	9	1017	0.0	37.12	19.0	4	1.078
	47	1023	5.3	1.7	11	859	0.0	0.93	20.0	9	1.679
	47	3108	5.5	2.7	16	861	0.0	0.07	2.0	6	0.782

Table B.6. Inventory Information of Good-Performing Sections within GPS-6B

Experiment	State	SHRP ID	Age (years)	Traffic (KESAL)	Original Thickness (in.)		Overlay Thickness (in.)		Overlay Age (years)
GPS-6B	2	1002	21	772	3.30	Thin	2.00		7
	2	1004	28	3900	3.60	Thin	1.80		14
	6	8534	35	8348	4.80	Thin	5.70		13
	30	7076	19	4412	4.50	Thin	2.40[a]	2.40	10
								2.40	3
	30	7088	24	7957	4.60	Thin	2.40[a]	2.40	4
								1.70	10
	30	8129	16	1544	3.00	Thin	3.80		1
	40	4086	34	5962	4.30	Thin	3.60		15
	40	4164	26	2455	4.60	Thin	1.00		10
	48	1130	33	1885	2.30	Thin	1.60		13
	56	2017	23	1432	2.40	Thin	1.20		6
	56	2019	19	2289	3.40	Thin	2.70		8
	56	7772	18	811	2.20	Thin	2.40		6
	6	8535	37	16686	6.60	Medium	5.30		13
	23	1028	32	5901	6.60	Medium	1.90		10
	42	1597	23	442	6.40	Medium	6.30		3
	42	1605	32	5165	8.10	Medium	2.70		8
	47	2001	27	9849	6.80	Medium	6.60		15
	47	3108	33	28429	5.50	Medium	2.70		16
	47	9024	29	933	5.10	Medium	1.30		11
	48	1096	25	3017	7.10	Medium	2.00		5
	48	1111	33	3094	6.90	Medium	2.70		6
	48	3835	12	2992	8.50	Medium	5.90		4
	18	1037	23	2046	14.40	Thick	4.30		11
	28	3094	24	6133	10.90	Thick	2.70		16

[a] Mill and fill.

little to no cracking, low rutting and IRI values after 13 and 16 years, with 16.7 and 28.4 million ESALs, respectively. Section 47-3108 was selected for mechanistic analysis. It is 33 years old with an original 5.5-in. HMA layer and a 2.7-in. overlay. It has been subjected to 28.4 million ESALs and the overlay age is 16 years at the latest survey date. It has no longitudinal cracking, very little fatigue and transverse cracking, 6 mm of rutting, and an IRI of 0.78 m/km.

GPS-7A: Existing AC Overlay on PCC Pavement

There are a total of 30 sections in 19 states within this experiment. Figure B.3 summarizes the frequency of overlay age within the experiment. Tables B.7, B.8, and B.9 summarize the relevant inventory and performance information on sections with the longest overlay ages, those with high ESAL, and those with the best performance in cracking and rutting.

Summary Interpretation

None of the sections with the longest overlay age is promising because they have a high level of transverse cracking after more than 20 years. One section subjected to heavy traffic may be promising: 13-7028. It has no longitudinal or fatigue cracking, but some transverse cracking. It has 7 mm of rutting and an IRI of 1.1 m/km after 12 years, with 16.8 million ESALs. Two good-performing sections are promising: 13-7028 and 31-7005. They

Table B.7. Inventory Information of Sections with the Longest Overlay Age within GPS-7A

State	SHRP ID	Original Pavement Type[a]	Traffic Open Date	Overlay Construction Date	Overlay Thickness (in.)	Overlay Age (years)	Traffic (KESAL)	Longitudinal Cracking (m)	Fatigue Cracking (%)	No. of Transverse Cracking	Rut Depth (mm)	IRI (m/km)
29	7054	JRCP	6/1/1957	1973	4.50	21	30246	No data	No data	No data	7	1.011
29	7073	JPCP	6/1/1964	1981	2.40	20	2314	0	0	70	3	1.501
41	7019	JRCP	6/1/1947	1976	2.10	22	7970	0	0	32	17	1.785
46	7049	JPCP	12/1/1954	1980	4.10	23	258	0	0	91	15	4.208

[a] JPCP, jointed plain concrete pavement; JRCP, jointed reinforced concrete pavement.

Table B.8. Inventory Information of Sections Subjected to High Volume Traffic within GPS-7A

Experiment	State	SHRP ID	Initial Structure Thickness (in.)	Original Pavement Type[a]	Overlay Thickness (in.)	Overlay Age (years)	Traffic (KESAL) per Year	Longitudinal Cracking (m)	Fatigue Cracking (%)	No. of Transverse Cracking	Rut Depth (mm)	IRI (m/km)
GPS-7A	13	7028	9.1	JPCP	6.0	12	1366	0.0	0.0	27	7	1.118
	17	5453	8.4	CRCP	2.7	13	1059	33.5	1.51	67	3	1.231
	29	7054	10.1	JRCP	4.5	21	829	No data	No data	No data	7	1.011
	39	7021	9.0	JRCP	2.6	14	1521	No data	No data	No data	6	2.444
	41	7018	7.7	JRCP	1.6	14	771	0.0	0.0	9	18	1.542

[a] CRCP, continuously reinforced concrete pavement; JPCP, jointed plain concrete pavement;
JRCP, jointed reinforced concrete pavement.

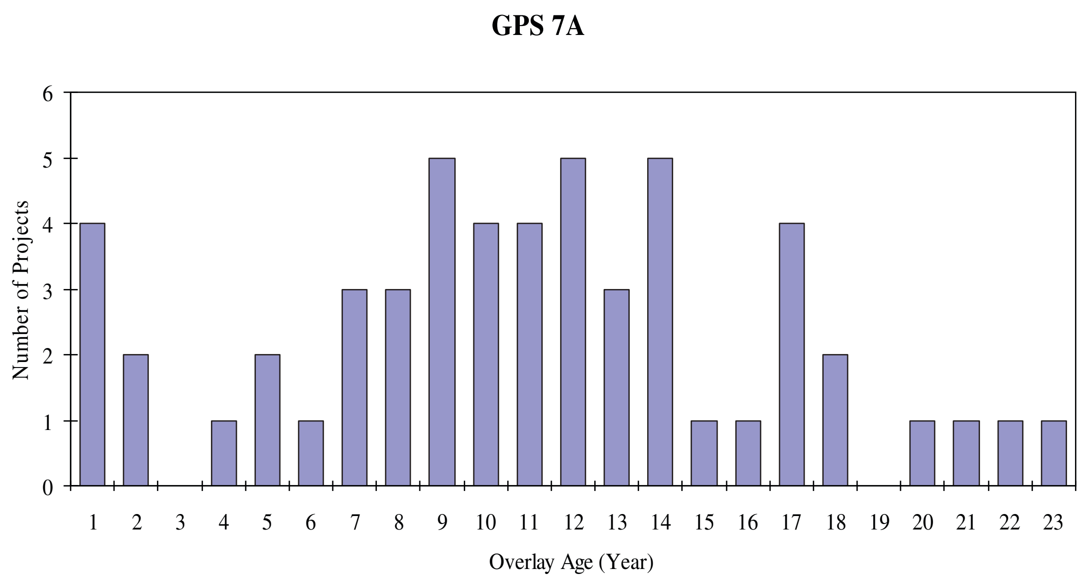


Figure B.3. Frequency of overlay age within experiment GPS-7A.

Table B.9. Inventory Information of Good-Performing Sections within GPS-7A

Experiment	State	SHRP ID	Age (years)	Traffic (KESAL)	Original Thickness[a] (in.)			Overlay Thickness (in.)		Overlay Age (years)
GPS-7A	44	7401	42	5129	8.20	Thin	JRCP	5.20[b]	2.60	17
									3.20	2
	46	7049	48	283	7.40	Thin	JPCP	4.10		23
	13	7028	17	16763	9.10	Medium	JPCP	7.00[b]	6.00	12
									2.50	5
	31	7005	44	17824	9.60	Medium	JPCP	5.30[b]	4.50	12
									2.00	10
	31	7050	42	21857	9.00	Medium	JRCP	4.50[b]	3.40	10
									1.50	8
									3.00	0
									1.40	1

[a] JPCP, jointed plain concrete pavement; JRCP, jointed reinforced concrete pavement.

[b] Mill and fill.

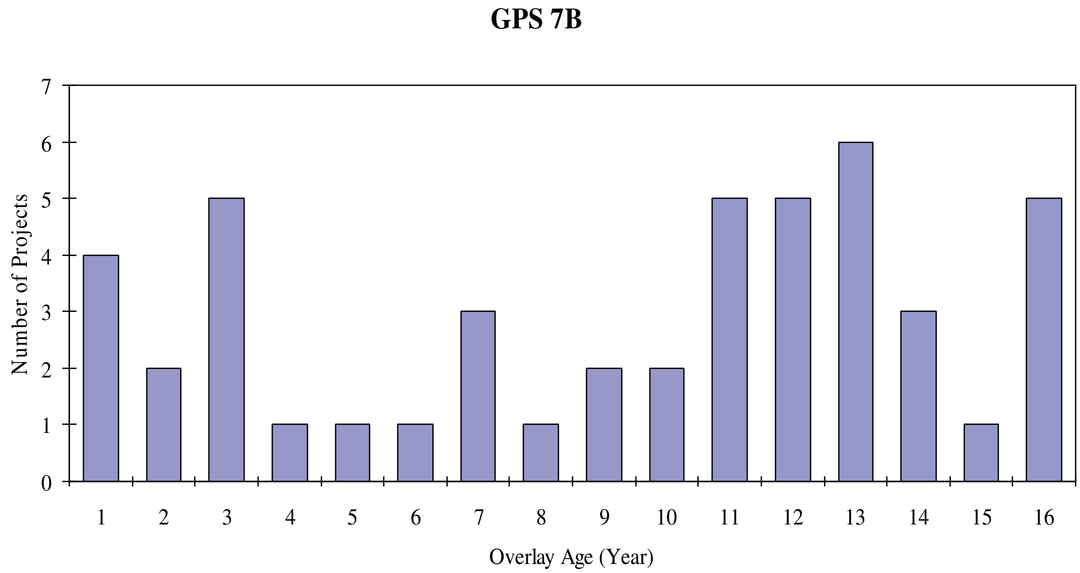


Figure B.4. Frequency of overlay age within experiment GPS-7B.

have very little to no cracking, low rutting and IRI values after 12 years, with 16.7 and 17.8 million ESALs, respectively. Section 13-7028 was selected for mechanistic analysis. It is 17 years old with an original 9-in. concrete slab and a 7-in. overlay. It has been subjected to 16.8 million ESALs and the overlay age is 12 years at the latest survey date. It has no longitudinal or fatigue cracking but has some transverse cracking, 7 mm of rutting, and an IRI of 1.1 m/km.

GPS-7B: AC Overlay with Conventional Asphalt Cement on PCC Pavement

There are a total of 43 sections in 18 states within this experiment. Figure B.4 summarizes the frequency of overlay age within the experiment. Tables B.10, B.11, and B.12 summarize the relevant inventory and performance information on sections with the longest overlay ages, those with high ESAL, and those with the best performance in cracking and rutting.

Summary Interpretation

One section with the longest overlay age may be promising: 42-1617. It has a 4.7-in. AC overlay over a continuously reinforced concrete pavement (CRCP). It has no longitudinal or transverse cracking and very little fatigue cracking and an IRI of 0.93 m/km, but has 9 mm of rutting and moderate traffic of 20 million ESALs. Two sections subjected to very heavy traffic (4.5 to 5.2 million ESAL/year) are promising: 18-5022 and 18-5518. They have 4- and 4.8-in. AC overlay over 9.8- and 9.3-in. CRCP pavements, respectively. They have no or very little cracking and less than 0.25 in. of rutting and an IRI of about 1 m/km. Out of the three good-performing sections, only one is promising since the other two have moderate traffic. Section 18-5022 is a 34-year-old CRCP with a 4-in. AC overlay that is 13 years old. It has been subjected to very heavy traffic of more than 177 million ESALs. It has been selected for further mechanistic analysis.

SPS-5: AC Overlay of AC Pavement

There are a total of 29 sections in 16 states within this experiment. Figure B.5 summarizes frequency of overlay age within the experiment. Table B.13 summarizes the relevant inventory and performance information on the sections with the longest overlay ages. None of the sections is promising for long life.

SPS-6: Rehabilitation of Jointed PCC Pavement

There are a total of 30 sections in 13 states within this experiment. Figure B.6 summarizes frequency of overlay age within the experiment. Table B.14 summarizes the relevant inventory and performance information on the sections with the longest overlay ages. The best-performing section (17-663) is 16 years old with an 8-in. AC overlay over a JRCP. It has no longitudinal or transverse cracking, only 2 mm of rutting, but about 5% fatigue cracking. Therefore, it does not promise to be a long-life pavement.

Rubblized Sections in the SPS-6 Experiment

The Strategic Highway Research Program (SHRP), during the planning of the Long Term Pavement Performance (LTPP) experiments, recognized an increasing interest in rubblizing portland cement concrete (PCC) slabs to reduce the occurrence of reflection cracks in HMA overlays. This repair strategy was

Table B.10. Inventory Information of Sections with the Longest Overlay Age within GPS-7B

State	SHRP ID	Original Pavement Type[a]	Traffic Open Date	Overlay Construction Date	Overlay Thickness (in.)	Overlay Age (years)	Traffic (KESAL)	Longitudinal Cracking (m)	Fatigue Cracking (%)	No. of Transverse Cracking	Rut Depth (mm)	IRI (m/km)
19	9126	JRCP	1/1/1965	6/16/1989	5.20	15	28144	1.60	1.27	32	4	1.793
29	5473	JRCP	10/1/1960	5/27/1989	1.80	15	40541	0	0	19	4	1.148
39	5010	CRCP	7/1/1975	6/1/1990	2.80	15	7632	0	8.95	20	6	1.063
42	1613	JRCP	6/1/1990	6/4/1990	3.70	15	14123	0	0.50	17	4	0.952
42	1614	JRCP	6/1/1995	7/1/1989	4.40	16	7569	2.50	2.12	16	12	2.190
42	1617	CRCP	6/1/1972	8/13/1990	4.70	15	20308	0	0.95	0	9	0.934

[a] CRCP, continuously reinforced, concrete pavement; JRCP, jointed reinforced concrete pavement.

Table B.11. Inventory Information of Sections Subjected to High-Volume Traffic within GPS-7B

Experiment	State	SHRP ID	Initial Structure Thickness (in.)	Original Pavement Type[a]	Overlay Thickness (in.)	Overlay Age (years)	Traffic (KESAL) per Year	Longitudinal Cracking (m)	Fatigue Cracking (%)	No. of Transverse Cracking	Rut Depth (mm)	IRI (m/km)
GPS-7B	9	5001	8.2	CRCP	4.7	8	946	0.0	8.2	9.0	9	1.311
	18	3003	10.2	JPCP	4.5	11	1439	0.0	0.0	26.0	4	1.327
	18	5022	9.8	CRCP	4.0	13	5170	0.0	0.0	0.0	6	1.011
	18	5518	9.3	CRCP	4.80	11	4495	0.0	0.23	5.0	7	0.996
	29	5473	7.9	JRCP	1.8	15	1107	0.0	0.0	19.0	4	1.148
	42	1613	10.2	JRCP	3.7	15	1027	0.0	0.5	17.0	4	0.952
	54	4004	9.9	JRCP	5.7	7	1263	0.0	0.0	12.0	3	1.301

[a] CRCP, continuously reinforced, concrete pavement; JPCP, jointed plain concrete pavement;
JRCP, jointed reinforced concrete pavement.

Table B.12. Inventory Information of Good-Performing Sections within GPS-7B

Experiment	State	SHRP ID	Age (years)	Traffic (KESAL)	Original Thickness[a] (in.)			Overlay Thickness (in.)	Overlay Age (years)
GPS-7B	39	3013	35	3720	8.30	Thin	JRCP	3.70	11
	18	5022	34	176836	9.80	Medium	CRCP	4.00	13
	29	5483	32	6746	9.00	Medium	JRCP	3.00	13

[a] CRCP, continuously reinforced concrete pavement; JRCP, jointed reinforced concrete pavement.

included in the LTPP specific pavement study (SPS) experiment defined as SPS-6. However, only a few of these SPS-6 projects actually included the rubblization process. Those projects with rubblization test sections included Alabama, Arizona, Illinois, Michigan, Missouri, Oklahoma, and Pennsylvania, which are listed in Table B.15. Some of the rubblized test sections had construction-related problems—soft foundations and nonuniform particle size distribution throughout the PCC slab thickness.

The 2005 LTPP database was reviewed by Von Quintus et al. (2007) to determine the current performance trends of these sections. The load-related cracking is still considered minimal and the IRI values are low. In general, the thicker the overlay, the lower amount of cracking, with the exception for longitudinal cracking outside the wheelpath. The predominant distress exhibited along these test sections is longitudinal cracking outside the wheelpath area. The sections without edge drains or those with rubblized pieces less than 2 in. in size have the higher levels of cracking.

PCC Renewal Projects

GPS-9: Unbonded Concrete Overlays

The LTPP general pavement study experiment GPS-9 includes unbonded JPCP, JRCP, or CRCP overlays with a thickness of

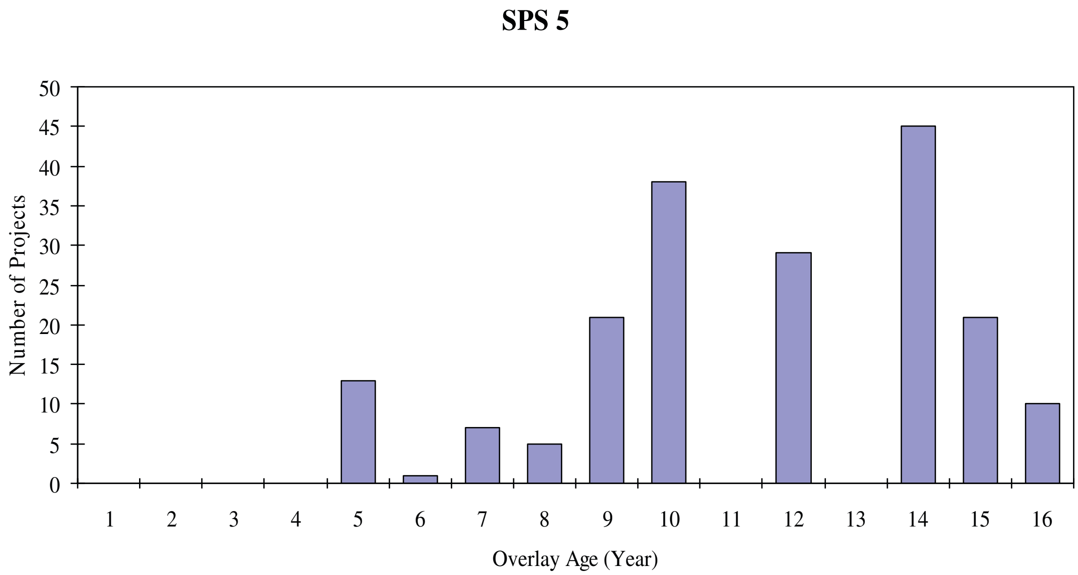


Figure B.5. Frequency of overlay age within experiment SPS-5.

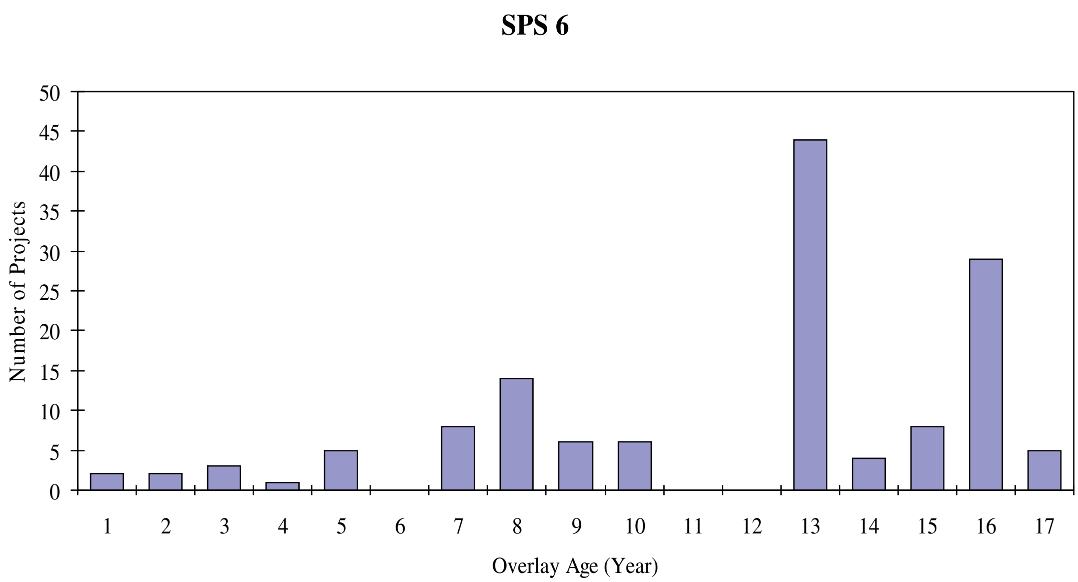


Figure B.6. Frequency of overlay age within experiment SPS-6.

Table B.13. Information of Sections with the Longest Overlay Age within SPS-5

State	SHRP ID	Assign Date	Overlay Construction Date	Overlay Thickness (in.)	Overlay Age (years)	Traffic (KESAL)	Longitudinal Cracking (m)	Fatigue Cracking (%)	No. of Transverse Cracking	Rut Depth (mm)	IRI (m/km)
4	502	1/1/1987	4/20/1990	2.70	16	6386	0	54.72	0	11	3.663
4	503	1/1/1987	4/20/1990	4.70	16	6386	91.30	1.74	70	7	1.916
4	504	1/1/1987	4/20/1990	4.80	16	6386	0	0.04	17	3	1.495
4	505	1/1/1987	4/20/1990	2.80	16	6386	1.60	57.39	96	6	1.890
4	506	1/1/1987	4/20/1990	5.20	16	6386	1.70	0.43	17	4	1.538
4	507	1/1/1987	4/20/1990	6.80	16	6386	0	0	6	7	1.441
4	508	1/1/1987	4/20/1990	6.50	16	6386	13.70	0	55	7	1.272
4	509	1/1/1987	4/20/1990	3.90	16	6386	62.50	8.20	96	9	3.671
4	559	1/1/1987	4/20/1990	6.00	16	6386	1.90	0	51	4	1.505
4	560	1/1/1987	4/20/1990	2.20	16	6386	7.40	32.58	58	3	1.859

Table B.14. Information of Sections with the Longest Overlay Age within SPS-6

State	SHRP ID	Original Pavement Type[a]	Assign Date	Overlay Construction Date	Overlay Thickness (in.)	Overlay Age (years)	Traffic (KESAL)	Longitudinal Cracking (m)	Fatigue Cracking (%)	No. of Transverse Cracking	Rut Depth (mm)	IRI (m/km)
17	603	JRCP	1/1/1987	5/24/90	3.70	16	6747	0	14.78	0	2	1.569
17	659	JRCP	1/1/1987	6/1/90	3.30	16	6747	0	12.25	15	2	1.885
17	662	JRCP	1/1/1987	6/1/90	3.50	16	6747	0	27.04	0	2	1.844
17	663	JRCP	1/1/1987	6/1/90	8.0	16	6747	0	4.65	0	2	1.128
17	664	JRCP	1/1/1987	6/1/90	6.0	16	6747	0	21.89	0	3	1.369

[a] JRCP, jointed reinforced concrete pavement.

Table B.15. LTPP SPS-6 Projects with Rubblized Test Sections

Project Agency	Rehabilitation Date	Test Section Identification	HMA Overlay Thickness (mm)	Comment
Alabama	6/1998	0661	102	Badger Breaker Machine (Model MHB); particles down to 3 in. in size.
		0662	203	
		0663	241	
Arizona	10/1990	0616	140	
		0619	140	
Illinois	6/1990	0663	152	High-frequency breaking unit; less than 6 in. in size; edge drains placed.
		0664	206	
Michigan	5/1990	0659	178	
Missouri	8/1992	0661	290	Edge drains placed.
		0662	185	
		0663	292	No edge drains placed.
		0664	175	
Oklahoma	8/1992	0607	114	Resonant Frequency Breaker; surface, 2–3 in. in size; bottom, up to 8 in. in size; edge drains placed.
		0608	201	
Pennsylvania	9/1992	0660	241	Edge drains placed.
		0661	330	

Source: Von Quintus et al. 2007.

125 mm (5 in.) or more placed over an existing JPCP, JRCP, or CRCP. An interlayer used to prevent bonding of the two slabs was required. The overlaid concrete pavement may rest on a base or subbase or directly on the subgrade.

Information about GPS-9 experiment (Unbonded PCC Overlay on PCC Pavement) was extracted from the LTPP DataPave Online (Release 21.0). There were 26 sections located in 14 states within this experiment. The continuously reinforced concrete pavement overlays are presented separately from jointed pavements (JRCP and JPCP) since the performance criteria are not entirely identical. Furthermore, JRCP overlays were not considered since state departments of transportation (DOTs) do not use JRC pavement systems anymore. After the removal of JRC overlays, 14 JPCP and 4 CRCP overlays were considered in the subsequent sections of this appendix.

Summary of Inventory Information

The original construction date for the GPS-9 sections ranged from the early 1950s to the mid-1970s. The location of the various LTPP test sections is shown in Figure B.7.

Table B.16 summarizes the maintenance events since overlay became part of the LTPP experiment. The blank cells under the construction change reason indicate no maintenance.

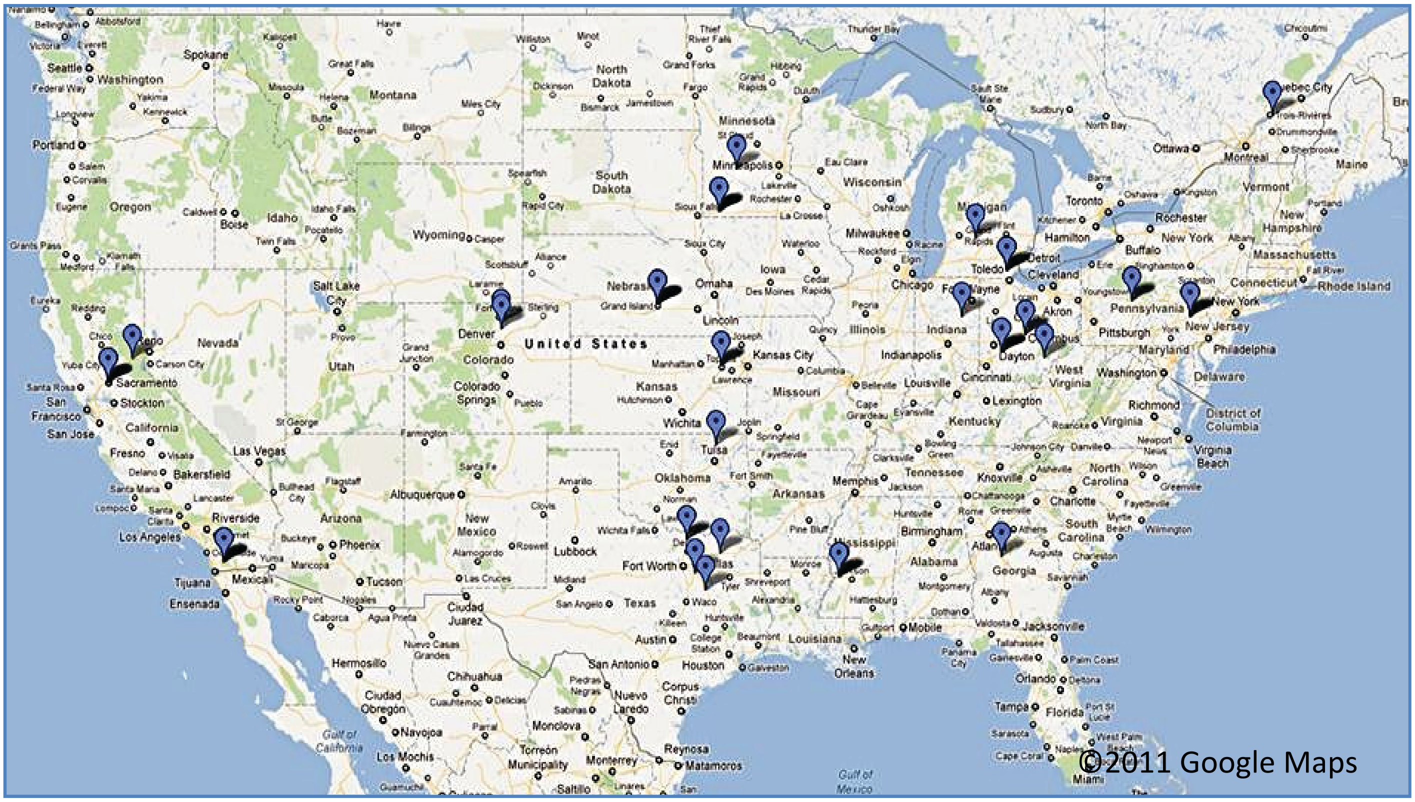
The overlay thicknesses of the various test sections range from 5 ft 8 in. to 10 ft 5 in. The distribution of unbonded overlay thickness is shown in Figure B.8. Unbonded concrete overlay projects are typically 4 ft 11 in. thick, depending on the level of traffic. Figure B.9 shows the distribution of the traffic (in ESALs) carried by the various test sections until the deassign date.

The distribution of separator layer types commonly used in the LTPP test sections is shown in Figure B.10. Typically, a fine-graded asphalt surface mixture is used for the separator layer. The thickness of the separator layer is a function of (1) the condition of the existing pavement and (2) the type of preoverlay repairs.

Figure B.11 shows the distribution of the thickness of the HMA separator layers used in the various sections. According to the review of the literature a minimum thickness of 1 in. is recommended for HMA separator layers. Thinner layers erode easily near joints and do not provide adequate isolation of the overlay from underlying PCC pavement.

Figure B.12 shows a couple of cross sections with thick asphalt interlayer. Section 18-9020 actually consists of two interlayers, whereas section 48-9167 has one interlayer.

Figure B.13 shows the distribution of transverse joint spacing. Based on the review of the literature, it is recommended to limit the joint spacing to 21 times the slab thickness. According to that rule of thumb, the transverse joint spacing of the GPS-9



Source: © 2011 Google Maps.

Figure B.7. Locations of GPS-9 sections.

sections should range between 10 and 18 ft (as shown by the dashed horizontal lines in Figure B.7). In general, the risk of premature cracking on unbonded PCC overlays can be minimized by limiting the joint spacing to 15 ft, even for very thick overlays.

Figure B.14 shows the distribution of various load-transfer mechanisms used across transverse joints in the GPS-9 test sections. Joint performance in unbonded concrete overlays is enhanced due to the presence of the underlying pavement as "sleeper" slabs. The load transfer across joints from the underlying slab can be maximized by mismatching joints. However, the use of doweled joints is highly recommended for overlays subjected to heavy truck traffic to avoid corner breaks and to minimize joint faulting.

Summary of Overall Field Performance

The pavement performance criteria selected for the summary include transverse cracking, IRI (and PSI), joint and crack faulting magnitude (JPCP), and punchouts (only for CRCP). The performance trends presented in this section are based on measurements documented in the latest year.

It should be noted that some of the figures in subsequent sections show the nominal performance of the sections that might include confounding (interaction) effects of two or more factors.

Transverse Cracking. The box-and-whisker plot shown in Figures B.15 (for jointed concrete overlays) and B.20 (for CRC overlays) shows the distribution of percent cracking for the test sections. The box-and-whisker plots presented here display data as follows: the median is represented by the horizontal line inside the box. The top and bottom of the box represent the third quartile (75th percentile) and the first quartile (25th percentile), respectively. The distance between these two is the interquartile range (IQR). In these plots, whiskers are drawn to the minimum and maximum observations.

Figure B.16 shows the magnitude of cracking as a function of overlay thickness for the jointed concrete pavements. Sections 6-9048 and 20-9037 with 28 and 14 cracks, respectively, are among the sections presented in the first category (5.1 to 6.5 in.). Sections 6-9049 and 31-6701 with 26 and 7 cracks, respectively, are among the sections represented in the second category (6.6 to 8.0 in.). As expected, the thicker overlays (>9 in.) exhibit fewer transverse cracks. It is worth noting that 11 of the 14 jointed concrete pavement overlays have exhibited little or no cracking in 18 years of service. These test sections exhibit the promise of long-life performance. Figure B.17 shows the

Table B.16. GPS-9 Construction Events Since Overlay Became Part of LTPP Experiment

Section ID	Construction No.	LTPP Assign Date	Construction Change Reason
6-9048	1	7/1/1988	
	2	4/18/2001	PCC slab replacement
6-9049	1	6/26/1988	
6-9107	1	7/1/1988	
8-9019	1	7/20/1988	
8-9020	1	7/20/1988	
13-4118	1	1/1/1987	
18-9020	1	1/1/1987	
20-9037	1	1/1/1987	
	2	9/15/1992	Full-depth patching of PCC pavement other than at joint
27-9075	1	1/1/1987	
28-7012	1	1/1/1987	
	2	3/15/1993	Asphalt concrete overlay, portland cement concrete overlay
31-6701	1	8/1/1988	
	2	1/15/2000	Crack sealing, lane-shoulder longitudinal joint sealing
	3	2/28/2002	Crack sealing, transverse joint sealing
	4	3/9/2004	Partial-depth patching of PCC pavement other than at joint
	5	2/15/2005	Partial-depth patching of PCC pavement other than at joint
40-4155	1	1/1/1987	
42-1627	1	12/1/1988	
48-3569	1	1/1/1987	
48-3845	1	7/1/1989	
48-9167	1	12/31/1987	
48-9355	1	12/31/1988	
89-9018	1	7/1/1988	

Note: Section ID is the unique number given to each test section in the LTPP program. Each test section began in the LTPP program at construction number 1. Sequential numbers are added any time maintenance or rehabilitation activities occur on the test section. LTPP Assign Date represents the date that the test section entered the LTPP program (construction number 1) or the date maintenance and rehabilitation was completed on the test section (construction numbers greater than 1).

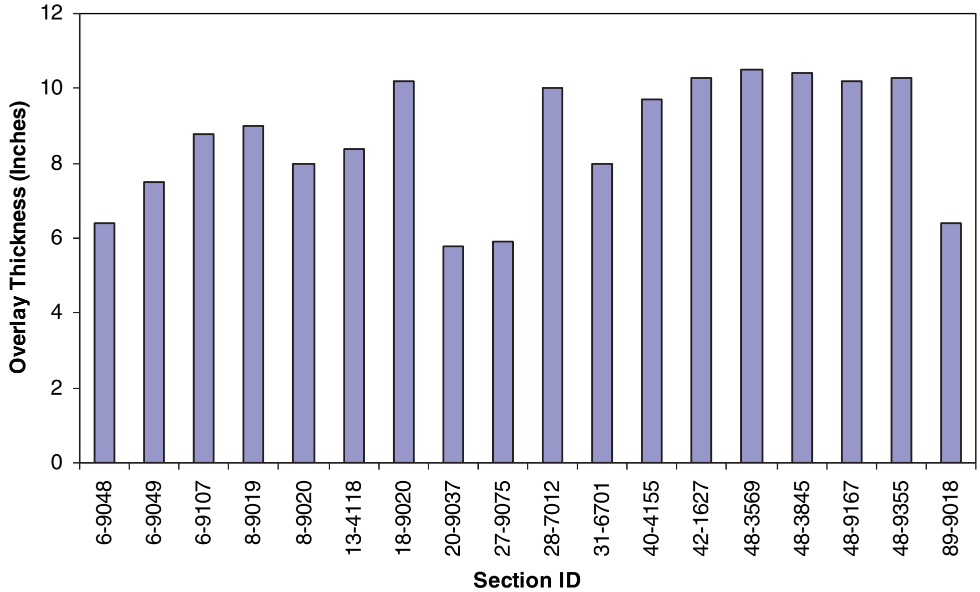


Figure B.8. Overlay thicknesses.

number of transverse cracks as a function of CRCP section. Figures B.18 and B.19 show the percent cracking as a function of overlay thickness for the CRCPs, and average crack spacing as a function of overlay thickness, respectively. Figures B.20 and B.21 summarize the number of punchouts in the CRCP overlays.

International Roughness Index (IRI). Figures B.22 through B.24 illustrate the progression of IRI and PSI for the various GPS-9 sections and the impact of overlay thickness on ride quality.

Joint and Crack Faulting. Figures B.25 and B.26 summarize the amount of joint and crack wheelpath faulting for the various jointed concrete pavement overlays. In Figure B.26, all the sections that belong to the last category (overlay thicknesses of 9.6 to 11.0 in.) are doweled pavements. All the sections belonging to the first three categories are without dowels except for one section (section 89-9018, with overlay thickness of 6 ft, 4 in., is a doweled pavement). It should be noted that the overall magnitude of the faulting is below 0.25 in. (the threshold considered for long-life pavements) and therefore does not appear to be an issue at this point.

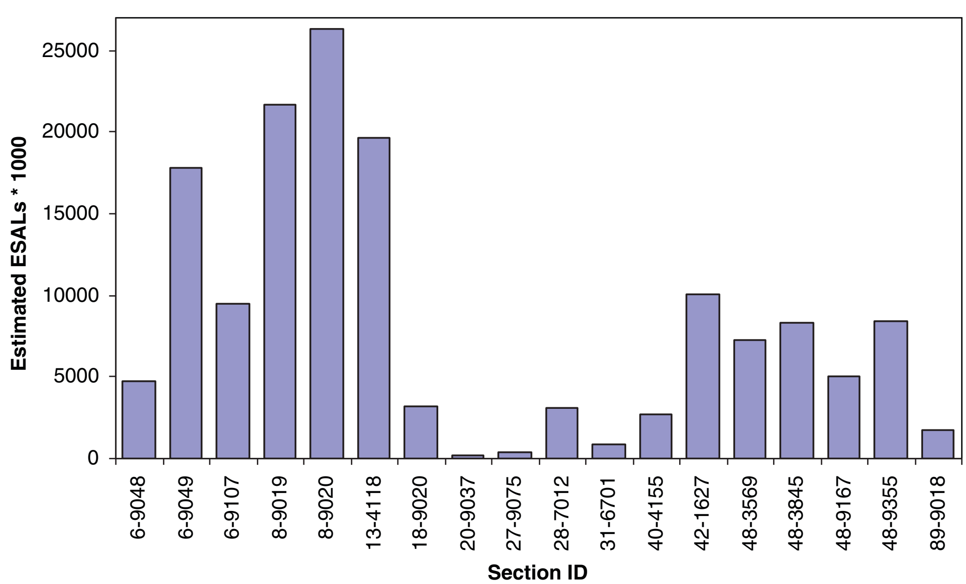


Figure B.9. Traffic after inclusion in the LTPP program.

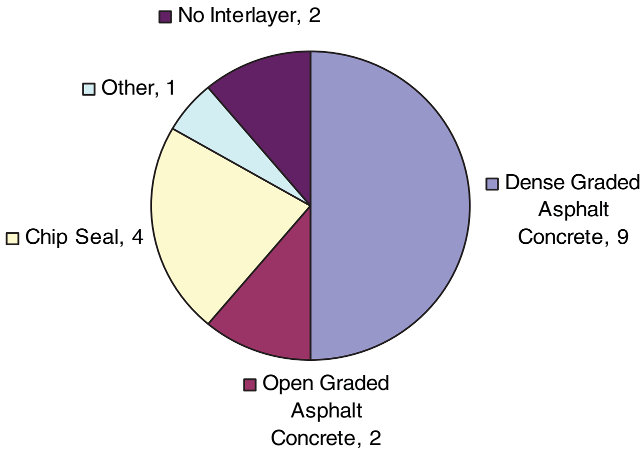


Figure B.10. Types of interlayer.

IMPACT OF INTERLAYER DESIGN ON PERFORMANCE. Figures B.27 and B.28 illustrate the impact of the interlayer type and thickness on transverse cracking of the overlay. In general, thicker interlayers tend to inhibit transverse cracking. Figure B.29 shows that thicker interlayers tend to be associated with less joint wheelpath faulting.

IMPACT OF LOAD TRANSFER MECHANISM ON PERFORMANCE. Figures B.30 through B.32 illustrate the impacts of dowels and increased pavement thickness on all pavement performance measures. In these figures, all the sections that belong to the first category (aggregate interlock) have overlay thicknesses of 9 in. or less. All the sections belonging to the second category (doweled) have overlay thicknesses of 10 in. or more except for one section (section 89-9018 has an overlay thickness of 6.4 in.).

SPS-7: Bonded Concrete Overlays

Information about the SPS-7 experiment (Bonded PCC Overlay on PCC Pavement) was extracted from the LTPP DataPave Online (Release 21.0). There were 39 sections located in four states within this experiment. CRCPs and PCPs (plain concrete pavements only used for SPS-7 overlays of CRCP) were separated from jointed pavements (JPCP), since the performance criteria are not entirely identical. PCP overlays are bonded overlays of CRCP where additional steel was not included in the overlay. CRCP overlays are concrete overlays to which steel was added so that the resulting pavement has two layers of steel. Furthermore, control sections with no overlays (sections ending with 0701) were not considered. Another section that was not considered (29-0759) had an asphalt concrete overlay. After the removal of these sections, data from 18 CRCPs, 9 JPCPs, and 8 PCPs are presented in the subsequent sections of this appendix.

Summary of Inventory Information

The location of the various SPS-7 test sections is shown in Figure B.33. Table B.17 summarizes the maintenance events since overlay became part of the LTPP experiment. The blank cells under the "construction change reason" indicate no maintenance.

Figure B.34 shows the distribution of overlay age until the deassign date. It should be noted that all SPS-7 sections have been taken out of the LTPP study and additional data are not available. The overlay thicknesses of the various test sections range from 3.1 to 6.5 in. The distribution of bonded overlay thickness is shown in Figures B.35 and B.36. All the

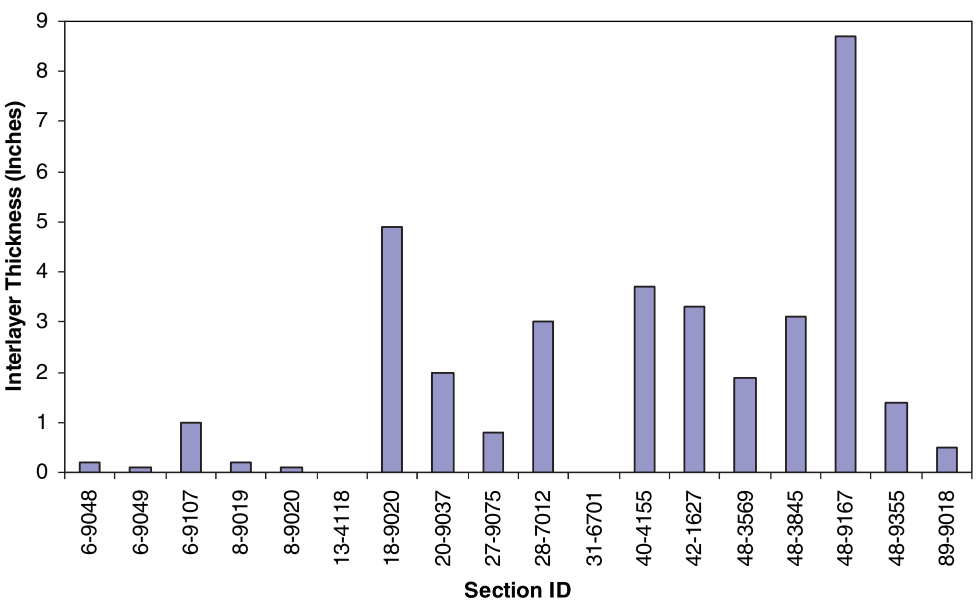
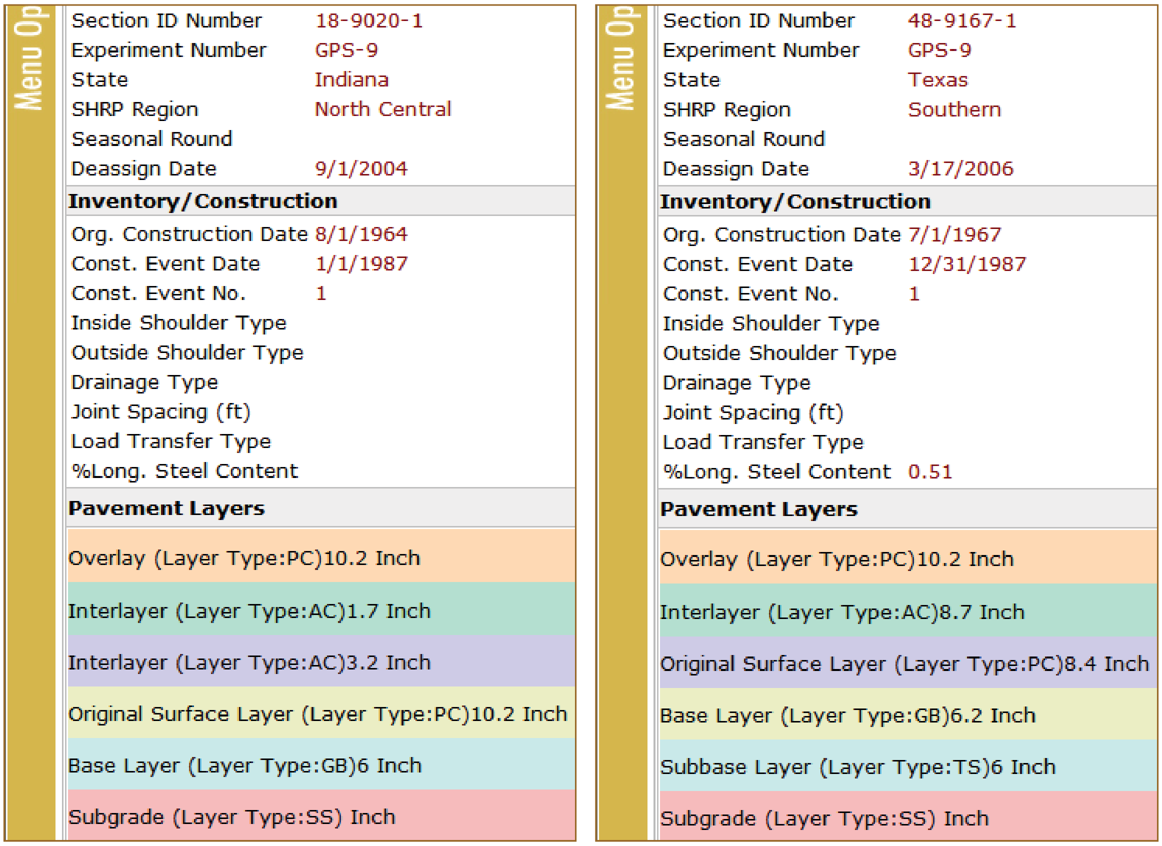


Figure B.11. Interlayer thicknesses.



Section ID Number	18-9020-1
Experiment Number	GPS-9
State	Indiana
SHRP Region	North Central
Seasonal Round	
Deassign Date	9/1/2004
Inventory/Construction	
Org. Construction Date	8/1/1964
Const. Event Date	1/1/1987
Const. Event No.	1
Inside Shoulder Type	
Outside Shoulder Type	
Drainage Type	
Joint Spacing (ft)	
Load Transfer Type	
%Long. Steel Content	
Pavement Layers	
Overlay (Layer Type:PC)10.2 Inch	
Interlayer (Layer Type:AC)1.7 Inch	
Interlayer (Layer Type:AC)3.2 Inch	
Original Surface Layer (Layer Type:PC)10.2 Inch	
Base Layer (Layer Type:GB)6 Inch	
Subgrade (Layer Type:SS) Inch	

Section ID Number	48-9167-1
Experiment Number	GPS-9
State	Texas
SHRP Region	Southern
Seasonal Round	
Deassign Date	3/17/2006
Inventory/Construction	
Org. Construction Date	7/1/1967
Const. Event Date	12/31/1987
Const. Event No.	1
Inside Shoulder Type	
Outside Shoulder Type	
Drainage Type	
Joint Spacing (ft)	
Load Transfer Type	
%Long. Steel Content	0.51
Pavement Layers	
Overlay (Layer Type:PC)10.2 Inch	
Interlayer (Layer Type:AC)8.7 Inch	
Original Surface Layer (Layer Type:PC)8.4 Inch	
Base Layer (Layer Type:GB)6.2 Inch	
Subbase Layer (Layer Type:TS)6 Inch	
Subgrade (Layer Type:SS) Inch	

Figure B.12. Cross sections with thick interlayer.

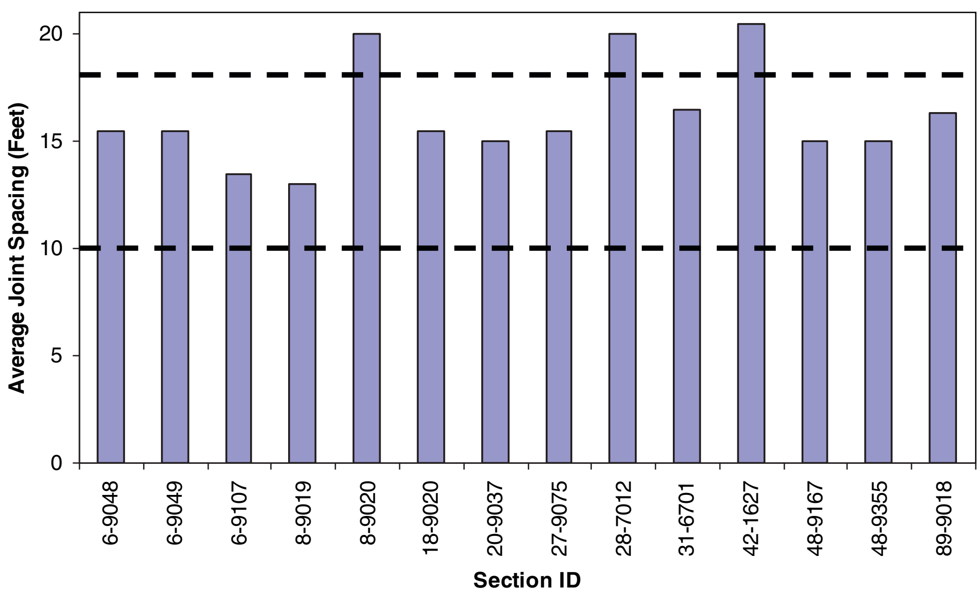


Figure B.13. JPCP average joint spacing.

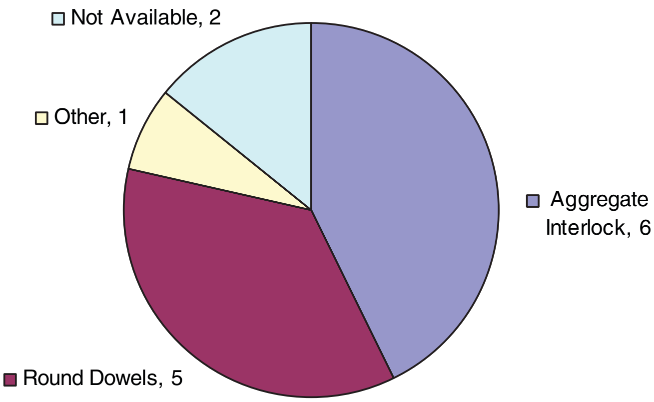


Figure B.14. JPCP load-transfer mechanisms.

JPCP overlays had transverse joint spacing of 20 ft. The distribution of bonding agent types commonly used is shown in Figure B.37.

Figure B.38 shows the distribution of the surface preparation methods used to create a bond in the various sections. The impact of the various surface preparations to create a bond on pavement performance is negligible.

Summary of Overall Field Performance

The pavement performance criteria selected for the summary include transverse cracking, IRI (and PSI), joint and crack faulting magnitude (JPCP), and punchouts (for CRCP and PCP). The performance trends presented in this section are based on measurements documented before the test section was taken out of the LTPP study.

Transverse Cracking. Figure B.39 (box-and-whisker plot) shows the distribution of percent cracking across the JPCP sections. The box-and-whisker plots presented here display data as follows: the median is represented by the horizontal line inside the box. The top and bottom of the box represent the third quartile (75th percentile) and the first quartile (25th percentile), respectively. The distance between these two is the interquartile range (IQR). In these plots, whiskers are drawn to the minimum and maximum observations.

Figure B.40 shows the magnitude of percent cracking as a function of overlay thickness for the joint concrete pavements.

Figure B.41 (box-and-whisker plot) shows the distribution of percent cracking across the PCP and CRCP sections. Figure B.42 shows the percent cracking as a function of overlay thickness for the CRCPs and PCPs.

Figure B.43 shows the distribution of the number of punchouts for PCP and CRCP sections. Figure B.44 shows the number of punchouts as a function of overlay thickness for the CRCPs and PCPs.

International Roughness Index (IRI). Figures B.45 through B.47 illustrate the progression of IRI and PSI for the various SPS-7 sections and the impact of overlay thickness on ride quality.

Summary

AC Renewal Projects

Four sections were selected for mechanistic analysis using the Mechanistic-Empirical Pavement Design Guide (MEPDG)

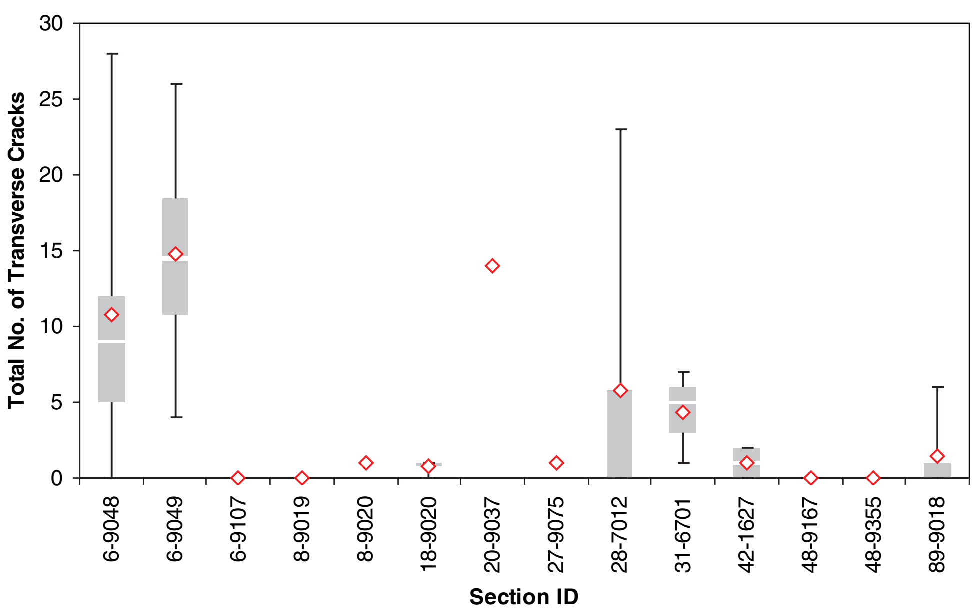


Figure B.15. Distribution of number of transverse cracks for JPCP sections.

and PerRoad software for performance prediction. They all met the criteria of "Heavy Traffic" and "Good Performance" and promise to be "long-life" pavements. Those sections are provided in Table B.18.

PCC Renewal Projects

In this appendix the performance of 18 GPS-9 sections and 35 SPS-7 sections has been summarized. A significant fraction of the GPS-9 test sections have a potential for long-life performance (50 plus years). Unfortunately, this cannot be verified based on field observations because all sections have been deassigned and no further data collection is planned. Therefore, the potential for long life was predicted using the MEPDG software.

Reference

Von Quintus, H. L., C. Rao, J. Mallela, B. Aho, Applied Research Associates, Incorporated, and Wisconsin Department of Transportation. 2007. *Guidance, Parameters, and Recommendations for Rubblized Pavements.* Project WHRP 06-13, Project 16730. National Technical Information Service, Alexandria, Va.

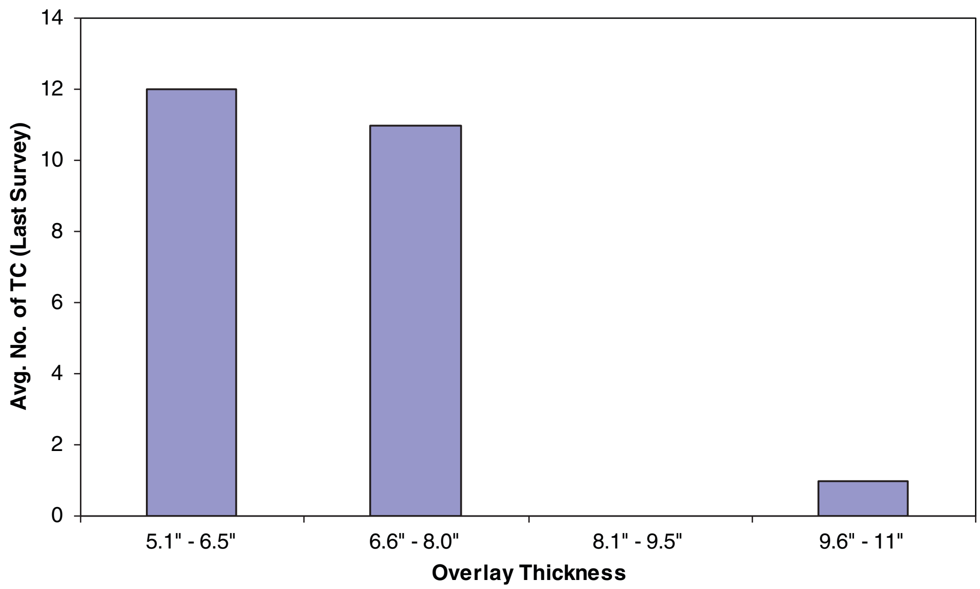


Figure B.16. JPCP overlay thickness versus average number of transverse cracks.

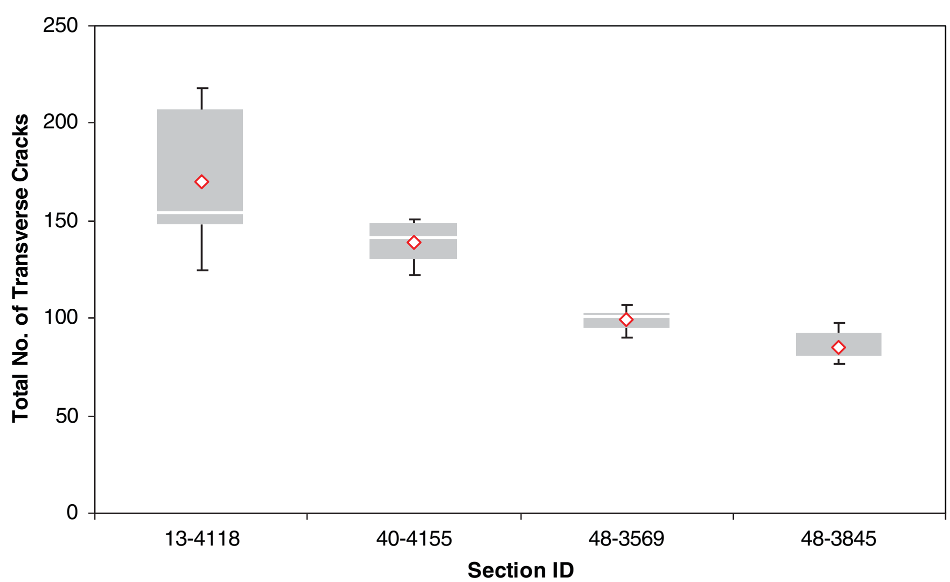


Figure B.17. Distribution of number of transverse cracks for CRCP sections.

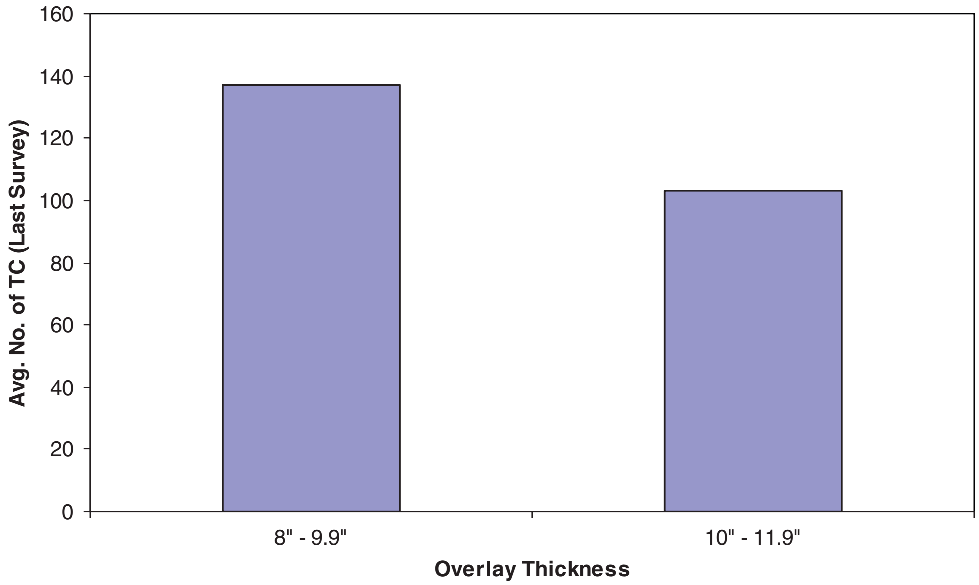


Figure B.18. CRCP overlay thickness versus average number of transverse cracks.

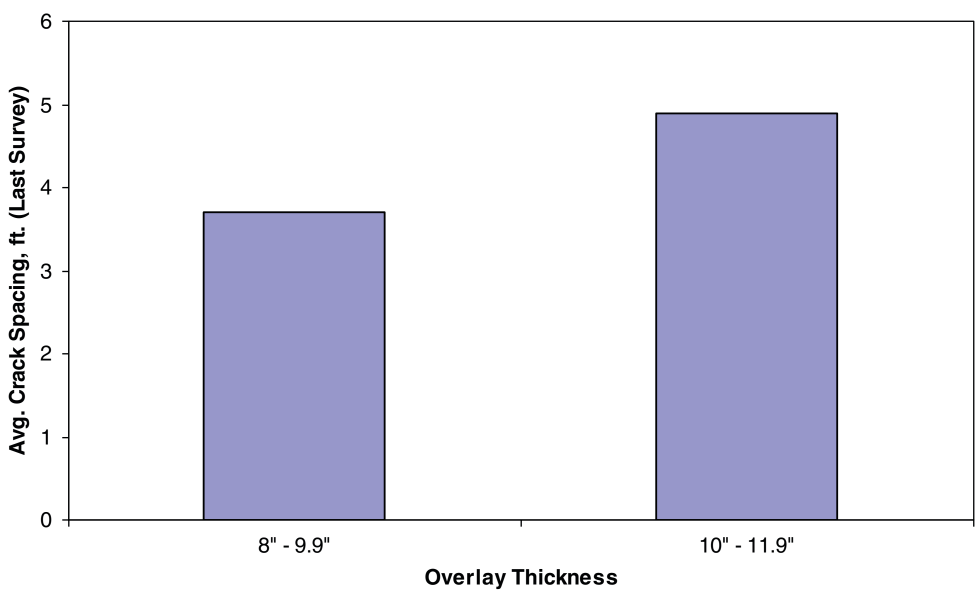


Figure B.19. CRCP overlay thickness versus average crack spacing.

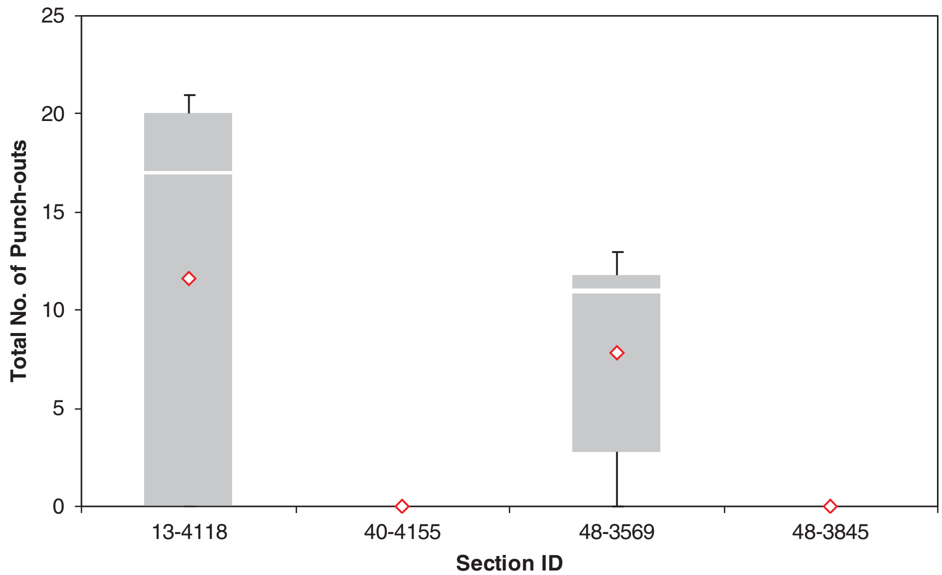


Figure B.20. Distribution of number of punchouts for CRCP sections.

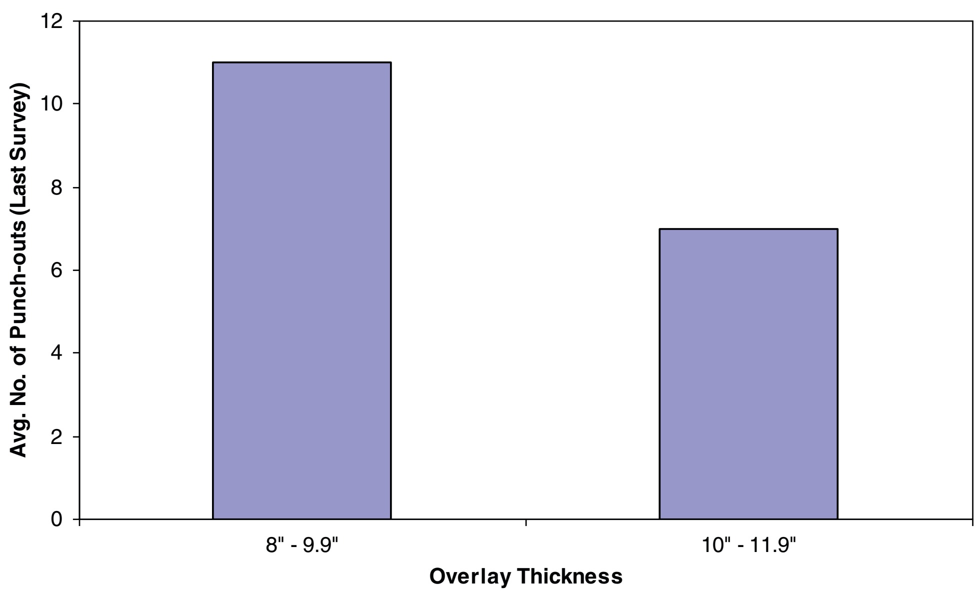


Figure B.21. CRCP overlay thickness versus average number of punchouts.

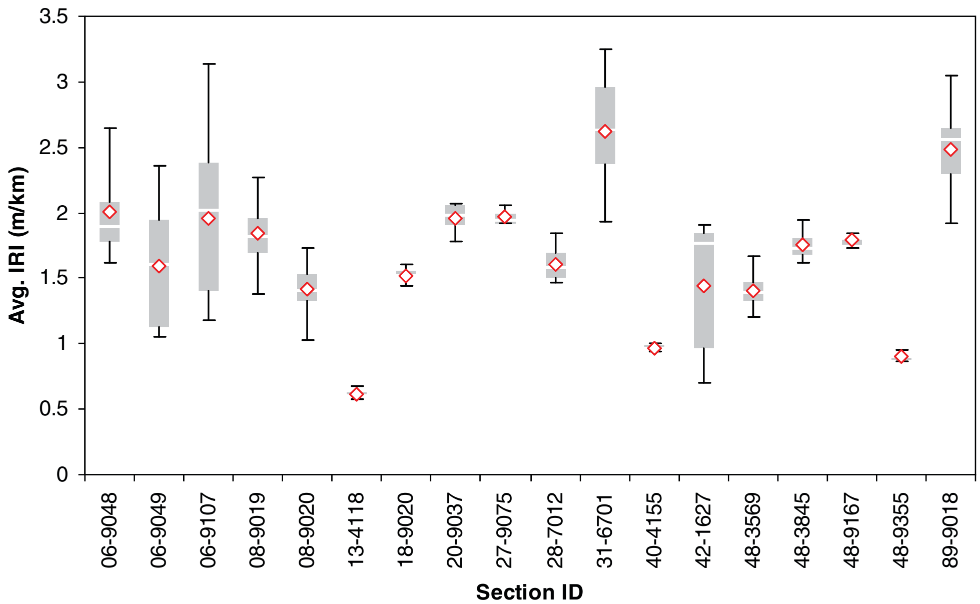


Figure B.22. Distribution of average IRI.

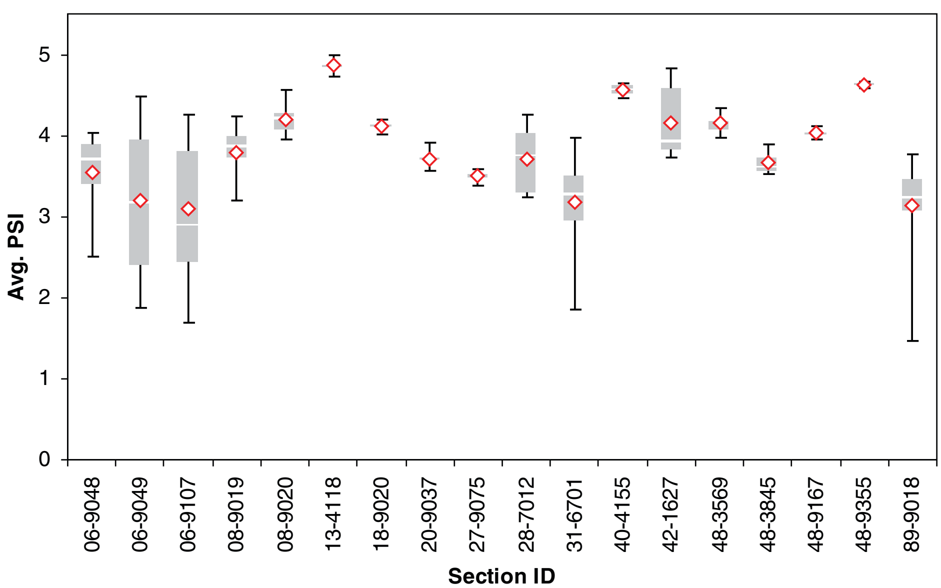


Figure B.23. Distribution of average PSI.

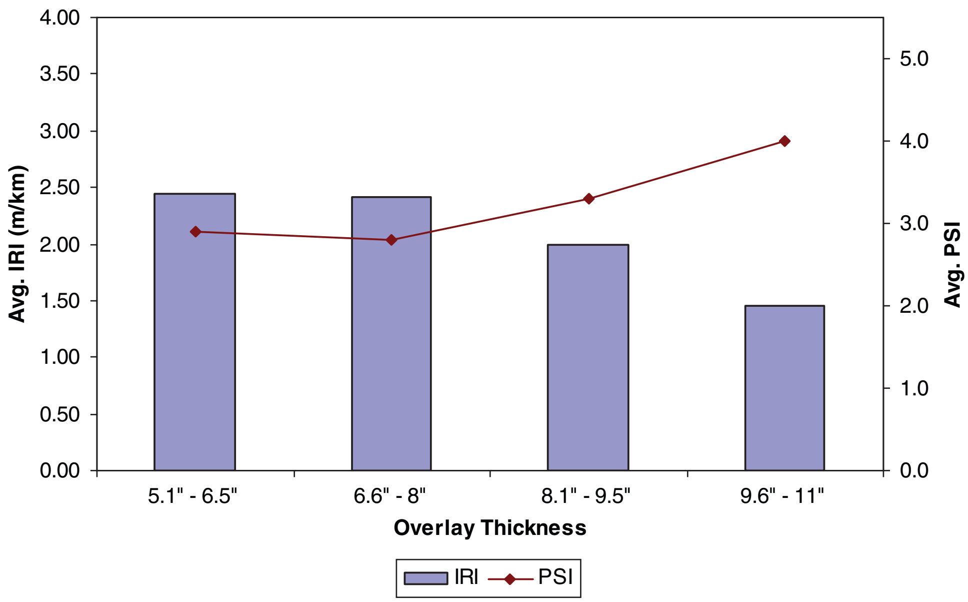


Figure B.24. Overlay thickness versus average IRI and average PSI.

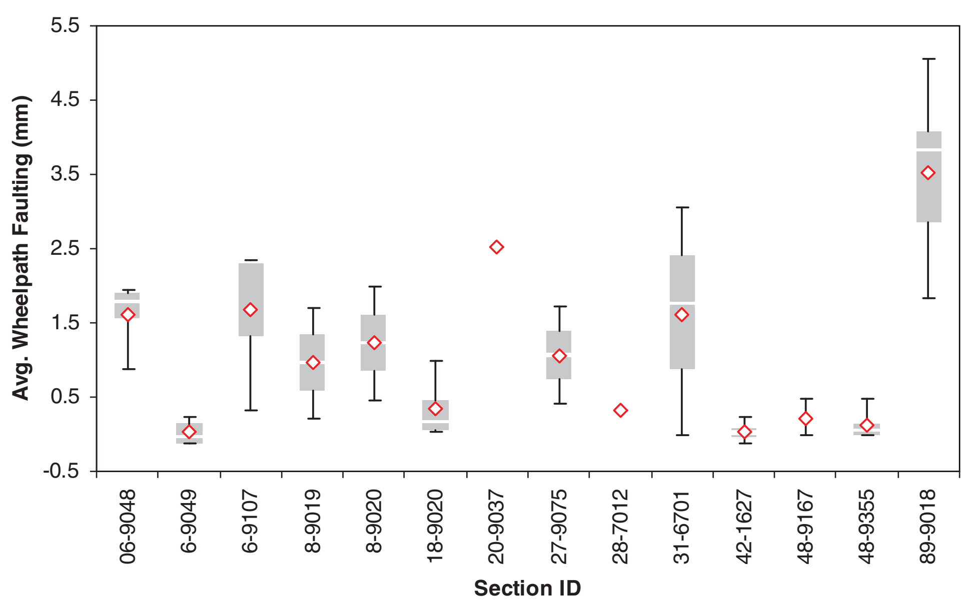


Figure B.25. Distribution of average wheelpath faulting by section.

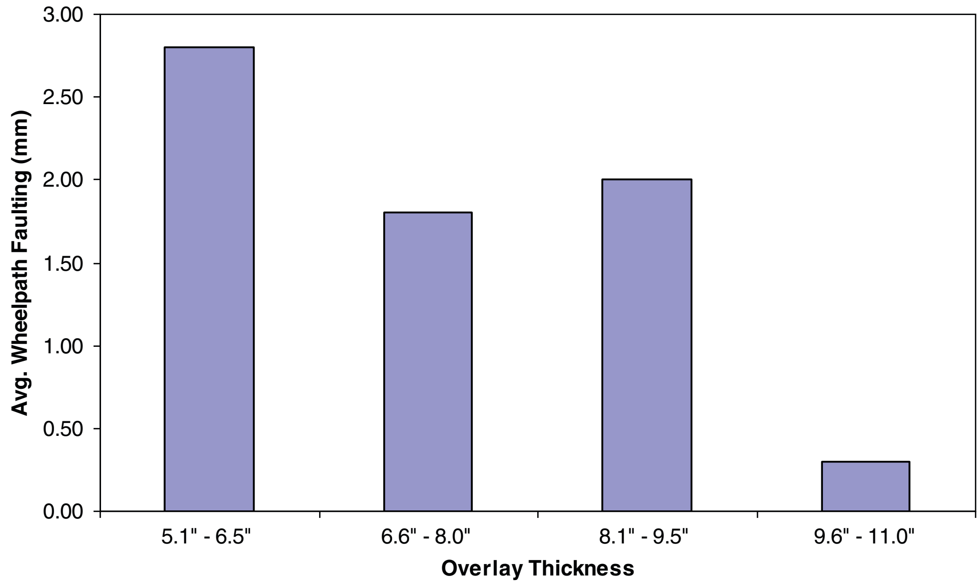


Figure B.26. Overlay thickness versus average wheelpath faulting.

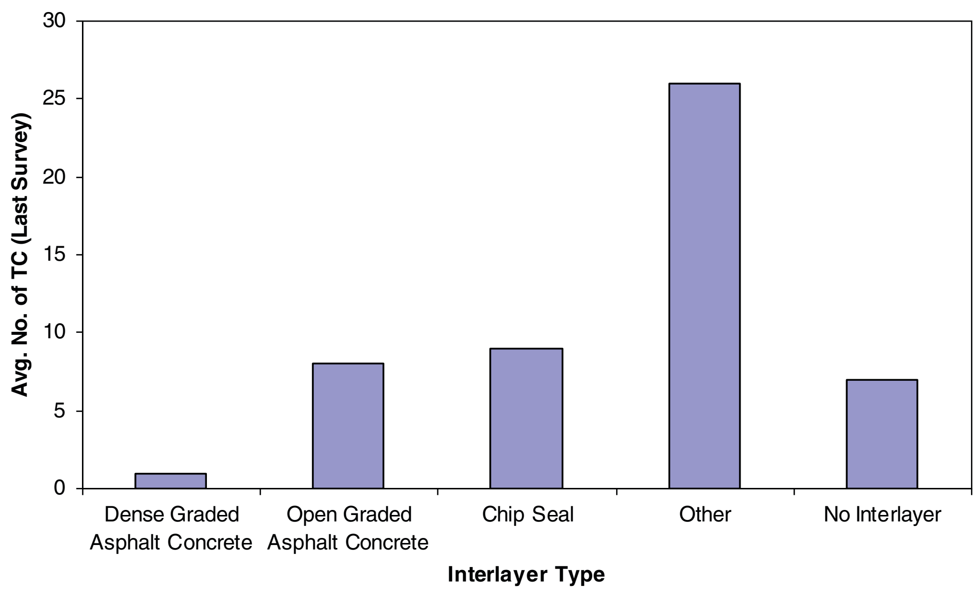


Figure B.27. JPCP interlayer type versus average number of transverse cracks.

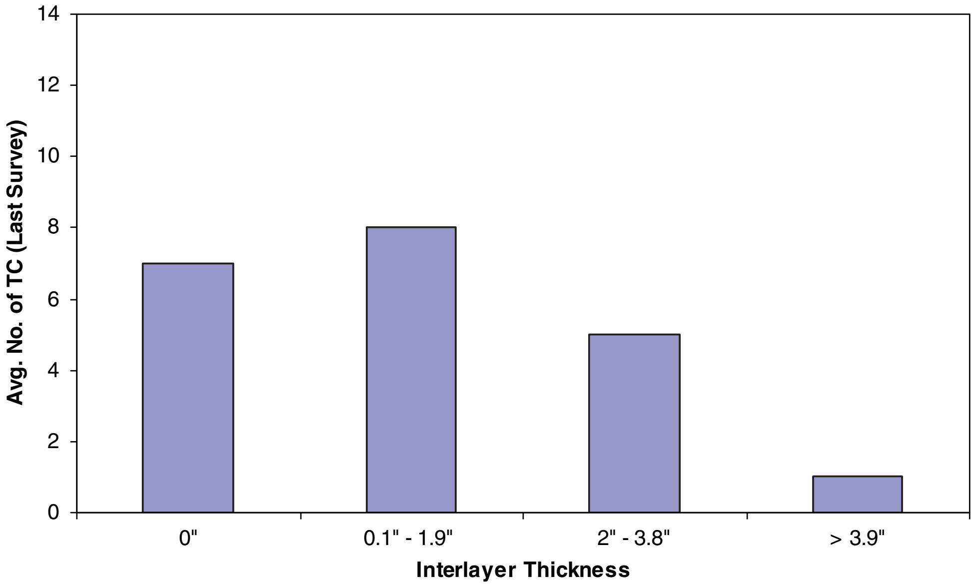


Figure B.28. JPCP interlayer thickness versus average number of transverse cracks.

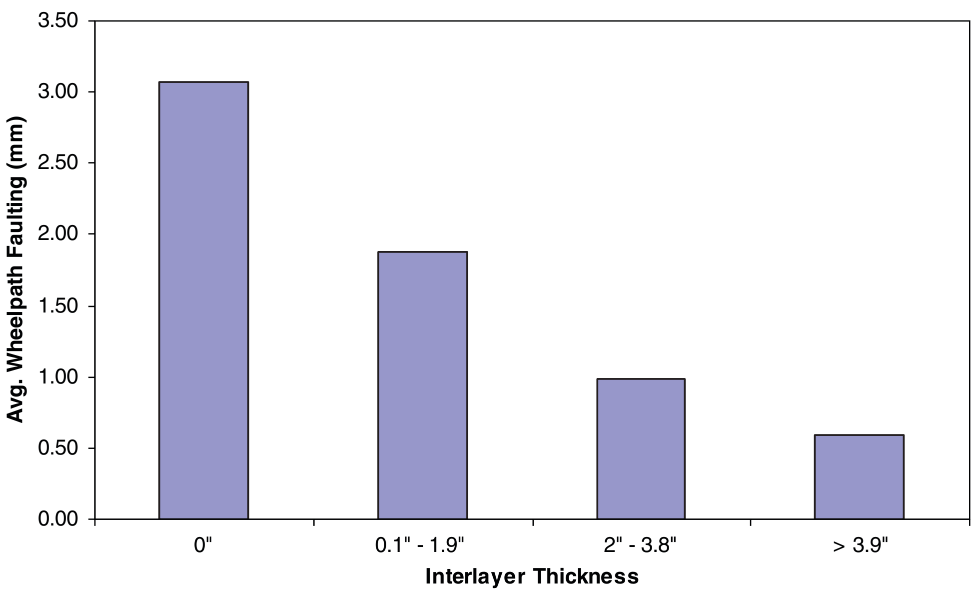


Figure B.29. JPCP interlayer thickness versus average wheelpath faulting.

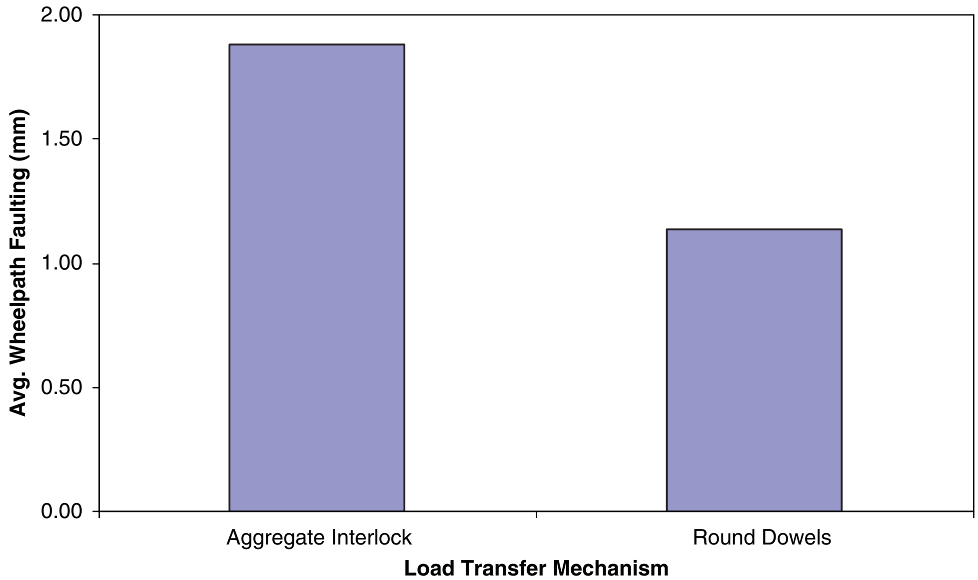


Figure B.30. JPCP load-transfer mechanism versus average wheelpath faulting.

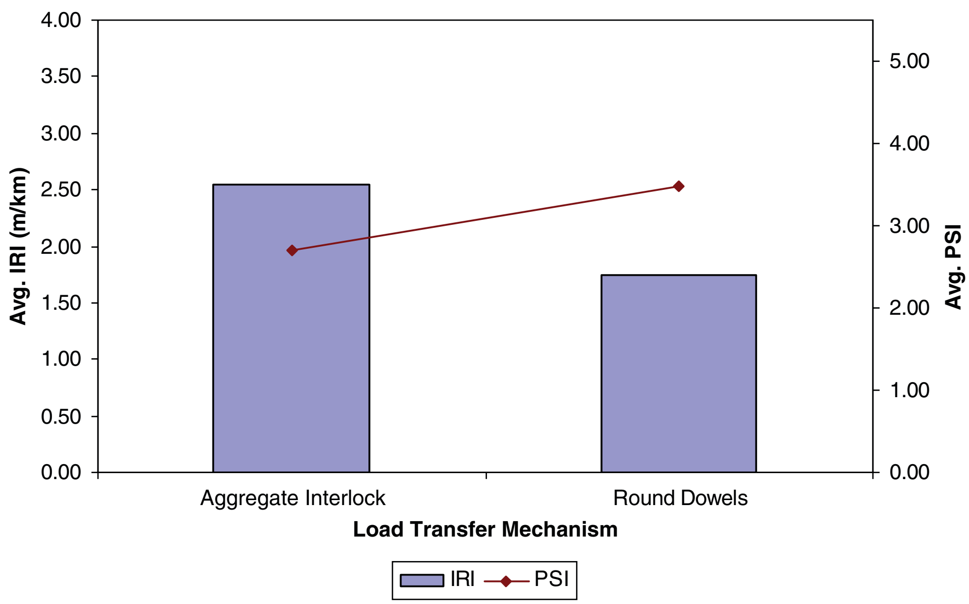


Figure B.31. JPCP load-transfer mechanism versus average IRI and average PSI.

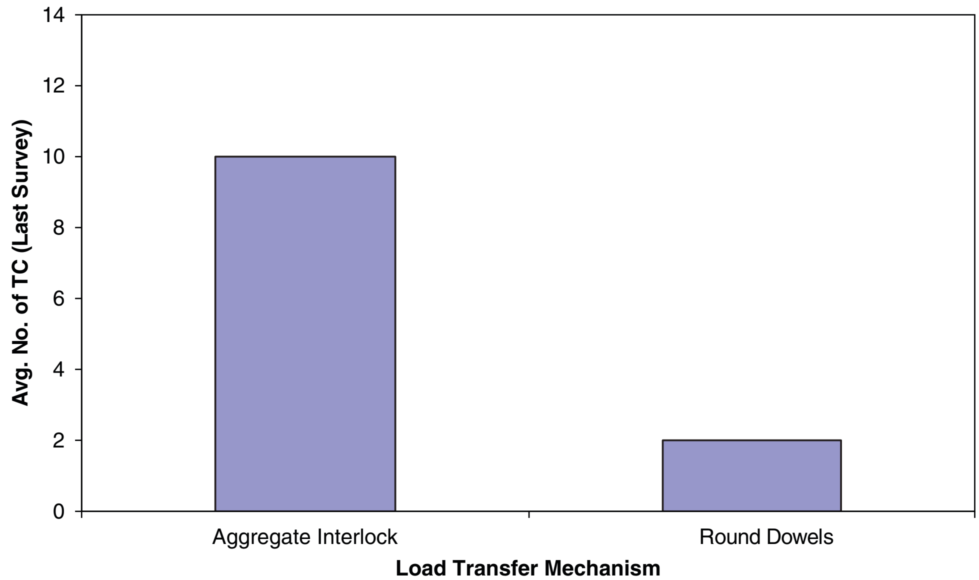
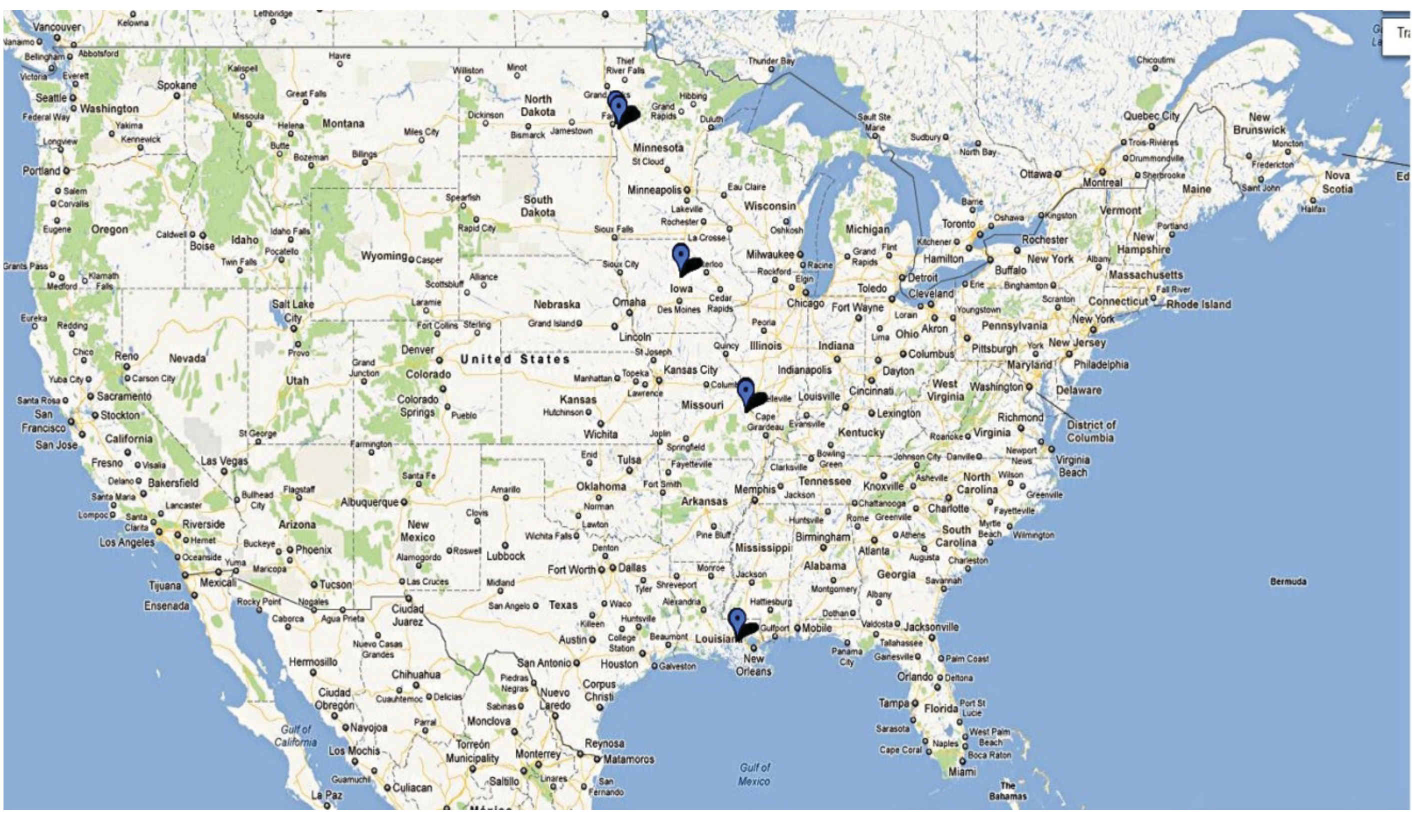


Figure B.32. JPCP load-transfer mechanism versus average number of transverse cracks.



Source: © 2011 Google Maps.

Figure B.33. Locations of SPS-7 sections.

Table B.17. SPS-7 Construction Events

Section ID	Construction No.	Construction Assign Date	Construction Change Reason
19-0702	1	1/1/1992	
	2	4/3/1992	Full-depth transverse joint repair patch, partial-depth patching of PCC pavements at joints.
	3	7/14/1992	Lane-shoulder longitudinal joint sealing, grinding surface, portland cement concrete overlay.
19-0703	1	1/1/1992	
	2	4/4/1992	Full-depth transverse joint repair patch, partial-depth patching of PCC pavements at joints.
	3	7/10/1992	Lane-shoulder longitudinal joint sealing, grinding surface, portland cement concrete overlay.
19-0704	1	1/1/1992	
	2	4/6/1992	Full-depth transverse joint repair patch, partial depth patching of PCC pavements at joints.
	3	7/10/1992	Lane-shoulder longitudinal joint sealing, portland cement concrete overlay.
19-0705	1	1/1/1992	
	2	4/6/1992	Full-depth transverse joint repair patch, partial depth patching of PCC pavements at joints.
	3	7/10/1992	Lane-shoulder longitudinal joint sealing, portland cement concrete overlay.
19-0706	1	1/1/1992	
	2	4/6/1992	Partial-depth patching of PCC pavements at joints.
	3	7/10/1992	Lane-shoulder longitudinal joint sealing, portland cement concrete overlay.
19-0707	1	1/1/1992	
	2	4/7/1992	Full-depth transverse joint repair patch.
	3	7/10/1992	Lane-shoulder longitudinal joint sealing, portland cement concrete overlay.
19-0708	1	1/1/1992	
	2	7/10/1992	Lane-shoulder longitudinal joint sealing, grinding surface, portland cement concrete overlay.
19-0709	1	1/1/1992	
	2	4/6/1992	Partial-depth patching of PCC pavements at joints.
	3	7/10/1992	Lane-shoulder longitudinal joint sealing, grinding surface, portland cement concrete overlay.
19-0759	1	1/1/1992	
	2	8/6/1993	Portland cement concrete overlay.
22-0702	1	1/1/1987	
	2	4/7/1992	Full-depth patching of PCC pavement other than at joint, grinding surface, portland cement concrete overlay, PCC shoulder restoration.
22-0703	1	1/1/1987	
	2	4/10/1992	Grinding surface, portland cement concrete overlay, PCC shoulder restoration.
22-0704	1	1/1/1987	
	2	4/21/1992	Portland cement concrete overlay, PCC shoulder restoration.
22-0705	1	1/1/1987	
	2	4/21/1992	Portland cement concrete overlay, PCC shoulder restoration.
22-0706	1	1/1/1987	
	2	4/22/1992	Portland cement concrete overlay, PCC shoulder restoration.
22-0707	1	1/1/1987	
	2	4/21/1992	Portland cement concrete overlay, PCC shoulder restoration.

(continued on next page)

Table B.17. SPS-7 Construction Events (continued)

Section ID	Construction No.	Construction Assign Date	Construction Change Reason
22-0708	1	1/1/1987	
	2	4/9/1992	Grinding surface, portland cement concrete overlay, PCC shoulder restoration.
22-0709	1	1/1/1987	
	2	4/9/1992	Grinding surface, portland cement concrete overlay, PCC shoulder restoration.
27-0702	1	1/1/1987	
	2	9/10/1990	Grinding surface, portland cement concrete overlay, longitudinal subdrains.
27-0703	1	1/1/1987	
	2	9/10/1990	Grinding surface, portland cement concrete overlay, longitudinal subdrains.
27-0704	1	1/1/1987	
	2	9/10/1990	Portland cement concrete overlay, longitudinal subdrains.
27-0705	1	1/1/1987	
	2	9/10/1990	Portland cement concrete overlay, longitudinal subdrains.
27-0706	1	1/1/1987	
	2	9/10/1990	Portland cement concrete overlay, longitudinal subdrains.
27-0707	1	1/1/1987	
	2	9/10/1990	Portland cement concrete overlay, longitudinal subdrains.
27-0708	1	1/1/1987	
	2	9/10/1990	Grinding surface, portland cement concrete overlay, longitudinal subdrains.
	3	9/1/1998	Partial-depth patching of PCC pavement other than at joint.
	4	7/1/2001	Partial-depth patching of PCC pavement other than at joint.
27-0709	1	1/1/1987	
	2	9/10/1990	Grinding surface, portland cement concrete overlay, longitudinal subdrains.
27-0759	1	1/1/1987	
	2	9/10/1990	Portland cement concrete overlay, longitudinal subdrains.
29-0702	1	1/1/1987	
	2	6/18/1990	AC shoulder restoration, grinding surface, portland cement concrete overlay.
29-0703	1	1/1/1987	
	2	6/15/1990	Transverse joint sealing, lane-shoulder longitudinal joint sealing, full-depth transverse joint repair patch, AC shoulder restoration, grinding surface, portland cement concrete overlay.
	3	2/15/2000	Crack sealing, transverse joint sealing, lane-shoulder longitudinal joint sealing.
29-0704	1	1/1/1987	
	2	6/26/1990	AC shoulder restoration, portland cement concrete overlay.
	3	2/15/2000	Crack sealing, transverse joint sealing, lane-shoulder longitudinal joint sealing.
29-0705	1	1/1/1987	
	2	6/28/1990	AC shoulder restoration, portland cement concrete overlay.
	3	2/15/2000	Crack sealing, transverse joint sealing, lane-shoulder longitudinal joint sealing.
29-0706	1	1/1/1987	
	2	6/29/1990	AC shoulder restoration, portland cement concrete overlay.
	3	2/15/2000	Crack sealing, transverse joint sealing, lane-shoulder longitudinal joint sealing.

(continued on next page)

Table B.17. SPS-7 Construction Events (continued)

Section ID	Construction No.	Construction Assign Date	Construction Change Reason
27-0708	1	1/1/1987	
	2	9/10/1990	Grinding surface, portland cement concrete overlay, longitudinal subdrains.
	3	9/1/1998	Partial-depth patching of PCC pavement other than at joint.
	4	7/1/2001	Partial-depth patching of PCC pavement other than at joint.
27-0709	1	1/1/1987	
	2	9/10/1990	Grinding surface, portland cement concrete overlay, longitudinal subdrains.
27-0759	1	1/1/1987	
	2	9/10/1990	Portland cement concrete overlay, longitudinal subdrains.
29-0702	1	1/1/1987	
	2	6/18/1990	AC shoulder restoration, grinding surface, portland cement concrete overlay.
29-0703	1	1/1/1987	
	2	6/15/1990	Transverse joint sealing, lane-shoulder longitudinal joint sealing, full depth transverse joint repair patch, AC shoulder restoration, grinding surface, portland cement concrete overlay.
	3	2/15/2000	Crack sealing, transverse joint sealing, lane-shoulder longitudinal joint sealing.
29-0704	1	1/1/1987	
	2	6/26/1990	AC shoulder restoration, portland cement concrete overlay.
	3	2/15/2000	Crack sealing, transverse joint sealing, lane-shoulder longitudinal joint sealing.
29-0705	1	1/1/1987	
	2	6/28/1990	AC shoulder restoration, portland cement concrete overlay.
	3	2/15/2000	Crack sealing, transverse joint sealing, lane-shoulder longitudinal joint sealing.
29-0706	1	1/1/1987	
	2	6/29/1990	AC shoulder restoration, portland cement concrete overlay.
	3	2/15/2000	Crack sealing, transverse joint sealing, lane-shoulder longitudinal joint sealing.
29-0707	1	1/1/1987	
	2	6/29/1990	AC shoulder restoration, portland cement concrete overlay.
	3	2/15/2000	Crack sealing, transverse joint sealing, lane-shoulder longitudinal joint sealing.
29-0708	1	1/1/1987	
	2	6/19/1990	AC shoulder restoration, grinding surface, portland cement concrete overlay.
	3	2/15/2000	Crack sealing, transverse joint sealing, lane-shoulder longitudinal joint sealing.
29-0709	1	1/1/1987	
	2	6/19/1990	AC shoulder restoration, grinding surface, portland cement concrete overlay.
	3	2/15/2000	Crack sealing, transverse joint sealing, lane-shoulder longitudinal joint sealing.
29-0760	1	1/1/1987	
	2	6/11/1990	Transverse joint sealing, lane-shoulder longitudinal joint sealing, full-depth transverse joint repair patch, AC shoulder restoration, grinding surface, portland cement concrete overlay.
	3	2/15/2000	Crack sealing, transverse joint sealing, lane-shoulder longitudinal joint sealing.

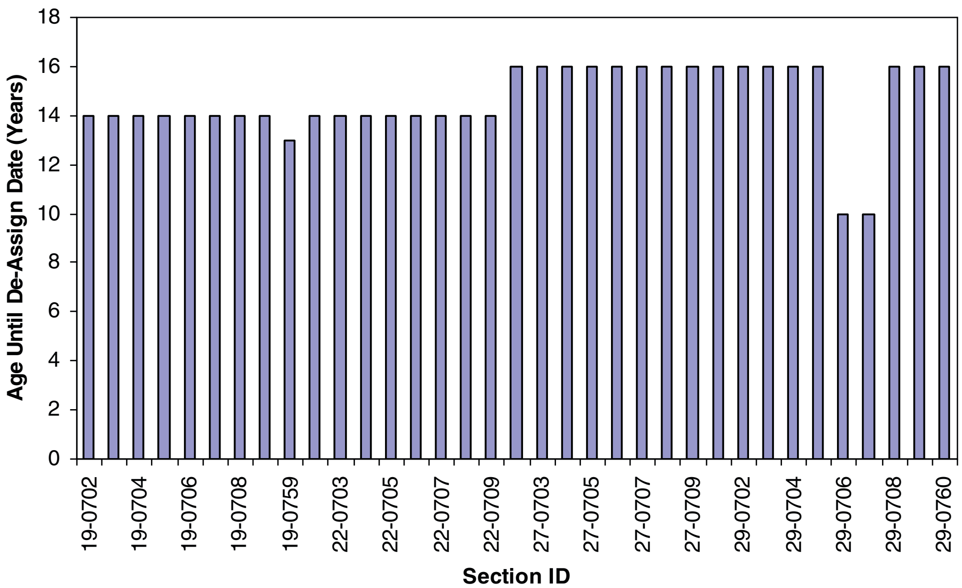


Figure B.34. Overlay age until deassign date.

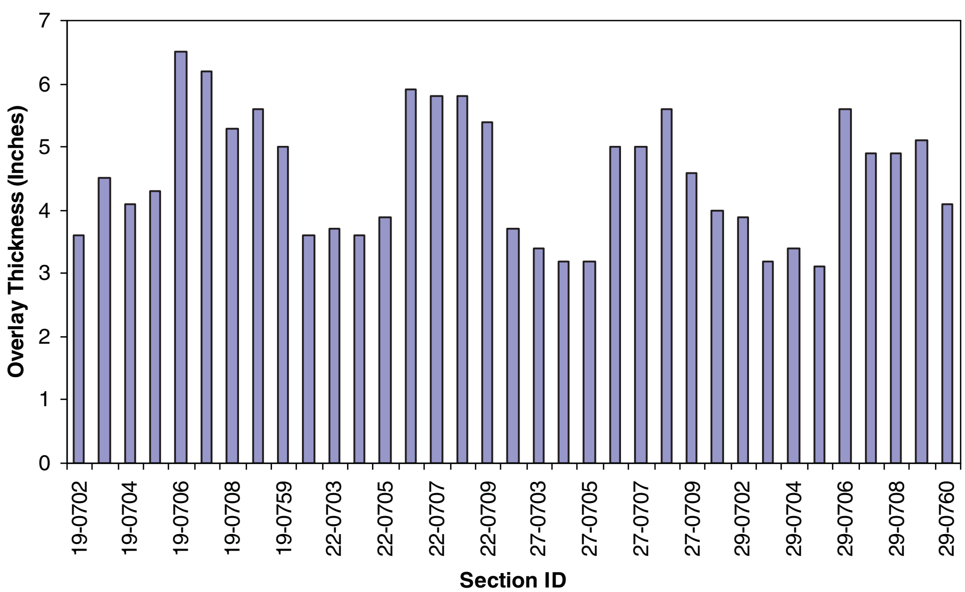


Figure B.35. Overlay thicknesses.

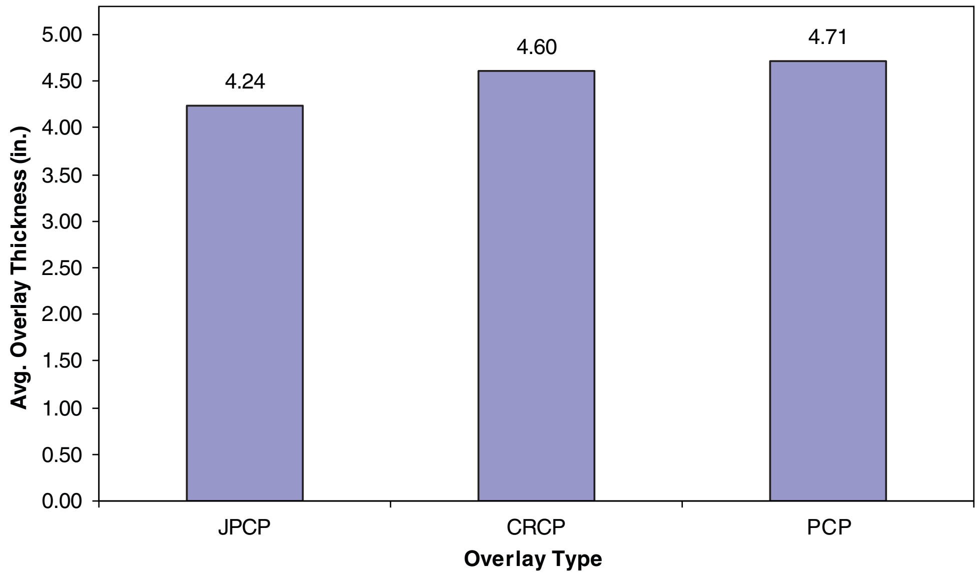


Figure B.36. Average overlay thickness for SPS-7 overlay types.

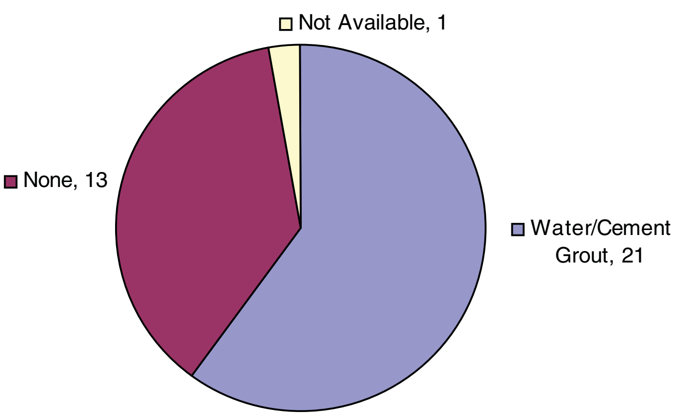


Figure B.37. Distribution of types of bonding agents.

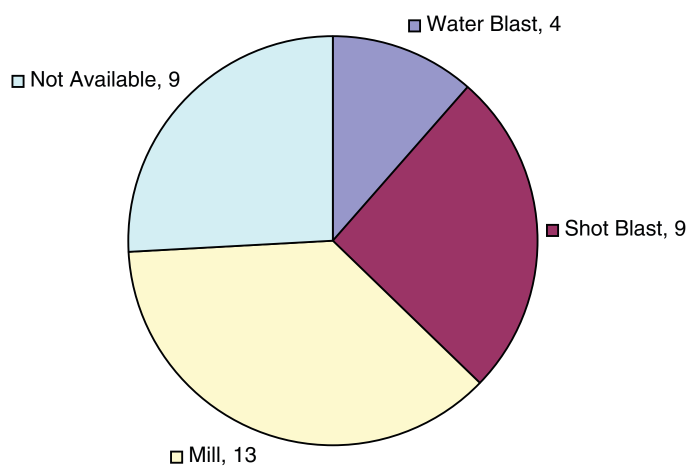


Figure B.38. Distribution of surface preparation methods.

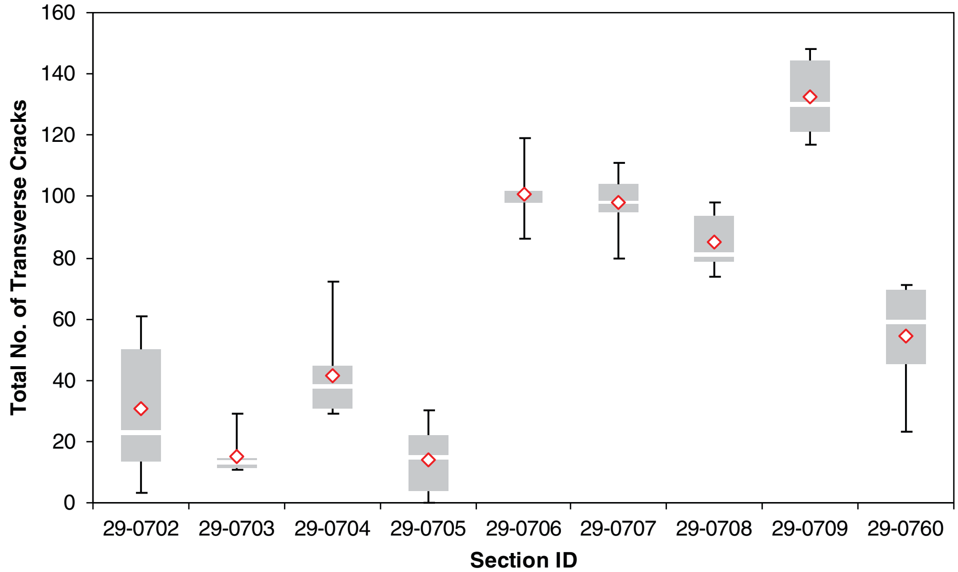


Figure B.39. Distribution of number of transverse cracks by JPCP sections.

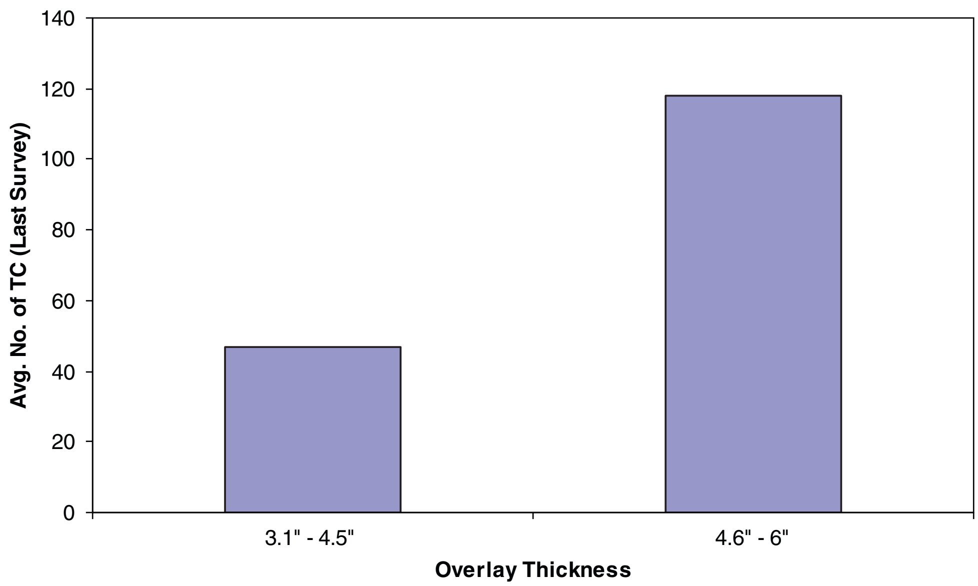


Figure B.40. JPCP overlay thickness versus number of transverse cracks.

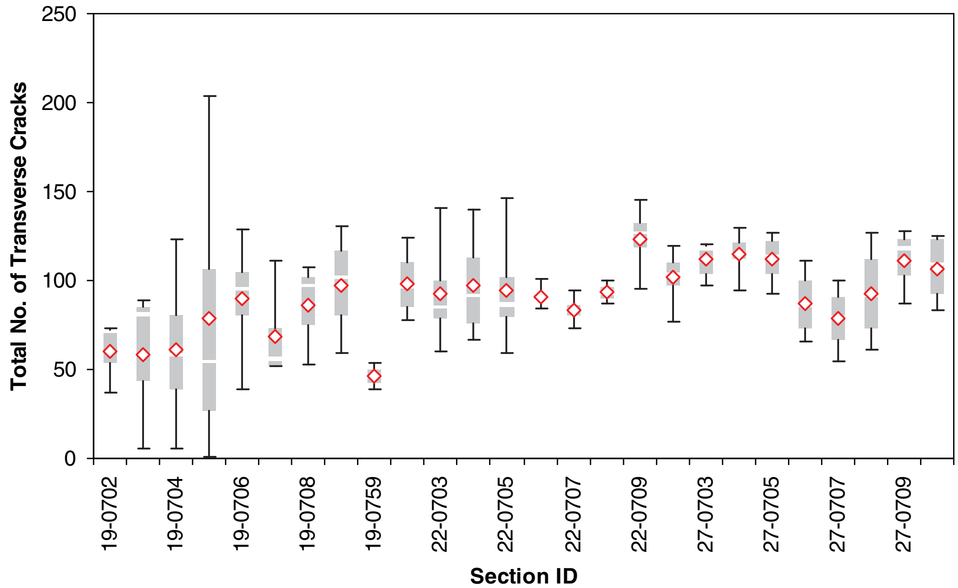


Figure B.41. Distribution of number of transverse cracks for CRCP and PCP sections.

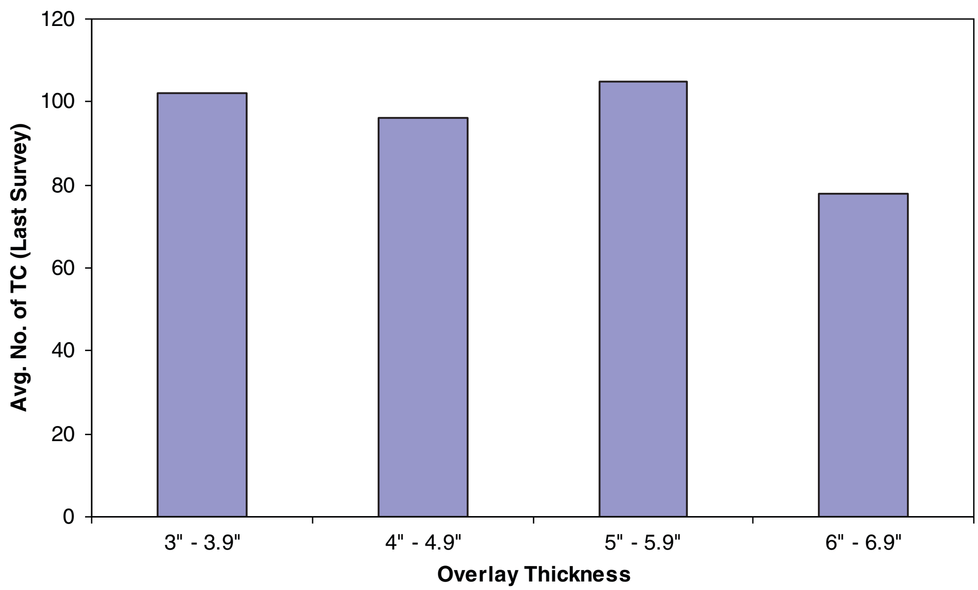


Figure B.42. CRCP and PCP overlay thickness versus number of transverse cracks.

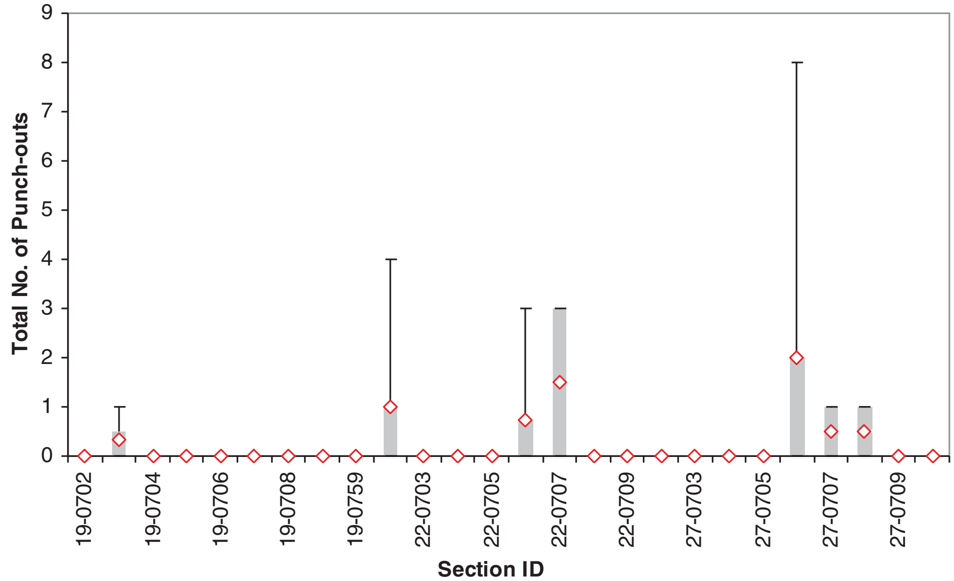


Figure B.43. Distribution of number of punchouts for CRCP and PCP sections.

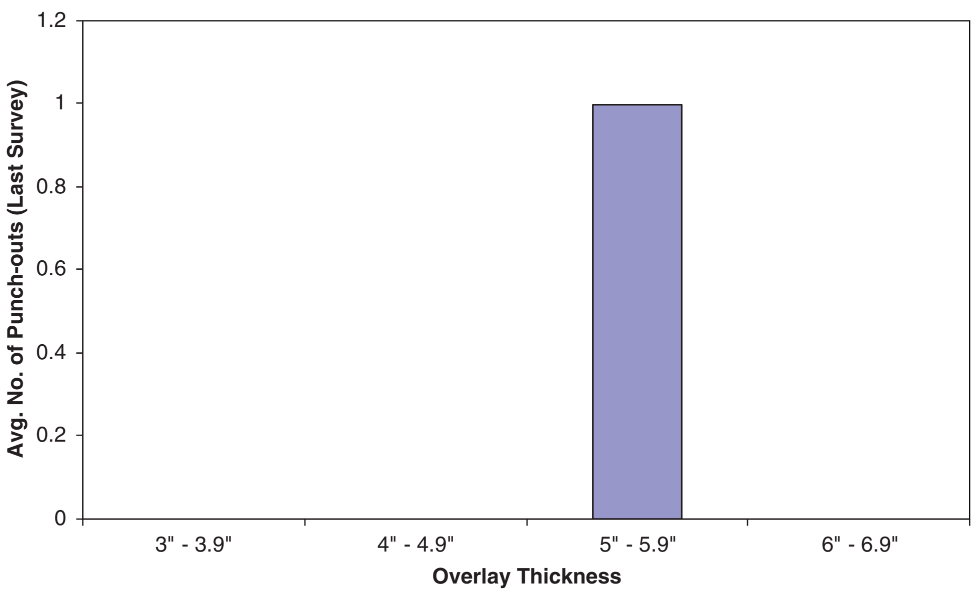


Figure B.44. CRCP and PCP overlay thickness versus number of punchouts.

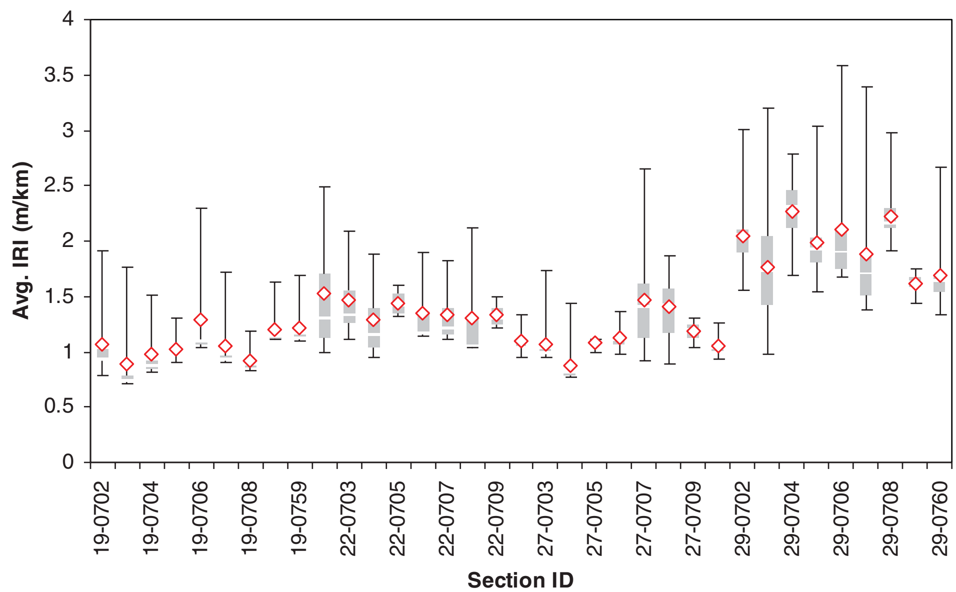


Figure B.45. Distribution of average IRI by section.

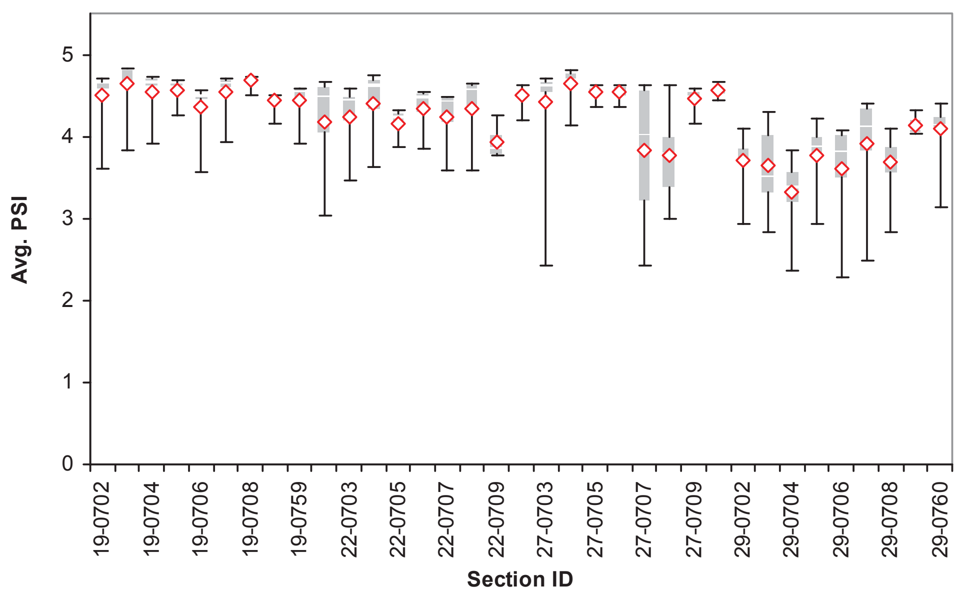


Figure B.46. Distribution of average PSI by section.

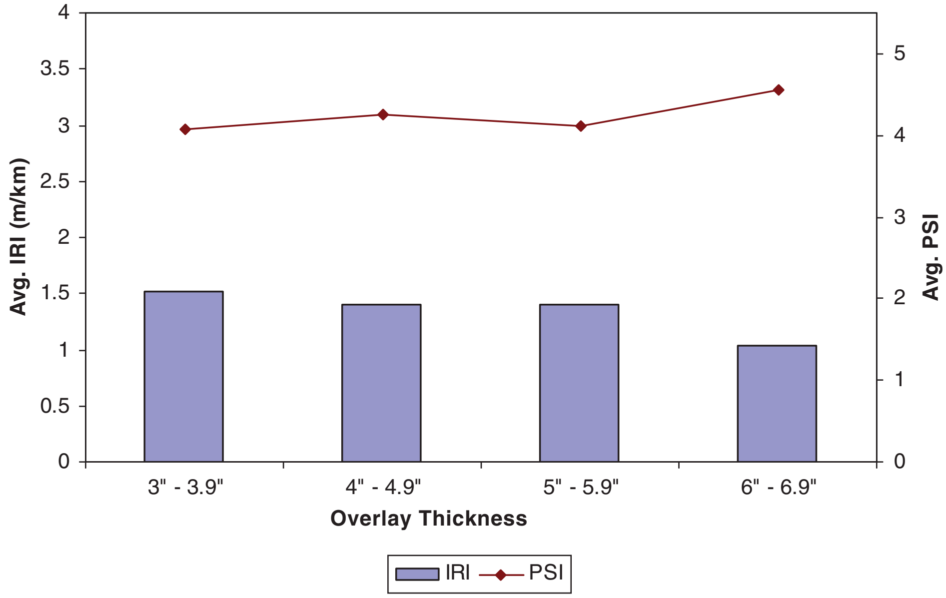


Figure B.47. Overlay thickness versus average IRI and average PSI.

Table B.18. Summary of AC LTPP Section Analyzed

<table>
<tr><th>Experiment</th><th>State</th><th>SHRP ID</th><th>Age (years)</th><th>Traffic (KESAL)</th><th colspan="3">Original Thickness (in.)</th><th colspan="2">Overlay Thickness (in.)</th><th>Overlay Age (years)</th></tr>
<tr><td>GPS-6A</td><td>47</td><td>6015</td><td>30</td><td>23647</td><td>8.8</td><td colspan="2">Medium</td><td colspan="2">5.5</td><td>19</td></tr>
<tr><td>GPS-6B</td><td>47</td><td>3108</td><td>33</td><td>28429</td><td>5.5</td><td colspan="2">Medium</td><td colspan="2">2.7</td><td>16</td></tr>
<tr><td rowspan="2">GPS-7A</td><td rowspan="2">13</td><td rowspan="2">7028</td><td rowspan="2">17</td><td rowspan="2">16763</td><td rowspan="2">9.1</td><td rowspan="2">Medium</td><td rowspan="2">JPCP</td><td rowspan="2">7.0</td><td>6.0</td><td>12</td></tr>
<tr><td>2.5</td><td>5</td></tr>
<tr><td>GPS-7B</td><td>18</td><td>5022</td><td>34</td><td>176836</td><td>9.8</td><td>Medium</td><td>CRCP</td><td colspan="2">4.0</td><td>13</td></tr>
</table>

APPENDIX C

Development of Rigid and Flexible Renewal Decision Matrices

The decision tables developed for the R23 project were based on extensive literature review, on pavement design analysis, and in working with a number of engineers from state departments of transportation (DOTs) and industry. The guidelines were developed to help designers in selecting either a rigid or flexible reconstruction approach that can reasonably be expected to provide long-life pavement performance. For this project, long-life performance was defined as providing 50 years of service without major structural deterioration. It is anticipated that any approach selected will require some form of rehabilitation or resurfacing during the service life of the pavement. The final selection of the most appropriate design should be based on a life-cycle cost analysis of the various approaches, including all rehabilitation or resurfacing costs over the life of the pavements.

The development of the decision matrices followed more or less the standard process where team members laid out an outline of the decision process on a blackboard. The outline had the basic form seen on the tables with pavement type, distress present, and potential renewal approaches for those conditions. The outline was circulated to the full team and modified as additional considerations were added. The outline was presented at the kickoff meetings and then circulated among the participating agencies for comment, and again adjustments were made to the outline. To make the process clearer, the decision matrix was put in a set of tables. The tables were then circulated again to the full R23 team and the participating agencies, which provided more comment (most likely because the tables were easier to follow than the outlines). The tables were then used to build an interactive Flash-based program that would simplify use of the decision matrix. In building the logic for the interactive program, a few more decision points were added based on the more rigorous nature of that process. After the program was developed, it was put through a series of trials on a wide range of potential applications, and the decision tables were adjusted again based on errors or omissions found in that process. The interactive program and the decision tables were again presented to the participating agencies for review and comment, and final adjustments were made to the program and the tables presented in this appendix.

General guidance was also developed on layer thickness that would be required to provide long-life pavement renewal. A set of tables was developed as described in Appendix D. Since these design tables are linked to the actions included in the decision tables, a fifth column was added to the decision tables. The information in this column, called "Design Resources," states the specific thickness design table to be used for those specific sets of conditions and renewal approach. These specific thickness design tables can be found in Appendix D. Where there was a clear repetition of actions and design resources, rules were used to reduce the verbiage in the columns.

The decision tables have been incorporated into the interactive program to help users develop a list of feasible approaches based on existing site conditions. Table C.1 provides details on the decision matrix for existing flexible pavements. Table C.2 provides details on the decision matrix for existing JPCP and JRCP. Table C.3 describes the decision process for existing CRCP, while Table C.4 details renewal alternatives for existing composite pavements. Three rules are commonly referenced in Tables C.2 through C.4 under the "Design Resources" column:

- *Rule 1:* Rubblization of existing portland cement concrete (PCC) followed by application of asphalt concrete (AC) overlay from Tables D.37 through D.39 (Appendix D). Rubblization guidelines include the following:
  - If the subgrade M_R < 6,000 psi or CBR < 4%, do not rubblize, thus defaulting to crack and seat only.
  - If the subgrade $M_R \geq$ 6,000 psi but < 10,000 psi, consult the TTI rubblization guidelines as to whether rubblization is viable (Sebesta and Scullion 2006).
  - If the subgrade $M_R \geq$ 10,000 psi, then rubblization is a viable option.

The selection of the AC thickness is based on a drop-down menu of subgrade moduli equal to 5,000 psi, 10,000 psi, or 20,000 psi. The existing pavement shall be characterized by one of four possible moduli: 30,000 psi, 50,000 psi, 75,000 psi, or 100,000 psi. It is recommended that an existing pavement modulus of 50,000 psi be used to reflect rubblized PCC.

- *Rule 2:* Crack and seat existing PCC followed by application of AC overlay from Tables D.37 through D.39 (Appendix D). The selection of the AC thickness is based on a drop-down menu of subgrade moduli equal to 5,000 psi, 10,000 psi, or 20,000 psi. The existing pavement shall be characterized by one of four possible moduli: 30,000 psi, 50,000 psi, 75,000 psi, or 100,000 psi. It is recommended that an existing pavement modulus of 75,000 psi be used to reflect crack and seated PCC.
- *Rule 3:* Use Table D.22 (Appendix D) for thickness determination of an unbonded PCC overlay and place on a 2-in.-thick AC bond breaker. The unbonded PCC overlay thickness is independent of subgrade support conditions.

Reference

Sebesta, S., and T. Scullion. 2007. *Field Evaluations and Guidelines for Rubblization in Texas.* Report FHWA/TX-08/0-4687-2. Texas Transportation Institute.

Table C.1. Feasible Renewal Alternatives for Existing Flexible Pavements

Distress Category	Specific Distress Description	Distress Present?	Renewal Pavement Type Option	Action	Design Resources
Environmental cracking	Transverse or block cracking	Yes	Flexible	Pulverize pavement structure full depth followed by a thick AC overlay.	Pulverize and use residual material as untreated base (50 ksi). Apply AC thickness from Tables D.37–D.39.
					Pulverize and treat residual material with emulsion or foamed asphalt resulting in a treated base (100 ksi). Apply AC thickness from Tables D.37–D.39.
			Rigid	No mitigation required, place an unbonded PCC overlay.	Use Table D.22 for thickness determination of an unbonded PCC overlay.
		No	—	Continue to “materials-caused distress.”	—
Materials-caused distress	Stripping	Yes	Flexible	If stripping is found through all layers, pulverize pavement structure full depth followed by a thick AC overlay.	Pulverize and use residual material as untreated base (50 ksi). Apply AC thickness from Tables D.37–D.39.
					Pulverize and treat residual material with emulsion or foamed asphalt resulting in a treated base (100 ksi). Apply AC thickness from Tables D.37–D.39.
				If stripping is found in specific layers, remove AC to maximum depth of stripping followed by a thick AC overlay.	Use Tables D.37–D.39 with 30-ksi base and the subgrade M_R to determine total depth of AC thickness, then subtract remaining AC thickness to determine overlay thickness.
			Rigid	Place unbonded PCC overlay. If grade limits require, mill existing pavement. AC overlay over stripped pavement may be required to stabilize HMA.	Use Table D.22 for thickness determination of an unbonded PCC overlay.
		No	—	Continue to “full-depth fatigue cracking.”	—
Full-depth fatigue cracking	Longitudinal or alligator cracking in wheelpaths	Yes	Flexible	<15% fatigue cracking: patch and repair, moderate thickness AC overlay.	Use Tables D.37–D.39 with 30-ksi base for AC overlay thickness, then subtract existing AC thickness to determine overlay thickness.
				>15% fatigue cracking: pulverize pavement structure full depth followed by a thick AC overlay.	Pulverize and use residual material as untreated base. Apply AC thickness from Tables D.37–D.39 with 50-ksi base.
					Pulverize and treat residual material with emulsion or foamed asphalt, resulting in a treated base. Apply AC thickness from Tables D.37–D.39 with 100-ksi base.
			Rigid	Patch severely cracked areas, place an unbonded PCC overlay. Profile elevation may require milling existing AC pavement.	Use Table D.22 for thickness determination of an unbonded PCC overlay.
		No	—	Continue to “top-down cracking.”	—
Top-down cracking	Longitudinal or alligator cracking in wheelpaths	Yes	Flexible	<15% patch and overlay.	Use Tables D.37–D.39 with 30-ksi base and the subgrade M_R to determine total depth of AC thickness, then subtract the thickness milled out to eliminate the top-down cracking (unless indicated, the assumed depth is 2 in.). Where patching only, subtract existing depth to calculate overlay.
				>15% mill down to bottom of cracking followed by a moderate thickness AC overlay.	
			Rigid	Place an unbonded PCC overlay.	Use Table D.22 for thickness determination of an unbonded PCC overlay.

Note: AC, asphalt concrete; HMA, hot-mix asphalt; PCC, portland cement concrete.

Table C.2. Feasible Renewal Alternatives for Existing JPCP and JRCP Pavements

Distress Category	Specific Distress Description	Distress Present?	Renewal Pavement Type Option	Action	Design Resources
Materials-caused distress	D-cracking with light Severity	Yes	Flexible option for JPCP	Rubblization or crack and seat JPCP followed by a thick AC overlay. For rubblization, apply TTI guidelines (Sebesta and Scullion 2007).	Apply Rule 1.
					Apply Rule 2.
			Flexible option for JRCP	Rubblization or saw, crack, and seat JRCP with a thick overlay. For rubblization, apply TTI guidelines (Sebesta and Scullion 2007).	Apply Rule 1.
					Saw, crack, and seat existing PCC followed by application of AC overlay from Tables D.37–D.39; otherwise, Rule 2 applies.
			Rigid option	Apply 2 inch AC overlay bond breaker followed by an unbonded PCC overlay.	Apply Rule 3.
		No	—	Continue to next level of “D-cracking.”	—
	D-cracking with moderate to high severity	Yes	Flexible option with rubblization if subgrade meets TTI guidelines	Rubblize followed by a thick AC overlay. For rubblization, apply TTI guidelines.	Apply Rule 1.
			Flexible option if does not meet TTI guidelines for rubblization	Do not use the existing pavement; requires all new pavement.	—
			Rigid option	Full-depth patch and apply 2-in. AC overlay bond breaker followed by an unbonded overlay.	Apply Rule 3.
		No	—	Continue to “alkali-silica reactivity.”	—
	Alkali-silica reactivity	Yes	Flexible option	Rubblize followed by thick AC overlay. For rubblization, apply TTI guidelines.	Apply Rule 1.
			Rigid option	Patch plus 2-in. AC bond breaker followed by unbonded PCC overlay.	Apply Rule 3.
		No	—	Continue to “pavement cracking.”	—
Pavement cracking	% multiple cracked panels	Yes	Flexible option for low to moderate multiple cracked panels (1% to 10% of panels)	Rubblization or crack and seat JPCP with a thick AC overlay. For rubblization, apply TTI guidelines (Sebesta and Scullion 2007).	Apply Rule 1.
			Rigid option for low to moderate multiple cracked panels (1% to 10% of panels)	Place a 2-in. AC bond breaker followed by an unbonded PCC overlay.	Apple Rule 3.
			Flexible option for moderate to high multiple cracked panels (>10% of panels)	If subgrade meets or exceeds TTI criteria, apply rubblization followed by a thick AC overlay.	Apply Rule 1.
				If subgrade does not meet TTI criteria, options include crack and seat or do not use existing pavement.	Apply Rule 2.
			Rigid option for moderate to high multiple cracked panels (>10% of panels)	Replace rocking or shattered slabs followed by a 2-in. AC overlay bond breaker followed by an unbonded PCC overlay.	Apply Rule 3.
		No	—	Continue to “joint faulting.”	

(continued on next page)

Table C.2. Feasible Renewal Alternatives for Existing JPCP and JRCP Pavements (continued)

Distress Category	Specific Distress Description	Distress Present?	Renewal Pavement Type Option	Action	Design Resources
Joint faulting	—	Yes	Flexible option for low faulting (< 0.25 inches)	Rubblization or crack and seat JPCP with a thick AC overlay. For rubblization, apply TTI guidelines (Sebesta and Scullion 2007).	Apply Rule 1.
					Apply Rule 2.
				Rubblization or saw, break and seat JRCP with a thick AC overlay. For rubblization, apply TTI guidelines (Sebesta and Scullion 2007).	Apply Rule 1.
					Saw, crack, and seat existing PCC followed by application of AC overlay from Tables D.37–D.39; otherwise, Rule 2 applies.
			Rigid option for low faulting (< 0.25 inches)	Place a 2 inch AC overly followed by an unbonded PCC overlay.	Apply Rule 3.
		Yes	Flexible option for high faulting (> 0.25 inches)	Rubblization or crack and seat JPCP with a thick AC overlay. For rubblization, apply TTI guidelines. (Sebesta and Scullion 2007)	Apply Rule 1.
					Apply Rule 2.
				Rubblization or saw, break and seat JRCP with a thick AC overlay. For rubblization, apply TTI guidelines (Sebesta and Scullion 2007).	Apply Rule 1.
					Saw, crack, and seat existing PCC followed by application of AC overlay from Tables D.37–D.39; otherwise, Rule 2 applies.
			Rigid option for high faulting (> 0.25 inches)	Place a 2-in. AC overlay followed by an unbonded PCC overlay. If joint deflections > 40 mils (0.040 in.), then consider crack and seat JPCP or saw, break, and seat JRCP to stabilize slabs.	Apply Rule 3.
		No	—	Continue to "pumping."	—
Pumping	—	Yes	Flexible	Crack and seat JPCP with a thick AC overlay if the drainage can be improved.	Apply Rule 2.
				Saw, crack, and seat JRCP with a thick AC overlay if the drainage can be improved.	Saw, crack and seat existing PCC followed by application of AC overlay from Tables D.37–D.39; otherwise, Rule 2 applies.
				If drainage cannot be improved, then AC based renewal should not be used.	—
			Rigid	If joint deflections >40 mils (0.040 in.), consider crack and seat followed by a 2-in. AC bond breaker followed by an unbonded PCC overlay. Drainage must be improved.	Apply Rule 3.
		No	—	—	—

Note: AC, asphalt concrete; JPCP, jointed plain concrete pavement; JRCP, jointed reinforced concrete pavement; PCC, portland cement concrete.

Table C.3. Feasible Renewal Alternatives for Existing CRCP Pavements

Distress Category	Specific Distress Description	Distress Present?	Renewal Pavement Type Option	Action	Design Resources
Punchouts	—	Yes	Flexible option with ≤5 punchouts per mile	Repair all punchouts; place thick AC overlay to achieve a longer service life.	Apply AC overlay from Tables D.37–D.39. The selection of the AC thickness is based on a drop-down menu of subgrade moduli equal to 5,000 psi, 10,000 psi, or 20,000 psi. The existing pavement is characterized by one of four possible moduli to select from: 30,000 psi, 50,000 psi, 75,000 psi, or 100,000 psi.
			Rigid option with ≤5 punchouts per mile	Repair major punchouts if slab load support in question. Follow repairs with a 2-in. AC bond breaker followed by an unbonded PCC overlay.	Apply Rule 3.
			Flexible option with >5 punchouts per mile	Rubblization of CRCP with a thick AC overlay. For rubblization, apply TTI guidelines (Sebesta and Scullion 2007).	Apply Rule 1.
			Rigid option with >5 punchouts per mile	Repair major punchouts if slab load support in question. Follow repairs with a 2-in. AC bond breaker followed by an unbonded PCC overlay.	Apply Rule 3.
		No	—	—	—

Note: AC, asphalt concrete; CRCP, continuously reinforced concrete pavement; PCC, portland cement concrete.

Table C.4. Feasible Renewal Alternatives for Existing Composite Pavements

Distress Category	Specific Distress Description	Distress Present?	Renewal Pavement Type Option	Action	Design Resources
Surface course in fair to poor condition	Can be a range of distress types. For the underlying PCC, these are mostly cracking related.	Yes	Flexible option	Remove existing AC surface(s). Apply rubblization if meets TTI criteria. Remove existing AC surface(s). Use crack and seat or saw, crack, and seat.	Apply Rule 1. Following crack and seat or saw, crack, and seat of existing PCC pavement, apply Rule 2.
			Rigid option	Place unbonded PCC overlay. If grade limits require, mill existing AC pavement.	Apply Rule 3.
Surface course in very poor condition	Can be a range of distress types. For the underlying PCC, these can include severe D-cracking and ASR.	Yes	Flexible option	Remove and replace existing pavement structure.	—
			Rigid option	Place unbonded PCC overlay. If grade limits require, mill existing AC pavement.	Apply Rule 3.

Note: AC, asphalt concrete; ASR, alkali-silica reactivity; PCC, portland cement concrete.

APPENDIX D

Development of Rigid and Flexible Renewal Thickness Design Tables

Rigid Renewal Thickness Design Table Development

The rigid pavement "overlay" designs contained in the interactive software and design guidelines were developed by two separate design procedures: AASHTO 93 and the Mechanistic-Empirical Pavement Design Guide (MEPDG) Version 1.1 (September 2009). Initial thicknesses were developed by use of AASHTO 93 as two-layer systems. The R23 team used these layer thicknesses to assemble the initial logic flow for development of the R23 design guidelines. The eventual goal was to model the required portland cement concrete (PCC) thickness as three-layer systems. The MEPDG software was selected for this task because of its versatility and focus on long-lasting pavement design.

Mechanistic-Empirical Pavement Design Guide (MEPDG)

The MEPDG has numerous features and inputs that need to be addressed. The MEPDG has three levels of inputs, and for this assessment, Level 3 was used. Some of the required decisions and inputs are the following:

1. There are three major input types for the MEPDG: traffic, climate, and structure.
2. One pavement type was analyzed via the MEPDG: jointed plain concrete pavement (JPCP), with three distress or performance types: joint faulting, transverse cracking, and international roughness index (IRI). The MEPDG inputs that follow are for JPCP only.
3. General information required to define the analysis period and type of design includes the following:
   a. Design life = 50 years.
   b. Construction month = June.
   c. Traffic opening month = July.
   d. Pavement type = JPCP.
   e. Shoulder condition = No tied shoulder.
4. For climate, data used to interpolate for Baltimore, Maryland, are given in Table D.1.
5. For traffic:
   a. General inputs for MEPDG are shown in Table D.2.
   b. Conversion of default load spectra (which was used to calculate performance for the various slab thicknesses) to equivalent single axle loads (ESALs; required for the R23 design guidelines) involved several steps. The following tables provide information on how this was done. The steps include the following:
      - The overall calculation of ESALs for a design life of 50 years is (ESALs/truck)(% of total truck traffic/vehicle class)(10 vehicle classes)(AADT/2)(365) $(((1 + i^n) - 1)/i)$ = Total ESALs, where i = truck growth rate, and $n = 50$ years.
      - ESALs/truck by vehicle class is the key element for converting load spectra to ESALs. Table D.3 shows a summary of ESALs/truck along with the percentage of total truck traffic (from Table 2.4.9 of NCHRP 2004b).
      - Tables D.4 through D.6 illustrate the needed information for detailed calculations to estimate ESALs/truck. Table D.4 is from NCHRP (2004b) and shows the average number of axles per vehicle. Table D.5 illustrates how default load spectra for Class 4 single axles are converted to ESALs/axle. The value of ESALs/truck is then the sum of ESALs/axle multiplied by the average number of axles per truck. Table D.6 is a summary of ESALs/axle for the various vehicle classes and axle types.
      - Table D.7 illustrates the level of daily truck traffic required to achieve the design ESALs used in the R23 design guidelines.
6. For analysis parameters, performance criteria follow:
   a. The reliability for terminal IRI, transverse cracking, and mean joint faulting = 90%.
   b. For transverse slab cracking (JPCP, maximum allowable over the design period), the range is given as 10% to 45% of the slab (NCHRP 2004a). Use 10%.

Table D.1. Location Information for Climate Data

	Baltimore-Washington International Airport	Ronald Reagan National Airport	Washington Dulles International Airport	York Airport	New Castle County Airport	Hagerstown Regional Airport
Latitude (degrees)	39.1	38.52	38.56	39.55	39.4	39.43
Longitude (degrees)	–76.41	–77.02	–77.27	–76.52	–75.36	–77.44
Elevation (ft)	196	3	309	475	95	737
Distance from given location (mi)	0.0	28.0	44.2	52.7	67.3	67.7

Table D.2. General Inputs

Number of lanes in design direction	2
Percent of trucks in design direction (%)	50
Percent of trucks in design lane (%)	100
Operational speed (mph)	60

Table D.3. Calculation Process for Converting Load Spectra to ESALs

Vehicle Class	ESAL/Truck[a]	Total Truck Traffic[b] (%)
4	0.67	3.3
5	0.30	34.0
6	0.68	11.7
7	1.34	1.6
8	0.69	9.9
9	1.03	36.2
10	1.06	1.0
11	1.69	1.8
12	1.42	0.2
13	2.18	0.3

[a] ESAL/truck based on Level 3 default values from two sources: (1) Table 2.4.11 from NCHRP 2004b, "Suggested Default Values for the Average Number of Single, Tandem, and Tridem Axles Per Truck Class," and (2) ESALs/axle calculated from MEPDG default axle load spectra [such as Tables 2.4.9 (single axles) and 2.4.10 (tandem axles) from NCHRP 2004b]. Refer to Tables D.4 through D.6.
[b] Percentages for total truck traffic are from Table 2.4.4 (NCHRP 2004b) for TTC 9 (intermediate light and single-trailer truck route).

c. For transverse joint faulting (JPCP, upper limit over the design period), the range is given as 0.1 to 0.2 in. (NCHRP 2004a). Used 0.1 and 0.2 in.
d. The smoothness range for terminal IRI is given as 150 to 250 in./mi (NCHRP 2004a). Used 170 in./mi (or 2.7 m/km, which is the FHWA break point from "acceptable" to "not acceptable"). Refer to Table D.8.
   - For initial IRI (as-constructed smoothness), the range is given as 50 to 100 in./mi (NCHRP 2004a). Used 60 in./mi (or about 1.0 m/km).
   - Terminal IRI = 170 in./mi.

Table D.4. Average Number of Single, Tandem, Tridem, and Quad Axles per Truck

Vehicle Classification	Number of Axles per Truck			
	Singles	Tandems	Tridems	Quads
4	1.62	0.39	0	0
5	2.00	0	0	0
6	1.02	0.99	0	0
7	1.00	0.26	0.83	0
8	2.38	0.67	0	0
9	1.13	1.93	0	0
10	1.19	1.09	0.89	0
11	4.29	0.26	0.06	0
12	3.52	1.14	0.06	0
13	2.15	2.13	0.35	0

Note: Based on LTPP data from NCHRP 2004b.

7. For structure and materials:
   a. For PCC/JPCP properties (Layer 1), see Tables D.9 through D.12.
   b. For base properties (Layer 2), refer to Tables D.13 through D.16.
   c. For Layer 3, refer to Tables D.17 and D.18.
   d. Layer 4 is the same as Layer 3, but the thickness is semi-infinite.
   e. All runs were done without tied shoulders.
   f. Values of surface shortwave absorptivity included range between 0 and 1, with 1 implying that all solar energy is absorbed by the pavement surface. Use default = 0.85 [recommended by NCHRP (2004a)]. Ranges provided by FHWA are included in Table D.19.

g. For JPCP design features, input the following:
   - Slab thickness: varies.
   - Permanent curl or warp effective temperature difference is −10°F. [recommended by NCHRP (2004a)].
h. For joint design:
   - For joint spacing, fix as 15 ft.
   - For dowel transverse joints, the dowel diameter is 1.5 in., and dowel spacing should be 12 in.

8. Other considerations:
   a. Consider reliability for performance predictions (Figure D.1).
   b. Figures D.2 and D.3 below show that the application of reliability shifts the predicted performance upward (in this case, an illustration of slab cracking).

Trial Runs

The MEPDG runs are summarized in Tables D.20 and D.21. The runs in Table D.20 used a faulting limit of 0.1 in. Subsequently, an additional faulting level equal to 0.2 in. along with higher cement content was examined due to the extreme slab thickness for weak subgrade (5,000 psi). The results from these additional runs produced the slab thicknesses shown in Table D.21.

Final Rigid Renewal Design Table

The final slab thicknesses selected for use in the R23 design guidelines are shown in the far right column in Table D.22. Additional thicknesses are shown for (1) AASHTO 93 and (2) Washington State Department of Transportation (WSDOT) design thicknesses from their Pavement Policy document. The WSDOT pavement design tables were used because WSDOT had just developed those tables based on extensive MEPDG runs calibrated with detailed performance data from their PMS. Thus, those tables were the best indicator of where other states may be in a couple of years using the MEPDG design procedures. The final slab thicknesses are a composite of all of these inputs.

Table D.5. Example Data for Conversion of Single Axle Load Distribution

Mean Axle Load (lb)	ESAL/Axle[a]	Axle[b] (%)	Mean Axle Load (lb)	ESAL/Axle[a]	Axle[b] (%)
3,000	0.0008	1.80	22,000	2.23	0.66
4,000	0.0023	0.96	23,000	2.66	0.56
5,000	0.006	2.91	24,000	3.16	0.37
6,000	0.0123	3.99	25,000	3.72	0.31
7,000	0.0229	6.80	26,000	4.35	0.18
8,000	0.039	11.45	27,000	5.06	0.18
9,000	0.0625	11.28	28,000	5.85	0.14
10,000	0.095	11.04	29,000	6.74	0.08
11,000	0.139	9.86	30,000	7.72	0.05
12,000	0.198	8.53	31,000	8.80	0.04
13,000	0.272	7.32	32,000	9.99	0.04
14,000	0.366	5.55	33,000	11.3	0.04
15,000	0.482	4.23	34,000	12.7	0.03
16,000	0.624	3.11	35,000	14.3	0.02
17,000	0.80	2.54	36,000	16.0	0.02
18,000	1.00	1.98	37,000	17.8	0.01
19,000	1.24	1.53	38,000	19.9	0.01
20,000	1.52	1.19	39,000	22.0	0.01
21,000	1.85	1.16	40,000	24.4	0.01
				Σ(ESAL/Axle)(Axle%)[c]	

Note: Default values for ESAL/Axle for Vehicle Class 4.
[a] ESAL/Axle approximated with (Mean Axle Load/18,000).
[b] Axle percentages from Table 2.4.9 of NCHRP 2004b.
[c] Σ [(ESAL/Axle)(Axle Percentage)] = 0.35 ESAL/Class 4 Axle.

Table D.6. ESAL/Axle for All Vehicle Classes from Default Load Spectra

Vehicle Classification	Single Axle	Tandem Axle	Tridem Axle
4	0.35[a]	0.27	0
5	0.15	0.16	0
6	0.29	0.39	0
7	0.66	0.80	0.58
8	0.25	0.15	0
9	0.20	0.42	0
10	0.21	0.56	0.22
11	0.37	0.32	0.10
12	0.29	0.33	0.34
13	0.29	0.62	0.61

[a] See example calculation in Table D.5.

Table D.7. Daily Trucks to Achieve Design ESALs Along with Level 3 Default Load Spectra

Average Annual Daily Trucks to Achieve Design ESAL Level with Default Load Spectra (Two Way)	ESALs (millions)
500	10
1,250	25
2,500	50
5,000	100
10,000	200

Table D.8. FHWA Smoothness Criteria

FHWA Ride Quality Terms	All Functional Classifications	
	IRI [m/km (in./mi)]	PSR Rating
Good	<1.5 (95)	Good
Acceptable	≤2.7 (170)	Acceptable
Not acceptable	>2.7 (170)	Not acceptable

Table D.9. General Properties

General Properties	
PCC material	JPCP
Layer thickness (in.)	Varied
Unit weight (pcf)	150
Poisson's ratio	0.2

Table D.10. Thermal Properties

Thermal Properties	
Coefficient of thermal expansion (per °F × 10^{-6})	**5.5**
Thermal conductivity (Btu/h-ft-°F)	**1.25[a]**
Heat capacity (Btu/lb-°F)	**0.28[a]**

[a] See NCHRP 2004a.

Table D.11. Mixture Properties

Mixture Properties	
Cement type	Type II
Cementitious material content (lb/yd^3)	500 and 560[a]
Water-to-cement ratio	0.42
Aggregate type	Limestone
PCC zero-stress temperature (°F)	Derived
Ultimate shrinkage at 40% RH (microstrain)	Derived
Reversible shrinkage (% of ultimate shrinkage)	50
Time to develop 50% of ultimate shrinkage (days)	35
Curing method	Curing compound

[a] A range of cementitious contents could be used. For example, Minnesota specifies a minimum cement content of 530 lb/yd^3, Missouri 560 lb/yd^3, and WSDOT 564 lb/yd^3 (see R23 Guide, Chapter 4, Specifications). FHWA (2007) notes that Germany and the Netherlands specify a minimum content of 540 lb/yd^3. Austria uses 540 lb/yd^3 for fix-form paving and 594 lb/yd^3 for slip-form paving. Thus, 500 lb/yd^3 represents a lower bound and 560 lb/yd^3 is the middle of the range.

Table D.12. Strength Properties

Strength Properties	
Input level	Level 3
28-day PCC modulus of rupture (psi)	690
28-day PCC compressive strength (psi)	NA

Table D.13. AC General Properties

Layer 2: Asphalt Concrete	
Material type	Asphalt concrete
General reference temperature (°F)	70
Layer thickness (in.)	10
Poisson's ratio	0.35 (user entered)
Erodibility index	Erosion resistant (Class 3)
PCC-base interface	Full friction contact
Loss of full friction (age in months)	361

Table D.14. AC Volumetric Properties

HMA Volumetric Properties as Built	
Effective binder content (%)	11.6
Air voids (%)	7
Total unit weight (pcf)	150

Table D.15. AC Mixture Properties

Asphalt Mix	
Cumulative % retained, ¾-in. sieve	0
Cumulative % retained, ⅜-in. sieve	23
Cumulative % retained, #4 sieve	40
% passing, #200 sieve	6

Table D.16. AC Binder Properties

Asphalt Binder	
Option	Superpave binder grading
A	9.4610 (correlated)
VTS	–3.1340 (correlated)

Table D.17. Subgrade Type

Layer 3: A-6	
Unbound material	A-6
Thickness (in.)	12

Table D.18. Subgrade Strength Properties

Strength Properties	
Input level	Level 3
Analysis type	Representative value (user input modulus)
Poisson's ratio	0.35
Coefficient of lateral pressure, K_o	0.5
Modulus (input) (psi)	5000
Moisture content (%)	–9999

Table D.19. Surface Properties

Material	Surface Shortwave Absorptivity
Weathered asphalt (gray)	0.80–0.90
Fresh asphalt (black)	0.90–0.98
Aged PCC layer	0.70–0.90

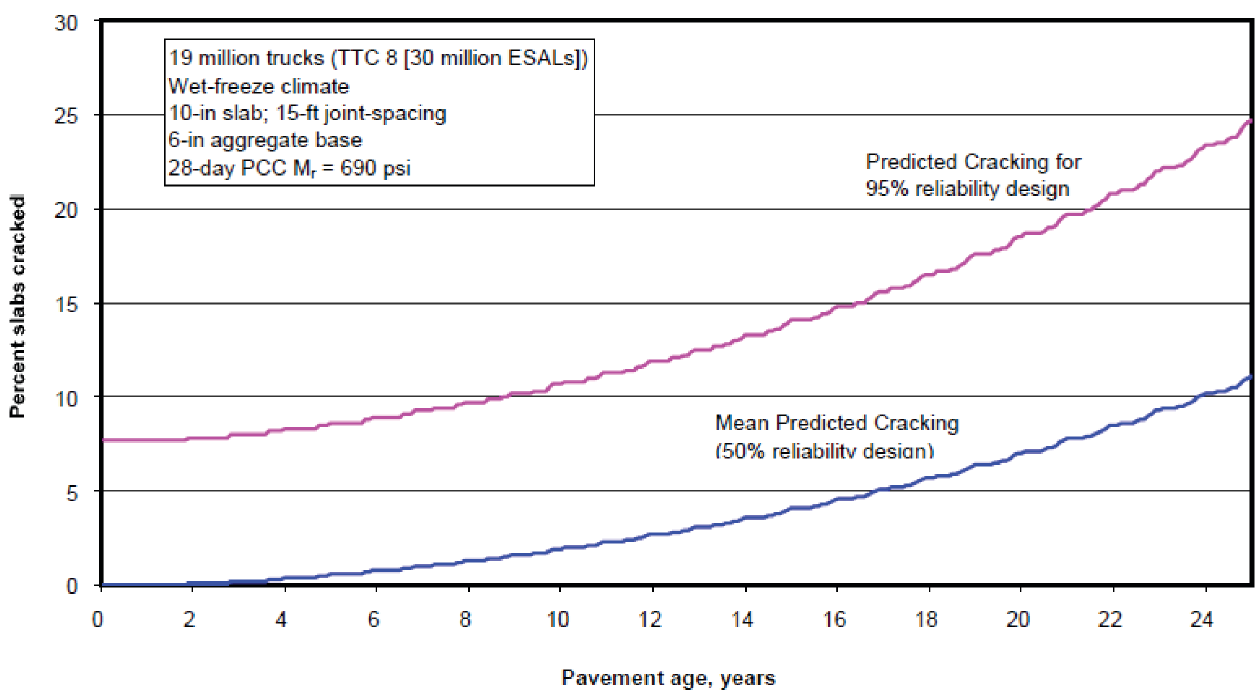
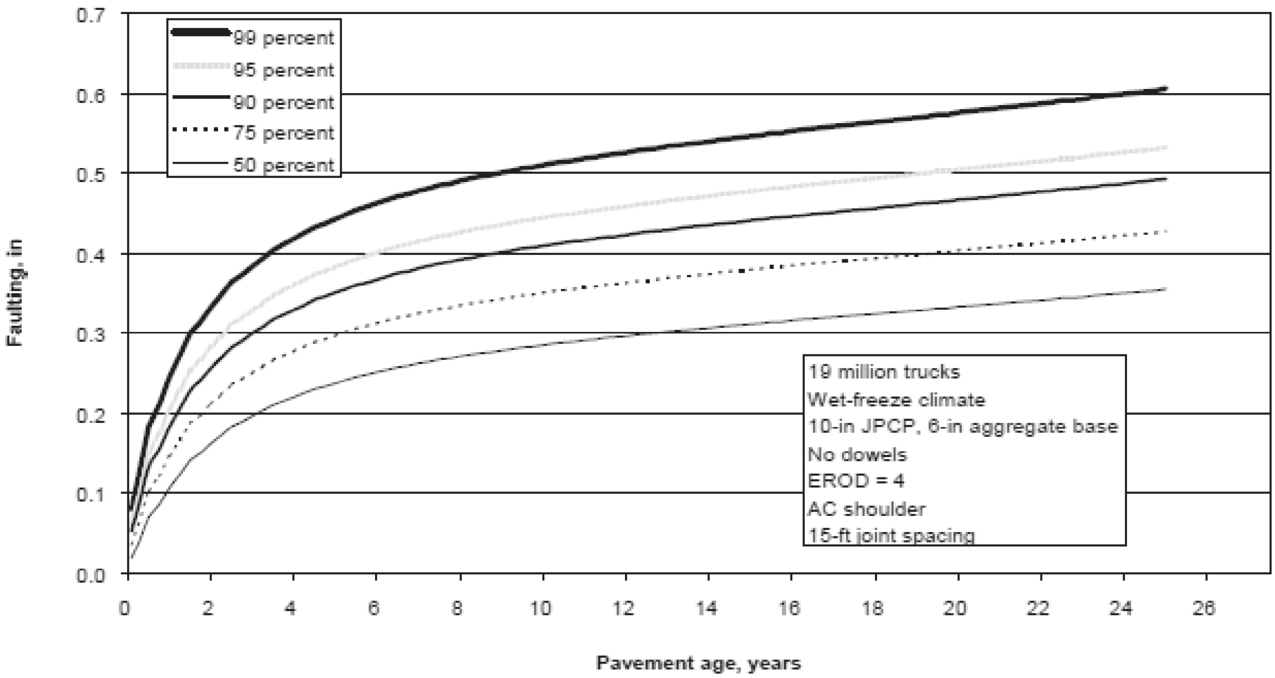
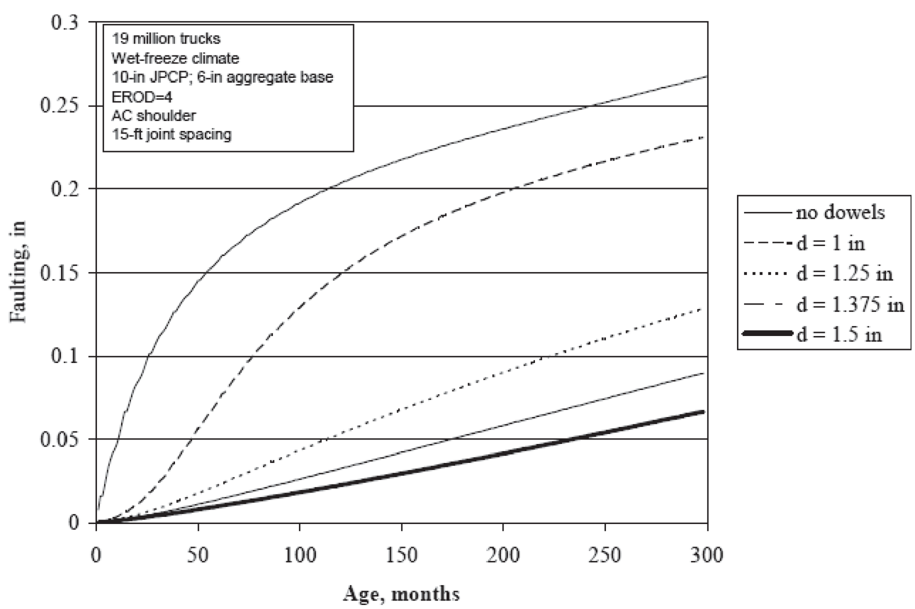


Figure D.1. Slab cracking.



Source: NCHRP 2004a.

Figure D.2. Joint faulting for no-dowel condition.



Source: NCHRP 2004a.

Figure D.3. Joint faulting ranging from a no-dowel condition up to dowel diameter of 1.5 in.

Table D.20. Initial MEPDG Runs with Limiting Joint Faulting Set = 0.1 in. and Cement Content = 500 lb/yd³

		Subgrade Modulus											
		5,000 psi				10,000 psi				20,000 psi			
Traffic MESAL/ AADTT	Performance Criteria	PCC Depth	DP	RP	A	PCC Depth	DP	RP	A	PCC Depth	DP	RP	A
10/500	Terminal IRI	8.25	82.6	99.88	Pass	7.75	80	99.94	Pass	7.75	80.2	99.94	Pass
	Transverse cracking		2.1	92.12	Pass		0	99.96	Pass		1.7	93.79	Pass
	Mean joint faulting		0.017	99.95	Pass		0.016	99.97	Pass		0.013	99.99	Pass
25/1250	Terminal IRI	9.00	89.4	99.45	Pass	8.75	88.2	99.56	Pass	8.50	87.7	99.61	Pass
	Transverse cracking		1.2	95.89	Pass		1.6	94.45	Pass		2.4	91.14	Pass
	Mean joint faulting		0.033	98.87	Pass		0.03	99.3	Pass		0.027	99.55	Pass
50/2500	Terminal IRI	9.25	100.3	97.46	Pass	9.25	97.3	98.22	Pass	9.25	96.1	98.48	Pass
	Transverse cracking		2	92.69	Pass		1.8	93.67	Pass		2.5	90.5	Pass
	Mean joint faulting		0.053	91.94	Pass		0.047	94.75	Pass		0.044	96.11	Pass
100/5000	Terminal IRI	12.25	99.1	97.77	Pass	12.00	97.9	98.06	Pass	11.50	99.2	97.73	Pass
	Transverse cracking		0	99.96	Pass		0	99.79	Pass		0.2	99.24	Pass
	Mean joint faulting		0.056	90.03	Pass		0.053	91.6	Pass		0.055	90.4	Pass
200/10000	Terminal IRI	19.25[a]	108.4	94.53	Pass	15.5[a]	97.7	98.07	Pass	15[a]	98.2	97.95	Pass
	Transverse cracking		0	99.96	Pass		0	99.96	Pass		0	99.96	Pass
	Mean joint faulting		0.076	73.59	Fail		0.055	90.65	Pass		0.056	90.22	Pass

[a] Mean joint faulting fails at 19.5 in., which is likely caused by load transfer (dowel) failure.

Note: Limiting values: (1) terminal IRI = 170 in./mi, (2) transverse cracking = 10%, and (3) mean joint faulting = 0.1 in. A, acceptable; AADTT, average annual daily truck traffic; DP, damage prediction; RP, reliability prediction.

Table D.21. Supplemental MEPDG Runs with Limiting Joint Faulting = 0.2 and Cement Content = 560 lb/yd³

			Subgrade Modulus											
			5,000 psi				10,000 psi				20,000 psi			
Traffic MESAL/ AADTT	Performance Criteria	DT	PCC Depth	DP	RP	A	PCC Depth	DP	RP	A	PCC Depth	DP	RP	A
200/10000 PCC% = 560 lb/yd³	Terminal IRI	170	11.75	116.9	90.30	Pass	11.25	117.1	90.19	Pass	11.25	116.9	90.30	Pass
	Transverse cracking	10		0.1	99.72	Pass		0.5	98.26	Pass		1.5	94.93	Pass
	Mean joint faulting	0.2		0.089	99.72	Pass		0.089	99.74	Pass		0.087	99.79	Pass

Note: A, acceptable; AADTT, average annual daily truck traffic; DP, damage prediction; DT, distress target (limiting value); RP, reliability prediction.

Table D.22. AASHTO 93, WSDOT, MEPDG, and SHRP 2 R23 Rigid Design Results

ESALs (millions)	AASHTO 93 for k = 500 pci	Design Thicknesses from WSDOT Pavement Policy	Thickness Range for MEPDG for M_R = 5–10 ksi[a]	PCC Slab Thickness for R23 Study (in.)
≤10	10.0	9.0	7.75–8.25	9.0
10–25	11.5	10.0	8.75–9.0	10.0
25–50	12.5	11.0	9.25	11.0
50–100	14.0	12.0	11.5–12.25	12.0
100–200	15.5	13.0	11.25–15.5	13.0

[a] For ESALs = 200 million, results generated using both levels of PCC cement content (500 and 560 lb/yd^3). Results from all other ESAL levels generated using one cement content (500 lb/yd^3).

Flexible Renewal Thickness Design Table Development

The flexible pavement "overlay" designs contained in the interactive software and design guides were developed by two separate design procedures: AASHTO 93 and PerRoad 3.5 (Asphalt Pavement Alliance). The decision was made to exclusively apply PerRoad due to its improved versatility. The software was obtained from www.eng.auburn.edu/users/timmdav/Software.html. The newest version is PerRoad 3.5, dated April 2010.

Determine HMA Thicknesses

The pavement structures, as modeled, contained three layers, which were the hot-mix asphalt (HMA) overlay over an existing processed layer (pulverized HMA, rubblized PCC, or crack and seat PCC), over subgrade.

The layer moduli for the processed layers were of special interest. A range of moduli was determined and summarized in Table D.23.

The ranges associated with each of these moduli are rather wide and were considered in setting up the PerRoad runs. To achieve a conservative set of guidelines, the final selection of processed layer moduli were somewhat lower. The four moduli selected were (1) 30 ksi, (2) 50 ksi, (3) 75 ksi, and (4) 100 ksi. These moduli cover the lower end of the expected field moduli for the processed layers.

Three subgrade moduli were selected: (1) 5 ksi, (2) 10 ksi, and (3) 20 ksi. These moduli span the majority of subgrades encountered in the field.

The overall goal is to determine the HMA thickness that will achieve a target value of either ≥ 10 years or ≥ 50 years for $D = 0.1$ for the given inputs. In PerRoad, $D = 0.1$ (in lieu of the commonly used $D = 1.0$ for a damage function) is recommended by the developer of the software, David Timm. It reflects a conservative view for assessing high-volume, long-life pavement designs. The 10-year criterion was a way for the study team to match a shorter span of time with $D = 0.1$. Additionally:

1. One level of limiting horizontal tensile strain (fatigue endurance limit) at the bottom of the HMA was used: 100 $\mu\varepsilon$.
2. One processed layer thickness was used: 10 in. Earlier work had applied two processed layer thicknesses, but the thinner of these was discarded as unrealistic.
3. The climate (temperatures) that directly influence the stiffness of the HMA were initially based on five cities:
   a. Minneapolis, Minnesota (used in the example runs below with PG 64-34).
   b. San Francisco, California.
   c. Phoenix, Arizona.
   d. Dallas, Texas.
   e. Baltimore, Maryland.

The results from the initial design runs indicated that the thickness values for San Francisco and Dallas fell within the range of values for the other three cities and did not affect the averages significantly. For that reason, San Francisco and Dallas were eliminated, leaving Minneapolis, Phoenix, and Baltimore.

Seasonal temperature characterization was required for each location, as shown in Table D.24.

Trial Runs

With a criterion for obtaining HMA thicknesses that results in a target value of ≥ 50 years for $D = 0.1$, selected cases were run. Since $D = 0.1$ seemed extremely conservative, it was decided to try HMA thicknesses that result in a value of ≥ 10 years for $D = 0.1$ as well. Note that ≥ 10 years for $D = 0.1$ is about the same as ≥ 50 years for $D = 0.5$, but years were easier to change in the program than D values. Note that a damage ratio of $D = 1.0$ would predict full-depth fatigue cracking in 50 years. All PerRoad runs are shown in Tables D.25 through D.36.

Final Design Tables

The final flexible renewal thickness design tables were developed based on the numerous runs made with PerRoads, the MEPDG, and AASHTO 93 design guidelines. Further refinements were made in consultations with state highway agency personnel and industry representatives. Tables D.37 through D.39 provide details on the final thickness design recommendations.

References

Federal Highway Administration. 2006. Geotechnical Inputs for Pavement Design: Thermo-Hydraulic Properties (Section 5.5). *Geotechnical Aspects of Pavements: Reference Manual.* Report FHWA NHI-05-037. FHWA, U.S. Department of Transportation. www.fhwa.dot.gov/engineering/geotech/pubs/05037/05d.cfm.

Federal Highway Administration. 2007. *Long-Life Concrete Pavements in Europe and Canada.* Report FHWA-PL-07-027. FHWA, U.S. Department of Transportation.

National Cooperative Highway Research Program (NCHRP). 2004a. Part 3: Design Analysis. Chapter 4: Design of New and Reconstructed Rigid Pavements. *Guide for Mechanistic-Empirical Design of New and Rehabilitated Pavement Structures.* NCHRP Project 1-37A. TRB, National Research Council, Washington, D.C.

National Cooperative Highway Research Program (NCHRP). 2004b. Part 2: Design Inputs. Chapter 4: Traffic. *Guide for Mechanistic-Empirical Design of New and Rehabilitated Pavement Structures.* NCHRP Project 1-37A. TRB, National Research Council, Washington, D.C.

Pearce, E. A., and C. G. Smith. 1990. *The World Weather Guide,* 2nd ed. Hutchinson Publications, London.

Table D.23. Layer Moduli Properties

Material	Description	Minimum Modulus (psi)	Maximum Modulus (psi)	Typical Modulus (psi)
AC	Asphalt concrete	50,000	4,000,000	
Cracked AC	Cracked asphalt concrete	50,000	500,000	
Pulverized HMA				40,000
PCC	Portland cement concrete	2,000,000	7,000,000	4,000,000
Rubblized PCCP	Rubblized concrete	40,000	700,000	150,000
Crack and seat PCCP	Crack and seated concrete	200,000	800,000	200,000
Break and seat PCCP	Break and seated concrete	250,000	2,000,000	
Granular base	Granular base	5,000	50,000	
Soil	Soil	3,000	40,000	
Rock	Bedrock	500,000	1,000,000	
Other	User defined	50	10,000,000	

Table D.24. Seasonal Properties

City	Overall Mean Temperature	Seasonal Duration (months and weeks) and Temperature		
Minneapolis	45°F	Winter Nov., Dec., Jan., Feb.	17 weeks	21°F
		Spring March, April, May	13 weeks	45°F
		Summer June, July, Aug.	13 weeks	70°F
		Fall Sept., Oct.	9 weeks	56°F
Phoenix	70°F	Winter Dec., Jan., Feb.	13 weeks	54°F
		Spring March, April, May	13 weeks	68°F
		Summer June, July, Aug., Sept.	17 weeks	87°F
		Fall Oct., Nov.	9 weeks	66°F
Baltimore	56°F	Winter Dec., Jan., Feb.	13 weeks	35°F
		Spring March, April, May	13 weeks	54°F
		Summer June, July, Aug., Sept.	17 weeks	74°F
		Fall Oct., Nov.	9 weeks	53°F

Sources: Pearce and Smith 1990; www.climatestations.com.

Table D.25. Summary of PerRoad Solutions for Subgrade = 5 ksi, Processed Existing Pavement = 30 ksi

ESALs (millions)	PerRoad Minneapolis, 10 years, *D* = 0.1	PerRoad Phoenix, 10 years, *D* = 0.1	PerRoad Baltimore, 10 years, *D* = 0.1	PerRoad Baltimore, 50 years, *D* = 0.1	R23 Selected Thickness
≤10	10.5	12	10	12	10
10–25	12.5	13.5	11	12.5	11
25–50	13	14.5	11.5	12.5	12
50–100	13.5	15	12	13	13
100–200	14	15.5	12.5	13	14

Table D.26. Summary of PerRoad Solutions for Subgrade = 10 ksi, Processed Existing Pavement = 30 ksi

ESALs (millions)	PerRoad Minneapolis, 10 years, *D* = 0.1	PerRoad Phoenix, 10 years, *D* = 0.1	PerRoad Baltimore, 10 years, *D* = 0.1	PerRoad Baltimore, 50 years, *D* = 0.1	R23 Selected Thickness
≤10	10	11.5	9.5	11	10
10–25	11.5	13	10.5	11.5	11
25–50	12	13.5	11	12	12
50–100	12.5	14	11.5	12	12
100–200	13	14.5	11.5	12.5	13

Table D.27. Summary of PerRoad Solutions for Subgrade = 20 ksi, Processed Existing Pavement = 30 ksi

ESALs (millions)	PerRoad Minneapolis, 10 years, *D* = 0.1	PerRoad Phoenix, 10 years, *D* = 0.1	PerRoad Baltimore, 10 years, *D* = 0.1	PerRoad Baltimore, 50 years, *D* = 0.1	R23 Selected Thickness
≤10	9.5	11	9	10.5	9.5
10–25	11	12	10	11	10
25–50	11.5	13	10.5	11	11
50–100	12	13.5	10.5	11.5	11.5
100–200	12.5	13.5	11	11.5	12

Table D.28. Summary of PerRoad Solutions for Subgrade = 5 ksi, Processed Existing Pavement = 50 ksi

ESALs (millions)	PerRoad Minneapolis, 10 years, *D* = 0.1	PerRoad Phoenix, 10 years, *D* = 0.1	PerRoad Baltimore, 10 years, *D* = 0.1	PerRoad Baltimore, 50 years, *D* = 0.1	R23 Selected Thickness
≤10	9	10	8.5	10	9
10–25	10.5	11.5	9.5	10.5	10
25–50	11	12	10	11	11
50–100	11.5	12.5	10.5	11	11.5
100–200	12	13	10.5	11.5	12

Table D.29. Summary of PerRoad Solutions for Subgrade = 10 ksi, Processed Existing Pavement = 50 ksi

ESALs (millions)	PerRoad Minneapolis, 10 years, *D* = 0.1	PerRoad Phoenix, 10 years, *D* = 0.1	PerRoad Baltimore, 10 years, *D* = 0.1	PerRoad Baltimore, 50 years, *D* = 0.1	R23 Selected Thickness
≤10	8.5	9.5	7.5	9.5	8
10–25	9.5	10.5	9	10	9
25–50	10	11.5	9	10	9.5
50–100	10.5	12	9.5	10.5	10
100–200	11	12	10	10.5	11

Table D.30. Summary of PerRoad Solutions for Subgrade = 20 ksi, Processed Existing Pavement = 50 ksi

ESALs (millions)	PerRoad Minneapolis, 10 years, *D* = 0.1	PerRoad Phoenix, 10 years, *D* = 0.1	PerRoad Baltimore, 10 years, *D* = 0.1	PerRoad Baltimore, 50 years, *D* = 0.1	R23 Selected Thickness
≤10	8	9	7	8.5	7.5
10–25	9	10	8.5	9	8.5
25–50	9.5	10.5	8.5	9	9
50–100	10	11	9	9.5	9.5
100–200	10.5	11.5	9	9.5	10

Table D.31. Summary of PerRoad Solutions for Subgrade = 5 ksi, Processed Existing Pavement = 75 ksi

ESALs (millions)	PerRoad Minneapolis, 10 years, *D* = 0.1	PerRoad Phoenix, 10 years, *D* = 0.1	PerRoad Baltimore, 10 years, *D* = 0.1	PerRoad Baltimore, 50 years, *D* = 0.1	R23 Selected Thickness
≤10	7	8	7	8.5	7.5
10–25	8.5	9	8	8.5	8.5
25–50	9	9.5	8.5	9	9
50–100	9.5	10	8.5	9	9.5
100–200	10	10.5	9	9.5	10

Table D.32. Summary of PerRoad Solutions for Subgrade = 10 ksi, Processed Existing Pavement = 75 ksi

ESALs (millions)	PerRoad Minneapolis, 10 years, *D* = 0.1	PerRoad Phoenix, 10 years, *D* = 0.1	PerRoad Baltimore, 10 years, *D* = 0.1	PerRoad Baltimore, 50 years, *D* = 0.1	R23 Selected Thickness
≤10	6.5	7.5	6.5	8	7
10–25	8	8.5	7.5	8	8
25–50	8.5	9	7.5	8.5	8.5
50–100	8.5	9.5	8	8.5	8.5
100–200	9	9.5	8	8.5	9

Table D.33. Summary of PerRoad Solutions for Subgrade = 20 ksi, Processed Existing Pavement = 75 ksi

ESALs (millions)	PerRoad Minneapolis, 10 years, *D* = 0.1	PerRoad Phoenix, 10 years, *D* = 0.1	PerRoad Baltimore, 10 years, *D* = 0.1	PerRoad Baltimore, 50 years, *D* = 0.1	R23 Selected Thickness
≤10	6.5	7	6	7.5	6.5
10–25	7.5	8	7	7.5	7
25–50	8	8.5	7.5	8	7.5
50–100	8	9	7.5	8	8
100–200	8.5	9	8	8	8.5

Table D.34. Summary of PerRoad Solutions for Subgrade = 5 ksi, Processed Existing Pavement = 100 ksi

ESALs (millions)	PerRoad Minneapolis, 10 years, *D* = 0.1	PerRoad Phoenix, 10 years, *D* = 0.1	PerRoad Baltimore, 10 years, *D* = 0.1	PerRoad Baltimore, 50 years, *D* = 0.1	R23 Selected Thickness
≤ 10	5.5	6	5.5	7	6
10–25	6.5	7	6.5	7	6.5
25–50	7	7.5	7	7	7
50–100	7.5	7.5	7	7.5	7.5
100–200	7.5	8	7	7.5	7.5

Table D.35. Summary of PerRoad Solutions for Subgrade = 10 ksi, Processed Existing Pavement = 100 ksi

ESALs (millions)	PerRoad Minneapolis, 10 years, *D* = 0.1	PerRoad Phoenix, 10 years, *D* = 0.1	PerRoad Baltimore, 10 years, *D* = 0.1	PerRoad Baltimore, 50 years, *D* = 0.1	R23 Selected Thickness
≤10	5.5	6	5	6.5	6
10–25	6.5	6.5	6	6.5	6.5
25–50	6.5	7	6.5	7	7
50–100	7	7.5	6.5	7	7
100–200	7	7.5	7	7	7

Table D.36. Summary of PerRoad Solutions for Subgrade = 20 ksi, Processed Existing Pavement = 100 ksi

ESALs (millions)	PerRoad Minneapolis, 10 years, *D* = 0.1	PerRoad Phoenix, 10 years, *D* = 0.1	PerRoad Baltimore, 10 years, *D* = 0.1	PerRoad Baltimore, 50 years, *D* = 0.1	R23 Selected Thickness
≤10	5	6	5	6	5.5
10–25	6	6.5	6	6.5	6
25–50	6.5	7	6	6.5	6.5
50–100	6.5	7	6.5	6.5	6.5
100–200	7	7.5	6.5	7	7

Table D.37. Final Flexible Renewal Thickness Design Table for Flexible Designs for Subgrade M_R = 5,000 psi

ESALs (millions)	Existing Pavement or Base Modulus			
	30,000 psi	50,000 psi	75,000 psi	100,000 psi
≤10	10.0	9.0	8.0	6.0
10–25	11.0	10.0	8.5	6.5
25–50	12.0	11.0	9.0	7.0
50–100	13.0	11.5	9.5	7.5
100–200	14.0	12.0	10.0	7.5

Table D.38. Final Flexible Renewal Thickness Design Table for Flexible Designs for Subgrade M_R = 10,000 psi

ESALs (millions)	Existing Pavement or Base Modulus			
	30,000 psi	50,000 psi	75,000 psi	100,000 psi
≤10	10.0	8.0	7.0	6.0
10–25	11.0	9.0	8.0	6.5
25–50	12.0	9.5	8.5	7.0
50–100	12.0	10.0	8.5	7.0
100–200	13.0	11.0	9.0	7.0

Table D.39. Final Flexible Renewal Thickness Design Table for Flexible Designs for Subgrade M_R = 20,000 psi

ESALs (millions)	Existing Pavement or Base Modulus			
	30,000 psi	50,000 psi	75,000 psi	100,000 psi
≤10	9.5	7.5	6.5	5.5
10–25	10.0	8.5	7.0	6.0
25–50	11.0	9.0	7.5	6.5
50–100	11.5	9.5	8.0	6.5
100–200	12.0	10.0	8.5	7.0

Related SHRP 2 Research

Geotechnical Solutions for Soil Improvement, Rapid Embankment Construction, and Stabilization of the Pavement Working Platform (R02)

Precast Concrete Pavement Technology (R05)

Using Both Infrared and High-Speed Ground Penetrating Radar for Uniformity Measurements on New HMA Layers (R06C)

Nondestructive Testing to Identify Delaminations Between HMA Layers (R06D)

Assessment of Continuous Pavement Deflection Measuring Technologies (R06F)

Composite Pavement Systems (R21)

Preservation Approaches for High-Traffic-Volume Roadways (R26)