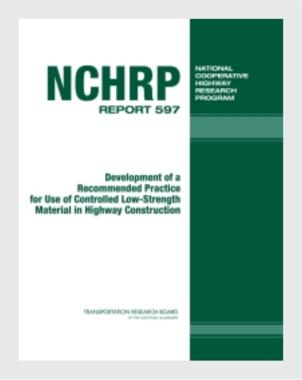

Development of a Recommended Practice for Use of Controlled Low-Strength Material in Highway Construction

DETAILS

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NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

NCHRP REPORT 597

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TRANSPORTATION RESEARCH BOARD

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NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

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

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

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FOREWORD

By Edward T. Harrigan
Staff Officer
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This report summarizes the results of a project to evaluate the use of controlled low-strength material (CLSM) in highway construction applications, in particular, as backfill, utility bedding, and void fill and in bridge approaches. A key product presented herein is a recommended practice for the use of CLSM that was validated through a series of full-scale field experiments. The report will be of particular interest to materials and construction engineers in state highway agencies and industry.

CLSM is a highly flowable material typically composed of water, cement, fine aggregates, and, possibly, fly ash or other by-product materials. CLSM is used in a wide range of highway construction applications where its ability to flow into and fill voids without the need for compaction provides significant benefits over the use of compacted fill.

As the use of CLSM has evolved, so has the need for well-founded methods and specifications for the design of CLSM and its control during placement as a backfill envelope or fill material in specific highway applications. Ideally, these methods and specifications will be based on achieving desired performance characteristics rather than merely producing a material satisfying a recipe-type specification. Thus, development of these design and construction methods and specifications presupposes a thorough understanding and knowledge of how (1) the characteristics of CLSM constituents are related to composite properties that control field performance and (2) key material properties may be monitored in the field.

Under NCHRP Project 24-12(01), "Controlled Low-Strength Material for Backfill, Utility Bedding, Void Fill, and Bridge Approaches," the University of Texas—Austin and its major subcontractor, Texas A&M University, were assigned the tasks of (1) defining the properties of CLSM necessary for its satisfactory use as backfill, utility bedding, and void fill, and in bridge approaches; (2) developing, for these applications, test methods and specification criteria for the performance-related properties of CLSM, including its corrosion potential and possible environmental impact; (3) identifying how the properties of its constituent materials influence the performance of CLSM; (4) developing field methods to monitor in-place properties of CLSM for construction acceptance; and (5) preparing design criteria and construction guidelines for CLSM that take advantage of its properties for backfill, utility bedding, void fill, and bridge approaches.

The research team designed and conducted a major program of laboratory and field experiments to accomplish these tasks. The results of this experimental program demonstrated that CLSM is an effective, innovative material providing excellent short- and long-term performance in all applications of interest. As with any highway construction material, CLSM must be used in conjunction with a good quality acceptance program and with an awareness of its unique properties in order to avoid improper usage.

The research also provided guidance on potential problems with the use of CLSM and precautions to avoid them. For example, excessive long-term strength gain of CLSM can lead to difficulties in its future excavation. Excessive strength gain was most commonly observed when fly ash was used as a CLSM component, especially in hot weather. Another issue of concern was the potential for corrosion of metallic pipe in CLSM. In general, embedding pipe in CLSM was found to reduce the potential for its corrosion due to the reduced permeability of CLSM compared with compacted fill as well as beneficial changes in pH and resistivity of pore solutions in the CLSM microstructure.

This report presents the full text of the contractor's final report of the project and three of the five appendices, which present the test methods (Appendix B), specifications (Appendix C), and practice (Appendix D) recommended for implementation. The corrosion study (Appendix A) and implementation plan (Appendix E) are available as *NCHRP Web-Only Document 116* on the TRB website (www.trb.org/news/blurb_detail.asp?id=8714).

CONTENTS

SUMMARY

Development of a Recommended Practice for Use of Controlled Low-Strength Material in Highway Construction

This report summarizes the results of a study on the use of controlled low-strength material (CLSM) in backfill, utility bedding, void fill, and bridge approach applications. CLSM, used in lieu of compacted fill in these applications, is a highly flowable material typically composed of water, cement, fine aggregates, and often times, fly ash or other by-product materials.

This study, which included substantial laboratory and field components, demonstrated that CLSM is an effective and innovative material that can be used in each of the key target applications, with good short- and long-term performance. CLSM, however, must be used in conjunction with a good quality control and quality assurance plan, and users must be aware of the unique properties of the material to avoid improper usage. This study highlighted some of these potential issues of concern and this report provides guidance on how to recognize potential problems and take precautions to avoid them.

One area that was evaluated in detail was the issue of excessive long-term strength gain, which can lead to difficulties in future excavation. Through the laboratory and field components, the parameters that impact long-term strength gain were identified, including the effects of materials, mixture proportions, and climatic conditions. Long-term strength gain and potential problems with excavatability were most commonly observed when using fly ash, especially in hot-weather applications. By recognizing that these factors have a major impact on excavatability, users can take the necessary precautions to avoid problems, such as performing more long-term strength testing and/or subjecting test specimens to elevated temperatures during curing.

Significant research was performed on the corrosion of metallic pipe materials in CLSM. In general, CLSM was found to be beneficial in reducing corrosion (compared to typical compacted fill) when pipes are completely embedded in CLSM. The reduced permeability of CLSM can reduce the ingress of chlorides, and the microstructure of CLSM can improve corrosion resistance through changes in the pH and resistivity of the pore solution. However, a potential for corrosion exists when pipes are embedded in both CLSM and surrounding soil or conventional fill, thereby setting up a galvanic cell that can increase corrosion activity. This situation is similar in nature to metals embedded in dissimilar soils, and similar precautions can be taken to ensure the desired service life.

A hallmark of CLSM technology is the ability to safely and effectively utilize a range of by-product and waste materials. The by-product materials tested in this study were found to be non-toxic. However, a protocol was developed to evaluate other by-product materials that might be more of a concern with regard to leaching and environmental impact. This approach involves the testing of total heavy metals, possibly followed by the toxicity characteristic leaching procedure (TCLP) (if the total heavy metals are above certain threshold values), and possibly followed by leachate testing from CLSM containing the subject material (if the TCLP values exceed certain thresholds).

Based on the findings of the laboratory component of this project, test methods, specifications, and guidelines were developed and later validated in the field testing component. Six field tests were performed throughout the United States that aimed to validate the tests, specifications, and guidelines developed under this project and to fill in the gaps in understanding that could only be addressed through field applications. The overall findings of these field tests confirmed the above products of the research and demonstrated the benefits of using CLSM in backfill, utility bedding, void fill and bridge approach applications. Some of the field tests will require long-term follow-ups, especially those involving corrosion of metals in CLSM, owing to the long-term nature of corrosion.

The main deliverables emanating from this project are contained in the appendixes, including recommended test methods, recommended specifications, recommended practices, and an implementation plan to push the key findings and deliverables into state highway practice.

CHAPTER 1

Introduction and Scope

Introduction

CLSM is a relatively new technology whose use has grown in recent years. CLSM, often referred to as flowable fill, is a highly flowable material typically composed of water, cement, fine aggregates, and, often times, fly ash. Other byproduct materials—such as foundry sand and bottom ash—and chemical admixtures—including air-entraining agents, foaming agents, and accelerators—also have been used successfully in CLSM.

CLSM is typically specified and used as an alternative to compacted fill in various applications, especially for backfill, utility bedding, void fill, and bridge approaches. Backfill includes applications such as backfilling walls (e.g., retaining walls) or trenches. Utility bedding applications involve the use of CLSM as a bedding material for pipe, electrical, and other types of utilities and conduits. Void-filling applications include the filling of sewers, tunnel shafts, basements, and other underground structures. CLSM is also used in bridge approaches, either as a subbase for the bridge approach slab or as backfill against wingwalls or other elements.

There are various inherent advantages of using CLSM instead of compacted fill in these applications. These benefits include reduced labor and equipment costs (due to self-leveling properties and no need for compaction), faster construction, and the ability to place material in confined spaces. The relatively low strength of CLSM is advantageous because it allows for future excavation, if required. Another advantage of CLSM is that it often contains by-product materials, such as fly ash and foundry sand, thereby reducing the demand on landfills, where these materials may otherwise be deposited.

Despite these benefits and advantages over compacted fill, the use of CLSM is not currently as widespread as its potential might predict. One reason is that CLSM is somewhat a hybrid material; that is, it is a cementitious material that behaves more like a compacted fill. As such, much of the information and discussions on its uses and benefits have fallen between the cracks of concrete materials and geotechnical engineering. Although considerable literature is available on the topic, CLSM is often not given the level of attention it deserves by either group.

Many states have developed specifications (in some cases, provisional) that govern the use of CLSM. However, these specifications differ from state to state and, moreover, a variety of different test methods are currently being used to define the same intended properties. This lack of conformity, both on specifications and testing methods, has also hindered the proliferation of CLSM applications.

There are also technical challenges that have served as obstacles to widespread CLSM use. For instance, it is often observed in the field that excessive long-term strength gain may make it difficult to excavate CLSM at later ages. This strength gain can be a significant problem that translates to added cost and labor. Other technical issues deserving attention are the compatibility of CLSM with different types of utilities and pipes, the potential leaching of constituent materials and elements, and the durability of CLSM subjected to freezing and thawing cycles.

In summary, CLSM represents a significant and important technology that will likely continue to grow in popularity and usage. However, because of the challenges described in previous paragraphs, research is needed to better understand the behavior of CLSM and to apply this knowledge to appropriate test methods, specifications, and design criteria. This report summarizes research performed under NCHRP Project 24-12(01) that aimed at filling these gaps and developing standard test methods, specifications, and guidelines for using CLSM in backfill, utility bedding, void fill, and bridge approach applications.

Research Objectives

The objectives of the research were (1) to define the properties of CLSM necessary for its use as wall backfill, utility bedding and backfill, void fill, and bridge approaches; (2) for these applications, to define test methods and develop criteria for the necessary properties of CLSM, including its corrosion potential and possible environmental impact; (3) to define the relationships between the properties of CLSM and its constituents; (4) to define field methods to monitor in-place properties of CLSM for construction acceptance; and (5) to prepare design criteria and construction guidelines for CLSM to take advantage of its properties for backfill, utility bedding, void fill, and bridge approaches.

Overview of Report

The report is organized as follows:

- Chapter 2, State of the Art and Current Practice
  - Provides synthesis of current practice and available literature on CLSM.
  - Describes materials, mixture proportions, applications, relevant properties of CLSM, and research needs
- Chapter 3, Laboratory Testing Program
  - Describes materials and mixture proportions used in laboratory program
  - Summarizes results of tests on fresh properties, hardened properties, and durability aspects of CLSM
- Chapter 4, Field Evaluations of CLSM
  - Describes six field tests conducted throughout the United States
  - Summarizes efficacy of test methods and specifications in field applications
- Chapter 5, Conclusions and Suggested Research
  - Summarizes key findings and conclusions from project
  - Identifies topics and issues that deserve further attention in future research
- Appendices
  - Appendix A, Corrosion Study (available in *NCHRP Web-Only Document 116*)
  - Appendix B, Recommended Test Methods for CLSM
  - Appendix C, Recommended Specifications for CLSM
  - Appendix D, Recommended Practice for CLSM
  - Appendix E, Implementation Plan (available in *NCHRP Web-Only Document 116*)

CHAPTER 2

State of the Art and Current Practice

Introduction

Research performed under this project included a comprehensive literature review and a survey of state Department of Transportation (DOT) practice regarding CLSM use for backfill, utility bedding, void fill, and bridge approaches. A more detailed review of literature and information related to CLSM was included in the Phase I Interim Report for NCHRP Project 24-12 (Folliard et al. 1999); only a brief synthesis is provided in this chapter.

The remainder of this chapter presents a brief summary of information gathered on CLSM, focusing mainly on laboratory and field research projects. It is based on a comprehensive literature search and interactions with various state DOTs, the American Concrete Institute (ACI), the Portland Cement Association (PCA), the National Ready Mixed Concrete Association (NRMCA), the American Public Works Association (APWA), and other agencies and organizations. Much of the information on current state DOT practice was obtained through the use of a written survey distributed in 1998 as part of the aforementioned Phase I Interim Report for NCHRP Project 24-12.

Historical Background

The development of CLSM can be viewed as a natural evolution of plastic soil-cement, with the main improvements related to increased flowability and improved quality control. One of the earliest records of the use of CLSM was in 1964 by the U.S. Bureau of Reclamation as the bedding of a 515-km long pipeline in the Canadian River Aqueduct Project (Adaska 1997). Since then, CLSM has been used on many projects for backfill (Brewer 1992; Sullivan 1997), utility and pipe bedding (Adaska and Krell 1992; Larsen 1993), void fill (Gray et al. 1998; Hook and Clem 1998), and bridge approach applications (Snethen and Bensen 1998). Other applications include using CLSM for structural fill (ACI Committee 229 1999; Clem et al. 1995; Buss 1989), encapsulation of contaminated soils (Gardner 1998), soil stabilization (Green et al. 1998), and erosion control (Larsen 1988, 1993).

Over the past 40 years, various terms have been used to describe what is currently known as CLSM, including flowable fill, unshrinkable fill, controlled density fill, flowable mortar, plastic soil-cement, soil-cement slurry, and K-Krete®. In 1984, ACI Committee 229 was formed, and the ACI-approved term "controlled low-strength material or CLSM" was adopted. In its 1999 committee report, ACI Committee 229 defined CLSM as a self-compacted, cementitious material used primarily as a backfill alternative to compacted fill (ACI Committee 229 1999). Today, CLSM has been used throughout the United States for a wide range of applications, using a spectrum of different materials.

Materials

This section describes the most common constituent materials used in CLSM, including portland cement, fly ash, aggregates (including foundry sand), chemical admixtures, and other by-product materials. A significant benefit of CLSM is the ability to use a wide range of local materials, including by-product materials. Because of the relatively high material cost of CLSM (compared to compacted fill), the ability to specify and use by-products such as fly ash and foundry sand will be critical to the continued growth of CLSM usage.

Portland Cement

Although any type of portland cement can be used in CLSM, ASTM C 150 Type I is the most commonly used. The prevailing criteria are the local availability and cost of cement, and as such, Type II or Type I/II cements may be more common in some regions of the United States. Because of the comparatively low cement contents found in CLSM, common concrete durability problems, such as alkali-aggregate reaction and internal sulfate attack, appear quite unlikely. Type III portland cement has been successfully used in CLSM to achieve higher early strengths and to reduce subsidence.

Supplementary Cementitious Materials

Fly Ash

About 62 million tons of fly ash, a by-product of coal combustion, were estimated to have been generated in 2001. Fly ash is used mostly in portland cement concrete, but its use in CLSM has grown considerably in recent years. Although fly ash has become an important construction material, approximately 70 to 75 percent of the fly ash generated annually is still disposed in landfills (FHWA 1997). Much of this unused fly ash does not meet specifications for use in portland cement concrete (ASTM C 618), sometimes because of high percentages of unburned carbon, as measured by the loss on ignition (LOI) test. Fortunately, it has been demonstrated that CLSM can be successfully produced using a wide variety of fly ash types and sources, including high-carbon fly ash that is not typically permitted in concrete. Both Class F and Class C fly ash (according to ASTM C 618) are commonly used in CLSM, as well as ashes that do not conform to ASTM C 618.

The use of fly ash in CLSM provides for excellent flowability and helps to minimize segregation, as well as reduces the cost of the mixture (as fly ash is typically less costly than portland cement). Fly ash is used in higher dosages in CLSM than in conventional concrete mixtures; typically fly ash composes more than half the binder, and in the case of rapid-setting CLSM, fly ash is used as the only binder, without portland cement. Based on the 1998 survey of current practice (Folliard et al. 1999), of the forty-two states specifying CLSM, twenty-seven states had specifications for CLSM containing fly ash, and eleven states allow fly ash that did not meet ASTM C 618 specifications to be used in CLSM.

More specific information on types and dosages of fly ash used in typical CLSM mixtures is provided later in this chapter, and the laboratory and field evaluations described in Chapters 3 and 4 included the use of a range of different fly ashes.

Other Supplementary Cementitious Materials

Although fly ash is the most commonly used supplementary cementitious material (SCM) in CLSM, other SCMs can and have been used. Materials such as slag, metakaolin, silica fume, and rice husk ash are all suitable for use in CLSM.

Aggregates

Various aggregate types have been used successfully in CLSM. With the exception of CLSM paste mixtures (typically containing just fly ash, portland cement, and water), most CLSM contains fine aggregate (most commonly concrete sand). Only a small percentage of CLSM used in practice contains coarse aggregate.

Concrete Sand

A wide range of fine aggregates may be used successfully in CLSM, but conventional concrete sand (ASTM C 33) is the most common, especially for CLSM produced at ready-mixed concrete plants (the dominant source of CLSM). Sand that does not meet ASTM C 33 requirements (e.g., gradation) can be and often times has been used in CLSM production, provided that the specified flowability and constructability requirements are satisfied.

Foundry Sand

Foundry sand, a by-product of the metal-casting industry, has been studied and used successfully in CLSM and its use has increased in recent years (Bhat and Lovell 1996; Tikalsky et al. 1998). Foundry sand is becoming a more viable candidate for use in CLSM because of its lower cost, increasing availability, and satisfactory performance. It is estimated that for every ton of metal castings produced and shipped that a typical foundry generates approximately one ton of waste sand (Kennedy and Linne 1987).

A concern with using foundry sand in CLSM is the potential for environmental impact caused by leaching of heavy metals present in the foundry sand. Therefore, ferrous foundry sands are more commonly used in CLSM because of the concerns about the heavy metals content of nonferrous foundry sands. The most commonly used waste foundry sand in CLSM is “green sand,” a term applied when the original sand is treated with a bonding agent (usually clay) to optimize the efficiency of the sand in the molding process.

Bottom Ash

Bottom ash and fly ash are both by-product materials of coal combustion. Bottom ash is formed by large noncombustible particles that cannot be carried by the hot gases. These particles descend on hoppers or conveyors, at the bottom of the furnace, in a solid or partially molten condition. Then, the particles gradually cool to form bottom ash. Bottom ash particles are typically porous and angular in shape. As a by-product material, bottom ash is commonly disposed of in ponds. In this process, bottom ash is passed through a crusher to reduce the size of large particles and is transported hydraulically through pipelines to the pond shore. The typical range of particle sizes falls between 75 μm and 25 mm. Researchers and practitioners have successfully used bottom ash in CLSM (Naik et al. 1998; Karim et al. 1996).

Gravel and Crushed Stone

CLSM has mostly evolved using only sand as aggregate. However, in the Pacific Northwest, many CLSM mixtures use gravels up to 25 mm top size (Fox 1989). The reasons for the use of gravel center on availability of sand, economy, and performance. Concrete technology demonstrates that if the largest top-size aggregate is used, the lowest void content in the combined aggregates will be achieved. Reduced voids result in a lower paste requirement, which correspondingly reduces the cost of cementitious materials. Gravel can be a viable material as aggregate in CLSM proportions. Economics are likely to determine whether gravel is used or not. Performance of CLSM mixtures with gravel may be expected to be similar to those with sand only.

Water

There are no special requirements for water to be used in CLSM. As a general rule, any water that is suitable for concrete will work well for CLSM, including recycled wash water for ready-mix concrete trucks.

Chemical Admixtures

Air-Entraining Agents and Foaming Agents

Air-entraining agents (AEAs) are the most commonly used chemical admixture in CLSM. AEAs are typically added as part of the batching process, with air contents in the 20 to 30 percent range being common. These AEAs are formulated specifically for use in CLSM to obtain higher air contents than conventional concrete. For even higher air contents, a foaming gun can apply a foaming agent to CLSM to produce a fluid, lightweight product. The advantages of CLSM with relatively high air contents include low density, improved insulation properties, reduced segregation and bleeding, decreased water and/or cement content, improved frost resistance, and lower material cost. Also, high air contents may be used to limit long-term strength gain to assure future excavatability.

Other Chemical Admixtures

Set accelerators have been used to a lesser extent to increase the speed of construction (e.g., earlier opening of traffic) and to minimize subsidence of CLSM. Dyes can be incorporated in the mixture to distinguish CLSM from the surrounding soils, which facilitates identifying the CLSM backfill. Other chemical admixtures can be used in CLSM to obtain specific target properties.

Other Materials Used in CLSM

One advantage of CLSM technology is its capacity to include constituent materials outside the field of conventional concrete. In addition to the aggregate materials previously described, there are other materials used in CLSM as aggregates. Colored glass that cannot be recycled by local bottle manufacturers has been crushed to pass a 12.5 mm (0.5 in.) sieve and was successfully used in CLSM as an aggregate (Ohlheiser 1998). A special process was utilized so that the crushed glass could be handled with bare hands. Phosphogypsum is a by-product of the production of phosphoric acid and has been shown to be a viable aggregate for CLSM (Gandham et al. 1996).

Crushed limestone is a favorite coarse aggregate for concrete. However, the leftover screening fines (about 15 to 20 percent of total aggregates) during rock processing are piled up. CLSM is a potential way to bring value to this by-product material (Crouch et al. 1998). Higher air content was found to be important for these mixtures. Another source of high-fines aggregate is recycled concrete. Current practice usually only involves using recycled concrete as coarse aggregate, leaving an abundance of fines (passing 300 μm sieve), which may be well suited for use in CLSM.

Cement kiln dust (CKD) is a powder by-product of portland cement manufacturing in rotary kilns. It is used to treat or stabilize soft or contaminated soil or sludge. Pierce et al. (2003) examined its use as the replacement for cement in CLSM. Various contents of CKD were found to produce excavatable CLSM mixtures. Katz et al. (2002) found that use of finer CKD particles results in higher water demand. The durability aspects of using CKD in CLSM have not been studied in detail and further work may be needed.

Mixture Proportions

Currently no standard mixture proportioning method for CLSM has been widely adopted. There has been considerable research done on factors affecting proportioning (Janardhanam et al. 1992; Bhat and Lovell 1996), but there is no single, unified method (such as ACI 211 for conventional concrete). The wide range of materials used in CLSM, including various off-spec or by-product materials, makes it quite difficult for standard mixture proportioning techniques to be widely applicable. However, several fairly typical approaches to designing CLSM mixtures have emerged and can be grouped in broad classes. Regardless of the approach to mixture proportioning, key properties sought are fluidity with minimal segregation, acceptable setting times, and adequate strength gain (also a function of whether excavatability may be needed in the future).

Table 2.1. Typical CLSM materials and proportions.

CLSM Mixture Types		Fly Ash (kg/m^3)	Sand (kg/m^3)	Cement (kg/m^3)	Water (kg/m^3)	Air (%)
A[a]	Range	119 - 297	1483 - 1780	30 - 119	198 - 494	0.5 - 4.0
	Typical	178	1542	59	297	
B[a]	Range	949 - 1542	None	47 - 74	222 - 371	1 - 5
	Typical	1234	None	62	247	
C	Range					
	Typical	275	1500		165	1
D	Range		1200 - 1500	30 - 60	130 - 300	15 - 30
	Typical					

[a] After FHWA (1997)

Unconfined compressive strength of CLSM is always an important design parameter, and the vast majorities of applications are designed for future excavatability and typically have strengths of 1.0 MPa or less. For these mixtures, low cement contents are used (e.g., 30 to 60 kg/m^3), with or without fly ash. In general, fluidity is achieved by high water contents (and low cement contents), and segregation is addressed through the use of AEAs and high fines contents (from fly ash, sand, etc.).

Table 2.1 summarizes four of the more common CLSM mixture types that have been widely used. Note that this table does not implicitly include CLSM modified with a foaming agent/gun, but any of the mixtures can be treated by this process to increase air content. The mixture types are referred to herein as Groups A through D, with the mixtures described in Groups A and B adopted from FHWA (1997). The materials typically used in any of these CLSM mixture designs are portland cement, sand, fly ash, water, and AEA, but the spectrum of mixtures used in the field can be highlighted by considering that some mixtures have no portland cement (Group C: only fly ash as binder in rapid-setting CLSM, typically produced in volumetric mixer on site), and some have no aggregates (Group B: a paste composed of about 95 percent fly ash and 5 percent portland cement, with water added as needed for fluidity). Mixtures in Group A typically include relatively small amounts of portland cement and moderate levels of fly ash, combined with sand and water. Lastly, Group D is a typical mixture that relies upon portland cement as the only binder, with AEAs used to generate air contents in the 15 to 30 percent range.

Batching, Mixing, and Transporting

CLSM is typically batched, mixed, and transported in similar fashions as concrete. Most flowable fill is batched at ready-mixed plants and mixed in truck mixers. The high fluidity of CLSM may create difficulties in transporting full or near-full loads in ready mixed trucks. To address this potential problem, some producers hold back part of their mixing water for on-site addition, and many will add liquid AEAs (or use pneumatic guns to generate air) at the job site, rather than at the plant, thereby reducing the mixture volume in the truck en route to the site. Some CLSM mixtures are produced using volumetric, mobile-type mixers. Rapid-setting CLSM mixtures, which typically contain high–calcium oxide (CaO) fly ash as the only binder, are almost always produced on site using volumetric mixers because of the short handling time of such mixtures before setting.

Properties of CLSM

This section provides information on the properties of CLSM that most affect its performance in key applications. The most important *fresh, hardened, and durability-related properties* are briefly described next.

Fresh CLSM Properties

Flowability

One of the most important attributes of CLSM is its ability to flow easily into confined areas, without the need for conventional placing and compacting equipment. The self-leveling properties of CLSM significantly reduce labor and increase construction speed. Because the enhanced flow properties of CLSM are critical to successful placement and performance, flowability is measured routinely and is an important quality control parameter.

ASTM D 6103, “Flow Consistency of Controlled Low Strength Material,” has gained some acceptance since its adoption by ASTM. The test method uses a 75 × 150 mm cylinder, which is lifted, allowing the CLSM to slump and increase in diameter. The final diameter is typically used to differentiate between various degrees of flowability. A final diameter of 200 mm or higher is typical of a highly flowable mixture.

ASTM C 939, “Flow of Grout for Preplaced-Aggregate Concrete,” measures the efflux time of CLSM as it passes through a flow cone. Several state DOTs have, over the years, specified this test method for CLSM, and the Florida and Indiana DOTs required or require an efflux time of 30 seconds ± 5 seconds (ACI Committee 229 1999).

Segregation and Bleeding

Because of the high fluidity of CLSM mixtures, the potential for excessive segregation and bleeding exists, especially with very high water contents. Generally, the use of fly ash and AEAs is beneficial in minimizing the potential for segregation and excessive bleeding. The use of low-density CLSM with high air contents (e.g., 15 to 35 percent by volume) allows for reductions in water content and bleeding (Hoopes 1998).

ASTM C 940, "Expansion and Bleeding of Freshly Mixed Grouts for Pre-Placed Aggregate Concrete in the Laboratory," is a simple, but effective method of measuring the total volume and accumulation of bleed water on the top of CLSM. Although there are no commonly used methods available to measure the segregation of CLSM, visual observations during mixing and placing serve as good, practical indicators.

Hardening Time

Hardening time is the approximate period of time required for CLSM to gain sufficient strength to support the weight of a person (ACI Committee 229 1999). The hardening time can be as short as 1 hour, but generally takes 3 to 5 hours (Smith 1991). The early hardening characteristics of CLSM are affected by several parameters, including mixture proportions, climatic conditions, and the surrounding environment, especially drainage conditions. Because measuring the early age compressive strength of CLSM is not practical, test methods for penetration resistance are most commonly used to quantify setting and hardening time. Laboratory penetrometers (e.g., ASTM C 403, "Time of Setting of Concrete Mixtures by Penetration Resistance"), as well as soil pocket penetrometers, are commonly used to measure the setting and hardening of CLSM. Design penetration values are sometimes specified to schedule construction practices and the time to opening of traffic. Other techniques sometimes used for CLSM include the dynamic cone penetrometer and Kelly ball.

Subsidence

Subsidence occurs when CLSM loses water (through bleeding and absorption into surrounding soil) and entrapped air, resulting in a reduction in volume. CLSM with high water content has been found to exhibit a subsidence depth equal to approximately 1 to 2 percent of the trench depth (McLaren and Balsamo 1986). The actual amount of subsidence that occurs for a given placement depends on the materials and mixture proportions used, as well as placement heights, the environmental conditions and permeability of surrounding soil. Subsidence generally only occurs during CLSM placement and up until the mixture hardens. Using sufficient fines (e.g., fly ash), accelerating admixtures, or high early-strength cement may be effective in limiting subsidence by minimizing the propensity for subsidence or decreasing the window of vulnerability of CLSM.

Hardened CLSM Properties

Compressive Strength

The compressive strength (or unconfined compressive strength to be consistent with geotechnical terminology) of CLSM is the most common hardened property measured, and the one most commonly found in state DOT specifications. Compressive strength and flowability were the two most commonly specified CLSM properties in the 1998 survey of current practice (Folliard et al. 1999); these and other CLSM properties and tests are highlighted in Table 2.2.

CLSM compressive strength values are often used as an index for excavatability or digibility (e.g., maximum allowed values of 0.35 to 1.0 MPa), when future excavation may be required. Materials and mixture proportions must be selected to ensure that these strength values are not exceeded in the long term. Also, for some applications, early-age compressive strength may be specified for constructability reasons (e.g.,

Table 2.2. CLSM properties typically specified and measured by state DOTs.

Property	Number of States Testing	Common Test Method(s)
Flow	18	ASTM D 6103 (or similar) and ASTM C 143
Compressive strength	17	AASHTO T 22 and ASTM D 4832
Unit weight	14	AASHTO T 121
Air content	10	AASHTO T 152
Set time	7	ASTM C 403
Durability	2	pH and resistivity
Shrinkage	1	Visual
Geotechnical	1	Direct shear
Temperature	1	Modified ASTM C 1064
Chlorides/sulfates	1	Determination of ion contents
Permeability	0	None

Source: Folliard et al. (1999)

for subsequent paving or opening to traffic). Some applications (e.g., void fill) may not necessarily demand specific strength values, and in these cases, strength may not need to be measured. More information on applications of CLSM is discussed later in this chapter.

The development of CLSM compressive strength is different from conventional concrete in that it is thought to have two components of strength: particulate and nonparticulate (Bhat and Lovell 1996). The nonparticulate component of strength results from the cementitious (and pozzolanic) reaction of cement and fly ash with water, whereas the particulate component of strength is similar in nature to that of granular soil. Water-cement ratio plays an important role in the development of unconfined compressive strength (Bhat and Lovell 1996), but in some instances, cement content may be more influential (Brewer 1992) or easier to control. The type and amount of fly ash (if used) also has a major effect on compressive strength, especially on long-term compressive strength.

ASTM D 4832, "Preparation and Testing of Controlled Low-Strength Material (CLSM) Test Cylinders" is the most common method used by state DOTs for evaluating CLSM strength. The most critical potential problem with this and related compression test methods for CLSM is the relatively low strength of CLSM. This characteristic low strength creates difficulties in handling CLSM test specimens (e.g., stripping cylinders) and in testing cylinders, where large-capacity concrete compression machines have poor accuracy in the required low load range. Many load frames used by research laboratories for testing CLSM are in the 1,300 to 2,220 kN capacity range (Folliard et al. 1999). For a 150 × 300 mm cylinder with a compressive strength of 1.0 MPa, the maximum load at failure is only about 18 kN, or approximately 1 percent of the load frame capacity. The precision of these larger load frames in the lower compressive load range is not sufficient in most cases to produce an accurate measure of compressive strength. This problem becomes exacerbated when smaller diameter cylinders are used or lower strength CLSM is used, especially at early ages. Concerns regarding machine capacity and accuracy, as well as curing conditions, cylinder mold types, and other aspects of compression testing were evident in the 1998 survey conducted under this project, and significant emphasis was placed in the laboratory phase of this project (Chapter 3) on improving the test method. A revised version of this test is recommended in Appendix B.

Excavatability

Easy removal of CLSM from trenches is essential when utilities fail or require repair. Undesired long-term strength gain may prohibit the removal of CLSM using conventional means of shovels or backhoes. Prior studies have been performed using actual excavation equipment to assess the ease of excavating CLSM in trenches, and correlations were made with other CLSM properties, such as unconfined compressive strength (Landwermeyer and Rice 1997). Similar efforts were also part of the current project, as discussed in Chapters 3 (laboratory evaluations) and 4 (field studies).

Many CLSM users have specified maximum unconfined compressive strength values to ensure that CLSM can be excavated at later ages. Another approach, outlined in the Hamilton County (Ohio) Performance Specification for CLSM, is to specify a removability modulus, which is both a function of 28-day unconfined compressive strength and density of CLSM in the field. If the calculated value of the removability modulus is less than 1.0, the specific CLSM is considered to be removable.

The majority of states require that CLSM compressive strengths not exceed some pre-defined early strength in order for the material to meet excavatability requirements. Performance-based specifications based on locally available materials in some cases have proven to be acceptable in limiting the long-term strength gain. An alternative approach is to limit the cement content of the CLSM mixes. About 20 percent of the states place limits on the amount of cement that can be added to CLSM, thus limiting the ultimate strength of the mixture (Folliard et al. 1999).

The ability to predict long-term strength gain is paramount to assuring that CLSM will remain excavatable. Thus, methods of predicting strength gain for various combinations of constituent materials were a prime focus on research conducted under this project, and correlations between excavatability and various CLSM properties (e.g., compressive strength, tensile strength, etc.) and test values (e.g., dynamic cone penetrometer) were attempted (see Chapter 3).

Permeability

The permeability of CLSM to both liquids and gases has a significant impact on performance of CLSM in various applications. The permeability of CLSM affects several important properties, including drainage characteristics, durability, and leaching potential. An advantage that CLSM has, compared to conventional concrete, is that actual water permeability tests can be conducted (conventional concrete is too impermeable for practical measurements of water permeability).

The most common method of assessing CLSM permeability is ASTM D 5084, "Measurement of Hydraulic Conductivity of Saturated Porous Materials Using a Flexible Wall Permeameter." Typical values for CLSM obtained from this test method are in the range of 10^{-4} to 10^{-5} cm/s, but higher strength mixtures may reduce the permeability to as low as 10^{-7} cm/s (ACI Committee 229 1999). Low-density, air-entrained CLSM mixtures tend to have significantly higher permeability. CLSM mixtures with 30 and 21 percent air were found to yield permeability values of 1.7×10^{-2} and 1.2×10^{-3} cm/s, respectively (Hoopes 1998).

Shear Strength

As the use of CLSM continues to spread into more engineered applications as an alternative to conventional compacted fill, it is becoming more important to quantify CLSM properties in terms of geotechnical engineering parameters by either direct measurement or by developing correlations between geotechnical and concrete test results. The shear properties of CLSM are particularly important and can be assessed using both a direct shear test (ASTM D 3080) and a triaxial shear–consolidated drained test (U.S. Army Corps of Engineers [USACE] 1986). The equipment required for both test methods is standard in most state DOT soils laboratories.

Some studies have focused on the shear properties of CLSM (Bhat and Lovell 1996; Dolen and Benavidez 1998; Hoopes 1998). The shear properties of CLSM are quite high and often exceed typical compacted fill shear strengths, especially at later ages as hydration proceeds (Hoopes 1998). In triaxial shear testing, CLSM showed an internal friction angle ranging from 20 to 30 degrees (FHWA 1997).

California Bearing Ratio and Resilient Modulus

California bearing ratio (CBR) testing is used to determine the strength of subbase and subgrade materials. The resilient modulus assists in providing design coefficients for multilayered pavements by defining the relationship between stress and the deformation of granular base and subbase layers. This is especially important when considering CLSM for use in bridge approaches or whenever CLSM will serve as a functional base or subbase material.

Common soil test methods that could potentially be applied to CLSM include AASHTO T 193, "Standard Method of Test for the California Bearing Ratio," AASHTO T 274, "Resilient Modulus of Unbound Granular Base/Subbase Materials and Subgrade Soils," AASHTO T 292, "Resilient Modulus of Subgrade Soils and Untreated Base/Subbase Materials" and AASHTO T 307, "Determining the Resilient Modulus of Soils and Aggregate Materials."

Consolidation

The consolidation of CLSM can be measured using ASTM D 2435, "One-Dimensional Consolidation Properties of Soil." This method is easy to perform, requires minimal equipment, and can be used to estimate both the rate and total amount of settlement for CLSM used in various applications. In addition, values obtained from consolidation testing are used to derive bedding factors and soil stiffness values needed for pipe bedding design (Hoopes 1998).

Drying Shrinkage

Compared to conventional concrete, CLSM typically has a very high water-cement ratio and water content, two factors that are known to cause excessive drying shrinkage in concrete. However, the limited studies that have focused on CLSM shrinkage have not found it to be a significant factor. Typical linear shrinkages have been reported in the range of 0.02 to 0.05 percent (ACI Committee 229 1999). Gandham et al. (1996) also found the drying shrinkage of CLSM to be minimal. Katz et al. (2002) found the drying shrinkage of CLSM mixtures is affected by the water content and the mixtures' ability to hold the water during drying conditions.

The standard concrete method to measure shrinkage, AASHTO T 160 may not be appropriate for CLSM. This method requires embedding gage studs at both ends of the specimen, and the method also requires significant handling of the shrinkage prisms during form removal and subsequent measurements. Because of the low strength and fragile nature of CLSM specimens, the gage studs may not bond sufficiently, and the specimens may be damaged because of the handling. Limited testing of drying shrinkage properties was performed under this project, as described in the next chapter. These efforts focused on in-situ measurements of shrinkage in specially designed molds that allowed for length-change measurements immediately after casting, without the need to remove the specimen from the formwork.

Thermal Conductivity

The transport of high-temperature fluids through pipes is common. Due to the nature of CLSM and because one of its major uses is for pipe backfill, CLSM can be used as an insulating material to prevent heat loss from the pipe. Low-density, air-entrained CLSM is particularly well suited for pipe backfill because of its enhanced insulating properties. Though rarely measured, the thermal and insulating properties of CLSM are important parameters. Methods that may be applied to CLSM include ASTM D 5334, "Determination of Thermal Conductivity of Soil and Soft Rock by Thermal Needle Probe Procedure," and ASTM C 177, "Steady-State Heat Flux Measurements and Thermal Transmission Properties by Means of the Guarded-Hot-Plate Apparatus."

Durability and Environmental Issues Related to CLSM

At the time that this research project was initiated, no major problems had been reported related to inadequate durability of CLSM in field applications. Similarly, no significant problems were cited regarding the leaching of CLSM constituent materials (e.g., heavy metals from fly ash or foundry sand) into the surrounding environment. However, because durability problems typically take years to manifest, there may be some concerns over the long-term durability of CLSM. This section provides a brief overview of relevant issues related to durability and leaching.

Freezing and Thawing Resistance

Several studies have focused on the resistance of CLSM to freezing and thawing (Bernard and Tansley 1981; Krell 1989; Burns 1990; Nantung 1993; Gress 1996). The unique structure of CLSM creates some intriguing challenges when its freezing and thawing resistance is being assessed. First, CLSM may be damaged by both internal hydraulic pressure and frost heave when exposed to freezing and thawing cycles. Second, test methods that have been developed for conventional concrete have been found to be too severe for testing CLSM. In particular, Nantung (1993) found that AASHTO T 161, the most common method used for concrete, was far too severe for testing CLSM. He proposed modifications to the method to provide for less severe freezing conditions that better simulate field conditions.

Gress (1996) performed laboratory and field testing of CLSM and found that CLSM can survive freezing and thawing damage, but proposed that the top 50 to 150 mm of CLSM trenches be removed after set and backfilled with a frost heave–compatible base material to ensure uniform heaving of pavement and trench. When laboratory test methods to assess frost resistance of CLSM are being considered, the potential for frost heave damage can not be overlooked.

ASTM D 560, “Freezing and Thawing of Compacted Soil-Cement Mixtures,” has been used to measure the freeze-thaw resistance of CLSM (Janardhanam et al. 1992). This method is much less severe than AASHTO T 161 and may be a more viable test method for CLSM.

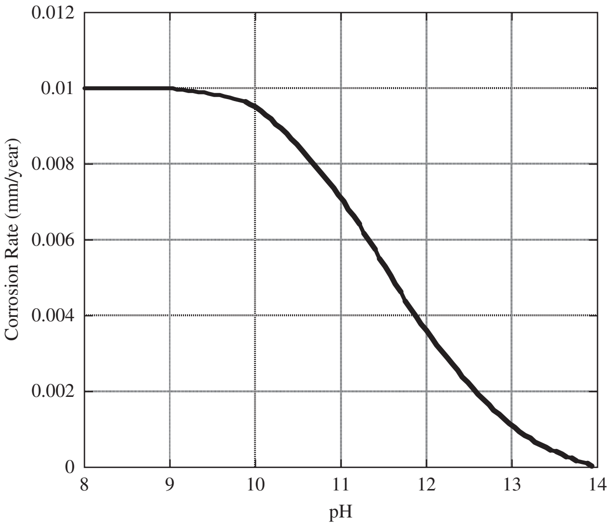
Corrosion

Corrosion deterioration of metal pipes placed in CLSM has not yet surfaced as a serious problem in field applications. But, because of the long-term nature of corrosion and other durability problems, it could prove to be an important aspect of CLSM durability. Very few studies have focused on the corrosion of metals in CLSM (Abelleira et al. 1998; Brewer 1991), but considerable information and data exist on the corrosion of metals in soils. The following section summarizes studies on steel corrosion in CLSM, as well as in conventional compacted fill, with particular emphasis on the mechanisms of corrosion likely to occur in CLSM.

Before initiation of the NCHRP research described in this report, there were no available guidelines on the corrosion performance of metallic materials embedded in CLSM. Existing guidelines on the corrosivity of soils around metallic materials, which do not consider the characteristics of a cementitious material (i.e., CLSM), often indicate that CLSM could be detrimental to the corrosion performance of pipes embedded in CLSM. Probably one of the most common methods used to determine the corrosivity of soils around ductile iron pipes is the ANSI/AWWA C105/A21.5, “American National Standard for Polyethylene Encasement for Ductile-Iron Pipe Systems.” This standard, shown in Appendix B, assigns points for various soil backfill characteristics (such as pH, resistivity, moisture content, etc.), and, if the sum of the points from all characteristics is more than 10, the soil is assumed to be corrosive. For soils with pH values greater than 8.5, the standard notes that these soils are generally quite high in dissolved salts, resulting in lower resistivity values and higher assigned point values. However, the high pH of the CLSM results from the hydroxyl ions and alkalis present in the pore solution and not from dissolved salts. High-pH pore solutions have been well documented to result in stable, protective, passivating oxide films on iron products (Broomfield 1997). Information on other CLSM properties that may impact corrosion are described briefly in the following paragraphs.

Several key CLSM parameters affect the likelihood of corrosion, including permeability, pH, resistivity, buffering capacity, presence of chlorides, and exposure conditions (i.e., type and nature of native soil, etc.). The permeability of CLSM to water and oxygen is critical because both water and oxygen are required for the corrosion process to occur. The migration rate of chloride is critical because these ions can significantly increase localized corrosion. Water permeability tests (ASTM D 5084), air permeability tests, and chloride diffusion data can be used to design CLSM to protect metals from corroding. In addition, the absorption capacity of CLSM also may be measured using ASTM C 642, “Density, Absorption, and Voids in Hardened Concrete,” to determine the degree of moisture available for corrosion in CLSM mixtures.

The effects of pH on corrosion rate are shown in Figure 2.1. At high values of pH, iron is passivated, with a very low corrosion rate, but as the pH decreases, the corrosion rate increases rapidly. Because CLSM typically exhibits a pH (from extracted pore water) of greater than 11.5, corrosion is not expected to be a severe problem. However, the pH of CLSM has been measured to drop when high dosages of fly ash are used, and when some types of foundry sand are used (FHWA 1997). ASTM G 51, “Measuring the pH of Soil for Use in Corrosion Testing,” has been used to assess the pH of CLSM. However, pH values by themselves are not sufficient to predict or design against corrosion, but can be very effective in conjunction with other basic test results.



Source: After Whitman et al. (1924)

Figure 2.1. Influence of pH on corrosion rate.

Resistivity measurements indicate the relative ability of an electrolytic material to carry electrical currents. When metallic samples are placed in a medium, the ability of the medium to conduct electrical currents will influence the degree of corrosion activity. For soils, resistivity is one parameter used to determine the "corrosivity." Table 2.3 shows typical corrosivity classifications for different soil resistivities. The Wenner four-electrode method (ASTM G 57) is typically used to determine soil resistivity and can be easily used to measure CLSM resistivity.

The rate of chloride diffusion through CLSM is an important parameter that can provide important information about CLSM applications in saline environments. Although this type of testing has not been reported in the literature for CLSM applications, it is widely recognized for concrete applications. This test could be accomplished by following the typical approach for concrete, in which chloride profile data can be used with Fick's Second Law to predict the rate of chloride penetration through CLSM.

Because CLSM is used in a range of applications, the exposure conditions and corrosion resistance will vary widely. For trench backfill and bedding applications, the corrosion activity of embedded metallic piping systems can be increased by the development of galvanic cells. Galvanic cells can develop when the metallic pipe is embedded in two different material types. For trench backfill applications, a typical scenario includes a lateral pipe across the trench. For pipe bedding applications, galvanic cells can develop when the metallic pipe displaces the CLSM bedding material and rests on the original soil. Because the CLSM is often significantly different than the original soil conditions, the potential for high corrosion rates may exist.

Table 2.3. Classification of corrosivity of soils.

Soil Resistivity (ohm-cm)	Corrosivity Classification[a]
0 to 1000	Very severe
1000 to 2500	Severe
2500 to 5000	Moderate
5000 to 10000	Mild
Greater than 10000	Very mild

[a]General classifications from industry and published data.

Test methods typically used to measure corrosion in concrete may be applied to CLSM, including ASTM G 109, "Determining the Effects of Chemical Admixtures on the Corrosion of Embedded Steel Reinforcement in Concrete Exposed to Chloride Environments"; ASTM G 59, "Conducting Potentiodynamic Polarization Resistance Measurements"; and ASTM G 1, "Preparing, Cleaning, and Evaluating Corrosion Test Specimens." In addition, Abeleirra et al. (1998) have proposed a simple test method that measures the corrosion of metal coupons immersed in CLSM. With this test method, CLSM, as compared to a conventional fill, was shown to reduce the corrosion of embedded metals. The method, however, did not study the galvanic effects of metals embedded in both CLSM and soil.

Significant research, including both laboratory and field evaluations, was performed under this NCHRP project to evaluate the potential for corrosion of metals in CLSM. Information on these efforts is provided primarily in Chapters 3 and 4, and information gleaned from these efforts was ultimately integrated into recommended test methods and specifications for CLSM.

Leaching and Environmental Impact

The tendency for leaching and subsequent environmental impact appears more critical in the case of CLSM (compared to conventional concrete) because of its higher permeability and also because of the common use of by-product materials, such as fly ash and foundry sand, which may contain heavy metals. Leaching is a relatively slow process and because CLSM is a relatively new technology, sufficient long-term field data and observations are not available to make an informed assessment of CLSM leaching effects.

Research at Purdue University focused on the effects of foundry sands on CLSM leachate and environmental impact (Bhat and Lovell 1996). Tests to determine pH and leachate characteristics (using a bioassay method) found that only one of eleven mixtures showed unusually high concentrations of heavy metals in the expressed pore solution. Naik et al. (1998) found relatively high concentrations of total dissolved solids in leachate extracted from CLSM containing clean coal ash.

Gandham et al. (1996) used the TCLP (EPA SW-846, Method 1311) to test CLSM containing phosphogypsum. The toxic contents of the mixtures were found to be well below the EPA leachate standards.

CLSM Applications

CLSM is used as an alternative to compacted fill mainly for backfill, utility bedding, void fill, and bridge approach applications. Before summarizing the current practice of using CLSM for these applications, a brief overview of the general benefits of using CLSM in each application is provided.

Backfill

The fluidity of CLSM makes it a rapid and efficient backfilling material, compared to conventional compaction. Time-consuming compaction is not needed and the quality of backfill depends on only the mixture specified. The efficiency of using CLSM is especially evident when limited space prevents or hinders the use of compaction machinery. The backfilling rate of CLSM (by volume) is about 50 times that of manual compaction by a laborer. RSMeans (1995) estimated that five common laborers could backfill at a rate of 46 m^3/day including compaction of the soil, which makes the average rate per laborer approximately 9 m^3/day. Sullivan (1997) noted that CLSM can be placed at a rate of approximately 60 m^3/h, significantly higher than conventional backfill. As such, CLSM can improve productivity and decrease construction costs. In addition, the use of CLSM provides a safe working environment.

Utility Bedding

Proper bedding for pipes and utilities is critical for pipe performance. However, preparation of pipe or utility bedding is a time consuming process, with either compacted soil or hardened concrete. Proper compaction in the haunch zone is a particular challenge. CLSM can be an effective alternative to both concrete and granular materials because of its flowability and strength characteristics. Its use for bedding applications can be of high quality and cost effective.

Void Fill

Underground structures or other voids that have been taken out of service have the potential to fail and cause additional damage to surrounding structures. Because of its fluidity, CLSM is an ideal material for void fill applications. The strength of CLSM can be adjusted to meet the excavation requirement. In addition, CLSM costs less than conventional concrete for such applications.

Bridge Approaches

A common problem associated with conventional compacted fill is the consolidation of the fill material with time. The so-called "bump at the end of the bridge" syndrome is common on many bridge approaches and is caused by the settlement of soil at the interface of the bridge and the approach slab. CLSM can serve as a desirable alternative to conventional compacted fill for bridge approaches because of its low compressibility and ease of application. CLSM can be used either in the initial construction to prevent long-term settlement or as a replacement option for existing bridge approaches.

Other CLSM Applications

In addition to the four major applications previously discussed, CLSM has been utilized in various applications and new applications are expected to surface as the construction community gets more familiar with this material. Current applications embrace bridge replacement (Iowa DOT), structural fill, insulation and isolation fill, erosion control, and others.

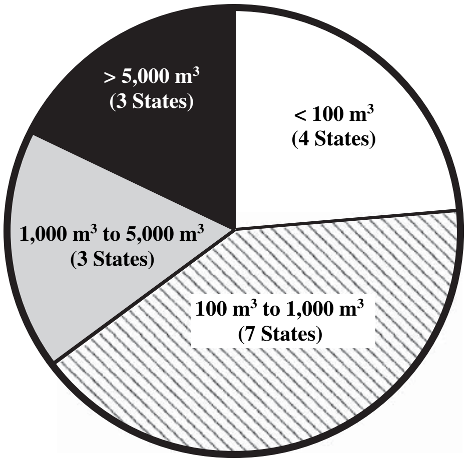
Summary of 1998 Questionnaire

In the early stages of this NCHRP project, a survey was distributed to all state DOTs, with the majority of the states responding. Detailed information on this survey can be found in Folliard et al. (1999). For conciseness, only limited information is provided in this section.

CLSM Usage by State DOTs

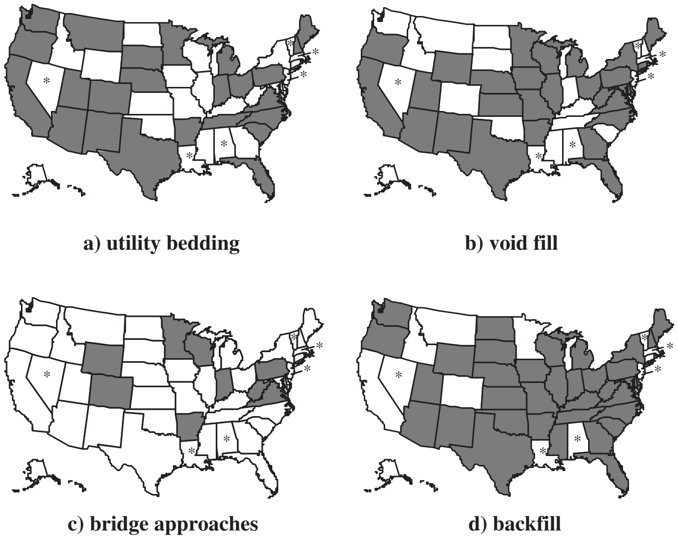
Even though CLSM was proven to be flexible for many applications and most state DOTs had specifications for its use, the quantity of CLSM used was relatively low in 1998. Figure 2.2 shows the state DOT survey results on the estimated quantity of CLSM used annually. The survey results indicate that the relatively high cost of CLSM and lack of knowledge on the use, testing, and performance of CLSM were hampering its widespread use.

CLSM is used by state DOTs mainly for backfill, utility bedding, void fill, and bridge approach applications. Other applications for CLSM include bedding for granite curbs, engineered fill, and as a lightweight fill to cover swamp areas. Of the forty-four states that responded to the survey, only two states were not then specifying the use of CLSM. Figure 2.3 shows the 1998 applications of CLSM for each state agency. The use of CLSM was quite new to some state DOTs, as shown in Figure 2.4. The dominant applications were backfill and bedding material. The majority of CLSM was pro-



Seventeen states provided estimated quantities; other states did not respond or quantity was unknown.

Figure 2.2. Annual quantity of CLSM used by state DOTs.



a) utility bedding

b) void fill

c) bridge approaches

d) backfill

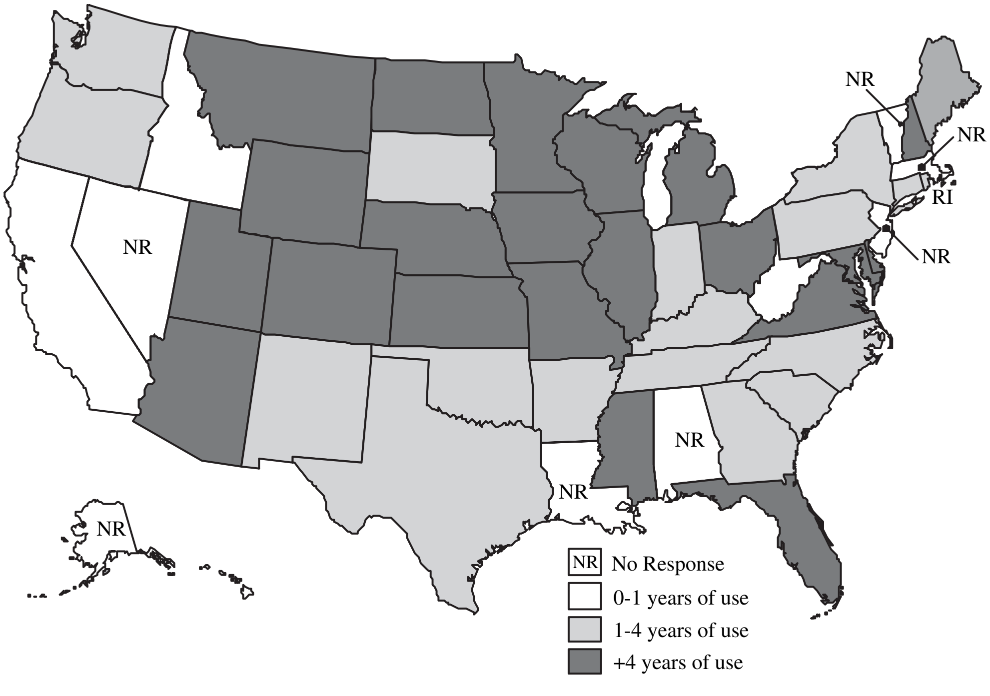
(* = no response)

Figure 2.3. CLSM applications by state in 1998.

duced at ready-mixed concrete plants. According to a 1995 survey, 90 percent of the 3,000 ready-mixed concrete producers in the United States produce some type of flowable fill (U.S. EPA 1998). The benefits of using CLSM as a backfill material were then recognized by at least forty-two state DOTs.

However, the survey found that CLSM was not a problem-free product as it seemed to be. Because of the mismatch between CLSM and compacted fill, in certain backfill applications a "bump" may form due to the settlement of compacted fill. However, for utility bedding, the advantages of CLSM were recognized not only by state DOTs but also by city agencies.

Void fill is another common application of CLSM products. Although the majority of states use CLSM for void fill applications (~70 percent), only seven of the forty-four states stated that using CLSM for void fill was their dominant application. This situation is most likely because the majority of states



Source: After Folliard et al. (1999)

Figure 2.4. Duration of CLSM use by state DOTs (up to 1998).

have more pipe installation work than void fill work, and not necessarily a result of CLSM being more applicable for bedding/backfill applications than void fill applications.

A fairly new application for CLSM is for use as a subbase/base under bridge approaches. For example, the Delaware Department of Transportation (DelDOT) favors the use of CLSM for many of its bridge approaches. Research by Oklahoma DOT and Oklahoma State University indicated satisfactory results (Snethen and Bensen 1998). Based on these applications, CLSM appears to be effective, compared to compacted fill, at reducing settlement and minimizing the "bump at the end of the bridge."

CLSM has been used in significant volumes by most states for only a few years (up to 1998); therefore, there are still challenges that must be overcome to further increase usage. Figure 2.4 shows the number of years each state DOT has been using CLSM. Almost half of the states that responded to the survey have used CLSM for less than 4 years (as of 1998).

Quality Assurance and Quality Control

Quality assurance and quality control are essential for the successful long-term performance of materials and structures. CLSM is a unique material with a variety of applications. Quality assurance serves as a management tool, is generally developed within the owner's organization, and encompasses quality control and independent assurance programs. Results from the survey indicate that approximately half of the states have quality assurance programs for CLSM within their materials department. Almost all DOTs have some type of quality assurance program in place.

Quality control is generally a contractor's tool to ensure that a product meets specification requirements. For CLSM applications, this could include material handling (in the field and in the laboratory); construction practices; and material sampling, testing, and inspection. Interestingly, approximately 40 percent of responding state DOTs perform quality control within their organization for CLSM applications. Nearly all other state DOTs hold the contractor or supplier responsible for quality control.

Responses from the 1998 survey found that CLSM is specified by a variety of state DOT sections, including materials, geotechnical, roadway design, bridge design, utility design (also known as pipe design or hydraulics), and construction. Because so many different parties are involved in the specifying and testing of CLSM, logistical and management difficulties may occur. A more standardized quality assurance program where CLSM specifications, testing procedures, and construction methods are clearly organized and managed should lead to a better understanding of CLSM performance and lead to more widespread use.

Summary

This chapter briefly described the history and background of CLSM, including information on relevant materials, mixture proportions, properties, and applications. A review of this information highlights some of the key research needs that existed prior to conducting the research described in the remainder of this report:

- Lack of standardized test methods, specifications, and construction guidelines for CLSM
- Concerns over long-term strength gain (and impact on excavatability)
- Potential concerns over long-term durability of CLSM, especially related to corrosion of utilities

It is hoped that the findings from this project (highlighted in Chapters 3 and 4) will help fill some of the gaps in understanding related to CLSM and will lead to an increase in CLSM usage in a range of transportation applications.

CHAPTER 3

Laboratory Testing Program

Introduction

The key objectives of the laboratory component of this project were to identify the most important CLSM properties affecting performance in the four target applications (backfill, utility bedding, void fill, and bridge approaches), to develop and recommend a suite of test methods to assess these properties, and to understand what CLSM characteristics (e.g., materials, mixture proportions) most impact performance. This chapter summarizes the key findings of the laboratory study performed under NCHRP Project 24-12(01) and is aimed at meeting the above objectives.

Information on the research approach, constituent materials, mixture proportions, and test methods are described in this chapter. A more comprehensive summary of this laboratory testing was provided in the NCHRP Project 24-12(01) Interim Report (Folliard et al. 2001). In addition, more detailed information on the corrosion testing and service life estimation models is provided in Appendix A. The main findings of this laboratory component, coupled with the field testing program (Chapter 4), led to the development of appropriate test methods (Appendix B), recommended specifications (Appendix C), and recommended practices (Appendix D).

Research Approach

As a precursor to the laboratory program, the important (or potentially important) CLSM properties were identified that may impact performance in the four target applications. These properties are identified in Table 3.1.

Based on the application-specific properties listed in Table 3.1 and combined with a synthesis of available literature, a general classification of CLSM properties was developed, whereby the various CLSM properties of interest were grouped into three categories (important, potentially important, and less important):

I. **Important CLSM properties**
  - Flow
  - Setting time
  - Unconfined compressive strength
  - Corrosion

II. **Potentially important CLSM properties**
  - Excavatability
  - Subsidence
  - Freezing and thawing
  - Segregation and bleeding
  - Triaxial shear
  - CBR
  - Resilient modulus
  - Water permeability
  - Drying shrinkage
  - Leaching/environmental impact

III. **Less important CLSM properties**
  - Direct shear strength
  - Air/gas permeability
  - Consolidation
  - Thermal conductivity

The general classification of the properties by relative importance, as shown above, was then used in developing the laboratory testing program described in this chapter, resulting in significant efforts being placed on evaluating the "important" properties, less emphasis being placed on the "potentially important" properties and no laboratory testing centered on the "less important" properties. Information on specific materials and mixture proportions is provided next, followed by discussion on the overall testing matrix, which was developed using the classification of the CLSM properties by relative importance.

Materials

A range of materials, summarized in Table 3.2, was selected for inclusion in the laboratory study to ensure widespread applicability of test results. General information about the

Table 3.1. CLSM applications and relevant properties.

CLSM Application	Important Properties	Potentially Important Properties
Backfill	Flow Compressive strength Excavatability Hardening time Settlement Corrosion of metal utilities Subsidence	Freeze-thaw resistance Leaching and environmental impact
Utility bedding	Flow Compressive strength Hardening time Corrosion of metal utilities	Freeze-thaw resistance Leaching and environmental impact Thermal conductivity
Void fill	Flow Subsidence Settlement	Unconfined compressive strength
Bridge approaches	Flow Compressive strength Hardening time Shear strength Resilient modulus/CBR Settlement Freeze-thaw resistance	Leaching and environmental impact

portland cement and the three fly ashes (Class F, Class C, and high carbon) used is provided in this table, and more specific information about the chemical and physical properties of these materials can be found in the NCHRP Project 24-12(01) Interim Report (Folliard et al. 2001). Three types of fine aggregates were used throughout this project: concrete sand conforming to ASTM C 33, foundry sand especially blended for CLSM, and bottom ash passing a No. 4 (4.75 mm) sieve. Figure 3.1 compares the gradations of the three materials. The concrete sand meets the requirements of ASTM C 33 but approaches the coarse limit of the gradation band. The bottom ash was found to be slightly coarser and the foundry sand slightly finer than the ASTM C 33 gradation limits.

Mixture Proportions

Based on a survey of current practice (performed as part of the original NCHRP Project 24-12), the most common types of CLSM mixtures were selected for the laboratory study. These common mixture types were further delineated by defining a range of typical proportions (e.g., 30 to 60 kg/m^3 of portland cement). For convenience, the mixtures selected for the laboratory study can be classified as follows:

- **CLSM (with fine aggregates)**
  - Type I portland cement: 1 type, 2 levels (30 kg/m^3, 60 kg/m^3)
  - Fly ash: 3 types, 3 levels (0 kg/m^3, 180 kg/m^3, 360 kg/m^3)
  - Fine aggregate: 3 types, 1 level (1500 kg/m^3)
  - Air content: 3 levels (entrapped air only, 15% to 20% air, 25% to 30% air) (Air-entraining agents were not used for CLSM containing fly ash)
- **CLSM (without fine aggregates)**
  - Type I portland cement: 1 type, 1 level (60 kg/m^3)
  - Fly ash: 3 types, 1 level (1200 kg/m^3)
  - Air content: 1 level (entrapped air only)
- **CLSM (with set accelerator)**
  - Selected mixtures from the test matrix

Table 3.2. Materials included in the laboratory program.

Material[a]	Description
Portland cement	ASTM C 150 Type I (S.G.=3.15)
Fly ash	ASTM C 618 Class F (CaO=1.6%, LOI = 2.9%, S.G.=2.41) ASTM C 618 Class C (CaO=26.7%, LOI = 0.37%, S.G.=2.51) High-carbon fly ash (CaO=6.0%, LOI = 14.44%, S.G.=2.09)
Fine aggregate	ASTM C 33 concrete sand (S.G.=2.60, Absorption=1.0%, FM = 3.0) Foundry sand (ferrous) (S.G.=2.36, Absorption=5.6%, FM = 2.14, LOI=4.5%) Bottom ash[b] (S.G.= 2.28, Absorption = 8.9%, FM = 2.89)
Chemical admixtures	Air-entraining agent (liquid, designed specifically for CLSM) Accelerating admixture (non-chloride)

[a] More information on these materials can be found in NCHRP Project 24-12(01) Interim Report (Folliard et al. 2001).

[b] Bottom ash is classified as a fine aggregate because of similar particle size.

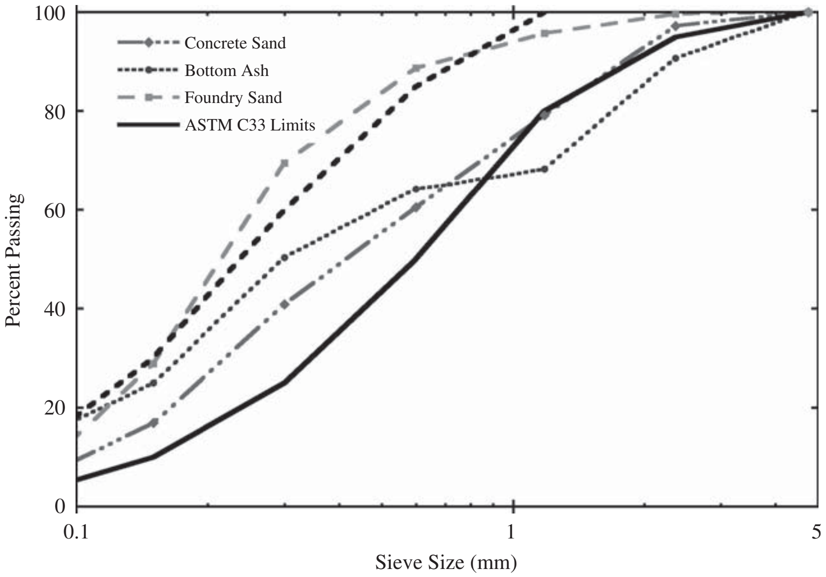


Figure 3.1. Gradations of aggregates used in study.

For each of these mixtures defined above, the types and amounts of cement, fly ash, and aggregates were selected prior to mixing (as described later), and the water content of each mixture was then adjusted to achieve a flow of 200 to 250 mm, as measured by ASTM D 6103. The 38 mixtures included in the initial laboratory study were classified and tested according to their expected ability to provide information on the following three groups of CLSM properties (based on expected level of importance):

- I. **Important CLSM properties** (flow, setting time, unconfined compressive strength, and corrosion)
  - – Measured for all *38* mixtures in initially proposed Phase I study
- II. **Potentially important CLSM properties** (excavatability, subsidence, freezing and thawing, segregation and bleeding, triaxial shear, CBR, resilient modulus, water permeability, drying shrinkage)
  - – Measured for selected mixtures only (6)
  - – Only "order of magnitude" values sought
- III. **Less important CLSM properties** (direct shear strength, air/gas permeability, consolidation, thermal conductivity, leaching/environmental impact)
  - – Not included in laboratory study
  - – Literature-based and existing-practice–based coverage only

After selecting representative materials and a range of mixture proportions, as previously defined, a statistical software program (ECHIP) was used to generate the majority of the mixtures within the test matrix. This software uses experimental design concepts to produce statistically significant results with a minimal number of trials. In other words, rather than producing CLSM with every possible combination of material and dosage, which would not be feasible, an optimized test matrix was produced that could be used to predict test results across the entire spectrum of variables. In addition, the program can be used to statistically compare the results of one test to another or the effects of individual or combined variables on test results. The program was also designed to assess the repeatability of test results by requiring duplication of certain mixtures within the test matrix.

Initially, two separate mixture series were generated using the statistical software: one for non–air-entrained CLSM (with fly ash) and one for air-entrained CLSM (without fly ash). The non–air-entrained mixtures are shown in Table 3.3 (a mixture number followed by "r", such as 1r, denotes a mixture repeated or duplicated for statistical purposes).

The air-entrained mixtures originally proposed for study were selected using the statistical software, but after difficulties were encountered in generating entrained air in certain mixtures, the decision was made to include mixtures covering all of the selected variables. That is, two cement contents (30 kg/m^3 and 60 kg/m^3), two target air contents (15 to 20 percent and 25 to 30 percent), and two aggregate types (concrete sand and bottom ash) were used in all combinations to create a total of eight mixtures. From these eight mixtures, three were selected for replicate mixtures, bringing the total number of air-entrained mixtures to eleven, as shown in Table 3.4.

The mixtures shown in Table 3.5 were strategically chosen to investigate specific mixture types of interest to the research team. The mixtures represented typical CLSM paste mixtures

Table 3.3. Non–air-entrained CLSM mixture proportions (using statistical software)[a].

Mixture	Cement Content (kg/m^3)	Fly Ash Type[b]	Fly Ash Content (kg/m^3)	Fine Aggregate Type[c]	Water Demand (kg/m^3)	Flow (cm)	Total Bleeding (%)	Air Content (%)	Fresh Density (kg/m^3)
1	30	C	180	CS	211	20.0	NA	0.9	1965
2	60	C	180	CS	206	20.0	2.45	1.0	2108
1r	30	C	180	CS	206	21.0	2.08	0.9	1974
15	30	C	360	FS	486	20.0	0.13	2.8	1741
3	60	C	360	BA	577	17.8	4.32	1.7	1754
8	60	HC	180	FS	532	24.1	1.04	3.3	1647
10	30	HC	180	BA	628	14.0	4.81	2.0	1681
9	60	F	360	FS	520	20.0	0.54	2.5	1684
5	60	F	180	BA	600	17.8	5.84	2.5	1739
12	30	C	360	BA	572	21.6	3.64	2.7	1774
4	30	F	360	CS	220	20.0	0.39	2.2	2199
7	30	F	180	FS	501	20.0	0.57	2.1	1817
3r	60	C	360	BA	541	20.0	2.58	2.1	1997
4r	30	F	360	CS	220	21.6	2.92	1.8	2211
13	60	C	360	FS	499	20.0	0.00	1.8	1902
5r	60	F	180	BA	600	16.0	7.20	1.4	1887
14	60	F	360	CS	216	21.6	1.00	1.3	2174
2r	60	C	180	CS	206	25.0	0.21	0.5	2291
11	60	HC	360	BA	573	23.0	6.42	1.7	1743
6	30	HC	360	CS	315	20.0	2.26	1.3	2103

[a] *ECHIP randomizes order of mixtures and provides for duplicates*

[b] *C = Class C, HC = High Carbon, F = Class F.*

[c] *CS = Concrete Sand, FS = Foundry Sand, BA = Bottom Ash. Fine aggregate content was held constant at 1500 kg/m^3.*

(i.e., 5 percent cement, 95 percent fly ash) and also included mixtures containing an accelerating admixture. Lastly, this table includes non–air-entrained CLSM mixtures containing foundry sand (selected after the difficulties encountered in entraining air in mixtures containing foundry sand).

After casting and testing the initially proposed mixtures (as summarized in Tables 3.3 to 3.5), additional mixtures were cast to further investigate or refine selected test methods or to study selected CLSM properties in more detail. The mixtures were based in most cases on previously cast mixtures (from the original 38 mixtures), but there were other mixtures, such as rapid-setting CLSM containing only Class C fly ash as a binder, that were included to better reflect current practice in some parts of the country. Nine sets of additional mixtures were cast and will be referred to throughout this report by as mixture series A through I, as summarized in Table 3.6. Because the compressive strength of CLSM is the most common property measured (and often the only

Table 3.4. Air-entrained CLSM mixture proportions.

Mixture	Cement Content (kg/m^3)	Fly Ash Type[b]	Fine Aggregate Type[c]	Water Demand (kg/m^3)	Flow (cm)	Total Bleeding (%)	Air Content (%)	Fresh Density (kg/m^3)
18	60	None	CS	200	21.6	0.70	16.5	1836
17[a]	30	None	BA	582	12.7	4.35	20.0	1447
16	30	None	CS	295	20.0	2.33	16.0	1922
21	30	None	CS	170	18.0	0.62	25.5	1789
22	60	None	CS	131	20.0	0.05	26.5	1748
22r	60	None	CS	136	18.0	0.43	25.5	1802
16r	30	None	CS	295	19.1	2.35	15.5	1874
19[a]	30	None	BA	492	13.0	1.08	25.0	1385
20[a]	60	None	BA	525	13.0	3.41	18.5	1485
23	60	None	BA	454	14.0	1.30	28.5	1382
20r	60	None	BA	525	13.0	1.44	15.5	1511

[a] *These mixtures were substituted for the originally proposed mixtures because of extreme difficulty in entraining air in mixtures containing foundry sand. The originally proposed mixtures containing foundry sand were still cast, but without entrained air.*

[b] *Fly ash was not used for these mixtures.*

[c] *Fine aggregate content was held constant at 1500 kg/m^3. CS = Concrete Sand, BA = Bottom Ash.*

Table 3.5. Additional CLSM mixtures.

Mixture	Cement Content (kg/m^3)	Fly Ash Type[b]	Fly Ash Content (kg/m^3)	Fine Aggregate Type[c]	Water Demand (kg/m^3)	Flow (cm)	Total Bleeding (%)	Air Content (%)	Fresh Density (kg/m^3)
25	60	HC	1200	None	853	24.0	7.38	1.3	1322
27	60	F	1200	None	486	23.0	1.28	0.7	1638
28[a]	60	F	180	CS[d]	220	20.0	1.33	1.4	2182
29[a]	60	None	0	FS[d]	373	23.0	0.28	2.6	1812
24	60	F	1200	None	486	24.0	2.25	2.8	1635
30[a]	30	None	0	FS[d]	414	20.0	0.40	2.0	1789
26[a]	60	None	0	CS[d]	136	16.5	0.00	25.5	1802

[a] *Mixtures contain accelerating admixture.*
[b] *HC = High Carbon, F = Class F*
[c] *CS = Concrete Sand, FS = Foundry Sand*
[d] *Fine aggregate content was held constant at 1500 kg/m^3.*

hardened property measured), the research team placed particular emphasis on developing a refined test that is more reliable and reproducible. Issues such as load rate, curing condition, temperature effects, and capping methods were studied in detail. The development of an improved compressive strength test method is also critical because of the inclusion of strength in most specifications, especially as in relation to excavatability.

Tables 3.7 through 3.15 show the mixture proportions, along with selected fresh properties, for the additional investigations. To be consistent with the initial mixtures that contain aggregates, the aggregate content was held constant at 1500 kg/m^3. These tables also contain some information on fresh CLSM characteristics and in some cases data are provided on properties, such as compressive strength. The findings of these investigations are provided in more detail later in this chapter.

Because of relevance to field applications and based on important findings related to corrosion of ductile iron specimens embedded in the initial 38 CLSM mixtures, an expanded and detailed long-term corrosion study was performed (Phase II). In Phase II, additional CLSM mixtures were prepared and different corrosion scenarios were evaluated. The mixture proportions and fresh properties for the mixtures in Phase II are shown in Table 3.16.

Testing Program

Overview

This section provides information on the test methods used. Test methods are grouped into three categories based on the characteristics that they are intended to measure; fresh properties, hardened properties, and durability characteristics. Some characteristics were studied in more detail than others. A summary of the measured characteristics and used methods is provided in Table 3.17.

Mixing Procedure

Trial mixing was performed for the initial 38 mixtures to determine their approximate water demand for a target flow of 200 to 250 mm. Flow was measured following ASTM D 6103.

After determining the quantities of water for the target flow, the actual mixtures were cast and test samples were prepared. For the smaller mixture volumes, a 0.028 m^3 drum mixer was used. For the larger mix volumes (needed for measuring additional characteristics on the selected mixtures), a high-capacity (0.056 to 0.070 m^3) laboratory mixer was used.

Mixing procedures were different for non–air-entrained and air-entrained mixtures. For non–air-entrained mixtures,

Table 3.6. Mixture series and their descriptions.

Mixture Series	Description	Number of Mixtures
A	Effects of load rate on compressive strength (Table 3.7)	7
B	Effects of curing and air drying on compressive strength (Table 3.8)	2
C	Long-term strength gain and excavatability (Table 3.9)	9
D	Freeze-thaw resistance (Table 3.10)	11
E	Alternative capping materials for compression cylinders (Table 3.11)	18
F	Effects of drainage on compression cylinders (Table 3.12)	8
G	Effects of storage conditions on compressive strength (Table 3.13)	10
H	Effects of temperature and humidity on compressive strength (Table 3.14)	6
I	Permeability and triaxial shear strength (Table 3.15)	6

Table 3.7. Mixture proportions for load rate study.

Mixture	Cement Content (kg/m^3)	Fly Ash Type[a]	Fly Ash Content (kg/m^3)	Fine Aggregate Type[b]	Water (kg/m^3)	Flow (mm)	Air Content (%)	Density (kg/m^3)
A-1	60	None	0	CS	156	175	25.0	1739
A-2	60	F	360	FS	520	200	1.9	1755
A-3	60	F	1200	None	486	213	1.6	1620
A-4	30	C	180	CS	265	330	1.7	2161
A-5	30	C	180	CS	213	216	–[c]	2226
A-6	60	F	1200	None	501	216	–[c]	1635
A-7	60	None	0	CS	156	165	24.5	1740

[a] *F = Class F, C = Class C.*
[b] *CS = Concrete Sand, FS = Foundry Sand.*
[c] *Too low to measure.*

Table 3.8. Mixture proportions for cylinder curing/conditioning study.

Mixture[a]	Cement Content (kg/m^3)	Fly Ash Type	Fly Ash Content (kg/m^3)	Fine Aggregate Type[b]	Water (kg/m^3)	Flow (mm)
B-1	30	Class C	180	CS	203	250
B-2	30	Class C	180	CS	189	200

[a] *B-1 and B-2 were cast on different days and different water contents were used to obtain the desired flow.*
[b] *CS = Concrete Sand.*

Table 3.9. Mixture proportions used for excavation boxes and companion samples.

Mixture	Cement (kg/m^3)	Sand Content (kg/m^3)	Fly Ash Content (kg/m^3)	Fly Ash Type[a]	Water (kg/m^3)	Flow (mm)	Air Content (%)	Density (kg/m^3)
C-1	60	None	1195	F	485	200	Entrapped	1637
C-2	0	2000	275	C	252	229	Entrapped	2148
C-3	30	1500	0	None	112	178	28.0	1642
C-4	15	1500	180	F	177	200	Entrapped	2192
C-5	30	1500	180	F	175	200	Entrapped	2158
C-6	15	1500	180	HC	224	216	Entrapped	2095
C-7	30	1500	180	HC	224	216	Entrapped	2115
C-8	15	1500	180	C	170	206	Entrapped	2190
C-9	45	1500	0	None	103	178	25.5	1652

[a] *F = Class F, C = Class C, HC = High Carbon.*

Table 3.10. Mixture proportions used for freezing and thawing study.

Mixture	Cement (kg/m^3)	Fine Aggregate Type[a]	Fly Ash Type[b]	Water (kg/m^3)	Flow (mm)	Air (%)	Density (kg/m^3)	28-Day Strength (MPa)
D-1	30	CS	None	119	180	27.0	1630	0.13
D-2	30	CS	F	205	200	Entrapped	2196	1.02
D-3	30	CS	HC	256	229	Entrapped	2078	0.79
D-4	30	CS	C	200	216	Entrapped	1980	1.47
D-7	30	FS	F	425	238	Entrapped	1835	0.11
D-6	30	FS	HC	481	229	Entrapped	1757	0.12
D-5	30	FS	C	399	200	Entrapped	1800	0.20
D-8	30	BA	F	357	200	Entrapped	1870	0.38
D-9	30	BA	HC	407	200	Entrapped	1733	0.25
D-10	30	BA	C	282	200	Entrapped	1896	0.53
D-11	45	CS	None	96	152	30.0	1569	0.34

[a] *CS = Concrete Sand, FS = Foundry Sand, BA = Bottom Ash. Fine aggregate content was 1500 kg/m^3.*
[b] *F = Class F, HC = High Carbon, C = Class C. When included, fly ash content was 180 kg/m^3*

Table 3.11. Mixture proportions for alternative capping materials study.

Mixture	Cement Content (kg/m^3)	Fly Ash Type[a]	Fly Ash Content (kg/m^3)	Concrete Sand (kg/m^3)	Water (kg/m^3)	Flow (mm)	Air[d] (%)	Density (kg/m^3)
E-1	60	F	1140	None	480	200	1.4	1630
E-2	None	C	180	2000	250	200	1.2	1626
E-3	30	None	0	1500	109	175	29.0	1651
E-4	15	F	180	1500	184	200	1.7	1693
E-5	30	F	180	1500	176	200	2.5	2180
E-6	15	HC	180	1500	202	200	1.8	2122
E-7	30	HC	180	1500	229	225	E	2136
E-8	15	C	180	1500	179	200	1.8	2235
E-9	30	C	180	1500	238	21	E	2176
E-10	15	F	180	1500	241	19	E	2130
E-11	60	None	0	1500	153	18	29.1	1622
E-12	60	F	1200	0	500	22	E	1602
E-13	0	C	224	1672	165	19	4.0	2179
E-14	30	None	0	1500	130	20	29.5	1539
E-15	60	None	0	1500	130	22	28.5	1539
E-16	60	F	1200	0	485	42[b]	1.0	1795
E-17	30	F	180	1500	175	10[c]	2.3	2051
E-18	60	F	180	1500	175	14[c]	2.5	2083

[a] *F= Class F, C = Class C, HC = High Carbon.*
[b] *Difficult to obtain adequate flow by simply adding water.*
[c] *Too much water included in the mixture.*
[d] *E = Entrained.*

Table 3.12. Mixture proportions for drainage condition study.

Mixture	Cement Content (kg/m^3)	Fly Ash Type[a]	Fly Ash Content (kg/m^3)	Concrete Sand (kg/m^3)	Water (kg/m^3)	Flow (mm)	Total Bleeding (%)	Air Content (%)[b]	Fresh Density (kg/m^3)
F-1	60	F	1140	None	480	200	2.30	1.4	1630
F-2	None	C	180	2000	250	200	0.00	1.2	1626
F-3	30	None	0	1500	109	175	0.00	29.0	1651
F-4	15	F	180	1500	184	200	2.07	1.7	1693
F-5	30	F	180	1500	175	200	0.87	–	2170
F-6	15	HC	180	1500	224	213	2.50	–	2100
F-7	30	HC	180	1500	224	225	3.04	–	2142
F-8	15	C	180	1500	170	200	0.85	–	2218

[a] *F = Class F, C = Class C, HC = High Carbon.*
[b] *"–" = too low to measure.*

Table 3.13. Mixture proportions for cylinder storage study.

Mixture	Cement (kg/m^3)	Fly Ash Content (kg/m^3)	Fly Ash Type[a]	Fine Aggregate Type[b]	Water (kg/m^3)	Flow (mm)	Air content[c] (%)
G-1	60	1140	F	None	485	200	E
G-2	0	275	C	CS	252	200	E
G-3	30	0	None	CS	112	187	29.0
G-4	15	180	F	CS	177	200	E
G-5	30	180	F	CS	175	200	E
G-6	45	0	None	CS	103	190	30.0
G-7	30	180	F	FS	349	216	E
G-8	30	180	C	FS	352	190	E
G-9	30	180	F	BA	424	140	E
G-10	30	180	C	BA	367	152	E

[a] *F= Class F, C = Class C.*
[b] *Fine aggregate content was 1500 kg/m^3. Only G-2 had 2000 kg/m^3. CS = Concrete Sand, FS = Foundry Sand, BA = Bottom Ash.*
[c] *E = Entrained air.*

Table 3.14. Mixture proportions for the temperature and drying effects study.

Mixture	Cement Content (kg/m^3)	Fly Ash Type[a]	Fly Ash Content (kg/m^3)	Concrete Sand (kg/m^3)	Water (kg/m^3)	Flow (mm)	Air Content (%)	Density (kg/m^3)
H-1	60	F	1200	None	492	220	2.4	1631
H-2	15	F	240	1500	197	240	1.2	2191
H-3	15	C	240	1500	175	240	1.4	2212
H-4	30	C	180	1500	181	200	1.2	2163
H-5	30	F	180	1500	188	220	1.4	2210
H-6	60	None	0	1500	123	190	25.5	1603

[a] *F= Class F, C = Class C.*

dry materials (fine aggregate, fly ash, and cement) were first mixed with approximately half of the expected mixing water (based on trial mixing) for 3 minutes, followed by a 2-minute rest period. After the rest period, the remainder of the batched water was added, followed by 3 additional minutes of mixing. Immediately after mixing, flow measurements were taken. In most cases, because of the benefit of trial mixing, the target flow of 200 to 250 mm was obtained. If the flow was less than desired, small amounts of water were added, followed by an additional minute of mixing to obtain the target flow. For some mixtures the desired minimum flow was difficult to achieve because of tendencies for bleeding and segregation. In those cases flow values less than 200 mm were accepted.

For mixing air-entrained CLSM, mixing water was held back and a relatively dry consistency (i.e., zero slump) mixture was obtained in the mixer. An AEA specifically formulated for CLSM was then added with additional water. This process was necessary because of the high potency of the AEA. If the AEA was added to an already fluid mixture, the flow would far exceed the desired range and the mixture would often suffer from excessive bleeding. The researchers found obtaining both the desired flow and air content to be challenging (but generally feasible).

The researchers did not focus on optimizing the mixture proportions for optimal workability (i.e., flow, bleeding, etc.); the main objective was to obtain valid and direct comparisons of constituent material types and contents. However, with high amounts of fines and/or air entrainment, selected mixtures can be modified to obtain desired workability levels. For example, introducing additional fly ash to CLSM containing bottom ash has been shown by the researchers (and others) to be an effective method of reducing segregation and bleeding while maintaining the required workability.

Fresh CLSM Test Methods

Flow

Immediately after mixing, the flow was measured following ASTM D 6103. This method, which measures the diameter of a CLSM "pancake" after a 75 × 150 mm cylinder is slowly lifted, was found to be generally easy to perform and was also quite reproducible.

Air Content and Unit Weight

ASTM C 231 (pressure method), which is typically used for conventional concrete, was used, with slight modification, to measure the air content and unit weight of fresh CLSM mixtures. The only modification was that the material was placed in one layer without rodding, instead of being placed in three equal layers and then consolidated.

Setting Time and Bleeding

Setting and hardening of CLSM mixtures were evaluated using three methods: needle penetration (ASTM C 403), soil penetrometer (or "pocket" penetrometer), and pocket vane

Table 3.15. Mixture proportions for triaxial shear and water permeability studies.

Mixture	Cement (kg/m^3)	Fly Ash (kg/m^3)	Sand (kg/m^3)	Water (kg/m^3)	Flow (mm)	Air Content (%)	Fresh Density (kg/m^3)	Dry Density (kg/m^3)	Moisture Content (%)
I-1	30	180	1500	283	200	1.3	2036	1746	16.55
I-2	60	180	1535	327	210	1.3	2077	1748	18.79
I-3	120	180	1485	335	220	0.7	2087	1759	18.61
I-4	60	0	1471	212	190	22.5	1607	1415	13.59
I-5	60	0	1181	172	210	27.0	1569	1381	13.65
I-6	60	1200	0	500	200	0.5	1529	1133	35.00

Table 3.16. CLSM mixtures for corrosion study and their fresh properties.

Mixture	Cement (kg/m^3)	Fine Aggregate Type[a, b]	Fly ash (kg/m^3)	Fly Ash Type[a, c]	Water (kg/m^3)	Flow (mm)	Air Content (%)	Density (kg/m^3)
A1a	63	CS	1200	F	184	209	1.5	1605
A1b	63	–	1200	F	432	203	1.3	1591
A1c	63	–	1200	F	515	200	1.0	1605
A2a	–	S	206	C	134	200	1.5	2177
A2b	–	S	206	C	200	305	0.6	2180
A3a	30	CS	–	–	98	178	30.0	1602
A3b	30	S	–	–	118	200	25.0	1695
A3c	30	S	–	–	112	200	29.0	1593
A4a	15	CS	180	F	190	216	1.5	2194
A4b	15	S	180	F	204	229	1.3	2169
A4c	15	S	180	F	196	216	1.5	2167
A5a	30	CS	180	F	184	203	2.0	2185
A5b	30	S	180	F	188	203	2.3	2163
A5c	30	S	180	F	170	225	1.0	2177
A6a	15	CS	180	HC	190	210	2.0	2115
A6b	15	S	180	HC	224	203	2.0	2097
A6c	15	S	180	HC	216	206	1.0	2084
A7a	30	CS	180	HC	232	203	2.3	2099
A7b	30	S	180	HC	232	203	1.3	2111
A7c	30	S	180	HC	214	206	1.8	1978
A8a	15	CS	180	C	168	216	4.8	2155
A8b	15	S	180	C	168	216	1.8	2220
A8c	15	S	180	C	174.4	200	1.5	2179
B4a	30	CS	180	C	186	216	4.8	2170
B4b	30	S	180	C	144	216	1.3	2225
B4c	30	S	180	C	184	200	1.8	2228
B6a	30	CS	180	HC	472	209	2.3	1753
B6b	30	FS	180	HC	494	203	1.8	1765
B6c	30	FS	180	HC	524	200	1.5	1750
B7a	30	FS	180	C	484	222	1.5	1795
B7b	30	FS	180	C	426	229	3.0	1848
B9a	15	BA	180	HC	324	165	1.8	1821
B9b	30	BA	180	HC	324	145	2.8	1760
B10a	30	BA	180	C	318	175	1.5	1852
B10b	30	BA	180	C	318	200	2.0	1848

[a] *“–” indicates that this item was not used in the mixture.*

[b] *Fine aggregate content was kept constant 1500* kg/m^3*. CS = Concrete Sand, S= Sand, FS = Foundry Sand, BA = Bottom Ash.*

[c] *F = Class F, C = Class C, HC = High Carbon.*

shear testing. The setting and hardening of fresh CLSM samples that were placed in 150 × 150 mm containers were measured using a needle penetrometer and a soil penetrometer. A larger container was used for measurements using the vane shear tester. Before each measurement, the bleed water was removed and weighed.

Depth of penetration for the needle penetrometer and the soil penetrometer was approximately 25 mm and 6.4 mm, respectively. The pocket vane shear tester only measures the shear resistance of CLSM at the upper 3 mm layer.

Segregation

The segregation of six selected CLSM mixtures was measured quantitatively. A specially designed mold, which consisted of three separate cylindrical sections, was used for this purpose. Each cylindrical section had a diameter of 100 mm and a height of 75 mm. The sections were connected vertically to produce a sample cylinder with a diameter of 100 mm and a height of approximately 225 mm. After the samples had set, steel plates, acting as “guillotines,” were inserted at the junctions between the cylinder sections, thus yielding three separate samples (upper, middle, and lower). Each sample was then wet sieved, using the No. 4, No. 8, No. 16, No. 30, No. 50, No. 100, and No. 200 sieves. Each portion retained on these sieves was then dried in the oven at 110°C for 24 hours and weighed. Material passing the No. 200 sieve was not collected. Using the resultant gradation from each of the three sections, a “pseudo” fineness modulus (FM) was calculated, using the same mathematical approach as typically

Table 3.17. Overview of laboratory testing program.

CLSM Characteristic	Initial Study	Additional Studies
Flow	ASTM D 6103	
Setting/ hardening time	ASTM C 403	Soil pocket penetrometer
		Pocket torvane
Compressive strength	ASTM D 4832	Sample size effect
		Small vs. large machine
		Loading rate
		Effect of drying samples
		Alternative capping materials
		Effects of drainage
		Curing methods, conditions
CLSM vs. sand	ASTM G 1	
Galvanic cells	ASTM G 1, modified G 109	
pH	ASTM G 51	
Resistivity	ASTM G 57	
Segregation, bleeding	ASTM C 940	
Subsidence	No Standard	
Triaxial shear strength	USACE EM 1110-2-1906	
California bearing ratio	AASHTO T 193	
Resilient modulus	AASHTO T 292	
Water permeability	ASTM D 5084	
Drying shrinkage	No standard	
Excavatability	No standard	Splitting tensile strength
Chloride diffusion	ASTM C 1152	
Freezing and thawing	ASTM D 560	Effects on permeability
Direct shear strength	None	
Thermal conductivity	None	
Air/gas permeability	None	
Consolidation	None	
Leaching	None	Chemical and toxicity analyses

used for determining the FM of the fine aggregate. As is the case with the normal treatment of FM, two different gradations can yield the same FM. Therefore, the overall gradation was also considered when the results were analyzed, as described later. Details of this test method can be found in Appendix B.

Subsidence

The surface settlement of a 100 × 600 mm cylindrical CLSM sample was monitored with time. The mold was prepared by stacking three 100 × 200 mm molds. A PVC pipe is also a good alternative. A small device to facilitate accurate measurement of the surface height changes was developed, as described in Appendix B.

Hardened CLSM Test Methods

Unconfined Compressive Strength

Because of the importance of the compressive strength of CLSM in specifications, design, and construction, considerable effort was placed in developing a test method with improved accuracy and reliability, and upon developing this method, work was done to better understand the effects of materials and mixture proportions on CLSM strength. This section describes the basic procedures followed to test the unconfined compressive strength of the initial 38 mixtures, including methods of preparing test cylinders, curing, capping, and testing. After describing this approach, information is provided on the various modifications and improvements investigated using the mixtures previously shown in Tables 3.7 through 3.15. The results of the initial compressive strength study, as well as the findings of the various follow-up studies, were used to develop and recommend an improved unconfined compression test for CLSM, as presented in Appendix B.

Because the strength of CLSM is relatively weak (compared to concrete), careful handling of the test cylinders is necessary, especially when stripping the cylinders from the molds. Therefore, plastic cylinder molds were pre-cut down the sides (two vertical cuts from top to bottom on opposite sides of the cylinder) and taped closed. After the CLSM was mixed, the cylinders were filled, while being tapped lightly on the sides to remove large entrapped air voids. Plastic lids were then placed firmly on the cylinders, and the specimens were moved immediately to the moist-curing or “fog” room, which was maintained at 100 percent relative humidity (RH) and 23°C. For most of the mixtures tested, the cylinders were kept in the molds for 7 days (or less for tests performed at earlier ages) and were then stripped by simply removing the tape and removing the CLSM specimens from the cylinders. Conventional stripping tools were not used because of possible damage to the specimens. The cylinders were then kept outside of their molds in the fog room until testing. Some CLSM mixtures tend to leach and soften upon long-term fog-room exposure. Further studies on this issue and other cylinder storage issues are described later in this chapter.

Moist curing was selected for this study so that test results can be compared from one laboratory to another, even though CLSM is rarely, if ever, moist cured in the field. The same argument can also be presented for concrete testing. That is, concrete is rarely moist cured for more than 7 days (if at all) in field applications, but standard curing in a fog room provides a benchmark for specification and construction acceptance.

Although an ASTM method currently exists for measuring the unconfined compressive strength of CLSM (ASTM D 4832), some modifications were made to the method for this project, as described later. Most of the compression tests were performed on a relatively low-load capacity machine

(100 kN Instron), but some testing was also performed on a larger capacity machine (1780 kN Tinius Olson) to evaluate the effects of machine capacity. When using the smaller machine, displacement control was used. Additional testing was performed to examine the effects of cylinder size (75 × 100 mm, 100 × 200 mm, and 150 × 300 mm), using a constant apparent strain rate. For this testing, the crosshead displacement was set at 0.38 mm/min for the 100 mm high specimen, 0.51 mm/min for the 200 mm high specimen, and 0.76 mm/min for the 300 mm high specimen. The objective was to produce failure in about the same amount of time for each cylinder size for a given mixture. A floating, spherical head was used to minimize eccentricities in loading.

For the larger capacity compression machine, load-controlled testing was employed, as is the case for concrete testing. The typical load rates used for concrete, 138 to 345 kPa/s, would fail most CLSM specimens in a matter of seconds. Thus, a lower load rate was selected (6.9 kPa/s). This lower load rate was possible on the machine for this study but may not be available for many standard concrete compression machines.

Sulfur capping was used for almost all of the cylinders, except for some weaker mixtures at early ages where use of sulfur caps was not possible. For these mixtures, neoprene pads were used. As previously mentioned, several variations were investigated for the unconfined compressive test, including cylinder size, machine capacity, capping method, load rate, and curing. A description of these investigations is presented next, and the findings are included later in this chapter.

Effects of Loading Rate on Compressive Strength. ASTM D 4832 gives little guidance regarding load rate, stating only to "Apply the load at a constant rate such that the cylinder will fail in not less than 2 min." Because of the vagueness in defining the load rate, additional testing was performed to investigate the effects of loading rate on compressive strength. Using the seven CLSM mixtures summarized in Table 3.7, the effects of displacement rate (cross-head displacement of small load-frame) on compressive strength and deformation at peak load were studied. The following loading rates (or more accurately, deflection rates) were evaluated: 0.13 mm/min, 0.25 mm/min, 0.38 mm/min, 0.51 mm/min, and 0.89 mm/min. The aim was to determine a suitable load rate range that produces repeatable compressive strength values and can be performed in a relatively short time. The latter concern was because several mixtures from early research took a relatively long time (i.e., greater than 10 to 15 minutes) to fail in compression under displacement control, which would not be ideal for a testing laboratory that must test many cylinders daily.

Cylinder Curing and Conditioning. Another possible source of error and confusion in ASTM D 4832 involves the curing conditions and the treatment of cylinders before testing. According to ASTM D 4832, CLSM cylinders are cured in the molds (in the fog room) until the time of testing. This procedure is different from the normal concrete approach to stripping the cylinders from their molds after about the first day of curing and then curing them in the fog room. ASTM D 4832 also specifies test cylinders must undergo a drying time of 4 to 8 hours after their moist-curing period ends and before they are tested in compression. Concrete cylinders, on the other hand, are specified to remain moist until the time of testing, with no required drying time. Research was conducted to investigate the effects of cylinder storage (i.e., in or out of molds) and specimen conditioning or drying prior to testing.

To evaluate the effects of different curing (or specimen storage) regimes, the 10 mixtures in Table 3.13 (mixtures G-1 to G-10) were cast and test cylinders were prepared. This study aimed to identify possible differences in compressive strength when four different curing conditions were used, as summarized in Table 3.18. Curing condition A, described as "normal" in the table, was the method used most throughout this project, and curing condition C was identical to the method specified in ASTM D 4832. For curing condition D, the cylinders were placed outside the laboratory and were exposed to the high summer temperature and dry atmosphere of Austin, Texas. All cylinders were capped with sulfur capping compound and tested at a loading rate of 0.38 mm/min.

The mixtures listed in Table 3.8 were used to study the effects of drying time (0.5, 2, 4, and 8 hours) on strength values. Cylinders for this test were cured for various ages (7, 28, and 91 days) in a fog room, and then dried for the different time periods. The cylinders were then sulfur capped and tested in a deflection-controlled machine (0.38 mm/min).

Effects of Curing Temperature and Humidity on Compressive Strength. As already addressed, the temperature to which CLSM is exposed during its strength-gain process may be very important, especially when mixtures containing

Table 3.18. Additional curing regimes evaluated.

Curing Condition	Curing Regime
A (Normal)	Keep sample in mold with cap on, for 7 days in fog room. Then strip cylinder and keep cylinders in fog room until time of testing.
B (Mold)	Keep sample in mold, with cap on, for 7 days in fog room. Then remove cap and keep cylinder in mold in fog room until time of testing.
C (Cap)	Keep sample in mold, with cap on, in the fog room until time of testing.
D (Outside)	Keep sample in mold, with cap off, outdoors until time of testing.

certain fly ashes are used. Because CLSM is used in many different environments in practice, the same mixture proportions could exhibit different strength values. This study was intended to identify factors affecting strength gain of CLSM mixtures. This study was a follow-up to earlier testing that suggested that temperature plays a major role in CLSM strength development.

Three curing temperatures (10°C, 21°C, and 38°C) and six CLSM mixtures (H-1 to H-6 in Table 3.14) were selected to study the strength gain of CLSM across a range of practical construction conditions. CLSM was cast into standard cylinder molds (75 mm × 150 mm) and moved to the appropriate temperature-controlled chamber until the date of testing. The cylinders were stored in two different manners. Half the cylinders from each mixture were stripped after 3 days and returned to the same chamber until the time of testing (without control over relative humidity in the chamber). This condition is designated later in this report as "dry" curing. Temperature and humidity were monitored throughout the test. The other half of the specimens from a given mixture were kept inside the molds with the caps firmly placed on top until the day of testing (designated as "wet" curing). These cylinders were placed directly next to the cylinders that had already been stripped.

Cylinders were tested for compressive strength at 7, 28, and 91 days. The moisture contents of tested specimens were measured to assess the effects of curing conditions on the moisture content (or evaporable water content) and strength of CLSM.

Effects of Drainage Conditions on Compressive Strength. Unlike conventional concrete, CLSM is very rarely, if ever, cured. During the strength-gain process of CLSM, it is often continuously in contact with the surrounding soil and/or structure. Different environments may significantly affect the final strength of CLSM as the water-cement ratio may be affected by the seepage of water into surrounding materials or the loss of water through evaporation of bleed water.

The effects of seepage and evaporation were investigated in a study using the mixtures detailed in Table 3.12 (F-1 to F-8). This study also investigated the effects of temperature on strength gain, using the fog room as a control and ambient conditions (hot Texas summer weather) as a test condition. As described later in this report, the findings of this temperature effects study were quite interesting, and subsequent testing was performed using controlled-temperature environments to further elucidate the influence of temperature on CLSM strength, especially for mixtures containing high volumes of fly ash.

To simulate field conditions, plastic molds were buried in loose sand and CLSM mixtures were cast directly into the molds. Before the cylinders were cast, the plastic molds were subjected to different treatments to simulate various drainage conditions. To simulate the condition of no water loss, CLSM mixtures were cast in plastic molds without holes and tight lids were placed on the cylinders (condition "cap"). To simulate the condition that only surface water evaporation is possible, mixtures were cast in plastic molds without holes and lids (condition "no cap"). To simulate moderate water seepage, mixtures were cast into molds (without caps) with seven uniformly distributed 3.6 mm diameter holes on the bottom (condition "bottom holes"). To simulate a more severe drainage condition, mixtures were cast into molds with holes not only on the bottom but also on the side (condition "side holes"), again without caps being placed on the top of the cylinders. There were thirty-six holes on the walls and seven holes on the bottom per mold. All drilled holes were 3.6 mm in diameter. To avoid local effects, CLSM specimens from a given mixture were randomly placed throughout the test box.

Alternative Capping Materials for Compression Testing. In preliminary testing, as well as the testing of the initial 38 mixtures included in this study, sulfur capping was found to be an effective method of obtaining repeatable compressive strength data. However, for early age samples and/or for particularly low strength cylinders, it may not be possible to cap cylinders with sulfur because of the risk of specimen damage. Neoprene pads were used in these cases, but because only limited testing was performed, the researchers decided to significantly expand the scope of the original work to investigate a range of neoprene (or other) pads with varying properties.

It is well established that higher strength concrete requires higher neoprene durometer values, and vice versa. Thus, for CLSM, softer neoprene pads (much softer than those used for concrete) were expected to be needed. Other motivations for studying alternatives to sulfur capping are the potential health concerns over the fumes generated from sulfur capping stations and the length of time needed to cap cylinders with sulfur.

To address these important capping-related issues, a comprehensive investigation of alternative capping materials was launched. Included in this study were sulfur caps, gypsum (or hydrostone) caps, and neoprene pads with durometer values of 20, 40, 50, 60, and 70. In a previous study, Sauter and Crouch (2000) used soft neoprene pads made of wet-suit rubber to measure the compressive strengths of excavatable CLSM cylinders. This idea was extended under this project to examine soft non-neoprene rubber pads and two-layer systems. A commercially available sorbothane viscoelastic polyurethane rubber material was identified and chosen for this study. The Shore OO durometer hardness of this material is 50, which is approximately a Shore A durometer hardness of 5, according to the producer. Pads were single-layer rubber sheets with a thickness of 12.7 mm. In the early stages of this study, the researchers were concerned that the polyurethane pads may be too soft to dissipate the stress concentrations. As a result, a two-layer pad system was also tested, which consisted of polyurethane-neoprene (P-N) pads. Testing of samples included glued and unglued systems. The glued system used rubber cement to bond the polyurethane and neoprene. For comparison, neoprene pads, 13 mm thick, with a Shore A durometer hardness of 50 were also used in certain tests. Table 3.19 summarizes the variables tested in this program. Nine mixtures (E-series) were used in this study, as previously described in Table 3.11.

Excavatability

The excavatability of CLSM was assessed for six of the original thirty-eight CLSM mixtures to gain an "order of magnitude feel" for the relative ease of excavating various CLSM mixtures. CLSM was cast into 450 × 450 × 300 mm plywood boxes and allowed to harden. Attempts were made to correlate "walkability" with soil penetrometer values as the CLSM gained strength in the first few hours. Long-term excavatability was assessed at an age of approximately 9 months using typical hand tools, including a shovel and a pick for six selected mixtures. The compressive strength of laboratory-cured cylinders was also measured. In addition, a relatively new instrument, the Humboldt GeoGauge, was used at the time of excavation to attempt to correlate excavatability with the stiffness of CLSM, as measured by the GeoGauge.

After the initial excavation study, a more comprehensive study on long-term strength gain and excavatability was launched. Nine CLSM mixtures (C-1 to C-9 in Table 3.9) were included in the study. A field penetrometer (field version of ASTM C 403) was used to evaluate the strength gain of CLSM mixtures. The dynamic cone penetrometer (DCP) was also used to estimate the excavatability of CLSM mixtures. The DCP is a modified and simplified version of the penetrometer used by the Country Roads Board, Victoria, Australia. It is used by geotechnical engineers to obtain an index of in-situ CBR and to estimate the strength of soil as a function of depth. The testing consists of dropping a hammer (8 kg in weight) from a height of 575 mm, which forces a steel rod with a conical head into the CLSM or soil. The penetration depth per blow was recorded. The corresponding DCP index value was used to estimate a soil strength value (CBR).

A second approach that was used in this study to predict excavatability follows a procedure developed and used in Hamilton County, Ohio. This approach uses a removability modulus (RE), as shown in Equation 3.1a:

$$RE = \frac{W^{1.5} \times 104 \times C^{0.5}}{10^6} \tag{3.1a}$$

where

W = In-situ unit weight (lb/ft^3)

C = 28-day unconfined compressive strength (psi)

When SI units are used, as required by AASHTO, the equation is rewritten as shown in Equation 3.1b:

$$RE = \frac{W^{1.5} \times 0.619 \times C^{0.5}}{10^6} \tag{3.1b}$$

where

W = In-situ unit weight (kg/m^3)

C = 28-day unconfined compressive strength (kPa)

Table 3.19. Summary of various capping systems used to test compressive strength of CLSM.

CLSM Mixture	Curing Condition	Sulfur Cap			Neoprene Cap		Polyurethane Cap				P-NU[a]		P-N[b]	
		7 d	28 d	91 d	7 d	28 d	3 d	7 d	28 d	91 d	7 d	28 d	7 d	28 d
E-9	Lab	✓	✓	✓		✓		✓	✓	✓	✓	✓		✓
E-10		✓	✓	✓		✓		✓	✓	✓	✓	✓		✓
E-11		✓	✓	✓	✓	✓		✓	✓	✓	✓	✓		✓
E-12		✓	✓	✓		✓		✓	✓	✓	✓	✓		✓
E-13									✓					
E-14		✓	✓				✓	✓	✓					
E-15		✓	✓			✓	✓	✓						
E-16		✓	✓				✓	✓	✓					
E-17		✓	✓			✓	✓	✓						
E-13	Field	✓	✓		✓	✓	✓							
E-14							✓	✓	✓					
E-15		✓	✓				✓	✓	✓					
E-16		✓	✓			✓	✓	✓						
E-17		✓	✓			✓	✓	✓						
E-18		✓	✓		✓	✓	✓							

[a] *P-N cap unbonded.*

[b] *P-N cap bonded.*

Engineers in Hamilton County, Ohio, and the city of Cincinnati have found this methodology to be effective in limiting long-term strength gain and ensuring future excavatability. The research team used the same approach in calculating RE values for the C-series mixtures and comparing the results to other direct or indirect indices of CLSM strength gain.

In preliminary investigations within this project, the splitting tensile strength of CLSM was identified as a potential indicator of excavatability. Splitting tensile strength is also a very simple property to measure (without the need to cap the cylinders). The stress conditions of CLSM specimens under splitting tensile testing may be quite similar to stress conditions of CLSM mixtures under digging conditions with a shovel or backhoe. The E-series mixtures (Table 3.11) were used to evaluate various capping materials and methods, with some of the key capping-related parameters shown in Table 3.19. In addition, mixtures E1 through E8 were tested extensively to evaluate the effect of durometer value (neoprene pad hardness) on CLSM strength, as described later in this report.

California Bearing Ratio

Moist-cured specimens were tested at an age of 28 days using a slightly modified version of AASHTO T 193. The only modification was that the CLSM was placed into the molds without compaction, as is required for testing soils. After 7 days of curing, the collar of the mold was removed, and the surface of the CLSM specimen was trimmed level using a straight edge.

Resilient Modulus

Moist-cured specimens were tested at an age of 28 days using a slightly modified version of AASHTO T 292, with the modification relating to the deviator stresses. In trial testing, the deviator stresses listed in Table 4 of AASHTO T 292 were not found to be sufficiently high to introduce deformations. The selection of deviator stresses was based on previous research performed at Texas A&M University. Load conditioning of 41 kPa was used for the 1000 repetitions. Since the completion of the laboratory component of this project, AASHTO T 292 has been replaced by AASHTO T 307. Research should be conducted using this new test method in the future to ensure that it is a viable test method for evaluating CLSM.

Water Permeability

The water permeability of six CLSM mixtures, moist cured for 28 days, was measured using ASTM D 5084. A back pressure of 69 kPa was applied and maintained until no additional water entered the sample (approximately 30 minutes). This condition was assumed to represent saturation. Because the samples were moist cured prior to testing, the samples were essentially already saturated prior to sample conditioning. Thus, the requirement that the B-value (ratio of pore water pressure to confining stress) be greater than or equal to 0.95 was waived for these tests. A confining pressure of 173 kPa was applied during the tests.

Triaxial Shear Strength

A commonly used soil triaxial test method (USACE EM 1110-2-1906) was used for testing the shear strength of CLSM. The samples were cast in Shelby tubes (approximately 70 mm diameter) and were stripped after 7 days. Testing was performed under consolidated and drained conditions at this time, and additional specimens were tested at an age of 28 days (note that the specimens were moist cured in a fog room from the time of stripping until the time of testing). The pore water pressure was maintained at 34.5 kPa, and the confining pressures were 69, 103.5, and 172.5 kPa. The loading rate was 0.38 mm/min, the same loading rate used for most standard unconfined compression tests. The test was terminated when the residual strength was reached or the stress-strain curve became essentially flat. By curve fitting, the effective internal friction angle, ϕ', and the effective cohesion, c', were determined. Various other shear strength test methods could also be used for evaluating CLSM; the method selected for this study should not be considered as the only viable approach.

Drying Shrinkage

No standard methods exist to measure the drying shrinkage of CLSM. A method commonly used in Germany for self-leveling floor screeds was modified and used in this study. CLSM was cast into an 87.5 × 26.3 × 1000 mm steel channel. The channel had one fixed end plate with an anchor and one movable end plate with an anchor. Before the CLSM was cast, wax paper was placed on the inside of the channel to reduce friction. CLSM was then placed in the channel forms. The amount of shrinkage was measured using a linear variable differential transformer (LVDT) that measured the displacement of the movable end plate. Shrinkage measurements were taken daily for the first week and once a week thereafter.

Durability Test Methods

Corrosion

A comprehensive laboratory corrosion program was performed, with the objective to characterize the corrosion performance of ductile iron and galvanized steel embedded in CLSM and to identify key parameters that significantly influence the corrosion performance of these materials. This research was performed in two phases: the first phase was a smaller scale study (using the 38 initial CLSM mixtures), and the second phase was a more significant follow-up study aimed at confirming the findings from the first phase and developing a thorough understanding of the corrosion of metals in CLSM.

Metallic coupons machined from ductile iron and galvanized steel pipes were tested in two conditions: uncoupled and coupled. Figures 3.2 and 3.3 show the samples for the uncoupled and coupled conditions, respectively.

In the uncoupled state, metallic coupons were embedded in 75 × 150 mm plastic cylindrical molds containing CLSM. The center of the metallic coupon was placed at the center of the cylinder, 50 mm from the top surface. Because CLSM is a low-strength material, care was taken not to damage the samples after casting. Precutting the plastic molds longitudinally and taping these cuts closed prior to casting minimized the damage for the uncoupled specimens. After casting, the tape was removed and the plastic mold was separated (not removed) from the CLSM sample surface.

Coupled samples were prepared to address the issue of metals not being completely embedded in CLSM in the field applications. For the coupled conditions, pairs of ductile iron or galvanized steel coupons were embedded in 100 × 200 mm plastic molds that were half-filled with CLSM and half with soil. In this condition, one of the metallic coupons was completely embedded in CLSM and the other coupon was completely embedded in soil and they were connected with a 10 ohm resistor at the top as shown in Figure 3.3. The metallic coupons were secured such that both were approximately 5 mm from the CLSM/soil interface. Six holes (4 mm diameter) were drilled at 15 mm above the bottom of each cylinder and the holes were wrapped with a filter paper that would allow the exposure solution to enter into the cylinders while preventing the soils from being washed from the molds.

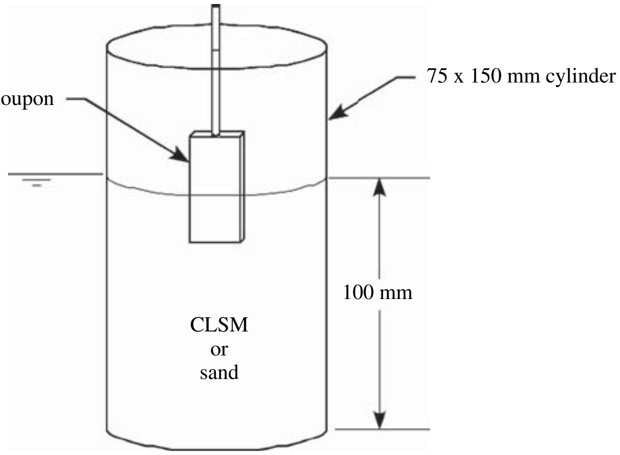


Figure 3.2. Corrosion test setup for comparing corrosion performance of coupons in CLSM and sand (uncoupled condition).

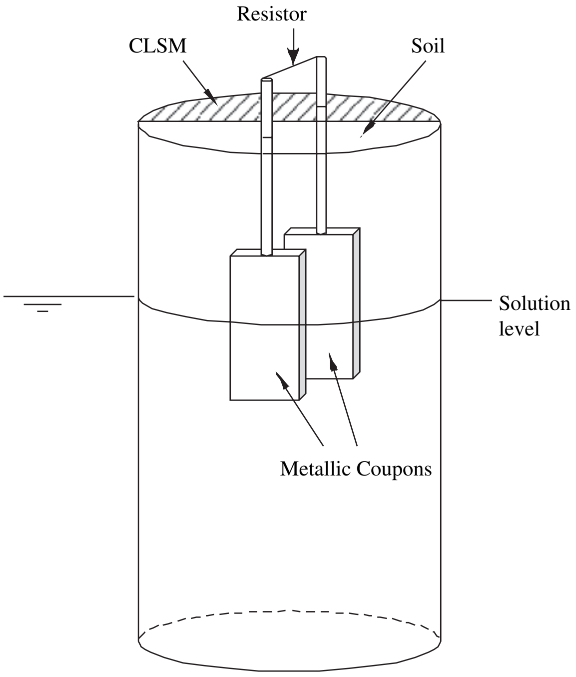


Figure 3.3. Corrosion test setup for comparing corrosion performance of galvanic coupled coupons in CLSM and sand.

Control samples were similar to the uncoupled samples, but metallic coupons were completely embedded in sand.

Ductile iron coupons, 13 × 24 × 4 mm in size, were machined from a 300 mm diameter commercially available ductile iron pipe (AWWA C151, Grade 60-42-10) and zinc galvanized steel coupons, 13 × 24 × 3.5 mm in size, were machined from a 300 mm diameter zinc galvanized steel culvert (uncoated thickness approximately 3.40 mm).

All CLSM samples were cured for 28 days at 23 ± 2°C and a relative humidity greater than 98 percent. Later, samples were exposed to a 3.0 percent sodium chloride solution or distilled water. The liquid level was maintained at a level of 90 mm throughout the test program.

As previously stated, the corrosion study was performed in two phases. In the first phase, a large number of CLSM mixtures were evaluated with a low number of samples per CLSM mixture. In the second phase, a lower number of CLSM mixtures were evaluated with a higher number of samples compared to the first phase. The number of samples was increased in the second phase for a better statistical analysis. In both phases, uncoupled and coupled samples were prepared and tested.

In the Phase I investigation, the initial thirty-eight CLSM mixtures (thirty mixtures and eight duplicates) were evaluated to determine the influence of CLSM constituent materials and proportioning on the corrosion of metals embedded in CLSM. The mixture proportions and fresh CLSM characteristics are shown in Tables 3.3 through 3.5. In this first phase, only ductile iron coupons were evaluated. Three coupled and uncoupled samples for each of the thirty-eight CLSM mixtures and five control samples were fabricated. All of the samples were exposed to 3.0 percent sodium chloride solution for 18 months. The control samples and the soil section of coupled samples were filled with a sand meeting the "graded sand" requirements of ASTM C 778, "Standard Sand."

In the Phase II investigation, a total of 13 CLSM mixtures were selected and cast to evaluate the corrosion of metals embedded in CLSM. The mixture proportions and fresh CLSM characteristics are shown in Table 3.16. Lower case letters added to the mixture designation indicate separate batches. Ductile iron and galvanized steel coupons were evaluated for corrosion activity. A minimum of five coupled and five uncoupled samples were prepared for each of the thirteen CLSM mixtures and exposure conditions. More than 1000 samples were evaluated in the Phase II study. Half of the samples were exposed to 3.0 percent sodium chloride solution and the remaining samples were exposed to distilled water. All samples were exposed for 26 months. Sand and clay were used to fill the soil section of each coupled sample. The sand met the "graded sand" requirements of ASTM C 778. The clay used was obtained from the National Geotechnical Experimentation Site located at the Texas A&M University Riverside Campus. The plastic and liquid limits of the clay were 20.9 percent and 53.7 percent, respectively, and the hydraulic conductivity coefficient was 5×10^{-4} m/year.

In both phases, metallic coupons were removed from the samples at the end of the exposure period and were evaluated for mass loss following ASTM G 1, "Preparing, Cleaning, and Evaluating Corrosion Test Specimens." Ductile iron coupons were cleaned using cleaning procedure C.3.5 and galvanized steel coupons were cleaned using cleaning procedure C.9.5. In the case of the coupled samples, only the coupons embedded in the sand were evaluated for mass loss as they were determined early in this study to be the anode. The coupon embedded in the CLSM section of these samples exhibited limited corrosion, if any. Evaluation of the corrosion performance of coupons was based on the percent mass loss due to corrosion (amount of mass loss resulting from corrosion divided by the original mass of coupons).

In the Phase I study, the resistivity of the CLSM and sand were evaluated using a resistivity box (or soil box) as described in ASTM G 57, "Field Measurement of Soil Resistivity Using the Wenner Four-Electrode Method." Resistivity measurements were obtained from saturated samples 182 days after casting. These samples were cast at the same time with the corrosion samples (i.e., the CLSM came from the same batch for both sample types). In the Phase II study, the resistivity of CLSM and soils were not measured from separately cast samples, but from each of the actual exposed uncoupled and coupled samples following ASTM G 57.

In the Phase I study, two 50 × 100 mm cylinders were cast for each CLSM mixture at the same time as the corrosion samples were cast to evaluate their pH. At 182 days after casting, the CLSM cylinders were removed from the curing room, and pore solution was extracted from the samples and immediately evaluated for pH. In the Phase II study, CLSM and distilled water solutions (1:1 by weight) were prepared from each exposed uncoupled and coupled sample to evaluate for pH. In both phases, a pH combination electrode connected to a bench top multimeter with a precision of 0.01 was used to measure the pH. In the second phase, the pH of soil samples used in the coupled samples was also determined using 1:1 by weight distilled water solutions. Because only one type of clay and only one type of sand was used in the samples, only randomly selected soil samples from coupled samples exposed to the chloride and distilled water environments were collected and tested. One soil pH value was determined for each type of soil exposed to each type of environment in a coupled sample.

Chloride contents were determined using a test method developed under the Strategic Highway Research Program. This method rapidly determines the chloride content in cementitious materials (Cady and Gannon 1992).

Freezing and Thawing

ASTM D 560, a method designed to measure the freeze-thaw resistance of soil-cement mixtures, was used with one modification: thawed specimens were not brushed because of the low strength of CLSM. CLSM samples were exposed to a temperature change from −18°C (a freezer) to 23°C (the fog room) in each cycle. Samples were exposed to 12 cycles, unless they suffered severe damage at an earlier time. Mass loss was monitored as an indicator of damage. In the initial study, six cylinders from each mixture were exposed to freeze-thaw cycles. Three of these cylinders were moist cured for 7 days and the other three were moist cured for 28 days prior to freeze-thaw cycling. Because the tests typically used for concrete, such as the ASTM C 666, were found to be too severe in preliminary trials for CLSM, the modified soil cement method was found to be a more suitable approach.

In addition to the original six mixtures, a follow-up study was conducted to specifically investigate the effects of freeze-thaw damage on CLSM permeability. Eleven mixtures (D-series in Table 3.10) were used to study the freezing and thawing effects on permeability. The specimens were 100 × 125 mm and were subjected to freezing and thawing cycles at an age of 28 days (as per the modified version of ASTM D 560 described in the previous paragraph). Because some CLSM specimens may suffer significant damage from freeze-thaw cycles, shrinkwrap was used to keep the specimens intact, thereby allowing for subsequent measurement of water permeability. Porous stones were secured at both ends of the specimens to facilitate the permeability measurements. After completing the freezing and thawing test, water permeability (or hydraulic conductivity) was measured using the falling-head method. For reference, specimens from each mixture that were not subjected to freeze-thaw testing were also tested for water permeability.

Leaching and Environmental Impact

Coal combustion products, such as fly ash, and other by-product materials, such as silica fume and slag, have been used successfully and safely for years in conventional concrete. CLSM has proven to be especially well-suited as a consumer of various by-product materials; further, by-product materials that are not typically allowed in conventional concrete, such as fly ash not meeting ASTM C 618, are routinely used in CLSM. Therefore, there has been some concern about the potential for leaching of constituents in by-product materials (e.g., heavy metals, organics) from CLSM and their impact on the environment. To address this issue, by-product materials evaluated in this project were tested to determine their chemical composition and potential for leaching from CLSM.

For each of the by-products included in the initial laboratory study (three fly ashes, one bottom ash, and one foundry sand), the total heavy metal concentration was determined following EPA Method 610, “Determination of Certain Polynuclear Aromatic Hydrocarbons in Municipal and Industrial Discharges Using Liquid-Liquid Extraction and HPLC and/or Gas Chromatography as Provided Under 40 CFR 136.1,” where nitric acid and hydrogen peroxide were used to digest the materials. The eight elements analyzed were arsenic, barium, cadmium, chromium, lead, mercury, selenium, and silver. Because this testing determines the total amount of heavy metals, and not the leachable amount, the extraction values may be 20 times the amount that might be leached in the TCLP limits (a “rule of thumb” value). If any of the by-products tested in this project yielded values in excess of the toxicity limits (20 times the TCLP limit), TCLP was then conducted to assess the type and amount of heavy metals that may be leached from the materials. The TCLP (EPA Method 1311) is one of the most common tests performed on materials to determine their potential for leaching. The concentrations of the eight heavy metals in the extracts were compared to the TCLP limits given in EPA publication 40 CFR 261.24 as shown in Table 3.20. As described later in this chapter, the materials tested in this project were found to easily “pass” the TCLP, meaning the heavy metal concentrations were very low and not of concern. However, if the TCLP values exceeded any of those listed in Table 3.20, another level of testing would have been initiated, specifically the American Nuclear Society leachate test (ANS 16.1). This test is a monolith test that measures the actual leachates from CLSM containing the by-product material of interest and is a better indicator of actual leaching potential.

Table 3.20. TCLP limits of heavy metals.

Element	TCLP Limits (ppm)
Arsenic	5.0
Barium	100.0
Cadmium	1.0
Chromium	5.0
Lead	5.0
Mercury	0.2
Selenium	1.0
Silver	5.0

Source: 40 CFR 261.24

Results and Discussion

The main findings from the laboratory study are presented next, with emphasis on selecting or developing appropriate test methods to measure key CLSM properties and building an understanding of how specific materials, mixture proportions, etc. affect CLSM performance.

Fresh Properties

An important aspect of this study was the assessment of the fresh or plastic properties of CLSM, both in terms of evaluating candidate test methods and determining the relationship among constituent materials, mixture proportions, and fresh CLSM properties. Tables 3.3 through 3.5 summarize some of the important parameters, including water demand (to obtain the target flow), air content, flow, unit weight, and bleeding (%) for the initial 38 mixtures. The air content, flow, unit weight, and bleeding tests were found to be effective and user-friendly. Clearly, any change in source material, mixture proportions, or curing regime would impact each of the relevant fresh properties of CLSM. For this project, given that the water content was adjusted for each mixture to achieve a target flow (200 to 250 mm), some interesting observations could be made about what factors most affect flow characteristics, as discussed next.

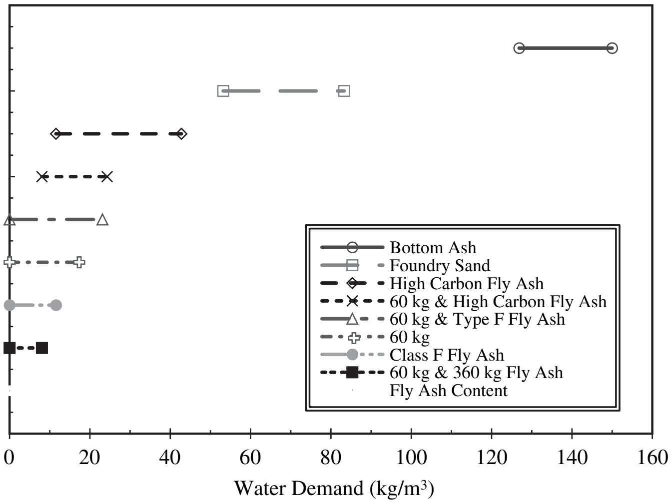
Water Demand

Throughout this study, water (and sometimes AEA) was added to CLSM mixtures so that their flow values were between 200 and 250 mm; this procedure allowed interesting information and trends to be gleaned from what most affects water demand. The effects of material type and quantity on the water demand of CLSM were analyzed using a statistical program (ECHIP) for the non–air-entrained mixtures; the results are shown in Figure 3.4.

The Pareto graph in Figure 3.4 illustrates the statistically significant variables that affect water demand. In this graph, the effect is the difference between the specified variable level and the reference variable level. The reference variable levels are concrete sand (river), Class C fly ash, 180 kg/m^3 fly ash content, and 30 kg/m^3 cement content. The difference was positive for bottom ash, foundry sand, and high-carbon fly ash. The difference was negative for 60 kg cement, Class F fly ash, 360 kg fly ash, 60 kg cement and high-carbon fly ash, 60 kg cement and Class F fly ash, and 60 kg cement and 360 kg fly ash. The figure shows that the fine aggregate type was the most significant factor affecting the water demand of mixtures. The use of high-carbon fly ash also increased the water demand. There is no significant difference between the use of the Class C and Class F fly ash. In addition, analysis of variance (ANOVA) calculations identified significant variables as fly ash type, fine aggregate type, and the interactions between cement content and fly ash type.

Bleeding and Segregation

Bleeding and segregation affect the subsidence and the uniformity of the placed CLSM mixtures. Using ECHIP, the effects of various factors on bleeding were evaluated. The use of foundry sand was found to reduce the bleeding significantly, while the bottom ash was found to significantly increase the bleeding. This finding indicates the importance of the fine aggregate on bleeding of water in fresh CLSM mixtures. The fly ash type had minimal effect on the bleeding of CLSM mixtures. Little segregation was found in the five selected CLSM mixtures.



Source: after Du et al. (2004)

Figure 3.4. Pareto-effects graph for water demand of non–air-entrained CLSM mixtures.

Setting and Hardening

The setting/hardening behavior of CLSM is important for many applications, especially for those where early strengths are needed to satisfy construction demands (i.e., timing between lifts or early opening to traffic). Test methods are needed to easily assess the setting of CLSM, both in the laboratory and in the field. This section discusses some of the important findings regarding the setting time of CLSM, as measured by the needle penetrometer (ASTM C 403), soil pocket penetrometer, and pocket vane shear test.

When the needle penetration of CLSM is measured, a certain minimum strength of CLSM is required to obtain meaningful test results. Thus, comparing the setting time of CLSM mixtures to each other at predefined time increments is often not feasible, but rather, the timing of measurements should be a function of constituent materials and mixture proportions. Also, because a needle penetrometer penetrates deeper into mixtures than a soil penetrometer, it is less subject to bleed water effects, as discussed next. Despite these differences in penetration depth and contact angle, there was a fairly reasonable correlation between soil penetrometer and needle penetrometer values for the 38 mixtures, as shown in Figure 3.5 (with an R^2 of approximately 0.75 for all the CLSM penetration data combined). Figure 3.6 shows the relationship between the soil pocket penetrometer and the vane shear device; although a general trend exists, it is not statistically strong.

The walkability time was assessed by preparing large CLSM boxes that were walked on at various ages. The soil penetrometer values were found to range from 4.32 to 7.35 kPa (average of 6.14 kPa) when CLSM mixtures were able to support the weight of an average person with about 6.4 mm indentation. More comprehensive (and realistic) data were generated in the field tests on walkability times and how they relate to penetration data and other parameters (described in Chapter 4).

Subsidence

All of the CLSM mixtures exhibited measurable subsidence, with the exception of mixture 23, which had relatively poor flowability. Except for mixture 23, a reasonable correlation existed between subsidence and bleeding. Mixture 6 had the highest subsidence of about 2.5 percent of the placement height. Comparison of the results obtained from mixtures 26

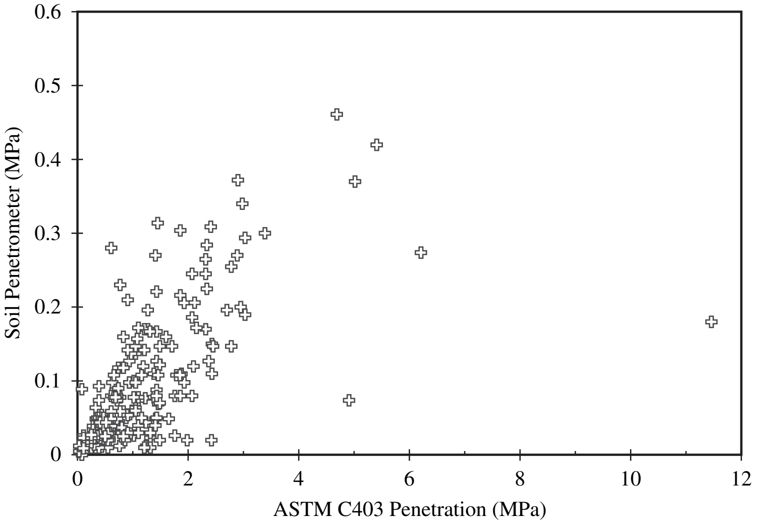


Figure 3.5. Comparison between ASTM C 403 and soil penetrometer values.

and 22r, which were identical except the use of an accelerating admixture in 26, indicated that the use of an accelerating admixture reduced bleeding and slightly reduced subsidence. The results of subsidence testing are shown in Table 3.21.

Hardened CLSM Properties

Unconfined Compressive Strength

A great deal of emphasis was placed in assessing the unconfined compressive strength of CLSM. This section first summarizes the findings from the initial mixtures (38 in all), in which several aspects of compression testing were examined, including the effects of cylinder size, capping material, and load rate. Based on these original mixtures, some useful predictive models were developed to predict the strength gain (short and long term) of CLSM. The original study led to several follow-up studies, each of which focused in more detail on issues involving testing parameters. Detailed investigations on load rate, curing and conditioning of cylinders, effects of drainage on strength, and the use of alternative capping materials were performed. The findings of the initial broad study and the later detailed studies were used to refine and improve existing methods of measuring the unconfined compressive strength of CLSM.

The unconfined compressive strengths of the originally proposed mixtures at 3, 7, 28, and 91 days are shown in Table 3.22.

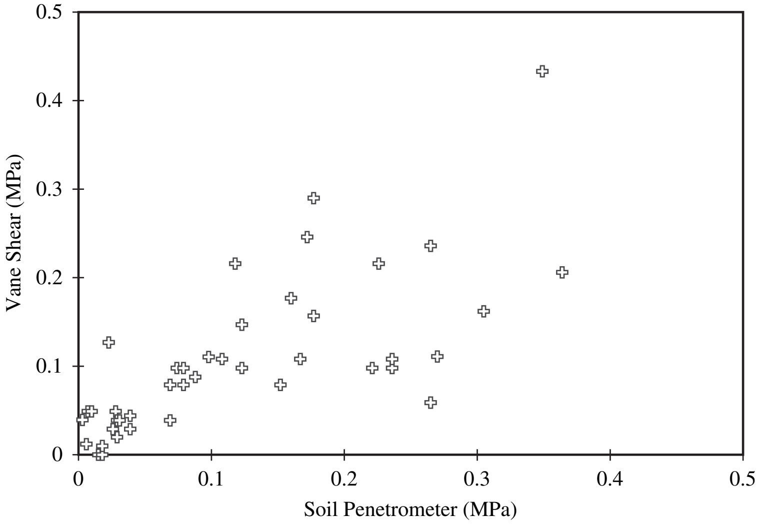


Figure 3.6. Comparison between soil pocket penetration and vane shear values.

Table 3.21. Subsidence results of six selected CLSM mixtures.

Mixture 4		Mixture 24	
Time (h)	**Subsidence (mm)**	**Time (h)**	**Subsidence (mm)**
1.25	3.0	3.0	5.3
2.30	3.4	5.5	6.8
3.57	3.4	6.0	6.8
4.57	3.5		
5.17	3.4		
Mixture 23		**Mixture 6**	
Time (h)	**Subsidence (mm)**	**Time (h)**	**Subsidence (mm)**
3	0.3	1.00	9.4
4	0.3	2.17	10.5
		3.33	12.7
		4.33	14.9
		6.50	15.9
Mixture 22r		**Mixture 26**	
Time (h)	**Subsidence (mm)**	**Time (h)**	**Subsidence (mm)**
3.17	1.2	3.67	1.5
5.17	2.2	5.67	1.5
6.33	2.2		

Note: The total specimen height was 600 mm.

Table 3.22. Unconfined compressive strength of original 38 CLSM mixtures.

Mixture	3-day f'_c (MPa)	C.O.V. (%)	7-day f'_c (MPa)	C.O.V. (%)	28-day f'_c (MPa)	C.O.V. (%)	91-day f'_c (MPa)	C.O.V. (%)
1	0.12	8.2	0.21	6.8	1.09	4.9	1.87	2.8
2	0.29	2.4	1.76	10.1	3.69	4.0	6.26	13.5
1r	0.13	14.4	0.24	1.2	1.35	7.7	2.34	0.3
15	0.07	8.2	0.11	5.7	0.18	4.0	0.25	1.4
3	0.33	10.5	0.57	2.4	1.36	6.8	2.02	2.9
8	0.09	9.8	0.11	8.3	0.25	4.7	0.33	10.6
10	0.12	2.3	0.16	15.1	0.22	7.9	0.26	1.3
9	0.09	9.7	0.13	12.4	0.22	5.0	0.25	2.9
5	0.14	13.2	0.18	8.2	0.46	16.1	0.57	5.3
12	0.30	16.2	0.27	6.2	0.57	4.7	0.86	3.4
4	0.34	4.9	0.48	6.2	0.79	11.0	1.08	13.6
7	0.09	3.2	0.11	3.4	0.12	9.7	0.16	5.8
3r	0.46	13.1	0.58	4.4	1.49	5.8	1.97	8.3
4r	0.41	13.6	0.57	5.8	0.94	4.0	1.03	6.9
24	0.34	4.8	0.22	1.4	0.44	0.1	0.58	4.6
23[a]	–	–	0.04	6.4	0.14	9.5	0.18	7.6
18[a]	–	–	0.33	6.8	0.70	1.1	0.79	4.0
14	0.58	6.6	1.07	13.5	2.15	8.1	3.49	16.8
2r	0.42	9.3	1.58	2.9	4.90	2.4	6.87	0.3
29	0.18	0.6	0.31	0.2	0.63	1.9	0.98	6.1
30	0.09	7.1	0.14	3.1	0.26	8.6	0.28	2.8
17[a]	–	–	0.01	31.8	0.07	18.9	0.13	16.8
11	0.33	1.7	0.42	4.3	0.75	3.5	0.94	4.7
6	0.40	10.2	0.47	0.7	0.83	4.9	1.09	4.7
16[a]	–	–	0.06	11.9	0.13	12.0	0.16	8.5
21[a]	–	–	0.09	10.6	0.16	11.8	0.18	11.7
22[a]	–	–	0.43	9.0	0.73	4.3	1.01	4.8
22r	0.32	4.2	0.50	9.7	0.96	17.5	0.93	7.0
5r	0.17	12.5	0.28	10.3	0.55	10.1	0.78	16.3
26	0.43	7.1	0.76	8.2	1.14	15.8	1.53	2.6
16r[a]	–	–	0.07	9.7	0.15	23.6	0.17	8.3
13	0.28	0.5	0.35	3.3	0.74	3.2	1.12	4.4
25	0.17	4.4	0.30	5.7	0.40	30.9	0.50	9.0
19[a]	–	–	0.02	0.71	0.06	45.0	0.06	13.2
20[a]	–	–	0.04	36.4	0.21	1.0	0.29	26.0
27	0.22	4.6	0.29	1.7	0.36	3.8	0.55	6.6
20r[a]	–	–	0.04	49.9	0.15	32.8	0.24	10.4
28	0.28	3.0	0.47	0.9	0.70	1.95	0.94	0.2

[a] Mixtures were too weak to be tested at 3 days.

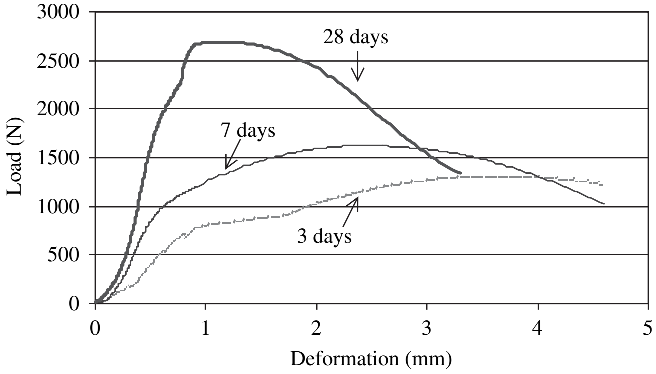


Figure 3.7. Load-deformation response of mixture 12 at 3, 7, and 28 days.

The data shown in this table were for small, sulfur-capped cylinders (75 × 150 mm) tested on a smaller capacity machine at a loading rate of 0.38 mm/min, as previously described. The results were found to be repeatable, with quite low values of coefficient of variation.

An interesting observation that illustrates the uniqueness of CLSM is that most mixtures show a drastic change in the load-deflection curve as the curing time is increased. Figure 3.7 illustrates this behavior for Mixture 12, which was typical of most CLSM mixtures. At early ages, CLSM acts more like a soil, with more ductile behavior, but as time progresses, CLSM begins to act more like concrete, with higher strength and lower ductility.

Efforts were made in this project, based on the strength results for the initial 38 mixtures, to develop predictive models for the compressive strength of CLSM. Various models and statistical approaches were considered. No single model was found to work well for the entire range of materials and mixture proportions; however, predictive models for subsets of the mixtures were found to be quite accurate. For instance, separate models were developed for air-entrained (both for "high" and "moderate" air contents) and non–air-entrained CLSM.

The results obtained from mixtures containing bottom ash or foundry sand were not included in the data that were used to develop the predictive compressive strength model of air-entrained CLSM (up to 91 days). These data were excluded because air entrainment was found to be too difficult in mixtures containing these aggregates. The model predicting the compressive strength of air-entrained CLSM mixtures is shown in Equation 3.2 (Du et al. 2002):

$$f'_c = a \cdot e^{b(w/c)} \tag{3.2}$$

where

f'_c = compressive strength (MPa)
$a = 0.3074 \cdot \ln(t) + 0.2289$
$b = 0.0086 \cdot \ln(t) - 0.272$
t = age (days)
w/c = water-cement ratio

The measured and predicted compressive strengths using the model shown in Equation 3.2 for air-entrained mixtures are plotted in Figure 3.8. There was very good correlation, with an R^2 value of 0.97. This model was also found to be effective in predicting long-term strength gain (i.e., beyond 91 days). For example, cylinders from mixture 22r that were tested for compressive strength after 256 days had an average strength of 1.0 MPa, compared to the predicted value of 1.1 MPa.

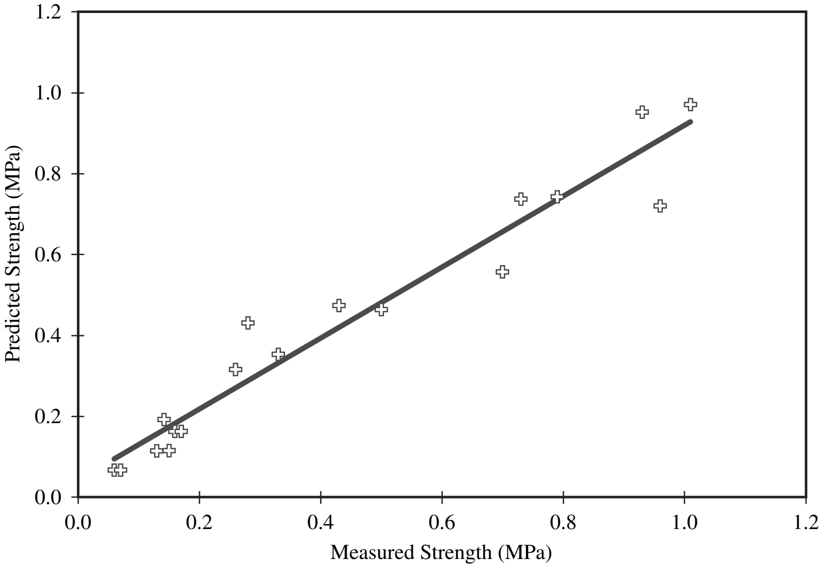


Figure 3.8. Measured vs. predicted strengths of air-entrained CLSM.

A predictive model was also developed for non–air-entrained CLSM mixtures. If the water-cement ratio was the only variable used to predict the compressive strength, the model yielded an R^2 value of 0.8. To improve this accuracy, a model was developed that included the water-cement ratio, aggregate type, fly ash type, and the fly ash content as strength-predicting variables. A critical aspect to this approach was to assign numerical values to the non-numerical variables used in the model. Through an iterative process, the constant, *k,* was selected for the materials used in this investigation. Concrete or river sand ($k_{\text{river sand}}$) was assigned a value of 1.0, foundry sand ($k_{\text{foundry sand}}$) a value of 0.2, bottom ash ($k_{\text{bottom ash}}$) a value of 1.0, Class C fly ash ($k_{\text{C ash}}$) a value of 2.2, Class F fly ash ($k_{\text{F ash}}$) a value of 1.0, and high-carbon fly ash ($k_{\text{HC ash}}$) a value of 0.75. The equation for predicting the compressive strength, *S(t),* is shown in Equation 3.3 (Du et al. 2002), and a comparison between predicted and actual compressive strengths is shown in Figure 3.9.

$$S(t)=b_0(t)\cdot\left(k_{agg.type}\right)^{b_1(t)}\cdot\left(k_{fly\,ash\,type}\right)^{b_2(t)}\cdot\left(w/c\right)^{b_3(t)}\cdot\left(k_{fly\,ash\,content}\right)^{b_4(t)} \tag{3.3}$$

where

$S(t)$ = compressive strength (MPa)

t = age (days)

$b_0(t) = 0.0007 \cdot t^2 + 0.13 \cdot t - 0.76$

$b_1(t) = 0.0001 \cdot t^2 + 0.013 \cdot t + 0.42$

$b_2(t) = 0.00008 \cdot t^2 + 0.015 \cdot t + 0.094$

$b_3(t) = 0.003 \cdot t - 1.03$

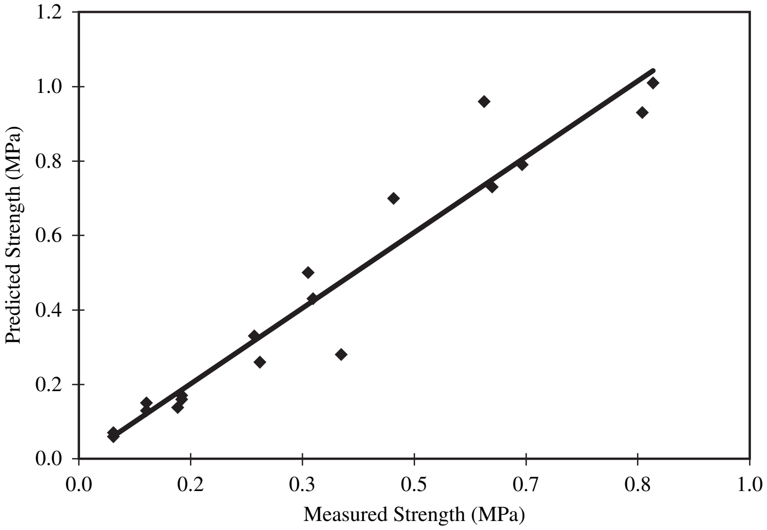
$b_4(t) = 0.75 - 0.018 \cdot t$ when $t \leq 30$ days

$b_4(t) = 0.22$ when $t > 30$ days

Although the models presented previously are valid for only the materials used in this project, they provide important insights into the strength development of CLSM mixtures. Most of the significant effects were related to the influence of water demand on compressive strength. Mixtures containing materials that increased the required water content for the target spread (such as foundry sand and high-carbon fly ash) generally yielded lower compressive strengths compared to mixtures with lower water contents. The chemical reactivity of fly ash was found to be critical, because the strength of CLSM mixtures containing Class C fly ash was higher than similar mixtures containing Class F or high-carbon fly ash. Class C fly ash has a higher CaO content than Class F fly ash (and the high-carbon fly ash used in this study) and it increases the early and final strengths of the mixtures. Because the developed models are valid for only the specific materials used in this study, the researchers recommend preparing and testing a series of trial mixtures to predict the strength of CLSM mixtures containing different materials.

As stated earlier, various modifications to the unconfined compression test were studied in the initial investigation, some of which were later addressed in more detailed research. The following paragraphs briefly discuss the findings from this initial investigation that focused on cylinder capping methods, cylinder size, and testing machine capacity.

Table 3.23 shows a comparison between sulfur-capped cylinders and neoprene-capped cylinders for the selected six CLSM mixtures. In general, sulfur-capped cylinders yielded



Source: Du et al. (2002)

Figure 3.9. Measured vs. predicted strengths of non–air-entrained CLSM mixtures.

Table 3.23. Comparison of compressive strengths with different capping materials and methods.

Mixture	3 days		7 days		28 days	
	Sulfur (C.O.V.) MPa (%)	Neoprene (C.O.V.) MPa (%)	Sulfur (C.O.V.) MPa (%)	Neoprene (C.O.V.) MPa (%)	Sulfur (C.O.V.) MPa (%)	Neoprene (C.O.V.) MPa (%)
4	0.34 (4.9)	0.25 (15.1)	0.48 (6.2)	0.34 (6.0)	0.79(11.0)	0.55 (14.4)
6	0.45 (6.8)	0.25 (14.7)	0.47 (0.7)	0.36 (6.3)	0.81 (4.9)	0.61 (3.2)
23[a]	–	–	0.04 (6.42)	0.03 (12.92)	0.14 (9.52)	0.12 (3.14)
24	0.34 (4.8)	0.15 (0.3)	0.22 (1.4)	0.19 (20.5)	0.44 (0.1)	0.30 (18.8)
22r	0.32 (4.2)	0.22 (8.1)	0.50 (9.7)	0.37 (10.6)	0.93 (17.5)	0.54 (4.4)
26	0.43 (7.1)	0.29 (9.1)	0.76 (8.2)	0.42 (11.2)	1.11 (15.8)	0.73 (7.2)

[a] Mixture was too weak to be tested at 3 days.

higher strengths than cylinders using neoprene pads. The neoprene pads used in this initial study had a durometer value of 50, which is a typical durometer value for conventional concrete cylinder testing. A more comprehensive study on capping materials, including neoprene pads with significantly lower durometer values, was subsequently performed, as described later in this chapter.

In a study focusing on the effects of cylinder size (75 × 100 mm vs. 150 × 300 mm), cylinder size across this range was found to have little impact on strength values. This study used deflection-controlled testing with all cylinders tested at the same effective strain rate. Thus, like conventional concrete, different cylinder sizes of CLSM can be used provided that the length-diameter ratio remains at 2:1, that the cylinder size is sufficiently large for the maximum aggregate size, and that the load capacity of the machine is adequate to accurately measure the peak load.

Most of the compression testing in this project used a smaller capacity testing machine under deflection control. However, many laboratories that typically test conventional concrete are currently using larger capacity concrete compression machines under load rate control. To assess the relative difference in strength values, a limited study was performed to compare the results of a small-capacity (100 kN) machine under deflection control to a larger capacity (1780 kN) compression machine using load control. It should be noted that in order to meet the time-to-failure limits described in ASTM D 4832 (not less than 2 minutes), a load rate of 6.9 kPa/s was used for the large machine. The results indicated significantly lower strength values and higher variations for the large compression machine, compared to the results from the smaller, deflection-controlled machine. Thus, caution should be taken when using a large-capacity (Tinius Olson, 1780 kN capacity) machine under load control. When using a large-capacity machine for testing CLSM, one must ensure the machine is properly calibrated in the lower range of load values typically encountered for CLSM.

Effects of Loading Rate. Because of the general lack of guidance provided in ASTM D 4832 regarding loading rate, the researchers placed additional emphasis on assessing the effects of loading rate on the compressive strength of CLSM. The loading rate is an important parameter when considering compression testing. The testing of CLSM cylinders should first of all be accurate. If strength values are found to be strongly influenced by loading rate, then a finite range must be defined and required for accurate testing. The loading rate also determines the length of time needed to test a given cylinder. This required length of time must be sufficient to ensure accuracy (i.e., not a sudden cylinder failure) and to complete a given test in a reasonable amount of time. In a laboratory or testing facility, the time required to test cylinders may be critical, especially if many tests are performed in a single day.

A deflection-controlled machine, often used to test soils, was used for this investigation with the following rates of deflection: 0.13 mm/min, 0.25 mm/min, 0.38 mm/min, 0.51 mm/min, and 0.89 mm/min. The deformation at peak load was used to determine if changes in loading rate resulted in changes in modes of failure, such as a change from relatively ductile to brittle failure.

The effects of load rate on compressive strength were found to vary, depending upon the type of mixture and the age of testing. Interestingly, some mixtures (e.g., mixture A-2) were relatively insensitive to load rate, whereas others were quite sensitive. No consistent trend among all mixtures suggested that compressive strength was either directly or indirectly proportional to load rate (based on the range of rates evaluated). In general, the range of loading rates from 0.25 to 0.64 mm/min produced the most consistent results. Also, within this range of loading rates, there was little impact on the deformation at peak load, suggesting that the mode of failure (e.g., ductile vs. brittle) was not greatly affected by loading rate modifications. Therefore, a range of loading of 0.25 to 0.64 mm/min is recommended (as detailed in Appendix B) based on the findings that these rates generated accurate and repeatable strength values in a reasonable amount of time.

Effects of Cylinder Curing and Conditioning. The overall objective of this study was to determine the most efficient and accurate method(s) of curing and conditioning CLSM test cylinders. CLSM samples were exposed to the four different curing conditions (A, B, C, and D), as previously described in Table 3.18. All cylinders were capped with sulfur capping compound and tested at a loading rate of 0.38 mm/min at 28 and 91 days. The curing regime recommended by ASTM D 4832 is labeled as curing condition C in this study.

The compressive strengths measured at 28 and 91 days are shown in Tables 3.24 and 3.25, respectively. The remainder of this section discusses these results and also describes some of the nuances observed when testing different materials and mixture proportions. Some interesting observations were made that illustrate that the strength of CLSM is significantly affected by variations in curing conditions, and further, that these variations are a function of specific materials and mixture proportions.

In general, there were substantial differences between the strength of CLSM cylinders stored outdoors (in hot Austin, Texas, weather) and cylinders cured in the fog room. However, there was not a consistent trend for all the mixtures studied, illustrating that the effects of temperature and curing conditions are sensitive to material type and proportions. Some mixtures lost strength when stored outdoors, whereas others showed significant increases in strength when stored outdoors.

The largest increase in strength for mixtures stored outdoors was observed for mixtures G-2, G-8, and G-10, which contained Class C fly ash, where the high temperatures helped to activate the fly ash. Mixture G-2, a rapid-setting mixture with 275 kg/m^3 of Class C fly ash and no portland cement, showed a 40 percent increase in strength when stored outside rather than in the fog room. Mixtures containing Class F fly ash also exhibited higher strengths for cylinders cured outdoors in a hot climate, but the differences were more pronounced for Class C fly ash. In fact, the difference between fog room–cured and outdoor-cured cylinders was as high as 250 percent for mixtures containing Class C fly ash. Thus, using laboratory-cured cylinders to assess the field performance of CLSM containing fly ash (especially high-calcium fly ash) in hot environments must be done with caution. The effects of temperature on CLSM hydration are especially important when large amounts of fly ash are used and when the fly ash–cement ratio is high. This temperature-driven impact on strength triggered a more comprehensive study on the effects of temperature on strength gain, as described later in this chapter.

For high air-content mixtures G-3 and G-6, the effects of curing methods varied with cement contents (and strength levels). Mixture G-3 contained 30 kg/m^3 of cement and exhibited relatively low strengths. In fact, mixture G-3 suffered such a reduction in strength when stored outdoors (compared to fog room curing) that cylinders could not be tested at an age of 28 days. At 91 days, cylinders could be tested, but the resultant strengths were significantly lower than fog room–cured cylinders. Mixture G-6, which contained 45 kg/m^3 of cement, exhibited less difference in strength (comparing outdoor curing to fog room curing) than the lower cement-content mixture (G-3). For mixture G-6, there was still a reduction in strength for outdoor-stored cylinders compared to fog-room cured cylinders at 28 days, but this difference became negligible at 91 days. These findings suggest that high air-content CLSM mixtures (without fly ash) benefit more from moist curing than they do from high-temperature exposures.

Overall, these findings regarding curing temperature and cylinder storage led the research team to initiate a final investigation on the effects of curing temperature and humidity on compressive strength, as discussed in the next section.

The effect of drying time on the compressive strength of CLSM cylinders was evaluated; the results are shown in Table 3.26. CLSM cylinders were first cured in the fog room for various time periods (7, 28, and 91 days) and then allowed to dry at room temperature for various time periods before compression testing.

Table 3.24. Compressive strength at 28 days using different curing conditions.

Mixture	Curing Condition A (Normal)		Curing Condition B (Mold)		Curing Condition C (Cap)		Curing Condition D (Outside)	
	Average (kPa)	C.O.V (%)	Average (kPa)	C.O.V (%)	Average (kPa)	C.O.V (%)	Average (kPa)	C.O.V (%)
G-1	559.1	3.2	365.1	2.3	344.3	6.0	536.0	5.9
G-2	246.8	16.5	267.9	4.7	269.2	14.3	380.1	5.2
G-3	89.5	24.1	93.6	24.6	59.4	6.5	–[a]	–[b]
G-4	247.8	11.6	167.0	16.1	164.9	4.8	–[b]	–[b]
G-5	893.5	1.7	877.0	3.3	991.3	4.4	1259.0	4.8
G-6	369.5	7.8	326.1	10.2	306.6	7.3	295.5	8.2
G-7	150.8	11.5	145.4	4.8	161.5	3.7	280.0	8.3
G-8	170.3	9.2	137.3	6.4	160.9	16.1	600.1	8.3
G-9	317.9	12.9	328.6	13.3	279.0	18.7	496.0	14.5
G-10	486.3	3.6	412.2	9.6	411.6	6.1	986.9	4.4

[a] Mixture was too weak to be tested.

[b] Not enough specimens were available for testing at this age.

Table 3.25. Compressive strength at 91 days using different curing conditions.

Mixture	Curing Condition A (Normal)		Curing Condition B (Mold)		Curing Condition C (Cap)		Curing Condition D (Outside)	
	Average (kPa)	C.O.V (%)	Average (kPa)	C.O.V (%)	Average (kPa)	C.O.V (%)	Average (kPa)	C.O.V (%)
G-1	754.6	7.7	500.7	5.0	479.4	6.0	808.8	2.3
G-2	346.1	7.8	308.6	11.1	266.5	15.3	422.7	4.5
G-3	101.9	7.3	97.4	2.0	96.3	15.5	49.6	6.1
G-4	305.8	11.4	272.9	7.9	239.0	8.1	408.5	7.1
G-5	1248.8	19.2	1342.3	14.2	1244.3	7.9	–[a]	–[a]
G-6	378.0	13.9	367.7	3.7	366.6	7.1	378.0	13.9
G-7	175.8	10.7	179.3	4.1	199.6	7.6	271.9	8.3
G-8	218.0	2.0	210.5	8.8	201.5	12.6	943.0	2.7
G-9	408.8	6.3	347.3	14.0	353.4	24.1	501.1	13.7
G-10	785.9	17.8	688.0	6.2	617.7	5.4	1080.1	6.3

[a] Not enough specimens were available for testing at this age.

The standard test for compressive strength of concrete cylinders, ASTM C 39, requires samples to be tested in a moist state. Neville (1996) pointed out that testing samples when moist would provide more reproducible results because the moisture conditions (especially near the surface) of dried samples may vary. For air-dried CLSM samples compressive strength first increased with increasing drying periods and then dropped. The largest compressive strength values were obtained from samples that were dried for 2 hours. Researchers observed that, similar to drying concrete, drying CLSM samples could increase the measured compressive strength values as much as 17 percent. This observation indicates that it is not necessary to air-dry CLSM cylinders for 4 to 8 hours before capping as required by the ASTM D 4832. This procedure eliminates any potential differences in strength due to variable moisture conditions of cylinders and increases the number of cylinders that can be tested in a given day at a testing facility.

Effects of Curing Temperature and Humidity on Compressive Strength. This study was a follow-up to previous testing that suggested that temperature plays a major role in CLSM strength development. Three curing temperatures (10°C, 21°C, and 38°C) and six CLSM mixtures (H-1 to H-6 in Table 3.14) were selected to study the strength gain of CLSM across a range of practical construction conditions. After casting the mixtures into plastic molds, the cylinders were immediately transported to the appropriate temperature-controlled chambers. After 3 days of storage in the chambers, half the cylinders from each mixture were stripped or removed from the molds and returned to the same chamber until the time of testing. This regime is referred to as "dry" curing in subsequent discussions. The other half of the cylinders from each mixture were kept inside the molds with the caps firmly in place until the day of testing (designated as "wet" curing). These cylinders were placed directly next to the cylinders that had already been stripped.

The results of compression testing at 7, 28, and 91 days are shown in Table 3.27. Also included in this table are the moisture contents of cylinders that were just tested in compression, which were measured to assess the effects of curing conditions on the moisture content (or evaporable water content) and strength of CLSM.

Mixtures containing fly ash exhibited significant strength gain at 38°C, compared to lower curing temperatures. The increase in strength was more pronounced for Class C fly ash, compared to Class F fly ash, mainly because of the difference in their reactivity. For example, at 38°C curing temperature, the increase in compressive strength of Class C fly ash–containing mixture H-5 was 160 percent. However the increase in compressive strength of Class F fly ash–containing mixture H-2 was only 40 percent. The CaO content of fly ash is generally the most important factor affecting the compressive

Table 3.26. Influence of air drying on compressive strength (mixture B-2).

Age	Drying Time							
	0-0.5 h		2 h		4 h		8 h	
	Strength (kPa)	C.O.V. (%)	Strength (kPa)	C.O.V. (%)	Strength (kPa)	C.O.V. (%)	Strength (kPa)	C.O.V. (%)
7 days	310.1	5.8	329.2	11.3	357.5	2.7	363.2	2.0
28 days	1575.1	1.9	1536.5	7.8	1447.2	5.7	1649.8	3.3
91 days	3289.4	2.0	3226.9	4.6	3430.4	3.9	3536.1	4.6

Table 3.27. Effects of temperature and relative humidity on CLSM compressive strength.

Mixture	Temp.[a] (°C)	Age								
		7 days			28 days			91 days		
		MC[b] (%)	CS[c] (kPa)	C.O.V.[d] (%)	MC[b] (%)	CS[c] (kPa)	C.O.V.[d] (%)	MC[b] (%)	CS[c] (kPa)	C.O.V.[d] (%)
H-1	10 D	36.9	328.6	3.5	17.8	548.5	7.4	2.0	258.5	2.7
	10 W	38.0	210.5	6.0	37.1	240.9	7.8	27.0	323.4	5.5
	21 D	18.1	367.5	2.8	1.6	607.3	6.5	1.1	480.2	6.5
	21 W	38.0	299.2	23.0	37.8	266.2	11.8	26.8	632.3	3.3
	38 D	19.5	828.5	2.2	1.8	722.3	4.4	1.1	756.7	12.2
	38 W	22.6	440.4	13.5	35.3	802.2	2.4	26.0	917.3	0.4
H-2	10 D	7.4	188.3	10.2	1.2	314.1	7.0	2.7	118.9	13.6
	10 W	10.3	151.9	8.6	9.6	194.2	12.3	5.5	260.5	3.6
	21 D	1.8	214.1	2.3	0.3	171.4	10.1	6.5	142.7	7.5
	21 W	9.8	172.4	2.1	9.1	233.1	6.5	3.3	345.3	10.2
	38 D	0.3	256.6	12.2	0.2	211.9	4.9	12.2	263.6	3.2
	38 W	8.6	220.9	11.7	8.9	458.2	7.3	0.4	634.6	2.9
H-3	10 D	6.0	1384.3	1.5	1.6	2315.4	4.9	1.1	1395.4	13.0
	10 W	8.7	937.7	16.2	9.1	1141.2	8.9	7.9	1367.9	3.2
	21 D	1.6	1213.4	5.1	0.6	963.6	9.6	0.5	852.9	8.9
	21 W	8.7	695.7	8.8	8.6	786.2	3.2	7.4	919.8	6.7
	38 D	0.3	1222.5	6.8	0.0	944.5	3.8	0.4	1042.0	13.5
	38 W	6.3	864.0	2.1	6.2	3844.8	7.4	2.3	3880.9	20.4
H-4	10 D	7.4	314.0	2.8	1.4	1486.2	2.8	1.1	895.8	14.8
	10 W	10.0	185.9	9.4	37.7	893.2	9.6	8.1	1670.3	4.9
	21 D	1.2	669.6	3.0	0.3	628.6	9.8	0.4	458.6	9.9
	21 W	8.8	501.7	4.1	7.7	1570.7	7.3	3.8	3743.6	4.9
	38 D	0.4	2615.0	8.5	0.9	2041.2	3.5	0.3	2060.6	5.6
	38 W	5.9	2098.8	9.2	3.7	12116.8	11.1	1.4	11512.6	7.0
H-5	10 D	8.7	273.1	6.9	1.4	711.4	3.2	0.8	421.9	5.8
	10 W	10.0	232.6	4.5	9.7	544.5	9.6	8.6	1362.6	6.3
	21 D	1.4	420.8	3.9	0.3	411.2	5.3	0.3	330.7	12.1
	21 W	10.7	316.8	6.7	10.2	815.2	2.9	8.8	1497.7	4.6
	38 D	0.3	1524.7	9.1	0.2	1423.7	4.6	0.1	1339.4	11.9
	38 W	7.4	1472.5	7.3	7.7	2282.0	8.6	3.5	2638.2	12.0
H-6	10 D	6.3	281.9	16.7	1.6	740.5	8.7	1.1	669.3	3.4
	10 W	8.7	210.6	6.9	8.1	470.5	1.2	7	922.2	5.6
	21 D	1.0	480.4	16.9	0.3	434.5	15.0	0.3	372.9	18.7
	21 W	7.5	371.4	15.8	6.2	744.7	7.2	6.2	929.6	9.4
	38 D	0.4	816.8	11.9	0.2	828.0	28.1	0.2	782.0	4.1
	38 W	6.1	562.5	10.7	4.8	786.3	12.6	0.4	991.3	7.7

[a] *D = cylinders stripped after 3 days, W = cylinders kept in mold until time of testing.*

[b] *MC = moisture content*

[c] *CS = compressive strength*

[d] *C.O.V. = coefficient of variation*

strength of CLSM mixtures, especially at high temperatures. In general, the compressive strength values of CLSM mixtures without fly ash were less sensitive to curing temperature than mixtures containing fly ash.

Air drying of CLSM cylinders from the third day of curing generally increased their 7-day strength, compared to the samples that were kept continuously in molds for 7 days. However, the 91-day compressive strength of air-dried cylinders was generally lower compared to the samples that were kept in molds. At 28 days, air-dried cylinders and the samples that were kept in molds gave mixed results.

This study reinforced the need to recognize that field installations of CLSM may possess vastly different strengths than one might predict from laboratory-cured tests, especially when CLSM contains fly ash and is used in hot climates. As such, CLSM mixtures that are produced with locally available materials for specific field applications should be tested in field conditions. Issues such as the long-term strength gain of CLSM mixtures in the field conditions should be addressed prior to the use of CLSM mixtures. An assessment of the on-site strength of CLSM should take into account laboratory-obtained test results, but it should also take into account climatic conditions. An understanding of material reactivity is helpful in extrapolating laboratory results to field performance.

Effects of Drainage Conditions on Compressive Strength. To evaluate the effect of different drainage conditions on the compressive strength of CLSM a specially designed "curing box" was constructed, as described earlier in this chapter. Researchers evaluated four different storage conditions, which ranged from "normal" curing in a fog room to curing in cylinders that allowed seepage from the bottom and/or sides and evaporation from the top (to mimic field conditions in a trench, for example). The "curing box" was kept at a higher temperature than fog room–cured cylinders, and therefore, this study also was intended to assess temperature-related effects.

The main finding from this study was that the effects of water seepage to adjacent sand and loss of water by evaporation did not significantly impact the strength of CLSM. The study also confirmed that temperature plays a key role in many CLSM mixtures and suggested that drainage and evaporation may not be as critical as temperature-induced effects.

Alternative Capping Materials for Compression Testing. The capping materials evaluated in this study included neoprene pads, sulfur caps, and gypsum caps (or "hydrostone"). Neoprene pads with Shore A durometer values of 20, 40, 50, 60, and 70 were evaluated. CLSM cylinders were capped and tested after 7, 28, and 91 days of curing using a load rate of 0.38 mm/min. Gypsum paste prepared for capping had a gypsum-water ratio of 0.3 and required approximately 40 minutes to harden. Because gypsum capping was a time-consuming process, it was only used for 28-day compression testing. Table 3.28 summarizes the strength data for the various capping methods and materials. Table 3.29 shows the corresponding coefficients of variation of measured compressive strength using the various capping methods.

For almost all cases, sulfur capping yielded the highest strength values for all eight mixtures tested. Also, in general, sulfur capping generated the lowest variations compared to the other capping methods. Lower strength cylinders tested with higher hardness value neoprene pads exhibited higher variations in the results. Compressive strength results obtained using durometer 20 neoprene pads performed better, especially with weaker cylinders, and exhibited only slightly larger variations than the results obtained using sulfur capping.

ASTM D 4832 states that capping systems are acceptable when the average strength obtained is not less than 80 percent of the average strength of companion cylinders capped with sulfur capping compound. According to this criterion, only the use of gypsum and neoprene pads with a durometer value of 50 could be qualified using the ASTM C 1231 method. However, the qualification method described in ASTM C 1231 is developed for concrete samples; if the ASTM C 1231 process is slightly modified to recognize the unique properties of CLSM (see Folliard et al. [2001] for more details), neoprene pads with a durometer value of 20 could be qualified as an acceptable capping material.

In an additional study, samples of four CLSM mixtures were tested after 7 days of curing using sulfur capping compound, neoprene pads with a Shore A durometer hardness of 50, polyurethane pads, and unbonded polyurethane-neoprene pads.

Figure 3.10 shows the ratios of compressive strength values obtained using different capping methods to the compressive strength values obtained using sulfur capping for similar samples. The abscissa of the plot is the mean compressive strength of the samples capped with sulfur compound. Results indicated that, for compressive strength values lower

Table 3.28. Compressive strength results using different capping materials.

Capping Material	Age	Mixture							
		E-1	E-2	E-3	E-4	E-5	E-6	E-7	E-8
Sulfur	7 days	0.31	0.11	0.08	0.13	0.20	0.34	0.43	0.19
	28 days	0.53	–	0.14	0.29	0.33	1.03	1.19	0.66
	91 days	0.85	–	0.14	0.45	0.48	1.58	1.71	1.24
Gypsum	28 days	0.52	–	0.11	0.24	0.36	0.95	1.11	0.59
Neoprene Pad D70	7 days	0.28	0.09	0.06	0.12	0.20	0.28	0.36	0.17
	28 days	0.42	–	0.11	0.24	0.34	0.92	1.05	0.42
	91 days	–	–	0.10	0.34	0.46	1.12	1.39	0.91
Neoprene Pad D60	7 days	0.29	0.09	0.05	0.11	0.16	0.33	0.36	0.18
	28 days	0.57	–	0.12	0.26	0.27	0.66	1.02	0.42
	91 days	–	–	0.10	0.37	0.31	1.29	1.50	0.89
Neoprene Pad D50	7 days	0.26	0.08	0.05	0.13	0.21	0.34	0.40	0.19
	28 days	0.51	–	0.10	0.25	0.28	0.87	0.96	0.47
	91 days	–	–	0.10	0.35	0.32	1.23	1.44	1.08
Neoprene Pad D40	7 days	0.27	0.07	0.04	0.13	0.22	0.33	0.34	0.21
	28 days	0.51	–	0.10	0.22	0.25	0.91	1.01	0.50
	91 days	0.79	–	0.14	0.33	0.45	1.36	1.37	0.80
Neoprene Pad D20	7 days	0.25	0.09	0.04	0.11	0.20	0.32	0.40	0.17
	28 days	0.71	–	0.09	0.24	0.31	0.90	0.96	0.57
	91 days	–	–	0.13	0.40	0.36	1.30	1.43	1.05

"–" = Not enough specimens were available for testing at this age.

Table 3.29. Coefficients of variation (%) for compressive strengths using different capping materials.

Capping Material	Age	Mixture							
		E-1	E-2	E-3	E-4	E-5	E-6	E-7	E-8
Sulfur	7 days	1.6	5.8	5.0	7.1	15.7	17.6	8.4	6.9
	28 days	16.3	–	14.2	5.7	20.7	13.3	4.0	10.3
	91 days	3.6	–	15.3	10.6	10.5	6.9	5.3	8.1
Gypsum	28 days	18.0	–	7.7	6.1	5.5	5.3	7.8	14.9
Neoprene Pad D70	7 days	5.3	12.4	20.3	5.9	3.7	12.0	9.7	9.5
	28 days	45.9	–	19.3	22.0	44.5	16.1	14.9	20.8
	91 days	–	–	22.8	6.8	24.9	8.3	3.0	3.7
Neoprene Pad D60	7 days	18.0	6.5	15.5	7.2	17.3	12.0	13.2	22.1
	28 days	12.9	–	2.9	2.5	4.0	23.9	7.6	22.0
	91 days	–	–	30.4	12.9	16.4	12.5	6.6	21.4
Neoprene Pad D50	7 days	17.5	5.7	28.7	15.9	7.4	0.7	4.6	30.0
	28 days	18.1	–	15.5	5.0	20.9	15.1	6.4	6.5
	91 days	–	–	17.0	22.2	12.6	4.2	4.0	11.5
Neoprene Pad D40	7 days	17.9	27.6	23.3	21.4	10.1	13.0	6.8	15.2
	28 days	15.4	–	14.0	9.5	20.5	19.5	10.8	11.2
	91 days	12.7	–	2.7	4.6	27.8	6.6	14.6	9.4
Neoprene Pad D20	7 days	16.5	1.9	20.5	15.8	10.3	7.3	9.6	16.6
	28 days	7.1	–	1.1	14.5	10.1	19.2	6.8	5.9
	91 days	–	–	6.1	7.4	22.2	9.1	6.0	23.5

"–" = Not enough specimens were available for testing at this age.

than approximately 200 kPa, the non-sulfur capping methods generally underestimate the compressive strength. However, for compressive strength values greater than 200 kPa, the use of non-sulfur capping methods provided results that were acceptable following the criteria given in ASTM D 4832. As noted, for different capping methods to be acceptable, the ASTM D 4832 standard requires the obtained compressive strength values to be not less than 80 percent of the corresponding values obtained using sulfur caps.

Based on these results, the following recommendations can be made with regard to generating acceptable strength data using unbonded pads:

- CLSM with compressive strength lower than 1.0 MPa should be tested using unbonded polyurethane pads (Shore OO 50, equal to Shore A durometer 5)
- CLSM with compressive strength between 1.0 and 2.0 MPa should be tested using either polyurethane pads (Shore OO 50) or neoprene pads (Shore A durometer 50)
- CLSM with compressive strength greater than 2.0 MPa should be tested using neoprene pads (Shore A durometer 50)

The selection of durometer 50 neoprene pads for higher strength CLSM mixtures was due to the general availability of these pads in concrete laboratories and because the pads can be

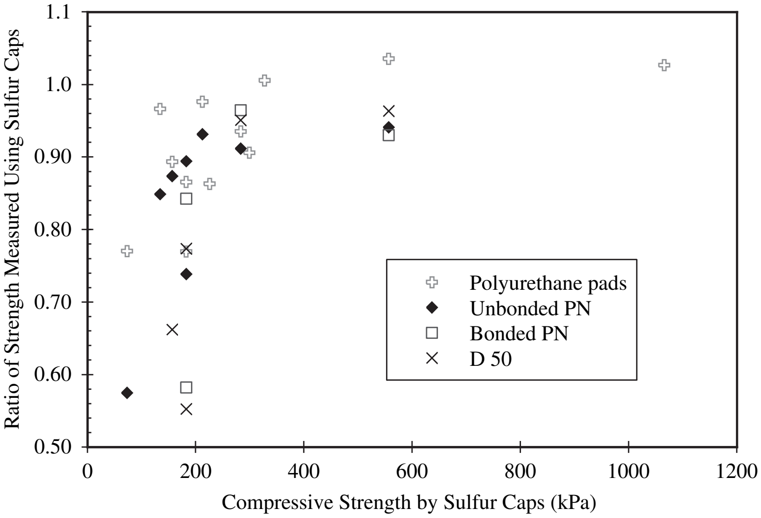


Figure 3.10. Comparison of strength values from different capping methods.

qualified in accordance with ASTM D 4832. Polyurethane pads were found to be too weak to use under high compression loads.

Excavatability

This section summarizes the results of tests that are directly or indirectly related to the excavatability of CLSM. Included are the initial findings from tests conducted on selected CLSM mixtures (six from the original mixture series) and the results of subsequent, more comprehensive testing on excavatability and related indices. The splitting tensile test was also evaluated as a potential index of excavatability, and as such, the tensile results are provided in this section.

As previously described in this chapter, the excavatability of CLSM was assessed for six of the original thirty-eight mixtures by casting CLSM into 450 × 450 × 300 mm plywood boxes. The early strength or stiffness of CLSM was assessed using a soil penetrometer, and these values were correlated with "walkability" or the time at which an average person can walk on the material. Soil penetrometer values in the range of 4.32 to 7.35 kPa were found to correlate with initial walkability. Long-term excavatability was assessed for the six CLSM mixtures at an age of approximately 9 months using typical hand tools, including a shovel and a pick. Just prior to assessing the excavatability, the "stiffness" of the samples was measured using the GeoGauge instrument (as described earlier). Compressive strengths of laboratory-cured cylinders were also measured at the time of excavation.

As shown in Table 3.30, there was no clear correlation between compressive strength, excavatability, and stiffness (as measured by the GeoGauge). For example, the laboratory-cured compressive strength of mixture 23 was quite low, but the field-cured excavation box was not excavatable. Previous testing has shown that laboratory-cured cylinders may not be accurate indicators of in-situ strength or stiffness, especially when CLSM is exposed to higher temperatures in the field (as was the case for these samples). Also, the results suggest that compressive strength, by itself, may not be a good predictor of excavatability. Another example of lack of correlation was the fact that mixture 24 had a higher stiffness than mixture 22r, yet it was much easier to excavate. The findings of this initial study led the researchers to perform more comprehensive research on excavatability, including the assessment of other test methods and indirect indices, as described next.

The researchers performed a comprehensive follow-up study to the initial excavatability investigation. A wide range of CLSM mixtures (C-series) was included in the investigation, and the following methods or approaches were assessed as possible indices (direct or indirect):

- Unconfined compressive strength (field-cured cylinders)
- Field penetrometer (field version of ASTM C 403 needle penetrometer)
- DCP
- CBR (estimated from DCP)
- Stiffness gauge (GeoGauge)
- RE
- Splitting tensile strength

Table 3.31 summarizes additional results from the excavatability study, including DCP values, stiffness values (using GeoGauge), and calculated RE values. The table also shows the compressive strength for laboratory-cured cylinders (at 28 days) and field-cured cylinders, which were cured adjacent to the excavatability boxes and tested at the time of excavation (240 days). The densities of the laboratory-cured and field-cured cylinders were measured before testing them in compression, and these values were used in RE calculations. The relative ease of excavation was assessed using a hand shovel.

The GeoGauge was used to assess the relative stiffness of the CLSM specimens. As CLSM mixtures were quite strong (relative to soil), a thin layer of wet fine sand was placed on the surface prior to testing, as per the recommendations of the manufacturer. Three readings were taken for each mixture.

Table 3.30. Results of initial excavation study.

Mixture	Compressive Strength (MPa)	Strength C.O.V. (%)	Stiffness[a] (MN/m)	Stiffness C.O.V. (%)	Relative Ease of Excavation (with shovel and/or pick)[b]
24	0.31	4.86	11.62	10.27	1
22r	1.01	5.49	9.76	5.40	7
6	0.92	9.66	13.20	6.72	9
4	0.70	5.24	30.72	9.10	10
26	1.61	5.91	34.57	2.09	10
23	0.12	22.31	17.15	7.51	9

[a] Stiffness was measured using the GeoGauge device.

[b] Each mixture was assigned an ease of excavation value from 1 to 10, where 1 is easiest (able to excavate with minimal pressure applied to shovel and/or pick) and 10 is most difficult (not able to excavate with shovel and/or pick, even under heavy pressure).

Table 3.31. Results of follow-up excavatability study.

Tests	Mixture								
	C-1	C-2	C-3	C-4	C-5	C-6	C-7	C-8	C-9
28-day compressive strength (lab-cured) (kPa)	533	807	144	292	1027	332	1192	658	417
Density (kg/m^3)	1512	1946	1724	1858	2094	2252	2143	2171	1660
240-day compressive strength (field-cured) (kPa)	1134	493	63	447	3290	362	1397	1615	199
RE (using 28-day lab-cured cylinders)	0.84	1.51	0.53	0.85	1.9	1.2	2.12	1.6	0.85
RE (using 240-day field-cured cylinders)	1.22	1.18	0.35	1.05	3.39	1.25	2.29	2.51	0.59
Modified RE (using 28-day lab-cured cylinders)	0.79	1.50	0.51	0.83	1.91	1.23	2.14	1.63	0.82
Modified RE (using 240-day field-cured cylinders)	1.16	1.17	0.34	1.03	3.42	1.29	2.32	2.55	0.57
DCP index (mm)	6.4	6.5	29	5.2	0.5	5	1.1	0.6	10
CBR (%)	37	36	7	46	100	48	100	100	22
Stiffness (using GeoGauge) (MN/m)	19.37	40.56	19.03	28.97	30.87	18.54	11.96	23.89	23.03
Relative ease of excavation (with shovel)[a]	3	7	1	6	9	8	8	10	4

[a] Each mixture was assigned an ease of excavation value ranging from 1 to 10, where 1 is easiest (able to excavate with minimal pressure applied to shovel) and 10 is most difficult (not able to excavate with shovel, even under heavy pressure).

The variations were quite high for the device, with coefficients of variation as high as 40 percent for some specimens. There was no clear trend between stiffness values and DCP, nor was there a clear trend between stiffness values and actual excavatability (by shovel). In general, the GeoGauge was not found to be an effective means of assessing the properties of CLSM, both because of poor reproducibility and inability to predict excavatability.

The DCP index value, which indicates the penetration depth per blow, was measured for each of the excavation boxes. The minimum value for a recordable blow corresponded to a penetration of at least 25 mm. DCP values were found to decrease until the specimens ultimately suffered large cracks. After the large cracks appeared, the DCP values progressively decreased. Thus, the lowest index value was taken for each mixture and used in Table 3.31 because it represented the most difficult portion to excavate, thus providing a conservative index.

The correlation between DCP index and the RE values (based on 240-day field-cured cylinders) is shown in Figure 3.11. As shown in the figure, a DCP index of 5 mm per blow correlated well with an RE value of 1.0. This correlation suggests that the DCP may be an effective, user-friendly method of assessing excavatability in the field. This approach was further investigated in the field testing component of this project (Chapter 4), where excavatability will be assessed not only using hand tools, but also using typical, commercial excavation equipment (i.e., backhoe).

Another parameter that may potentially be used as an index for excavatability is the splitting tensile strength of CLSM. Some preliminary trials found that tensile strength may, in fact, be more suitable than compressive strength in assessing excavatability. Although splitting tensile tests were not performed on the C-series mixtures, some tests were performed on other mixture series. The results are provided in this section because of the potential of applying tensile data to excavatability predictions.

The splitting tensile strengths of a range of CLSM mixtures (E-series) were measured, as shown in Table 3.32. A split cylinder from mixture E-1 is shown in Figure 3.12. For the E-series CLSM mixtures, the splitting tensile strength to compressive strength ratio ranged from 9 percent to 17 percent, which is higher than those typically observed for conventional concrete. Unlike concrete, this ratio did not substantially decrease with an increase in compressive strength.

Additional splitting tensile tests were performed using the E-series mixtures to assess the effects of drying on tensile strength and the tensile–compressive strength ratio. This testing was initiated because drying generally has a more profound effect on tensile strength than compressive strength, at least in the case of conventional concrete. This behavior is generally attributed to the effects of microcracks. The results, shown in Table 3.33, confirmed that drying had a similar effect on CLSM, significantly lowering the tensile–compressive strength ratio.

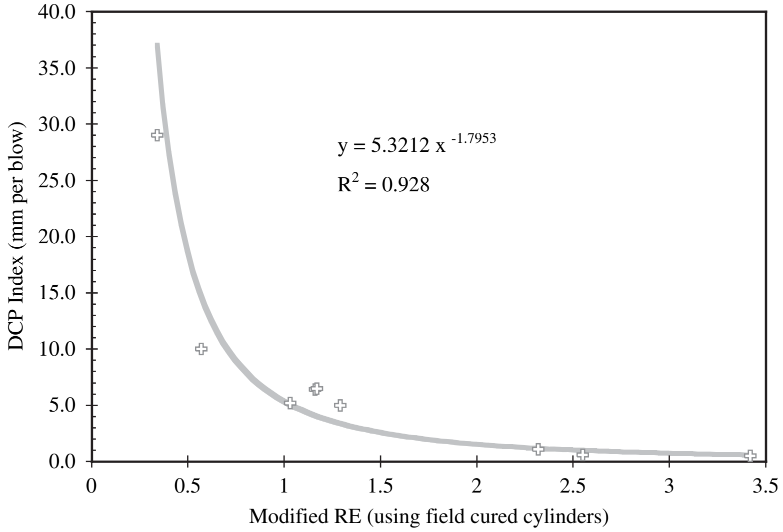


Figure 3.11. Correlation between DCP index and RE calculated using 240-day compressive strength (field-cured cylinders).

California Bearing Ratio and Resilient Modulus

CBR and resilient modulus of six CLSM mixtures were measured following modified AASHTO T 193 and T 292, respectively. Table 3.34 shows the measured CBR and resilient modulus values. With the exception of some mixtures that contained fly ash or high air content, observed CBR values were high, indicating that the tested mixtures would function as a suitable base or subbase material. More important, the results and experience confirm that it is feasible to determine CBR and resilient modulus values for CLSM using equipment commonly used to evaluate soils in typical testing laboratories.

Water Permeability

The water permeability (or hydraulic conductivity) test results of six CLSM mixtures (I-series) are shown in Table 3.35. According to Bowles (1984), all of these permeability values (measured after 28 days of moist curing) were in the range of silty clays, silty or clayey fine sands, silts, clayey silts, and clays. Results indicate that water-cement ratio was an important factor affecting the coefficient of permeability. Generally, permeability decreased with decreasing water-cement ratio. Interestingly, the high air content of mixture I-5 did not increase its permeability significantly, indicating that the entrained air bubbles were not well connected. The water permeability of the CLSM samples was easily measured using equipment commonly used to characterize soils. Additional information on the effect of freeze-thaw damages on water permeability of CLSM samples is provided in the section "Freezing and Thawing."

Triaxial Shear Strength

Using the same materials and mixture proportions as the water permeability study, the triaxial shear strength of several CLSM mixtures was measured. The results, shown in

Table 3.32. Compressive and splitting tensile strengths at 7, 28, and 91 days.

Mixture	7 days			28 days			91 days		
	Average (kPa)	C.O.V. (%)	f'_{st}/f'_c (%)	Average (kPa)	C.O.V. (%)	f'_{st}/f'_c (%)	Average (kPa)	C.O.V. (%)	f'_{st}/f'_c (%)
E-1	57.0	4.0	18.5	62.5	9.8	11.7	161.5	8.2	19.0
E-2	21.1	5.3	17.5	28.4	19.9	14.5	31.2	19.1	11.9
E-3	14.4	8.2	17.1	20.6	17.5	14.3	27.2	11.7	18.9
E-4	25.0	14.5	19.6	29.5	8.3	10.1	57.6	6.7	12.8
E-5	46.9	12.9	23.6	101.1	23.1	9.8	150.7	23.0	9.5
E-6	34.2	19.3	10.0	57.3	14.7	17.3	61.9	8.3	13.0
E-7	50.5	6.9	11.8	164.2	30.3	13.8	188.5	18.5	11.0
E-8	33.2	16.3	17.3	75.4	8.1	11.5	146.1	1.8	11.8

f'_{st} = splitting tensile strength
f'_c = compressive strength

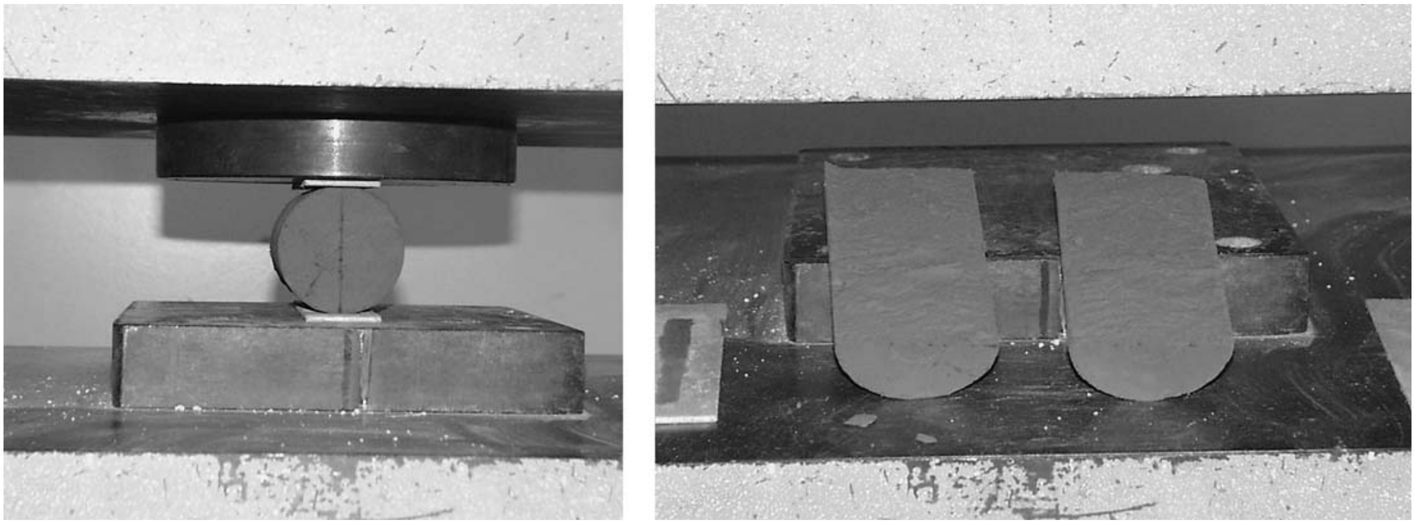


Figure 3.12. A cylinder from mixture E-1, before and after being tested for splitting tensile strength.

Table 3.36, confirmed the observation of other researchers (Bhat and Lovell 1996) that the strength of CLSM is composed of both chemical bonding and internal frictional resistance. For the mixtures investigated in the present study, the behavior was found to be a function of specific material and mixture proportions, and the effects changed with increased curing time.

For mixtures I-1, I-2, and I-3, the internal friction angles and cohesion both increased with time (between 7 and 28 days). Their friction angles at 28 days were in the range of very dense granular soil, and the mixtures behaved like dense sand, with lower residual strengths than ultimate strengths. For mixture I-4, the strength development was manifested mainly as an increase in internal friction angle, whereas for mixture I-5, an

Table 3.33. Effects of temperature and drying conditions on splitting tensile strength of CLSM.

Condition	Mixture H-1			Mixture H-2		
	Average (kPa)	C.O.V. (%)	f'_{st}/f'_c (%)	Average (kPa)	C.O.V. (%)	f'_{st}/f'_c (%)
10°C, dry	16.7	23.1	6.5	6.0	20.2	5.1
10°C, wet	25.6	19.3	7.9	–	–	–
21°C, dry	23.8	8.6	4.9	8.8	39.6	6.1
21°C, wet	89.0	27.9	14.1	–	–	–
38°C, dry	55.0	18.8	7.3	18.9	11.4	7.2
38°C, wet	74.5	6.1	8.1	53.4	15.5	8.4

Condition	Mixture H-3			Mixture H-4		
	Average (kPa)	C.O.V. (%)	f'_{st}/f'_c (%)	Average (kPa)	C.O.V. (%)	f'_{st}/f'_c (%)
10°C, dry	100.4	14.1	7.2	65.5	33.0	7.3
10°C, wet	166.3	32.1	12.2	95.8	101.4	5.7
21°C, dry	49.2	8.5	5.8	32.2	5.0	7.0
21°C, wet	114.5	15.5	12.4	455.9	36.0	12.2
38°C, dry	87.8	7.5	8.4	158.6	6.3	7.7
38°C, wet	525.4	30.9	13.5	1791.7	12.5	15.6

Condition	Mixture H-5			Mixture H-6		
	Average (kPa)	C.O.V. (%)	f'_{st}/f'_c (%)	Average (kPa)	C.O.V. (%)	f'_{st}/f'_c (%)
10°C, dry	28.8	12.3	6.8	56.1	67.5	8.4
10°C, wet	133.0	7.5	9.8	84.5	22.8	9.2
21°C, dry	25.6	16.6	7.7	64.1	5.3	17.2
21°C, wet	127.8	8.6	8.5	142.8	7.3	15.4
38°C, dry	106.8	9.1	8.0	114.1	16.6	14.6
38°C, wet	198.2	6.0	7.5	125.3	12.5	12.6

f'_{st} = splitting tensile strength
f'_c = compressive strength
"–" = Not enough specimens were available for testing at this age.

Table 3.34. Resilient modulus and CBR values for selected CLSM mixtures after 28-day moist curing[a].

Mixture	Regression Equation	R^2	CBR (%)
4	$M_r=3.00\times10^{10}(S_d)^{-3.3517}$ S_d (kPa) — Total M_r (GPa) 276 — 199.45 345 — 66.23 414 — 52.52	0.9155	215.93
6	$M_r=3.00\times10^{6}(S_d)^{-2.6284}$ S_d (kPa) — Total M_r (GPa) 69 — 69.28 138 — 3.01 207 — 1.94 276 — 2.06	0.8486	175.83
23	$M_r=1.46\times10^{5}(S_d)^{-2.2978}$ S_d (kPa) — Total M_r (GPa) 34.5 — 57.61 69 — 4.79 103.5 — 3.49 138 — 2.36	0.9155	20.01
24	$M_r=1.00\times10^{8}(S_d)^{-2.8847}$ S_d (kPa) — Total M_r (GPa) 138 — 134.32 207 — 20.63 276 — 11.19 345 — 8.47 414 — 4.74	0.9492	61.76
22r	$M_r=3.06\times10^{2}(S_d)^{-0.4929}$ S_d (kPa) — Total M_r (GPa) 207 — 23.33 276 — 17.99 345 — 16.6 414 — 15.77 483 — 15.25 552 — 13.54	0.9395	114.68
26	$M_r=6.57\times10^{5}(S_d)^{-1.4393}$ S_d (kPa) — Total M_r (GPa) 414 — 104.44 483 — 89.48 690 — 72.93 828 — 33.25	0.8122	150.00

[a] Confining pressure 21 kPa.
S_d = Deviator stress, M_r = Resilient modulus.

increase in cohesion was the dominant factor. These mixtures (I-4 and I-5) had high air contents and exhibited behavior similar to loose or uncompacted sands. It was interesting to note that for mixture I-6, the friction angle decreased and cohesion greatly increased with time.

Drying Shrinkage

As stated earlier, there are no standard methods to evaluate the drying shrinkage of CLSM and only limited emphasis was placed on this topic. A method developed in Germany to measure the shrinkage of conventional concrete for flooring applications was used without modification in this study to measure the shrinkage of CLSM mixtures. The results are shown in Table 3.37. The temperature during the testing period was 20°C and the relative humidity was approximately 60 to 65 percent. For mixtures without air entrainment, most of the shrinkage occurred during the first day, probably due to early bleeding and subsidence; however, the method used in this study could not detect this shrinkage. It is possible that all of the shrinkage could not be detected because CLSM did not exhibit sufficient early strength (or stiffness) to cause a detectable movement of the end anchor. More research is needed to examine drying shrinkage of CLSM and to develop a suitable test method. Because the topic of drying shrinkage was not identified as a critical issue for this project, no further research was performed on this topic.

Table 3.35. Water permeability of selected CLSM mixtures.

Mixture	Permeability (mm/s)
I-1	2.46×10^{-3}
I-2	5.33×10^{-4}
I-3	1.45×10^{-4}
I-4	4.20×10^{-3}
I-5	6.75×10^{-3}
I-6	2.89×10^{-4}

Durability Test Methods

Corrosion

Phase I, Uncoupled Samples. To evaluate the potential influence of resistivity, pH, fly ash type, fine aggregate type, water–cementitious materials ratio (w/cm), and cement content on the corrosion activity of ductile iron coupons embedded completely in CLSM or sand, the percent mass loss of coupons embedded in thirty different CLSM mixtures (and eight duplicated mixtures) was evaluated. The box plot showing the distribution of the percent mass loss values of the ductile iron coupons is given in Figure 3.13. Because mixtures 21 and 23 were not significantly different from other mixtures but the results obtained from them seem to be an anomaly, their data were not included in the statistical analysis.

A multiple regression analysis and an analysis of variance were performed with the logarithm of percent mass loss data of the 36 CLSM samples as the response variable. Comparison of all possible main effect models for the maximum adjusted R^2 and minimum mean sum of error (MSE) indicates that the best model to predict mass loss of ductile iron pipe completely embedded in CLSM has three explanatory

Table 3.36. Results of triaxial shear tests.

Mixture	7 days		28 days	
	Friction angle ϕ′ (°)	Cohesion c′ (kPa)	Friction angle ϕ′ (°)	Cohesion c′ (kPa)
I-1	36.14	31.8	42.81	40.1
I-2	36.07	96.1	38.73	174.7
I-3	39.35	251.7	47.86	346.2
I-4	21.99	43.9	23.92	43.1
I-5	19.48	89.8	18.47	130.0
I-6	37.30	44.4	33.86	93.4

Table 3.37. Drying shrinkage of selected CLSM mixtures.

Time	Shrinkage Strain (x 10^{-6})					
	Mixture 4	Mixture 24	Mixture 23	Mixture 6	Mixture 22r	Mixture 26
1 day	2260	2830	80	1440	90	10
2 days	2280	2850	80	1450	90	30
3 days	2280	2860	80	1450	90	50
4 days	2280	2860	80	1450	100	70
5 days	2300	2860	80	1460	100	100
6 days	2310	2880	80	1480	110	130
7 days	2330	2880	80	1500	120	160
2 weeks	2390	2930	160	1540	150	200
3 weeks	2410	2960	180	1590	150	190
4 weeks	2410	2980	180	1529	160	210
5 weeks	2410	2980	180	1600	160	220
6 weeks	2420	2960	180	1610	160	220
7 weeks	2410	2960	180	1600	–	–

"– " = Not enough specimens were available for testing at this age.

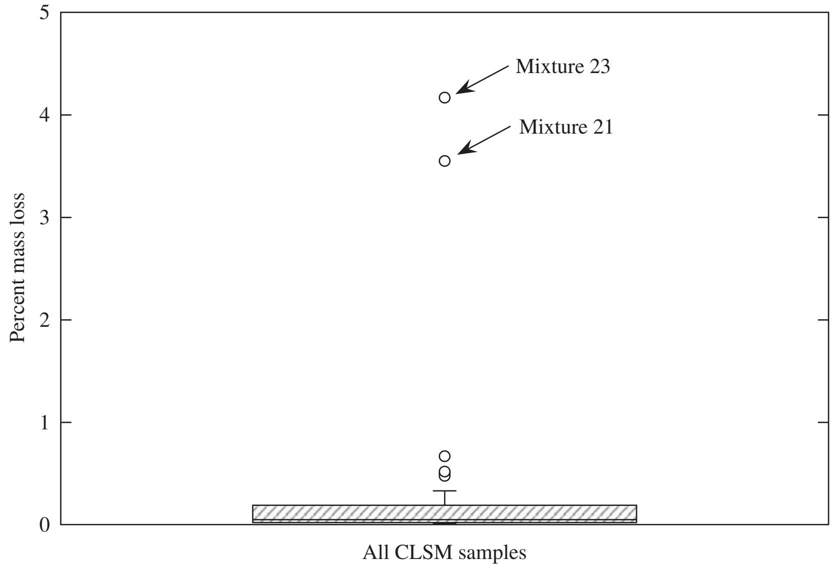


Figure 3.13. Box plot of percent mass loss values.

variables—fly ash type, fine aggregate type, and w/cm—as shown below:

$$\log_{10}(\%\ mass\ loss) = 0.056 - \gamma - \lambda + 0.0312 \cdot \frac{w}{cm} \qquad (3.4)$$

where

γ = 1.13, 1.07, 1.31, and 0.0 for bottom ash, concrete sand, foundry sand, and no fine aggregate, respectively

λ = 0.47, 0.61, 0.69, and 0.0 for Class C, Class F, high-carbon, and no fly ash, respectively.

The logarithm of the percent mass loss data is the response variable. The adjusted RP2P for this second model is 67 percent and its MSE is 0.0916. Appropriate coefficients should be used to predict the expected mean percent mass loss for specific CLSM mixtures. The coefficients for the fine aggregate type and the fly ash type are significant at the 95 percent confidence level and the coefficient for the w/cm is significant at the 89 percent confidence level.

Many field investigations on the corrosion of metals embedded in soils have reported that resistivity is a major controlling parameter affecting corrosion activity of the embedded metal (Spickelmire 2002, Kozhushner et al. 2001). Prior corrosion research in soils reported a non-linear relationship between mass loss and resistivity (Edgar 1989, Palmer 1989). However, the evidence for such a non-linear relationship for the CLSM data in this study is very weak. The sand used in the control samples exhibited a resistivity of $3.1 \times 10^4\ \Omega$-cm and the average percent mass loss for the control group was 0.39 percent. Ductile iron coupons embedded entirely in CLSM exhibited lower corrosion activity than the ductile iron coupons embedded in the control sand even though the resistivity of the control sand material was higher than the resistivity of all the CLSM mixtures. This result is contradictory to conventional soil corrosion studies.

Some utility agencies have voiced concern that the use of fly ash in CLSM could be detrimental to the corrosion performance of metals embedded in CLSM, because fly ash may cause a reduction in the pH, which could further result in higher corrosion activity. The results of this study indicate that the logarithm of the mean percent mass loss of mixtures without fly ash is statistically significantly higher than the mixtures with fly ash. This result indicates that the benefits of the fly ash on the microstructure and long-term passivation characteristics, as reported by Cao et al. (1994), likely have a more significant impact on corrosion performance than the relatively limited reduction in pH.

The mean pH of the pore solution from the CLSM mixtures evaluated in this study was 11.35. Although this high pH value was expected to decrease the corrosion activity of the ductile iron coupons, the results do not indicate a significant decrease in the percent mass loss as a result of the increased pH. As such, the pH of the pore solution alone does not seem to reliably estimate the corrosion performance of ductile iron coupons embedded in CLSM.

Statistical analysis of the data indicated that the mean logarithm of percent mass loss values for mixtures containing bottom ash, concrete sand, and foundry sand were statistically not different from each other. However, the mean logarithm of percent mass loss data for the coupons embedded in mixtures without fine aggregates were statistically different and higher than the other mixtures containing fine aggregates. The decrease in percent mass loss could be due to reductions in the diffusivity, permeability, and/or porosity of the CLSM mixtures containing fine aggregates.

As noted, the amount of cement used in CLSM mixtures is very low compared to the amount of water used. The statistical analysis indicates that the cement content had no significant effect on the percent mass loss of the ductile iron coupons embedded in the CLSM mixtures. However, the results indicated a slight increase in the logarithm of percent mass loss values with increasing water–cementitious materials ratio.

Phase I, Coupled Samples. To evaluate the mass loss (i.e., corrosion performance) of the coupled ductile iron coupons embedded in both CLSM and sand, a similar statistical analysis as described in the Phase I uncoupled samples study was performed. This analysis indicated that a good prediction of mass loss using the explanatory variables—cement content, fine aggregate type, fly ash type, etc.—was not possible for ductile iron coupons embedded in two different environments (i.e., the coupled sample).

The corrosion of uncoupled coupons was likely due to the formation of micro-galvanic corrosion cells on the surface of a single coupon. However, the major driving force of the corrosion of ductile iron coupons coupled in two different environments was likely the formation of macro-galvanic corrosion cells due to the potential difference between the ductile iron coupons. Because these macro-galvanic cells were the major driving force of the corrosion of coupled coupons, factors that significantly affected the corrosion of uncoupled coupons were insignificant for coupled coupons.

Figure 3.14 compares the logarithm of the distribution of percent mass loss of uncoupled coupons, coupled coupons, and the control group. The distributions are grouped by fly ash type. The figure indicates that the coupling of the ductile iron coupons has a significant impact: the mass loss of ductile iron coupons embedded in sand and CLSM (i.e., coupled) can be expected to be significantly larger than the mass loss of the coupons completely embedded in CLSM and the control group samples.

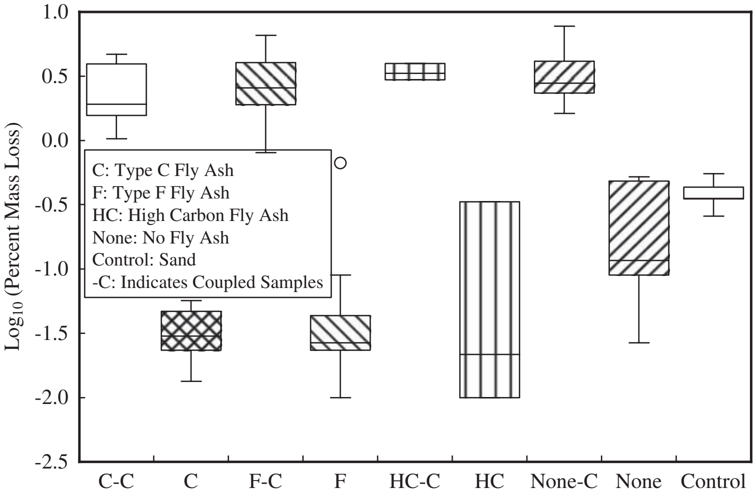


Figure 3.14. Uncoupled versus coupled log mass loss versus control group.

In general, the results of the Phase I study indicated the following:

- The corrosion activity for ductile iron pipe coupons completely embedded in CLSM was significantly lower than that of ductile iron pipe embedded in sand.
- CLSM may provide more protection against corrosion initiation and propagation when metallic structures are completely embedded in CLSM compared to compacted sand.
- Examination of the effects of the constituent materials on corrosion with a limited number of samples indicated that there was no significant difference between the fly ash types and the fine aggregate types used in this study. However, the corrosion of metal coupons in uncoupled samples that contained a fine aggregate or a fly ash was lower compared to the coupons in uncoupled samples without a fine aggregate or a fly ash.

Phase II, Uncoupled Samples. Figure 3.15 shows the box plot showing the distribution and the median of the percent mass loss data of the 361 galvanized steel and ductile iron coupons embedded in CLSM mixtures exposed to distilled water and chloride solution.

A multiple regression analysis and analysis of variance were performed on the data. The percent mass loss data were used as the response variable and the environment, fine aggregate type, fly ash type, resistivity, pH, metal type, water–cementitious materials ratio, percent chloride content, and cement content were used as the explanatory variables. Different possible models consisting of main effects and single interaction effects of the explanatory variables were applied to the data to find the best parsimonious model. Different models were compared using their adjusted coefficient of multiple determination (R^2) and root mean square values. Models were applied to the observed percent mass loss values, to their square root transformation, and to their logarithm. Trials indicated that a logarithmic transformation was more effective in decreasing the observed dependence of variability of residuals on the values of response variable. Among the models evaluated for the logarithm of percent mass loss (LPML) values, the following model had the highest R^2 value and smallest root means square error:

$$\begin{aligned}\log_{10}(\%\ \mathit{mass\ loss}) = 1.844 + \alpha + \beta + \gamma + (\delta + \kappa) \\ \bullet \log_{10}(\mathit{resistivity}) + \varepsilon \bullet pH + \phi + (\tau + \omega) \\ \bullet \frac{w}{cm} + \varphi + \eta + \lambda + \sigma \end{aligned} \tag{3.5}$$

The model includes the following relationships:

- The main effects of classification variables: environment (α), fine aggregate type (β), fly ash type (γ), and metal type (ϕ)
- The main effects of continuous variables: logarithm of resistivity (δ), pH (ε), and water-cementitious material (w/cm) ratio (τ)
- The interaction effects of classification variables with classification variables: fine aggregate type with metal type (φ), fly ash type with metal type (η), environment with metal type (λ) and fly ash type with environment (σ)
- The interaction effect of a classification variable with a continuous variable: logarithm of electrical resistivity with metal type (κ) and w/cm with metal type (ω).

However, further evaluation of the model indicated that the assumptions of residuals being normally distributed

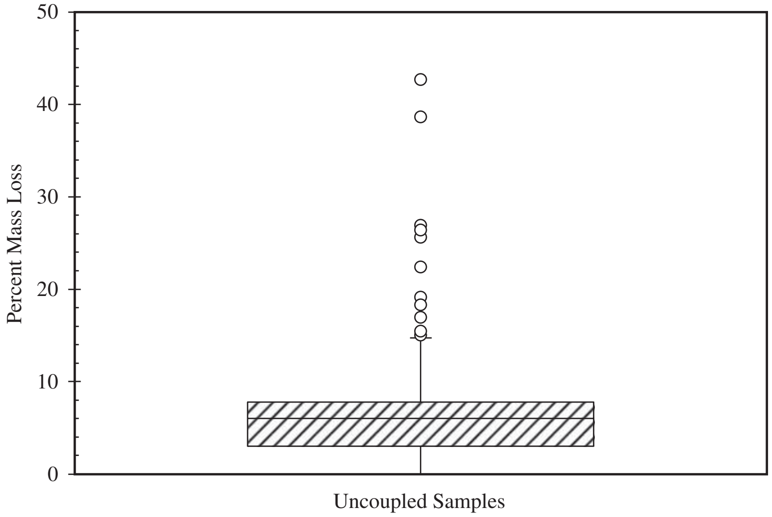


Figure 3.15. Percent mass loss distribution of metallic coupons.

and being independent of the predicted values of LPML were not satisfied very well. Because the assumption of constant variance was not satisfied, a weighted regression analysis was performed. The factors that had the largest effect on the LPML values were the environment and the metal type. The variances of the four groups obtained by separating the data by environment and metal type were calculated. The reciprocals of variances of these four groups were used as a weight variable for the weighted regression analysis. Evaluation of the studentized residuals of the weighted regression indicated that the normality assumption of residuals was satisfied much better compared to the earlier regression analysis. The R^2 value for the weighted regression analysis is 67 percent and the root mean square error value is 0.98. All of the factors included in the model were statistically significant.

The parameters defined in the model for the main effects of classification variables represent the expected value of the response variable for different levels of the corresponding classification variable, all other factors being the same. The parameters defined in the model for the main effects of continuous variables represent the amount of change in the expected value of the response variable for each unit change of the corresponding continuous variable, all other factors being the same. The interaction parameters in the model define how the response reacts to one variable based on the value or level of another variable. In the case of an interaction of a classification variable with a continuous variable, the coefficient of the continuous variable is changed based on the level of the classification variable. The values of the parameters are given in Appendix A.

In addition to the regression and variance analyses, comparisons of LPML values for the different levels of classification variables were performed using Tukey's comparison of means method at the mean values of three continuous variables and at the 64 selected combinations of these three continuous variables. Detailed information on the comparisons and the selection of combinations is given in Appendix A.

Analysis indicated that pH was significantly and inversely correlated to the observed LPML values. Environment was also a significant variable for all the samples. The samples exposed to a chloride solution exhibited significantly higher LPML values compared to the samples exposed to the distilled water. The effect of environment for galvanized steel coupons was larger compared to the ductile iron coupons.

There was a significant difference in the LPML values of different metal types. For low water–cementitious materials ratios and logarithm of resistivity values, ductile iron coupons exhibited significantly lower LPML values. However, at higher water–cementitious materials ratios and with increasing logarithm of resistivity, the difference in values became smaller and, at high enough values of these continuous variables, ductile iron coupons exhibited higher LPML values.

The effects of different fly ash types and fine aggregate types were more important for samples with ductile iron coupons. Samples that contained a fine aggregate exhibited lower LPML values compared to the samples without fine aggregates regardless of the type of the fine aggregate. The difference between the mean LPML values of samples containing bottom ash and sand as fine aggregates was statistically not significant. The samples containing foundry sand as fine aggregate exhibited a mean LPML value between that of the samples with bottom ash or sand and the samples without fine aggregates. Because of the high LPML variability of samples containing foundry sand, the difference between these samples and the samples without fine aggregates was not statistically significant.

Based on the materials used for this study, the results, from this phase only, indicate that the use of fly ash as a supplementary cementitious material may have adverse effects on the corrosion of embedded galvanized steel or ductile iron coupons, especially for the ductile iron coupons. Samples containing high-carbon fly ash or Class F fly ash exhibited higher LPML values compared to the samples without fly ashes, but the samples without fly ashes exhibited much larger variation. The mean LPML value of the samples containing Class C fly ash was lower than that of the samples with Class F or high-carbon fly ash but higher than that of the samples without fly ash. However, due to the high variance of the samples without fly ash, the difference between the samples containing Class C fly ash and samples without fly ash was not statistically significant.

Phase II, Coupled Samples. The histogram showing the percent mass loss of ductile iron and galvanized steel coupons embedded in CLSM and soil sections of coupled samples exposed to distilled water and chloride solution are shown in Figure 3.16.

Analyses indicate that the percent mass loss values of metallic coupons embedded in CLSM and soil were significantly correlated and the mass loss values of coupons embedded in the soil section of samples were higher compared to the mass loss values of coupons embedded in the CLSM section of samples. For the coupled coupons, the mass loss is believed to be mainly due to galvanic corrosion taking place between the metallic coupons embedded in different sections. The significantly higher mean percent mass loss values exhibited by the metallic coupons in the soil section indicate that these coupons were anodes and the coupons in the CLSM section were cathodes. Because the metallic coupons embedded in the soil sections of coupled samples represent the critical anodic areas of pipes for corrosion damage, further statistical analysis was performed on the percent mass loss data of these coupons.

The explanatory variables evaluated for the percent mass loss of coupons included environment, metal type, soil type, fine aggregate type, fly ash type, resistivity of CLSM, resistivity of soil, pH of CLSM, chloride content of the CLSM, and chloride content of the soil. Different possible models consisting of main effects and single interaction effects of the explanatory variables were applied to the data to find the best parsimonious model. Different models were compared using their adjusted coefficient of multiple determination (R^2) and root mean square values. Models were applied to the observed percent mass loss values, to their square root transformation, and to their logarithm. Trials indicated that a logarithmic transformation was more effective in decreasing the observed dependence of variability of residuals on the values of response variable. Among the models evaluated for the logarithm of percent mass loss values, the following model had the highest R^2 value and smallest root mean square error:

$$\log_{10}(\%\ \mathit{mass\ loss}) = 0.97 + \alpha + \beta + \delta + \varepsilon + \gamma + \phi + \varphi + \eta + \lambda \qquad (3.6)$$

The coefficients α, β, δ, ε, and γ are assigned values for the different levels of the classification variables: environment (α), soil type (β), fine aggregate type (δ), fly ash type (ε), and metal type (γ), respectively. The coefficients ϕ, φ, η, λ are assigned values for the two-factor interactions of classification variables: environment with metal type (ϕ), environment with soil type (φ), fly ash type with metal type (η), and fine

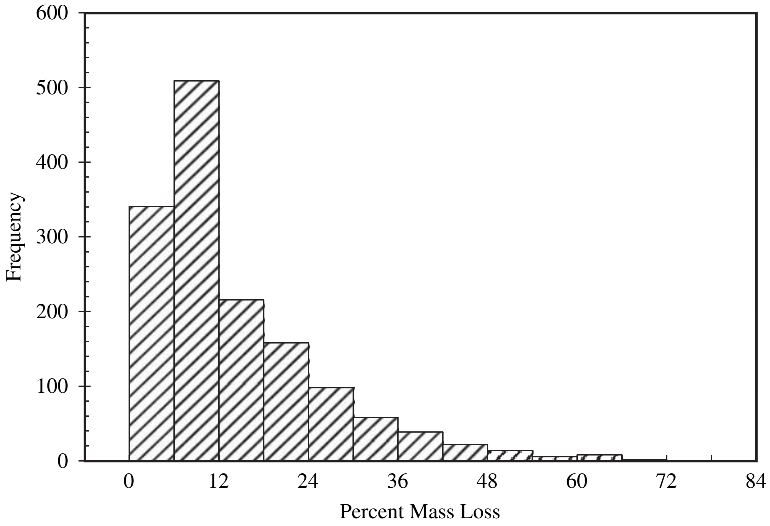


Figure 3.16. Percent mass loss of metallic coupons.

aggregate type with soil type (λ). The values of these coefficients are given in Appendix A.

Analysis showed that the overall model and all the factors included in the model were significant with the exception of metal type. However, because interactions of other variables with metal type were significant, this factor was left in the model for a complete hierarchy. All assumptions of the regression analysis were satisfied and the coefficient of determination (R^2) of the model was 35 percent. This low R^2 value indicates that a model solely built from these variables cannot be used to estimate the corrosion of metallic coupons with great accuracy.

Results indicated that samples exposed to chloride environment exhibited higher mean LPML values compared to the samples exposed to distilled water. The disturbance of the passive layer formation on the steel surface by chloride ions and the low resistivity of CLSM and soil samples exposed to chloride solution could both be the reasons for the higher mean LPML values of samples exposed to chloride environment.

Water–cementitious materials ratio had a statistically significant but small correlation with the chloride content in CLSM and a negative correlation with the logarithm of resistivity of CLSM.

Results indicated that coupons embedded in clay (soil section of coupled samples) exhibited statistically significantly higher LPML values compared to the coupons embedded in sand in both chloride and distilled water environments. However, the effect of environment was greater on the coupons that were embedded in sand compared to the coupons embedded in clay. Analysis also indicated that the resistivity and pH of clay samples were lower compared to the resistivity and pH of sand.

Although the metal type was overall not a statistically significant factor, analysis indicated that galvanized steel coupons exhibited a significantly higher mean LPML value compared to ductile iron coupons in a chloride environment.

The observed effect of fly ash on the LPML was contradictory to the findings of the uncoupled samples. Results indicated that, among the coupled samples, CLSM sections with fly ashes exhibited lower mean LPML values compared to the CLSM sections without any type of fly ash (similar to the Phase I study). However, the difference between the LPML values of CLSM sections containing fly ash and without fly ash was only statistically significant for the ductile iron coupons.

CLSM sections with bottom ash or foundry sand exhibited significantly higher LPML values compared to the CLSM sections with sand or without fine aggregates. Among the coupled samples that had clay in their soil section, CLSM sections with bottom ash exhibited the highest mean LPML value and among the coupled samples that had sand in their soil section, CLSM sections with foundry sand exhibited the highest mean LPML value.

In general, results from the Phase II study indicated the following:

- pH was significantly and inversely correlated to the observed LPML values.
- Environment was a significant variable for all the samples.
- The samples exposed to a chloride solution exhibited significantly higher LPML values compared to the samples exposed to the distilled water.
- The effect of environment for galvanized steel coupons was larger compared to the ductile iron coupons.
- There was a significant difference in the LPML values of different metal types.
- For low w/cm and logarithm of resistivity values, ductile iron coupons exhibited significantly lower LPML values.
- At higher w/cm and with increasing logarithm of resistivity, the difference in values became less and, at sufficiently high values, ductile iron coupons exhibited higher LPML values.
- The effects of different fly ash types and fine aggregate types were more important for samples with ductile iron coupons.
- Samples that contained a fine aggregate exhibited lower LPML values compared to the samples without fine aggregates regardless of the type of the fine aggregate.
- The difference between the mean LPML values of samples containing bottom ash and sand as fine aggregates was statistically not significant.
- The samples containing foundry sand as fine aggregate exhibited a mean LPML value between the samples with bottom ash or sand and the samples without fine aggregates.
- Because of the high LPML variability of samples containing foundry sand, the difference between these samples and the samples without fine aggregates was not statistically significant.
- The use of fly ashes may have adverse effects on the corrosion of embedded galvanized steel or ductile iron coupons, especially for the ductile iron coupons.
- Samples containing a high-carbon fly ash or Class F fly ash exhibited higher LPML values compared to the samples without fly ashes, but the samples without fly ashes exhibited much larger variation.
- The mean LPML value of the samples containing Class C fly ash was lower than that of the samples with Class F or high-carbon fly ash but higher than that of the samples without fly ash. However, because of the high variance of the samples without fly ash, the difference between the samples containing Class C fly ash and samples without fly ash was not statistically significant.

The following general conclusions were obtained from both phases of the study:

- The metallic coupons embedded in the soil section of coupled samples exhibited significantly higher percent mass loss values compared to the coupons embedded in uncoupled samples.

- Because the main driving force of corrosion is the potential difference in the coupled samples, the significance of the factors that affected the corrosion in uncoupled samples was generally lower for coupled samples.

Service Life of Ductile Iron and Galvanized Steel Coupons Completely Embedded in CLSM

ASTM G 1 provides a formula to predict the corrosion rate of metallic samples. By placing the LPML values obtained from the statistical model shown in Equation 3.5 into the formula given in ASTM G 1, a service life model for ductile iron and galvanized steel pipes completely embedded in CLSM can be derived. Assuming that the useful service life of the pipe will be over at the first perforation of the pipe wall due to corrosion, the service life of a pipe completely embedded in CLSM can be calculated using the following formula:

$$SL = \frac{D \cdot t \cdot 7978x10^{-2}}{10^{LPML()}\left[D^2 - (D-t)^2\right]} \tag{3.7}$$

where

SL = the service life (years)
D = the outside radius (cm)
t = the pipe wall thickness (cm)
$LPML()$ = the logarithm of percent mass loss obtained from Equation. 3.5

To obtain the LPML value from Equation 3.5, the values of the classification variables and the values of the three continuous variables (w/cm, resistivity, and pH) must be specified. However, only the values of the classification variables, such as fly ash type, fine aggregate type, environment, etc., can be specified. The values of the continuous variables are dependent values, i.e., they cannot be specified; they can only be measured from the samples of designed CLSM mixtures. Therefore, Equation 3.7 cannot be used to calculate a specific service life for a designed CLSM mixture. However, the formula can be used to perform a risk analysis by using different combinations of the continuous variables in the LPML formula. The data obtained in this study can be used to obtain an estimate of the expected range of the continuous variables for different levels of the classification variables.

It should also be noted that the coefficients of the LPML model were determined using a weighted regression analysis. The variance of each residual group that was used to determine the weight variables of the analysis can be used to obtain a distribution around the obtained service life value. Equation 3.8 shows how to obtain the required percentile of the LPML value using the variance and the LPML value obtained from Equation 3.5:

$$LPML_{\text{Pr.}} = LPML + \Phi^{-1}(\text{Pr.}) \times \sqrt{Variance} \tag{3.8}$$

where

$LPML_{\text{Pr.}}$ = the LPML for which probability of LPML $< \text{LPML}_{\text{Pr.}}$ is Pr.
Φ^{-1} = the inverse standard normal distribution function

After the values of the classification variables for a specific CLSM design are determined and a combination of the levels of continuous variables is chosen, a service life distribution graph can be generated for a ductile iron or galvanized steel pipe completely embedded in the specific CLSM mixture as shown in Figure 3.17.

Calculation of service life estimates for the galvanized and ductile iron pipes embedded in the specific CLSM mixtures that were evaluated in this study indicated that properly designed CLSM mixtures can provide a service life for ductile iron pipes similar to that in conventional backfill materials. Therefore, in selecting between CLSM and conventional backfill materials, factors other than service life—such as material cost, construction cost, construction time, and long-term settlement—should be considered. However, results indicated that the galvanized steel pipes completely embedded in CLSM can be expected to have service life values comparable to the galvanized steel pipes embedded in severely or moderately corrosive soils with low resistivity and pH values. Therefore, backfilling bare galvanized steel pipes with CLSM mixtures is likely not warranted.

Freezing and Thawing

Two studies were performed to evaluate the freeze-thaw resistance of CLSM mixtures. In the first study, six CLSM mixtures from the initial mixture series were tested using a modified version of ASTM D 560, originally developed for the assessment of soil-cement. The second study used the same method to assess a wider range of CLSM mixtures (D-series) and evaluated the effects of freeze-thaw damage on permeability.

Figure 3.18 shows the measured percent mass loss values plotted against the number of freeze-thaw cycles. The percent mass loss values shown in the figure were calculated assuming that the moisture content of all the specimens were constant throughout the test. According to the "soil-cement

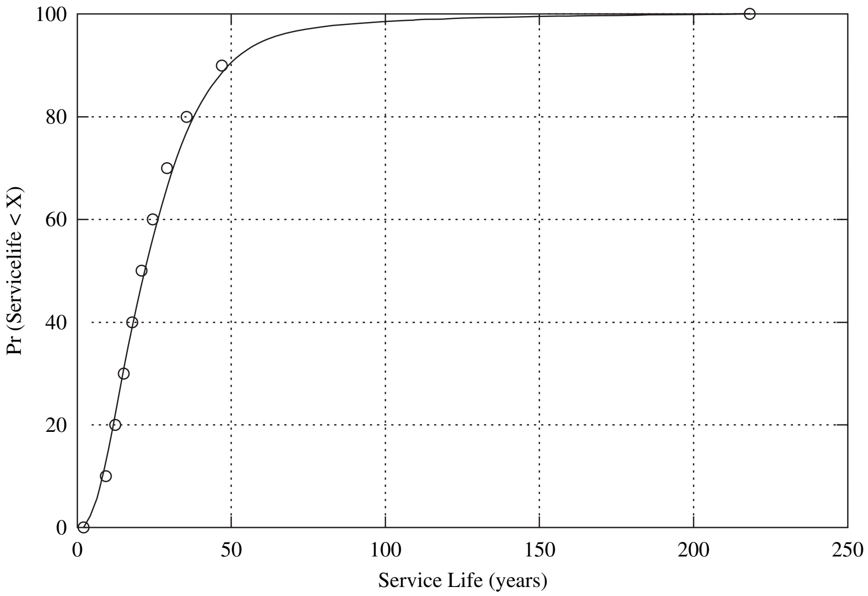


Figure 3.17. Probability distribution of service life.

laboratory handbook" the mass loss after 12 freeze-thaw cycles should not exceed 14 percent for a Group A-1 soil (PCA 1992). Soils in group A-1 are coarse grained and low in content of fines. Most of the CLSM mixtures (especially the ones that were cured for 28 days) containing high amounts of air satisfied this criterion. ASTM D 560 (with minor modifications) was found to be an effective and easy-to-perform method to assess the freeze-thaw resistance of CLSM mixtures.

The permeability or hydraulic conductivity of the D-series CLSM mixtures before and after exposure to freeze-thaw cycles is shown in Table 3.38. It is interesting to note that mixture D-1 (high-air mixture with 30 kg/m^3 of cement) did not survive the 12 cycles, whereas a similar mixture with 45 kg/m^3 of cement (D-11) did survive the entire 12 cycles, suggesting that both air-void system and strength contribute to freezing and thawing resistance. Mixture D-10 survived all 12 cycles, most likely due to its higher strength (contributed from the Class C fly ash). The remaining mixtures (D-2 through D-9) did not survive all 12 cycles. Mixtures were selected that would likely suffer freezing and thawing damage, allowing for the measurement of changes in permeability (before and after testing, as shown in Table 3.38). However, the effects of freezing

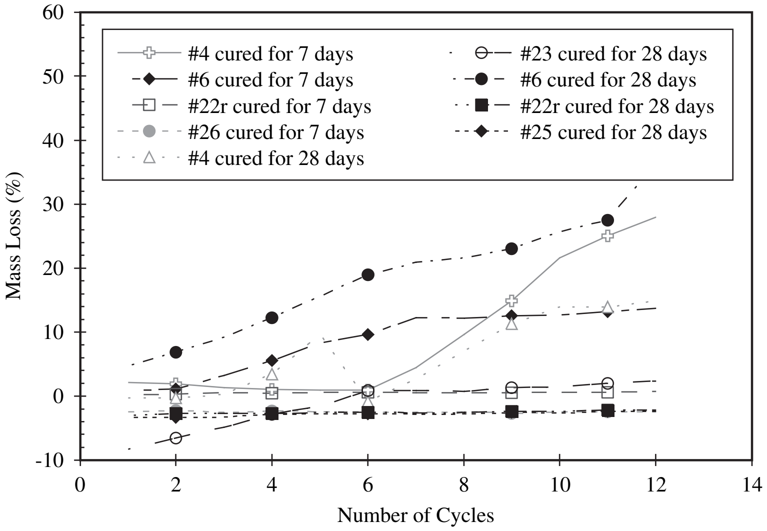


Figure 3.18. Mass losses vs. freeze-thaw cycles for selected CLSM mixtures.

Table 3.38. Frost resistance of CLSM (using modified ASTM D 560).

Measurement	Mixture										
	D-1	D-2	D-3	D-4	D-5	D-6	D-7	D-8	D-9	D-10	D-11
Original mass (kg)	1.38	1.77	1.70	1.86	1.53	1.47	1.46	1.50	1.55	1.56	1.33
Moisture content (%)	9.8	10.5	13.6	10.1	30.7	35.5	32.4	27.4	28	25.1	7.3
28-day strength (MPa)	0.13	1.02	0.79	1.47	0.11	0.12	0.20	0.38	0.25	0.53	0.34
1 cycle (%)	105.2	99.0	100.1	99.9	D	92.8	93.0	98.9	98.1	99.2	103.5
2 cycle (%)	102.3	95.3	97.3	99.8		D	D	94.9	94.8	98.1	105.9
3 cycle (%)	84.4	85.4	78.4	99.1				91.5	87.1	98.0	108.1
4 cycle (%)	74.1	75.7	73.2	96.4				88.0	83.6	98.1	110.3
5 cycle (%)	66.4	72.4	71.1	88.4				84.6	79.1	97.7	110.3
6 cycle (%)	59.6	55.4	63.8	61.0				81.4	73.5	97.3	110.3
7 cycle (%)	51.5	54.9	52.1	59.7				76.9	69.2	97.1	108.8
8 cycle (%)	45.8	46.3	54.3	57.9				73.7	62.1	95.8	108.2
9 cycle (%)	37.3	30.1	48.6	43.8				68.1	56.3	94.4	104.6
10 cycle (%)	33.6	D	D	40.3				56.1	D	92.2	103.6
11 cycle (%)	25.8			D				49.8		89.4	100.6
12 cycle (%)	D							D		85.1	97.5
Final moisture content (%)										28.7	21.3
Dry mass loss (%)										11.0	11.9
Permeability before 12 F-T cycles ($\times 10^{-2}$ mm/s)	7.38	0.35	0.21	13.02	6.60	3.87	1.63	1.60	3.08	3.63	8.06
Permeability after 12 F-T cycles ($\times 10^{-2}$ mm/s)	14.21	1.90	1.61	8.94	0.08	0.94	1.72	0.42	0.73	0.36	5.94

D = Damaged.

and thawing damage on water permeability were somewhat inconclusive, with some mixtures showing increased permeability and others showing decreased permeability. This result was most likely due to the test setup, which was designed to keep the samples intact, thus allowing for subsequent permeability testing. However, keeping the samples intact (and confined) may not have allowed for an accurate estimate of in-situ permeability. Because the samples were confined, the expansion due to freezing and thawing may have actually compacted the samples, resulting in an apparent reduction in permeability. More work is needed to elucidate the effects of freezing and thawing damage on permeability. Initially, the composition of the water flowing through the sample was to be analyzed to determine if freezing and thawing damage increased the leaching of constituent materials, specifically heavy metals. However, after analyzing the raw materials used in the study (as discussed in the next section), the researchers determined that the materials used were intrinsically non-toxic. Thus, the effluent from the freeze-thaw samples was not analyzed.

In general, the results of the freeze-thaw testing indicated that CLSM mixtures can be efficiently tested for freeze-thaw resistance following the modified ASTM D 560 with 12 cycles. Results also indicated that CLSM mixtures with high air content and high compressive strength exhibited good freeze-thaw resistance.

Leaching and Environmental Impact

Table 3.39 summarizes the total concentration of heavy metals present in the by-product materials used in this study. These results represent the total concentration of the eight key heavy metals. A “rule of thumb” that some practitioners use is that the concentration of total heavy metals can be up to 20 times the standard TCLP limits. In this study, arsenic concentration in bottom ash, Class C fly ash, and Class F fly ash exceeded this “rule of thumb” value. Thus, additional testing was performed (using the TCLP method) to determine the actual amount of heavy metals that are available to leach from these materials. Because the foundry sand and high-carbon fly ash did not have significant amounts of total heavy metals, the materials were classified as non-toxic, and no subsequent leaching tests were performed.

The TCLP results for Class C fly ash, Class F fly ash, and bottom ash are shown in Table 3.40. The concentration of heavy metals that leached from each material was well below the EPA-recommended TCLP limits; therefore, the materials were classified as non-toxic and suitable for use in CLSM. If any of the by-product materials had exhibited significant leaching of heavy metals (above the TCLP limits), the last step would have been to assess the actual leaching of heavy metals from CLSM containing the material(s) using the American Nuclear Society leachate test (ANS 16.1).

Table 3.39. Analysis of heavy metal concentration of raw material extracts.

Element	TCLP Limit (mg/L)	20 x TCLP Limit (mg/L)	Bottom Ash (mg/L)	Foundry Sand (mg/L)	Class C Fly Ash (mg/L)	Class F Fly Ash (mg/L)	High-Carbon Fly Ash (mg/L)
Arsenic	5.0	100	170.0[a]	7.7	280.0[a]	160.0[a]	58.0
Barium	100.0	2000	2000.0	240.0	1300.0	320.0	1200.0
Cadmium	1.0	20	0.23	0.28	1.55	2.1	0.51
Chromium	5.0	100	10.0	18.0	87.0	96.0	16.0
Lead	5.0	100	<0.2	18.0	<0.2	37.0	<0.2
Mercury	0.2	4	<0.2	<0.2	<0.2	<0.2	<0.2
Selenium	1.0	20	<0.2	<0.2	<0.2	2.4	<0.2
Silver	5.0	100	<0.2	<0.2	<0.2	<0.2	<0.2

[a] *Concentration exceeded the "rule of thumb" value of 20 times the TCLP limit.*

This systematic approach to testing leaching potential and environmental impact can be followed for any material being considered for use in CLSM. Although all the materials used in this study were deemed non-toxic, it may be possible that certain materials considered for a given CLSM application may be more of an environmental concern.

Summary

This chapter described a comprehensive laboratory program focusing on CLSM, with emphasis on developing/recommending appropriate test methods to assess key CLSM properties and understanding the impact of materials, mixture proportions, and curing regime on performance. Based on the results presented in this chapter, the following general conclusions can be drawn:

- Suitable test methods exist to measure most of the key CLSM properties affecting performance in the four target applications. The findings discussed in this chapter, coupled with the results from the field testing program (Chapter 4), helped to develop the test methods (Appendix B) and specifications (Appendix C).
- Models were developed to predict the water demand and compressive strengths for a range of CLSM mixtures. This information can be helpful in designing mixtures for applications where strength may be a key limiting factor, such as in the use of excavatable CLSM.
- Improvements were made to the ASTM D 4832 (unconfined compressive strength) test method to increase its accuracy and improve its user-friendliness.
- The effects of temperature on strength gain of CLSM mixtures can be very pronounced, especially when using Class C fly ash. One should be aware of this increased strength gain, especially when CLSM is being used in a hot climate. Keeping this strong temperature dependence in mind and accounting for it in design can help to effectively produce excavatable CLSM. Trial batching and testing at elevated temperatures helps to gain insight into long-term strength gain in field applications, especially when fly ash or other supplementary cementing materials are used.
- There is no single parameter that adequately predicts excavatability. Compressive strength can serve as a useful surrogate value in some cases, but one should try to capture the long-term strength gain when applying strength as a predictive tool. Basing long-term strength gain on short-term laboratory testing can be problematic for some CLSM mixtures (especially those containing fly ash). Calculating a removability modulus (RE) shows promise in predicting excavatability. Lastly, the dynamic cone penetrometer (DCP) was found to be a valuable method of assessing CLSM in the field and estimating ease of excavatability.

Table 3.40. TCLP test results for Class C, Class F, and bottom ash.

Element	TCLP Limit (mg/L)	Bottom Ash (mg/L)	Class C Fly Ash (mg/L)	Class F Fly Ash (mg/L)
Arsenic	5.0	0.12	0.074	0.37
Barium	100.0	3.61	0.30	0.17
Cadmium	1.0	0.001	0.004	0.024
Chromium	5.0	0.01	0.29	0.11
Lead	5.0	<0.01	<0.01	<0.01
Mercury	0.2	<0.01	<0.01	0.11
Selenium	1.0	<0.01	0.37	0.02
Silver	5.0	<0.01	<0.01	<0.01

- Significant research was performed on the corrosion of metallic pipe materials embedded in CLSM. In general, CLSM was found to be beneficial in reducing corrosion (compared to typical compacted fill) when pipes are completely embedded in CLSM. The reduced permeability of CLSM can reduce the ingress of chlorides and the microstructure of CLSM can improve corrosion resistance through changes in the pH and resistivity of the pore solution. There is a potential for corrosion when pipes are embedded in both CLSM and surrounding soil or conventional fill, setting up a galvanic cell than can increase corrosion activity. This situation is similar in nature to metals embedded in dissimilar soils, and similar precautions can be taken to ensure the desired service life.
- The by-product materials tested in this study were found to be non-toxic. However, a testing program was proposed to evaluate other by-product materials that might be more of a concern with regard to leaching and environmental impact. This method involves the testing of total heavy metals, possibly followed by TCLP (if the total heavy metals are above certain threshold values), and possibly followed by leachate testing from CLSM containing the subject material (if the TCLP values exceed certain thresholds).

CHAPTER 4

Field Evaluations of CLSM

Introduction

This chapter summarizes the studies on the field performance of CLSM and the use of the data collected and experience gained to validate and improve upon the test methods, specifications, and guidelines developed in the laboratory portion of the study. An overview of the research approach and objectives is provided, followed by discussions on the studies performed at six field sites throughout the United States. Lastly, some of the main findings of the overall field efforts are presented.

Research Approach

The key deliverables of this research project will be useful only if they are eventually applied in the field. Thus, a comprehensive field testing program was included in the latter stages of this project, which aimed to gain insight into specific technical or practical issues regarding CLSM. The objectives of the field testing plan included the following:

- Close the gap in understanding of CLSM by addressing key research needs
- Assess applicability and efficiency of test methods developed in laboratory
- Assess appropriateness and validity of test methods, specifications, and construction guidelines developed in laboratory and through a synthesis of current practice

Field Testing Plan

Several technical issues were identified in the early stages of this project as requiring significant attention in the laboratory portion of this project; some of these issues were further deemed to be important enough to address in actual field trials:

- Long-term strength gain/excavatability
- Short-term strength gain/constructability
- Corrosion of metals in CLSM
- Productivity and cost (especially relative to compacted fill)
- Resistance to freezing and thawing
- Construction issues (i.e., floating of pipes)
- Settlement
- Use of by-product materials
- Environmental issues
- Permeability (for various reasons, including drainage and leak detection)

After identifying the key unresolved technical issues regarding CLSM and selecting agencies to participate in the field testing, the research team developed a field testing program, as shown in Table 4.1. This program encompasses the most important technical issues and includes the CLSM applications relevant to this project. More emphasis was placed on the most common CLSM applications, such as backfill, whereas less emphasis was placed on less common applications, such as bridge approaches. The test matrix shown in Table 4.1 captures the main technical issues and addresses several common interests with the field testing partners. Unless otherwise noted, the test methods, specifications, and guidelines developed under this project were implemented in the various field tests.

The researchers recognized from the onset of this field testing program that not all of the long-term data (e.g., corrosion) would be generated or collected during the finite duration of this project. However, they attempted to generate and synthesize as much relevant data as was feasible; in some cases, field tests were continued beyond the completion of this project and will be monitored and evaluated through research collaborations formed as part of this project. This information, when available, will be presented to the relevant AASHTO committees for review and possible inclusion in future CLSM construction.

Table 4.1. Matrix of field testing issues and applications.

Issue/Application	Agency or Organization[a]					
	UT Austin[b]	NRMCA[c]	Hamilton County (OH)	EBMUD[d]	Texas DOT	TAMU[e]
Technical Issue						
Long-term strength gain/excavatability	√	√		√		√
Short-term strength gain/constructibility	√		√	√	√	√
Corrosion of metals in CLSM			√			√
Productivity and cost			√			√
Resistance to freezing and thawing			√			
Construction issues (i.e., pipe floating)						√
Settlement	√			√		
Use of by-product materials	√	√	√		√	√
Environmental issues			√			
Permeability/leak detection						
CLSM Application						
Backfill	√	√	√	√		√
Utility bedding			√			
Void fill				√		
Bridge approach					√	

[a] *Information on productivity and cost was also obtained from the New York DOT but is not included herein (for conciseness). Also, a field test was planned with the Florida DOT, but permitting issues prevented the field test from occurring.*
[b] *UT Austin = University of Texas–Austin*
[c] *NRMCA = National Ready-Mix Concrete Association*
[d] *EBMUD = East Bay Municipal Utility District*
[e] *TAMU = Texas A&M University*

Field Test at the University of Texas–Austin

Introduction

Significant field testing was performed at the J. J. Pickle Research Campus at the University of Texas–Austin. The main goals of these tests were to evaluate the use of CLSM as trench backfill; to establish a link between laboratory tests and field performance; and to study the impact of materials, mixture proportions, and curing regime on long-term strength gain and excavatability.

Materials and Mixture Proportions

Six CLSM mixtures were included in this study, as shown in Table 4.2. Each of the mixtures was procured from local ready-mix concrete producers, each of whom had experience with producing CLSM for various applications. The mixture proportions were based primarily on experience gained from the laboratory portion of this study. Mixtures were selected to span a range of materials and proportions and to generate strengths that would result in various degrees of ease of excavatability. Intentionally, no trial mixing was performed using materials similar to those used in the field test, specifically to determine if prescriptive mixture proportions (e.g., cement content, aggregate content, water added to achieve target flow) would result in desirable mixtures (e.g., target flow, minimal segregation/bleeding). On-site adjustments were available for these mixtures if they arrived at the field test either too dry or too wet in consistency, as discussed later. However, if the water added to the drier mixtures resulted in excessive bleeding or segregation, no further water was added.

Table 4.2. Mixture proportions for excavation study.

Mixture	Type I Cement (kg/m³)	Fly Ash Type	Fly Ash (kg/m³)	Concrete Sand (kg/m³)	Water Content (kg/m³)	Air Content (%)	Flow (mm)	Mixture Temperature (°C)	Density (kg/m³)
Flash	0	Class C	224	1672	165	4.0	190	35.2	2179
A1	30	–	0	130	130	29.5	200	33.6	1539
A2	60	–	0	130	130	28.5	220	34.5	1539
Paste	60	Class F	1195	485	485	1.0	420	42.5	1795
F1	30	Class F	180	175	175	2.25	100	36.8	2051
F2	60	Class F	180	175	175	2.5	140	35.2	2083

"–" = not used

Experimental Program

Six trenches, 3 m long, 1.2 m wide and 0.9 m deep, were prepared side by side on the Research Campus site of The University of Texas at Austin. The trenches were spaced 0.75 m apart. Each of the CLSM mixtures was placed in a single trench in the order listed in Table 4.2 (from Flash to F2), all on the same day.

The fresh properties of CLSM mixtures were measured at the site, including flow, density, air content, and mixture temperature. A needle penetrometer (ASTM C 403) was used to characterize the setting and hardening of CLSM backfills. A Kelly ball (following ASTM D 6024) was also used to evaluate early-age hardening. Additional samples were prepared and stored in a 23°C environment, and their setting and hardening behaviors were monitored and compared to the field evaluations. For each trench, two rows of thermocouple wires (one 0.3 m from the bottom and the other 0.6 m from the bottom) were installed to monitor the temperature changes every 10 minutes.

The unconfined compressive strength and splitting tensile strength of cylinders stored under standard laboratory conditions (23°C and 100 percent relative humidity) and outdoors (adjacent to the trenches) was measured at various ages.

The excavatability of the six CLSM mixtures was evaluated at an age of 10 months. Manual tools, such as shovel and pick, were used to evaluate the excavatability of CLSM. A dynamic cone penetrometer was used to estimate the strength profile of the backfill. A proprietary device, the GeoGauge, was evaluated in the field, despite the relatively poor performance of the device in the laboratory phase of the project. This device was included in this field test to determine if the past poor performance of the device was due to size effects and boundary conditions that might be present in laboratory testing, but perhaps not in field conditions.

Results and Findings

Fresh Properties

Table 4.2 presents the data on the fresh properties of the various CLSM mixtures. The target flow for the mixtures was 200 mm, but the mixtures as placed varied from very little initial flow (mixtures F1 and F2) to a very highly fluid mixture (Paste). Water was added to the stiff mixtures to remedy the flow, and fly ash was added to the Paste mixture to reduce the flow and minimize segregation. Subsequent testing of the constituent materials used in the various mixtures confirmed that the sand was poorly graded and contributed to the poor flowability of the mixtures. Although the adding of water at the jobsite can help boost the flowability, it also can lead to bleeding and segregation, especially for mixtures that are not optimized. Thus, on-site water additions, which are common options for CLSM (or concrete) producers, can be a useful tool in adjusting flow, but the ultimate ability to achieve a flowable, segregation-resistant mixture is dependent on the other mixture components, especially aggregate gradation and quality. One option employed in this field test was increasing the fly ash content to reduce fluidity (and segregation), although this option is not feasible in the field for ready-mix truck-delivered CLSM. The experience gained in this field test shows that prescriptive specifications may not always be applicable for CLSM, that there exists some ability to modify CLSM mixtures with jobsite adjustments, and that the ultimate ability to optimize CLSM for a given application and properties would benefit from trial mixing, when applicable.

The setting and hardening of CLSM backfills were monitored using several different approaches that had previously been studied in the laboratory phase of this project, as summarized in Table 4.3. There was generally a good correlation between the walk-on time and the soil penetrometer value, which suggests the latter can be used in the field practice to characterize the setting and hardening behaviors of fresh CLSM mixtures. However, the ball drop method (ASTM D 6024) seems to be too severe for CLSM mixtures. Even for mixture Flash, a hardening period of 11.6 hours was required to resist the ball drop. The use of the needle penetrometer (ASTM C 403) on the trenches and in parallel specimens stored at 23°C illustrated the significant impact that temperature has on setting and hardening. Using the needle penetrometer readings as an index, the trench mixture hardened

Table 4.3. Setting and hardening determined by different approaches.

Mixture	Walk-on time after placing (hours)	Time for soil penetrometer value to reach 6 kPa (hours)	Time for Kelly ball drop to generate dent diameter less than 76 mm (hours)
Flash	0.1	–	11.6
A1	3.7	2.0	Greater than 72 hours
A2	3.1	0.8	Greater than 72 hours
Paste	15.4	4.3	26.3
F1	1.7	1.6	15.8
F2	1.7	1.0	13.0

"–" = too stiff for measurement

Table 4.4. Compressive strength of CLSM mixtures from UT-Austin field test.

Mixture	7 days				28 days				90 days			
	Test Site		Fog Room		Test Site		Fog Room		Test Site		Fog Room	
	Average (kPa)	C.O.V. (%)	Average (kPa)	C.O.V. (%)	Average (kPa)	C.O.V. (%)	Average (kPa)	C.O.V. (%)	Average (kPa)	C.O.V. (%)	Average (kPa)	C.O.V. (%)
Flash	3351	15.3	–	–	6117	8.8	–	–	5974	9.2	–	–
A1	40	9.6	–	–	66	10.1	36	22.6	99	18.5	75	15.8
A2	326	9.0	303	28.2	458	19.5	446	3.2	508	10.3	504	5.5
Paste	352	5.8	73	17.3	484	30.1	222	13.7	653	30.2	391	31.3
F1	2014	8.2	680	3.1	3455	5.8	1876	6.3	3445	1.9	2898	7.2
F2	2693	3.9	1445	1.5	6573	6.8	3372	2.7	7744	3.9	7207	2.8

Mixture	180 days				300 days			
	Test Site		Fog Room		Test Site		Fog Room	
	Average (kPa)	C.O.V. (%)	Average (kPa)	C.O.V. (%)	Average (kPa)	C.O.V. (%)	Average (kPa)	C.O.V. (%)
Flash	6460	8.4	–	–	7299	8.6	–	–
A1	112	13.5	69	5.8	86	25.6	79	5.9
A2	435	19.3	550	0.3	598	23.0	–	–
Paste	–	–	537	21.3	761	7.4	–	–
F1	4194	19.2	–	–	3934	3.3	–	–
F2	7715	9.1	7961	4.2	8637	3.3	–	–

"–" = Not enough specimens were available for testing at this age.

much faster (about 10 hours' difference in reaching similar target penetration values) than the specimens stored in the laboratory.

Despite the high ambient temperatures during this field trial, the CLSM mixtures did not generate significant heat within the trenches. All of the mixtures, with the exception of Paste, remained at temperatures below 45°C during their hydrating phase. The trench containing Paste reached a maximum temperature of 64°C, which resulted in higher compressive strengths than previous laboratory testing would have suggested, as discussed in the following section.

Hardened Properties

Compressive and Splitting Tensile Strengths. The compressive and splitting tensile data for the various mixtures are shown in Tables 4.4 and 4.5, respectively. For mixtures A1 and A2 (no fly ash included), there was little difference in strengths between cylinders stored at the site and those stored in the fog room. This finding is consistent with laboratory findings from Chapter 3 that showed that straight cement mixtures were less sensitive to temperatures than mixtures containing fly ash. For CLSM mixtures containing fly ash, specimens cured at the site had much higher strengths than those in the fog room during the first 3 months. Ultimately, strengths of specimens cured in the fog room approached those of specimens cured on site at later ages (e.g., 10 months) in this study, as illustrated in Figure 4.1 for Mixture F2.

Two other mixtures that exhibited interesting behavior were Flash and Paste. The mixture referred to as Flash stiffened and gained strength rapidly, with a strength of about 600 kPa after 24 hours and a straight gain to 6 MPa after 28 days (with little increase in strength thereafter). Similar strength-gain behavior was observed for the mixtures used in the repair of bridge approaches in San Antonio, Texas, as described later in this chapter. The Paste mixture was found to have com-

Table 4.5. Splitting tensile strength of CLSM mixtures from UT–Austin field test.

Mixture	7 Days				28 Days				90 Days			
	Test Site		Fog Room		Test Site		Fog Room		Test Site		Fog Room	
	Average (kPa)	C.O.V. (%)	Average (kPa)	C.O.V. (%)	Average (kPa)	C.O.V. (%)	Average (kPa)	C.O.V. (%)	Average (kPa)	C.O.V. (%)	Average (kPa)	C.O.V. (%)
Flash	757	13.7	–	–	–	–	–	–	–	–	–	–
A1	–	–	–	–	10	11.2	–	–	–	–	7	17.5
A2	30	22.9	31	27.2	48	47.6	60	10.3	76	11.5	55	20.9
Paste	352	5.8	73	17.3	484	30.1	222	13.7	391	31.3	653	30.2
F1	197	30.4	80	18.2	296	3.3	170	25.4	503	10.4	350	16.9
F2	388	9.5	141	14.4	918	6.2	504	11.3	1149	11.1	981	14.5

"–" = cylinders were not available for testing

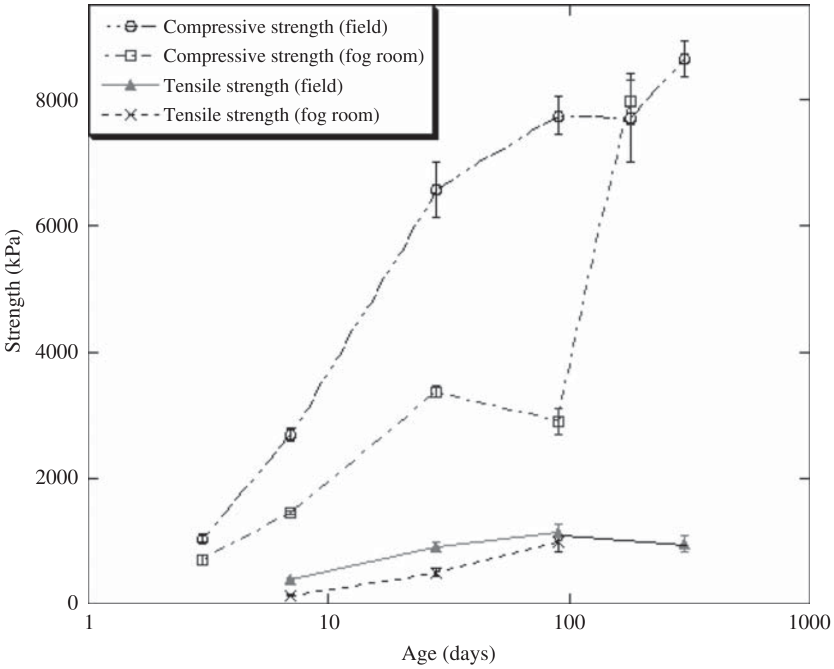


Figure 4.1. Compressive and splitting tensile strength developments of mixture F2 specimens cured on site and in fog room.

pressive strengths ranging from around 4.5 to 6.5 MPA after 90 days, which was significantly higher than mixtures cast previously in the laboratory (using different cement and Class F fly ash but similar proportions), which typically exhibited strengths less than 1 MPa after 90 days. The higher strengths observed in this field trial may be due to higher field temperatures (for the site-cured cylinders), differences in fly ash reactivity, jobsite modifications to the paste mixture, or other factors.

As shown in the data from Tables 4.4 and 4.5, the ratio between tensile and compressive strength for a given mixture and age of testing ranged from between about 8 to 15 percent, which is comparable to ratios observed for conventional concrete mixtures. However, this ratio did not necessarily correspond to the compressive strength of the mixture; that is, for conventional concrete, higher compressive strengths tend to yield lower tensile–compressive strength ratios. For CLSM, this inverse relationship does not necessarily exist, but rather, the actual ratio between tensile strength and compressive strength appears to be more related to constituent materials (e.g., presence of fine aggregate). This evaluation of tensile strength and its relation to other properties was included in this field test based on the findings from the laboratory phase, which suggested that tensile strength may be a better indicator of excavatability than compressive strength.

For conventional concrete, cores are often extracted from field structures to check compliance with project specifications. Although coring CLSM installations creates unique problems related to fragility of the material, it was attempted for this field trial as a proof of concept. The results were mixed; coring was possible only from the mixtures exhibiting quite high strength values. Three 100 × 200 mm cores were successfully extracted for subsequent strength testing from the trenches containing Flash, Paste, F1 and F2 mixtures. Of these mixtures, extracting cores from Flash, F1, and F2 was particularly difficult, which may explain the lower strengths measured on the cores (compared to specimens stored adjacent to the trench), as shown in Table 4.6. The cores from Paste were actually slightly higher than those cured adjacent to the trench, confirming that the higher temperatures experienced within the trench resulted in higher strength values. This exercise shows that coring is feasible for certain CLSM mixtures, provided they are strong enough to handle the coring action. It also shows that storing cylinders near the jobsite is a reasonable indicator of actual CLSM performance in adjacent installations; storing these specimens in the same ambient environment helps to elucidate the effects of temperature on actual strength development.

Excavatability. A major focus of this field test was the evaluation of excavatability as a function of materials, mixture proportions, age, and excavation method. A range of methods was used to evaluate ease of excavation, including direct methods (i.e., shovels, pick, and backhoe) and indirect indexing methods (i.e., DCP, Kelly ball, strength, GeoGauge, and removability modulus). Some tests were performed at various ages, and, for conciseness, only the tests conducted 300 days after trench placement are summarized in Table 4.6.

Table 4.6. Direct and indirect evaluation of excavatability (excavation performed 300 days after trench placement).

Methods[a]	Flash	A1	A2	Paste	F1	F2
Round-head shovel	Nearly impossible	Easy	Easy	Nearly impossible	Impossible	Impossible
Square-head shovel	Impossible	Easy	Easy	Impossible	Impossible	Impossible
Pick	Difficult	Easy	Easy	Difficult	Difficult	Very difficult
DCP (mm per blow)	0.2	12.5	5.6	0.3	0.05	Not penetrable
GeoGauge stiffness (MN/m)	41.1	13.7	24.7	29.8	45.8	41.3
Compressive strength[b] (kPa)	7299	86	446	7156	3934	8637
Tensile strength[b] (kPa)	1297	12.4	71.1	761	454	953
Fog room RE[c]	–	0.2	0.8	2.3	2.5	3.4
Field RE[c]	4.9	0.3	0.8	3.6	3.4	4.8
Kelly ball (cm)	4.1	12.7	11.4	4.4	3.5	No dent
Backhoe	Difficult	Very easy	Easy	Difficult (but possible)	Very difficult	Very difficult (nearly impossible)

[a] All testing performed 300 days after trench placement unless otherwise noted.
[b] Cylinders stored for 300 days on site prior to testing.
[c] RE is based on 28-day compressive strength.

Only the trenches containing mixtures A1 and A2 were able to be excavated manually (i.e., using shovels and picks). As one would expect, excavating mixtures A1 and A2 using a backhoe was also easy. The remaining trenches ranged from difficult but possible (Paste) to very difficult and nearly impossible (F2) to excavate with a backhoe. Following are discussions on indirect methods of evaluating or predicting excavatability.

The DCP was found to clearly differentiate the excavatability of the six CLSM mixtures. Because this penetrometer can be forced through the whole depth of the backfill and the lowest penetration index is selected, this approach has the advantage that it is not affected by a deteriorated surface. This advantage was also demonstrated in the testing of the two trenches at the National Ready Mixed Concrete Association (NRMCA) in Maryland (discussed later in this chapter). Although the data generated in these field tests, coupled with the excavatability tests described in Chapter 3, are extensive, providing absolute guidance on DCP values that separate excavatable CLSM from non-excavatable CLSM is not possible. However, based on the data generated within this project, a DCP index of 5 mm per blow can be proposed as a general rule of thumb, below which there could be problems for manual excavation. Stiffness values generated by the GeoGauge were able to differentiate A1 and A2 as being excavatable, but for the other trenches, where the stiffness of the backfill material is beyond the capacity of the equipment, the outputs seemed to be random. This phenomenon is clearly shown by the measurements of mixtures F1 and F2, where F2 should be stiffer as indicated by the DCP index and actual excavation experience.

The diameter of the dent caused by the dropping of the Kelly ball was also evaluated as an indicator of CLSM excavatability. Although this approach is acknowledged to measure only the properties of the upper layers of CLSM, the values did correlate quite well in this field test with DCP values, successfully predicting that Paste was easier to excavate than mixture F1.

Long-term compressive strength is often used as a criterion to assess the excavatability of CLSM (ACI 1999). For this field trial, cylinders were tested in compression and tension after having been stored on site for 300 days, as shown in Table 4.6. Clearly, the availability of this type data would be a luxury for an actual CLSM installation, but the data shown in Table 4.4 would often be available (particularly, the data from 28-day cylinders stored in the fog room). The two trenches that were easiest to excavate (those containing mixtures A1 and A2) also yielded low compressive strength values (for the site-cured specimens tested on the day of excavation) well below the 1 MPa value that is sometimes used in the field as a rough index of excavatability. While ease of excavation was linked to lower compressive strengths for these two trenches, the other mixtures exhibited no clear link between strength and excavatability. For instance, mixture Paste had a higher strength than mixture F1, yet Paste was easier to excavate. This result can mainly be attributed to the lack of aggregates in Paste, because, in general, CLSM containing aggregates is more difficult to excavate. Thus, compressive strength by itself is shown to be an unreliable indicator of excavatability. This shortcoming is further compounded by the limited availability of strength values, which are generally available for only laboratory-cured specimens and usually for only the first month or so after casting. These short-term tests do not adequately represent the long-term strength gain of field CLSM, nor do they capture the temperature-related effect that field installations experience. In summary, long-term strength behavior, with cylinders subjected to similar time-temperature histories, can serve as a better indicator of field behavior and excavatability, but even this approach would not recognize that the specific materials and proportions (e.g., presence or lack of sand) can profoundly impact excavatability.

As reported in Chapter 3, the splitting tensile strength of CLSM might be a better indicator of excavatability than compressive strength, because the actual excavation of CLSM mimics a tensile failure in the material. In this field trial, the tensile strength values correlated quite well with DCP indexes and ease of manual or mechanical excavation. Although tensile strength may be a better index of excavatability, the inherent variability in tensile results is higher than that for compression testing, and therefore, precautions should be taken to lessen observed variations.

The use of a removability modulus, as proposed by Hamilton County (Ohio), successfully predicted the excavatability of the six CLSM mixtures. As described in Chapter 3, this approach takes into account the 28-day laboratory-cured strength of a given mixture and its in-situ density to calculate a removability modulus. Values of RE greater than 1.0 are assumed to be non-excavatable. The RE data shown in Table 4.6 was based on 28-day laboratory-cured strength values, as per the Hamilton County approach. In addition, the field-cured 28-day values were also used to calculate RE, which slightly increased the RE values for the non-excavatable mixtures and had a negligible effect on the excavatable mixtures.

Excavation Study at NRMCA (Silver Spring, Maryland)

Introduction

A major concern historically with using CLSM in backfill applications is related to ease of excavation, for instance, when CLSM is used in utility applications. During the course of this project, major efforts were undertaken to investigate this issue by evaluating CLSM that was cast either in the laboratory or field and then later excavated by various methods. However, because of the finite duration of the project, excavatability was assessed within a matter of months (or a year or so in some cases) after CLSM placement. This limitation was addressed in a unique way in a field test performed at the NRMCA facility in Maryland: two CLSM trenches were excavated that had been placed about 6 years earlier as part of a separate CLSM research effort. Because the trenches were cast with the intention of tracking long-term CLSM properties, quite a bit of information and data were available, including earlier attempts at excavation. This section describes the excavation study and relates this experience to various engineering properties.

Background Information

In September 1996 NRMCA cast two CLSM mixtures into the two trenches evaluated in this field study. The two CLSM mixtures were cast despite the heavy rain from a hurricane. For convenience, the two trenches are referred to herein as Northeast (NE) and Northwest (NW). The CLSM mixture in NE consisted of 29.6 kg/m^3 portland cement; 1406 kg/m^3 high-carbon, Class F fly ash; and 292 kg/m^3 water (similar in nature to the Paste mixture from the UT–Austin study). The CLSM mixture in NW was composed of 28.5 kg/m^3 portland cement, 180.9 kg/m^3 Class F fly ash, 1409 kg/m^3 concrete sand, and 270 kg/m^3 water.

Testing Program

A range of tests was performed on the two trenches; in addition, limited testing (compression and splitting tensile) was performed on cylinders that remained in the fog room from the original mixtures. The following tests were performed (results are described later in this section):

- Excavatability (square-head shovel, round-head shovel, pick, backhoe)
- Needle penetrometer (field version of ASTM C 403)
- Soil penetrometer (hand or pocket)
- Torvane shear tester
- Kelly ball (after ASTM D 6024)
- GeoGauge
- Dynamic cone penetrometer
- Compressive strength
  - 75 × 150 mm and 150 × 300 mm cylinders (capped with sulfur)
  - 100 × 200 mm cylinders (capped with polyurethane pads)
- Splitting tensile strength (150 × 300 mm cylinders)

Results and Discussion

Excavatability

The two CLSM trenches evaluated in this study were buried approximately 0.6 m below grade, with a layer of soil above the trenches. A backhoe was first used to remove the soil and to expose the CLSM. Groundwater was found on the exposed NE trench, and a lower elevation was formed to drain the water. Both CLSM trenches were visibly in good condition, with no signs of freeze-thaw damage or other forms of distress. However, the CLSM in the NW trench had segregated, especially in the upper 80 to 100 mm.

Table 4.7 summarizes the results of various evaluations either directly or indirectly related to excavatability. The NE trench was quite easy to excavate manually, but the NW trench was very difficult, if not impossible, to remove manually, which

Table 4.7. Evaluation of excavatability of test trenches at NRMCA.

Method	NE Trench	NW Trench
Square-head shovel	Easy	Nearly impossible: only shallow dents were made on the surface
Round-head shovel	Easy	Very difficult: small pieces were removed
Pick	Easy	Difficult: pick could penetrate into the mixture
Kelly ball (ASTM D 6024)	Average diameter 95 mm	Average diameter 87 mm; C.O.V. 4.0%
Torvane shear tester	Average 3.9 kg/cm^2; C.O.V. 18.1%	Average 3.2 kg/cm^2; C.O.V. 9.9%
Needle penetrometer (field version of ASTM C 403)	5.7 MPa	Out of range
Soil penetrometer	4.0 MPa	Out of range
Stiffness (using GeoGauge)	Average 10.3 MN/m, C.O.V. 18.3%	Average 47.4 MN/m, C.O.V. 1.8%
DCP	4.5 mm per blow	1.3 mm per blow
RE	0.23	1.04
Backhoe	Easy	Easy

was somewhat surprising because manual excavation of this trench was possible 4 years earlier (2 years after placement). Both trenches were easily excavated using a backhoe (after the completion of the other tests).

The Kelly ball test and Torvane shear test (which measures the shear resistance of soil as the device twists) were not able to differentiate the manual excavatability of the two trenches. This inability may be because these two tests involve near-surface measurements of CLSM, and the surfaces of these trenches were somewhat disturbed during the removal of the top soil that covered the trenches.

The needle penetrometer (field version of ASTM C 403) and soil or pocket penetrometer were both used on these trenches, but as expected, the NW trench was impenetrable because of its higher strength. These devices are better for measurements of earlier CLSM properties and impact on constructability.

The GeoGauge (Model H-4140), which did not perform very reliably in the laboratory trials described in Chapter 3, was able to discern the difference in excavatability between the two trenches, with the measured stiffness of the NW trench found to be almost 5 times as high as the NE trench.

Figure 4.2 shows the DCP being used in the NW trench. The DCP is often used in pavement construction to evaluate the compaction or density of subgrade, subbase, and base materials. One advantage of this method is it allows for evaluation of CLSM penetrability as a function of depth of placement. The DCP index is defined as the penetration per blow and it has been correlated empirically with CBR values. Based on information provided by the DCP manufacturer, the CBR values along the depth of NE and NW materials were calculated and are shown in Figures 4.3 and 4.4, respectively. CBR values of 100 (which NW surpassed) correspond to a well-compacted stone backfill, which presumably would be difficult to excavate, as was NW. One interesting observation from the NW trench was the significant difference in the DCP values (and calculated

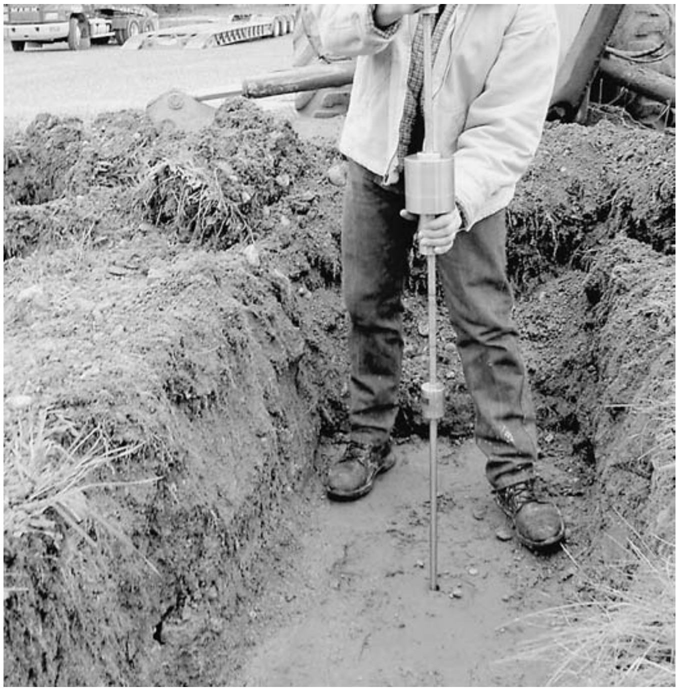


Figure 4.2. The DCP being used in the NW trench.

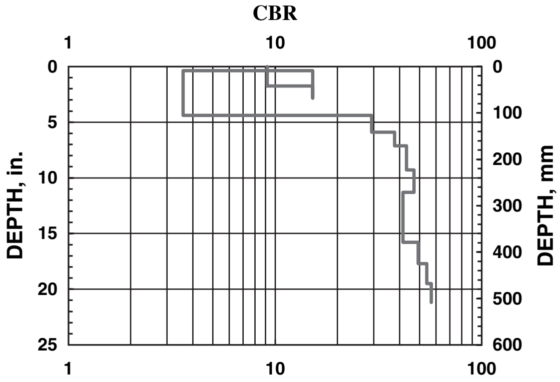


Figure 4.3. The CBR profile of NE trench.

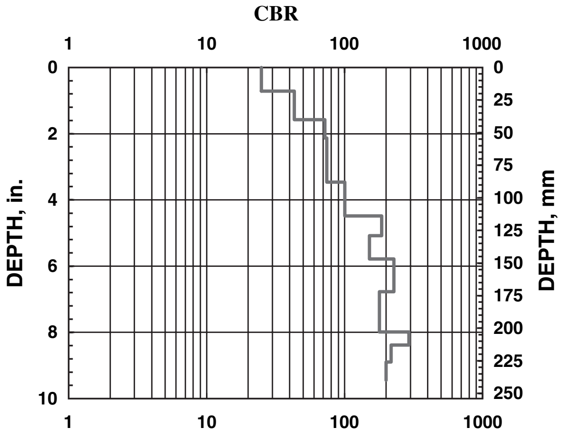


Figure 4.4. The CBR profile of NW trench.

CBR values) between the CLSM in the upper 80 to 100 mm of the trench and the CLSM below this point. To further evaluate this difference, the upper 80 to 100 mm portion of the trench was removed and found to be composed almost entirely of paste, without aggregates, clearly showing the effects of segregation. This segregation may have occurred as a result of the inherent segregation susceptibility of this specific mixture or because of a hurricane that occurred shortly after trench placement.

The calculation of RE was found to clearly differentiate the excavatability of the two trenches. This RE value was calculated based on strengths measured under the NRMCA project, and it is encouraging that the RE value was able to discern the removability of the two trenches, especially because the NW trench was originally designed to be excavatable.

Compressive and Splitting Tensile Strengths

Table 4.8 summarizes the strength tests performed on cylinders that had been stored in the fog room for about 6 years. Only a limited number of cylinders (four per mixture) were available for testing; three were tested in compression and one in tension from each set. The unbonded caps used for some of the compression tests had a Shore A durometer of about 5. By combining the strength data from this field test with previously published data (Mullarky 1998), the short- and long-term strength development can be plotted, as shown in Figure 4.5. This graph emphasizes the long-term strength gain exhibited by the CLSM in the NW trench, which ultimately resulted in difficulties in excavation.

Field Test at Hamilton County, Ohio

Introduction

Hamilton County (Ohio) has historically been one of the most innovative and advanced users of CLSM in the United States and was selected as a partner for a field test to tap into this experience. The objectives of this test were to investigate the constructability and early-age properties of CLSM and to evaluate the long-term corrosion performance of ductile iron pipes embedded in CLSM. This section briefly summarizes the main aspects of this field test; however, the key findings from the corrosion study will ultimately be collected by long-term monitoring of the site because of the long-term nature of corrosion in field installations.

Experimental Program

Three CLSM mixtures shown in Table 4.9 were chosen by Hamilton County engineers from a list of their approved CLSM mixtures. Mixture S10 is commonly used for backfill applications in the Hamilton County area. Mixture CDF1 is basically similar to S10, except the Class F fly ash used is high in carbon and is typically not allowed by state highway agencies for use in conventional concrete (mainly because of concerns with air entrainment) and sometimes not allowed by some agencies for use in CLSM. This mixture was selected to demonstrate that materials considered "off-spec" for some applications can be suitable for use in CLSM. The third mixture, designated as FF1, is a fast-setting mixture typically used for backfill applications when setting time is a critical issue. Flow and temperature were measured following ASTM D 6103, "Flow Consistency of Controlled Low Strength Material (CLSM)." Temperature was

Table 4.8. Compressive and tensile strength of CLSM cylinders (stored in fog room for 6 years).

Mixture	Compressive Strength				Splitting Tensile Strength		
	Dimension (mm)	Load Rate (kN/min)	Capping Method	Strength (kPa)	Dimension (mm)	Load Rate (N/min)	Strength (kPa)
NW	150 x 300	13.20	Sulfur	1779	154 × 304	6.60	170
	100 x 200	6.60	Sulfur	1864			
	100 x 200	6.60	Pads	1461[a]			
NE	150 x 300	1.32	Sulfur	408	154 × 303	0.66	42
	100 x 200	0.66	Sulfur	436			
	100 x 200	0.66	Pads	379[b]			

[a]The specimen was unintentionally crushed by sudden loading.
[b]Large cavities were observed on the specimen surface.

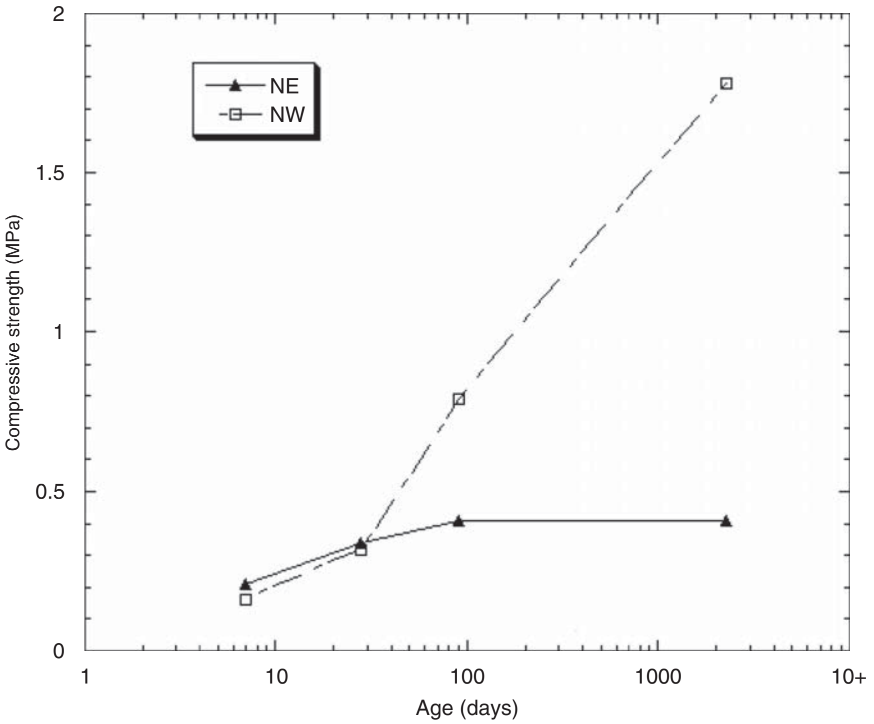


Figure 4.5. Compressive strength development of cylinders curing in the fog room.

determined following ASTM C 1064, "Temperature of Freshly Mixed Portland Cement Concrete."

The test site, identified by Hamilton County engineers, was adjacent to one of their ongoing project sites on Pontius Road, Cincinnati. The site layout for the trenches is shown in Figure 4.6. Two rows of three trenches were excavated by Hamilton County crews. The trenches were approximately 2.7 m long, 0.9 m wide, and 1.2 m deep. The 1.2 m depth was selected because Cincinnati Water Works engineers require a depth of 1.2 m for waterlines.

Hamilton County is a frequent user of CLSM for various applications and specifies it for backfill used in roadway cuts. Hamilton County has had very good success in essentially eliminating problems with settlement often encountered when conventional backfill was used. However, the major utility in the area, Cincinnati Water Works, has expressed reluctance to allow CLSM to be used in direct contact with water pipes. Therefore, in County projects involving water utilities, pipes are placed on sand beddings and backfilled with sand up to 150 mm from the crown of the pipe. The rest of the trench is then typically backfilled with CLSM. The research team believes that backfilling the trenches completely with CLSM, as opposed to using primarily sand topped off with CLSM, provides a faster construction method and potentially better long-term corrosion performance of the pipe. To test this belief, the research team used and evaluated the two backfill methods shown in Figure 4.7. The first method (Figure 4.7(a)) was the standard practice as just described; each of the three CLSM mixtures was placed into a trench on top of sand (row A in Figure 4.6). In the second method (Figure 4.7(b)), ductile iron pipes were elevated on wood blocks to allow CLSM to flow underneath the pipe and surround it

Table 4.9. Mixture proportions of the CLSM mixtures.

Mixture	Cement Content (kg/m^3)	Fly Ash Type (ASTM C 618)	Fly Ash Content (kg/m^3)	Concrete Sand (kg/m^3)	Water (kg/m^3)	Flow (mm)	Temperature (°C)
S10	24	Class F	148	1727	273	305	26.7
CDF1	30	Class F (high carbon)	148	1727	273	127	28.3
FF1	None	Class C	237	1721	Not specified[a]	305	30.0

[a] Water is added on jobsite to obtain the flow desired by the engineer.

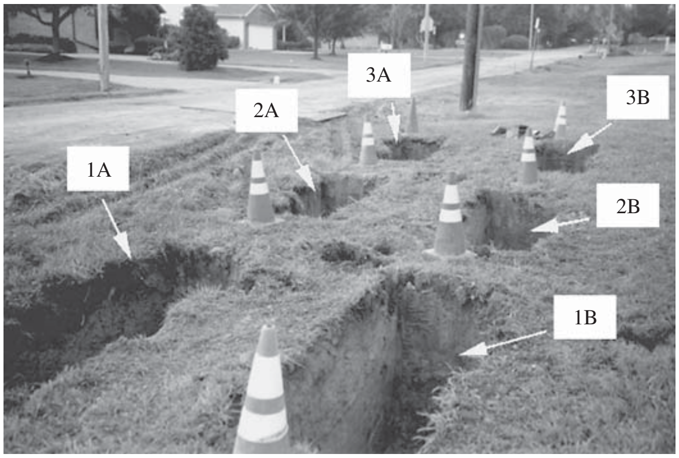


Figure 4.6. Site layout with six trenches shown.

Figure 4.8. Ductile iron pipes wired and capped.

completely, then each of the trenches (row B in Figure 4.6) was completely backfilled with one of the three CLSM mixtures.

Construction

The delivery of the ductile iron pipes to the site was arranged by Hamilton County personnel. The ductile iron pipes (152 mm diameter) had an asphalt coating on the outside and a cementitious coating on the inside. The pipes were capped to better simulate field conditions. Figure 4.8 shows ductile iron pipes being capped and wired before they were placed in the trenches.

After the ductile iron pipes were placed in position, the trenches were backfilled. CLSM was delivered to the site in ready-mix trucks (S10 and CDF1) and a volumetric mobile mixer (FF1). Mixture S10 was used in trenches 1A and 1B. Mixture FF1 (flash fill) was used in trenches 2A and 2B, and mixture CDF1 containing the "off-spec" fly ash was used in trenches 3A and 3B.

While there was no issue in placing CLSM into the trenches in row A, the pipes in the trenches in row B had to be held in place by a worker to keep them from falling from their supports (wood blocks) during the backfilling. This incident illustrates the need for diligence in placing CLSM in utility applications, where floating or dislodging of pipes/utilities can occur. Another observation was that, as expected, the time required to backfill the trenches that were filled completely with CLSM was less than the time required to backfill the trenches that had compacted sand around the pipes.

Test Results

Cylinders (75 mm × 150 mm) were cast for each mixture to evaluate their compressive strength at 14, 60, and 90 days. After

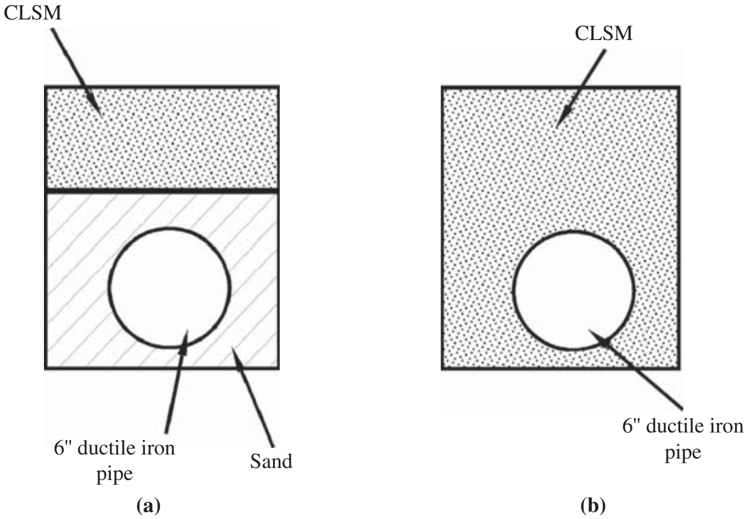


Figure 4.7. Trench cross sections (not to scale).

casting, plastic caps were placed on the cylinders to prevent evaporation of mixing water. These cylinders were then transferred, cured, and tested by Hamilton County engineers or a local testing laboratory. Compressive strength data showed that while mixtures S10 and FF1 had similar compressive strengths at 90 days, mixture CDF1 had a compressive strength more than twice the compressive strength of the other mixtures. The data also showed that this mixture experienced a decrease in compressive strength of approximately 100 kPa between 60 and 90 days; this loss may have been due to leaching away of hydration products upon moist storage.

Corrosion activity of the buried ductile iron pipes is being monitored using the potential difference between the pipes and a copper/copper-sulfate reference electrode. The potential difference between the electrode and the pipe is an indicator of the active or passive state of the buried pipe and can be measured with a high impedance voltmeter. For this purpose, the high impedance voltmeter is electrically connected to the pipe (connected to the wire attached to the pipe) and to the copper/copper-sulfate electrode. The copper/copper-sulfate electrode touches the ground above the buried pipe to close the electrical circuit between the electrode and the pipe. Potential readings are performed by the Hamilton County engineers using a copper/copper-sulfate electrode provided by the research team for this testing.

In addition to the potential difference study, metal coupons were fabricated from a ductile iron pipe and these samples were also buried in the trenches in row B to evaluate their mass loss due to corrosion. It is anticipated that their mass loss will be determined based on ASTM G 1, "Preparing, Cleaning, and Evaluating Corrosion Test Specimens." Ductile iron coupons were attached to 0.3 m long sample holders in groups of four and placed in the CLSM when it was still in fluid state. Figure 4.9 shows a schematic of ductile iron coupons attached to a sample holder.

As described in Chapter 3, CLSM is generally better than conventional fills in protecting embedded metals from corrosion when the metals are entirely encased in CLSM. It was also shown in Chapter 3 that if a metallic pipe backfilled with CLSM is also in contact with the surrounding soil, the potential for setting up a galvanic cell exists due to the dissimilar media (CLSM and conventional fill). To investigate this corrosion issue, four extra sample holders, each with three ductile iron coupons, were prepared. These four sample holders were coupled by connecting their coupons embedded in CLSM with coupons embedded in soil, as illustrated in Figure 4.10.

It is anticipated that Hamilton County and Cincinnati Water Works engineers, with the cooperation of the research team, will monitor the corrosion activity for the various testing configurations reported herein, and it is hoped that the data will prove of use to them and other users of CLSM dealing with utilities.

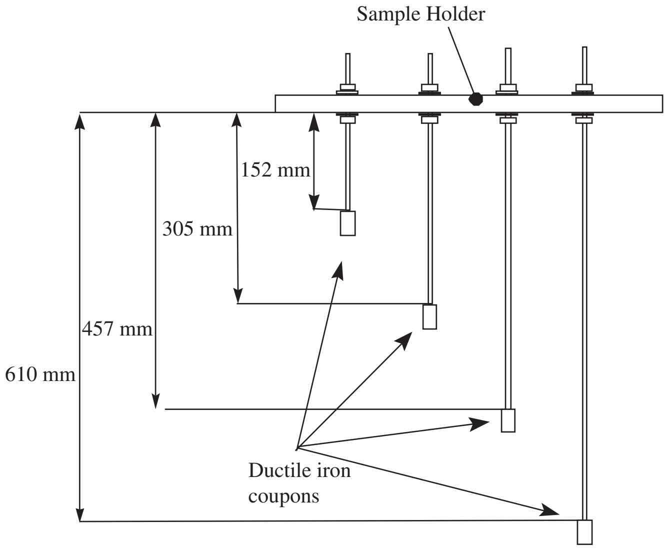


Figure 4.9. Ductile iron coupons attached to sample holder.

Field Test at East Bay Municipal Utility District

Introduction

The long-term strength gain and excavatability of CLSM mixtures have long been a concern for engineers at the East Bay Municipal Utility District (EBMUD). A unique aspect of this concern is that, because of a shortage of fine aggregate in the Bay Area, most CLSM in the area contains coarse aggregate as well. In general, coarse aggregate is rarely used in CLSM, and this field test was sought to determine the effect on excavatability. Also, this field test was selected to gain the perspective of the many utilities that are using CLSM for a range of backfill applications. The objective of the test was to investigate constructability issues related with the use of CLSM as a backfill

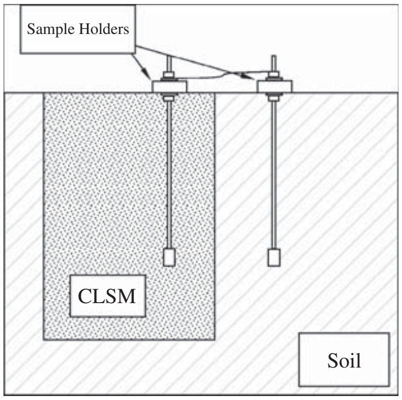


Figure 4.10. Coupled sample to evaluate galvanic corrosion (not to scale).

Table 4.10. Mixture proportions of three CLSM mixtures provided by local producers.

Mixture	Cement Content (kg/m^3)	Fly Ash Type (ASTM C 618)	Fly Ash Content (kg/m^3)	Coarse Aggregate (kg/m^3)	Fine Aggregate (kg/m^3)	Water (kg/m^3)	Air Content (%)
A	18	Class F	178	909	908	168	7
B	18	Class F	178	909	906	168	7
C	18	Class F	178	771	1008	197	5

material. These issues include flowability, compressive strength development, setting time, subsidence, and excavatability of CLSM.

Materials and Mixture Proportions

For the field test, mixtures from three CLSM producers in the Oakland, California, area were selected by EBMUD engineers. The proportions for the three mixtures (one per producer) are shown in Table 4.10. The raw materials (cement, fly ash, aggregates) varied from producer to producer, but the general mixture proportions were quite similar.

Experimental Program

Six trenches (referred to as trenches 1 through 6), approximately 1.2 m wide, 1.5 m deep, and 2.7 m long, were laid out by EBMUD staff. Each CLSM mixture was used to backfill two trenches. Flow and air content of each CLSM mixture were measured before placement, and adjustments were made to achieve the target flow of approximately 150 to 225 mm. Trenches 1 and 2 were filled with CLSM mixture A. The mixture was determined to be too stiff and 322 kg of water was added to increase its flow to 150 mm. Trenches 3 and 4 were filled with CLSM mixture B. The mixture had a good consistency and no water was added. Trenches 5 and 6 were filled with mixture C, with no additional water needed to achieve the target flow. Figure 4.11 shows one of the trenches being filled directly from the chute of a ready-mix truck, which was the method used for filling all the trenches.

Figure 4.11. Backfilling trenches with CLSM.

The field version of the needle penetrometer (ASTM C 403) was used to characterize the setting and hardening of CLSM mixtures in the trenches. Cylinders (75 × 150 mm) were also cast for compressive strength testing. The cylinders were capped to prevent moisture loss and were left at the site until the test date. Three days after casting the other samples were transported to a curing room at EBMUD. Samples were tested at 4, 7, 28, and 63 days by EBMUD technicians using neoprene pads (as per the recommendations provided in Appendix B)

The excavatability of the CLSM mixtures was investigated 63 days after their placement into the trenches by EBMUD engineers. Qualitative assessments were performed to determine the excavatability of the CLSM mixture with a hand shovel, a solid steel bar, and a backhoe.

Test Results

Fresh Properties

The flow and air content of the three CLSM mixtures are shown in Table 4.11, along with the ambient temperature and relative humidity at time of placement. The flow values for the three mixtures were adequate for the trench filling (some water was added to mixture A to obtain the desired flow). The air contents were less than expected (based on the mixture proportions provided by the three suppliers), but no adjustments were made to the air content of the field mixtures.

Setting and Hardening

Figure 4.12 shows the setting time and hardening data for the three CLSM mixtures used to backfill the six trenches during the field test. The data are based on field penetrometer

Table 4.11. Fresh properties for CLSM mixtures used in EBMUD field test.

Mixture	Flow (mm)	Air Content (%)	Ambient Temperature (°C)	Relative Humidity (%)
A	152	1.0	30	31
B	216	0.7	30	36
C	191	0.4	30	31

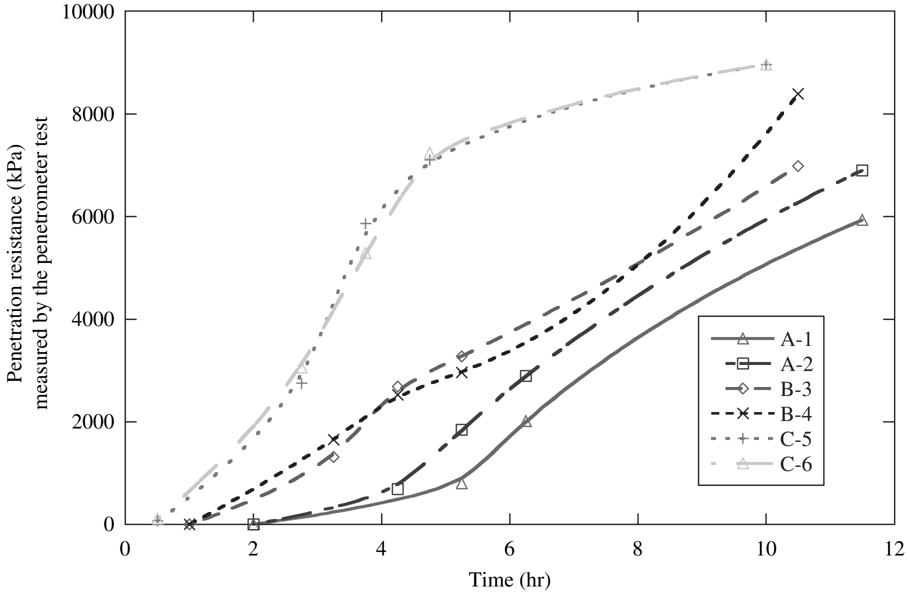


Figure 4.12. Field penetrometer data from EBMUD field test.

values taken from each of the trenches. Note that the legend denotes the mixture, followed by the trench number (for example, A-1 denotes mixture A placed in trench 1). The setting times for a given mixture were quite similar from one trench to another. Mixture A hardened quicker than the other two mixtures, which may be caused by one or a combination of several factors, including lower water content (as evidenced by stiffer consistency of as-received CLSM) and different cement and fly ash sources.

Compressive Strength

Compressive strength test results of the three CLSM mixtures are shown in Table 4.12. For each mixture, tests were conducted on cylinders stored adjacent to the trenches and in a fog room (standard curing). Cylinders were cured under two different conditions: field and moisture room. In virtually every case, the laboratory-cured cylinders exhibited lower strengths than the field-cured cylinders. This phenomenon is most likely due to the higher temperatures on site and perhaps also due to the leaching of hydration compounds from cylinders stored long-term in the fog room. The strength of mixture A, especially after 63 days, was substantially higher than the other mixtures.

Excavatability

The excavatability of one trench from each of the CLSM mixtures (trenches 2, 4, and 6) was evaluated 63 days after placement using manual methods (shovel and steel bar) and mechanical methods (backhoe). The difficulty of excavating the trenches was evaluated based on whether the power and time required was low, moderate, or high; the results are summarized in Table 4.13. As expected, trench 2 was the most difficult of the three to excavate, and when excavated with a backhoe, the chunks removed were quite large, which could be problematic when excavating around pipes.

Interestingly, trench 4 was fairly difficult to remove with a shovel, even though the compressive strength was less than 0.5 MPa at the time of removal. This difficulty in removing the CLSM with a shovel is likely attributed to the coarse aggregates contained in this mixture. This result illustrates that strength alone is not an adequate indicator of excavatability;

Table 4.12. Compressive strength of field- and laboratory-cured cylinders from EBMUD field test.

Mixture		4-Day Strength (kPa)	7-Day Strength (kPa)	28-Day Strength (kPa)	63-Day Strength (kPa)
A	Field-Cured	323	348	890	>1950
	Lab-Cured	310	410	779	>1950
B	Field-Cured	241	241	504	497
	Lab-Cured	212	263	351	381
C	Field-Cured	224	280	459	602
	Lab-Cured	221	246	358	314

Table 4.13. Excavatability of CLSM trenches.

Trench	Method	Difficulty Level
2 (Mixture A)	Shovel	High
	Steel Bar	Moderate
	Backhoe	Moderate
4 (Mixture B)	Shovel	Moderate
	Steel Bar	Low
	Backhoe	Low
6 (Mixture C)	Shovel	Low
	Steel Bar	Low
	Backhoe	Low

in fact, mixture C, which was removed easily from trench 6, had a higher compressive strength than mixture B. This test also illustrated how CLSM mixtures with similar proportions can behave completely different in field applications, owing to differences in raw materials, mixing action, and placement techniques.

Field Evaluation of CLSM for Bridge Approach Repair (TxDOT)

Introduction

A fairly new application for CLSM is its use as a subbase under bridge approaches. This section discusses the use of rapid-setting CLSM for the repair of several bridge approach slabs in San Antonio, Texas, which was done in close cooperation with the Texas Department of Transportation (TxDOT). This section first describes an unsuccessful attempt (before the initiation of this NCHRP project) at using rapid-setting CLSM for this application. Through forensic analyses and laboratory evaluations, the probable causes of this failed application were identified. A comprehensive study was then initiated to develop appropriate guidance for successfully repairing these bridge approaches using rapid-setting CLSM. The repair of four bridge approaches in San Antonio were then performed and inspected about 2 months after construction.

Research Program

Investigation of Initial Field Problems

Historically, the use of CLSM by the TxDOT has been mainly for repairing infrastructure. In August 2002, rapid-setting CLSM mixtures were used to repair severe settlements of bridge approaches at the intersection of I-35 and O'Conner Drive in San Antonio. Unfortunately, the setting and hardening of the installations were quite slow, and steel plates had to be placed to cover the backfill to accommodate the heavy traffic for the next morning. The steel plates were removed the next evening, and hot-mix asphalt was placed over the CLSM. However, severe rutting and settlement were observed within a few months. Because of the poor performance of rapid-setting CLSM in this application, TxDOT decided to place a temporary moratorium on the use of rapid-setting CLSM in bridge approaches in the San Antonio area. As part of NCHRP 24-12(01), efforts were initiated to investigate the cause of the poor performance and to provide guidance on future bridge approach applications.

In an effort to understand the cause of the initial failed CLSM bridge approach application, cores (100 × 200 mm cylinders) from the bridge approach were obtained and the compressive strengths were found to be in the range of 1.1 to 1.5 MPa, which indicates that long-term strengths and rigidity were not the problem. Efforts were then made to reproduce the "actual" job mixture using the limited amounts of raw materials retained from the original application and information retained from the job on the mixture proportions (see mixture A in Table 4.14). Given the small amount of remaining materials, a Hobart mixer was used, and three 50 × 50 mm cubes were prepared for each mixture following ASTM C 305 and tested using a geotechnical compression machine at the ages of 3, 8, and 24 hours. The results are summarized in Table 4.14. The flow was measured following ASTM D 6103. The setting and hardening processes were monitored through the penetration test as per ASTM C 403.

The mixture proportions provided by the contractor (mixture A) did not result in a self-leveling, fluid mixture. About 50 percent more water was needed to make the CLSM mixture fluid enough for the desired application, with dramatic effects on the rate of setting and hardening, as summarized in Figure 4.13. After significant evaluation, the fine aggregate used in the initial, unsuccessful bridge approach application was determined to be a dredged sand with most of the particles falling between 0.1 and 1 mm in size and a resultant fineness modulus of 1.33, well below the typical values for sands used in conventional concrete and many CLSM mixtures. Based on this investigation, it is quite possible that the use of the fine aggregate required such an increase in the water content in the field to get the desired fluidity that the early setting and hardening behavior was greatly affected.

Table 4.14. Mixture proportions (parts by mass) for rapid-setting CLSM.

Mixture	Sand (part)	Ash (part)	Water (part)	Flow (mm)	3-Hour Strength (kPa)	8-Hour Strength (kPa)	24-Hour Strength (kPa)
A	4.4	1	0.7	0	666	992	1309
B	4.4	1	0.87	130	407	723	768
C	4.4	1	1.04	270	256	513	550

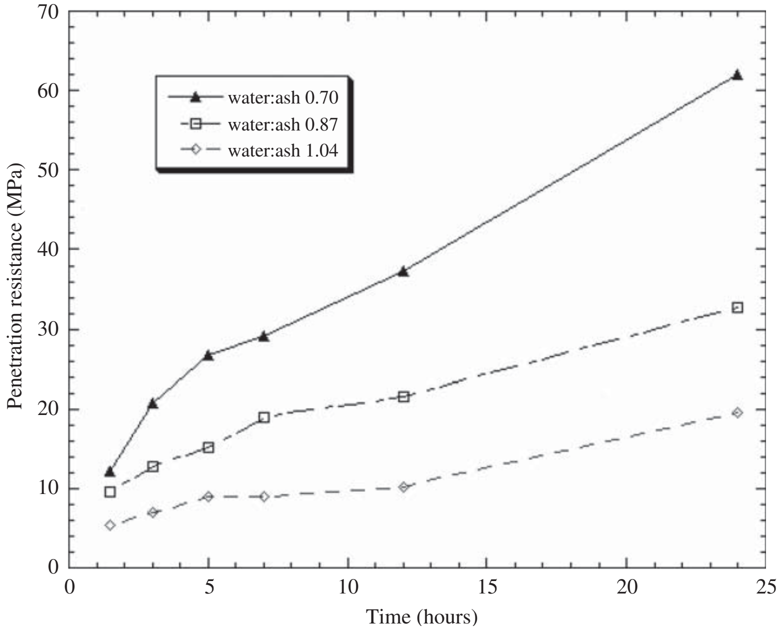


Figure 4.13. Setting and hardening of rapid-setting CLSM mixtures with varying water–fly ash ratios.

Materials Selection and Mixture Proportioning for Bridge Approach Repair

After determining the likely cause of the failed application of rapid-setting CLSM in the bridge approaches in Texas, the research team and TxDOT engineers decided to jointly develop a suitable mixture for the rapid repair of the approaches for two bridges in San Antonio. These two bridges at Branch Sala Trillo of Loop 1604 between I-10 and I-35 in San Antonio needed repair due to significant problems with differential settlement (i.e., the "bump at the end of the bridge"). To avoid the previously discussed problems with using rapid-setting CLSM for bridge approach applications, comprehensive laboratory testing was performed to select and specify the materials and mixture proportions for the proposed repair applications.

Although the hallmark of CLSM technology is the ability to efficiently and successfully use a wide range of materials that do not conform to conventional concrete specifications (e.g., ASTM C 33 for aggregates or ASTM C 618 for fly ashes), a somewhat conservative approach was taken for this application. Given that the initial problem with the bridge approach in San Antonio was likely caused by the fine aggregate that did not conform to ASTM C 33 gradation limits, the researchers and TxDOT engineers decided to specify locally available concrete sand that met ASTM C 33 for the newly proposed CLSM. They postulated that a well-graded sand would help control the water demand and would eliminate the need to add excess water at the jobsite. The selected fine aggregate, a natural river sand, was procured for the preliminary laboratory evaluations. A locally available ASTM C 618 Class C fly ash was specified and was also obtained by the research team for laboratory testing. Prior experience in this project revealed that the chemical and physical properties of Class C fly ash used in rapid-setting CLSM mixtures dramatically influence the fresh and hardened properties of mixtures. Therefore, a Class C fly ash was selected from the laboratory work that yielded the desired setting and hardening characteristics for the proposed repair application, and this fly ash source was then specified for the field work. The fly ash had a CaO content of 27.9 percent and was effective because of its rapid hardening in CLSM mixtures of this type. The research team believed that by specifying the actual materials to be used in the field trial, a higher level of quality assurance could be attained, and the true benefits of using CLSM for bridge approaches could be realized.

After selection of the specific sand and fly ash to be used in the field test, the mixture proportions were then developed by testing a range of sand–fly ash ratios and, for each of these ratios, studying the effects of water content on the flowability and strength gain. Sand–fly ash ratios of 5, 6, and 7 by mass were selected based on previous experience with such mixtures, as summarized in Table 4.15. The water content was modified for each combination to obtain a target flow in the range of 175 to 250 mm. The inherently fast setting characteristics of mixtures containing the selected fly ash created some challenges in the laboratory program. The fly ash provided by the contractor often set within 4 minutes after the introduction of water, which often limited the number of test specimens or fresh property tests that could be performed. This same rapid-

Table 4.15. Rapid-setting CLSM mixtures evaluated for bridge approach construction.

Mixture	Sand (part by mass)	Fly Ash[a] (part by mass)	Water (part by mass)	Flow (mm)
2A	5	1	0.78	220
2B	5	1	0.90	260
2C	5	1	0.67	160
3A	6	1	0.81	130
3B	6	1	0.95	230
3C	6	1	1.09	270
4A	7	1	1.25	270
4B	7	1	1.00	130
4C	7	1	1.12	220

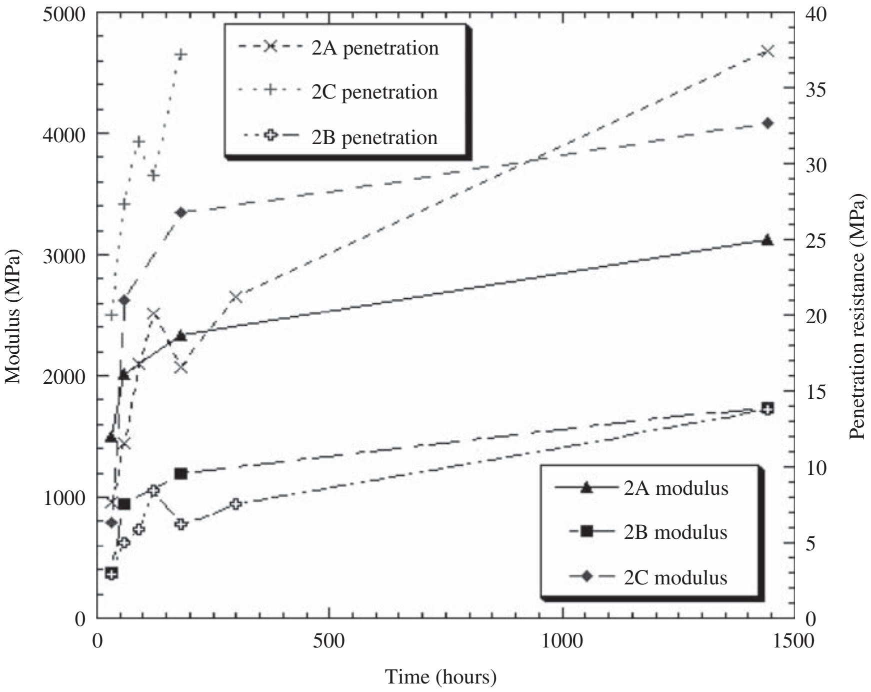
[a] ASTM C 618 Class C fly ash (CaO = 27.9%)

hardening behavior leads practitioners to use volumetric, on-site mixers for these types of mixtures that contain Class C fly ash as the only binder. Also, unlike many CLSM mixtures, the rapid-setting CLSM mixtures evaluated in this study evidenced little, if any, bleeding water. This phenomenon is mainly attributed to the rapid setting and hardening behavior and early formation of ettringite and other hydration products that tied up much of the available water.

The setting and hardening behavior of the various mixtures was evaluated using needle penetration (measured by ASTM C 403), unconfined compressive strength, and Young's modulus using the Spectrum Analysis of Surface Wave (SASW) method. The SASW testing was performed on three 100 × 200 mm cylinders.

There was generally a good correlation between modulus development and penetration resistance for the various mixtures, with a rapid increase in both properties for the first 3 hours, followed by little change thereafter. For conciseness, only the data for mixtures with sand–fly ash ratio of 5 are shown in Figure 4.14, but this trend was evident for all the mixtures tested. An important observation was that the early-age properties of rapid-setting CLSM were significantly influenced by the water–fly ash ratios. For instance, the penetration resistance of 3A after 30 minutes was higher than the corresponding value of 3B at 24 hours, while the water–fly ash ratios were different by only 0.14. The variations of water–fly ash mass ratios were greatly magnified in the different setting/hardening rates. The modulus of the 2C specimens (100 × 200 mm) was more than 3 times that of 2B specimens at 30 minutes even though the water–fly ash ratios differed by only 0.23. These observations suggest that the selected mixture not only should yield the target flow and hardening rate, but also should be fairly robust, that is, not very sensitive to small changes in water content. This extreme sensitivity deviates from the typical behavior of other common CLSM mixtures that do no exhibit rapid hardening at early ages.

The unconfined compressive strength of the various rapid-setting CLSM mixtures is plotted in Figure 4.15. For almost every mixture, the strength values were mainly determined by



Note: All mixtures had a sand–fly ash mass ratio of 5.

Figure 4.14. Comparison between needle penetration and modulus (using SASW).

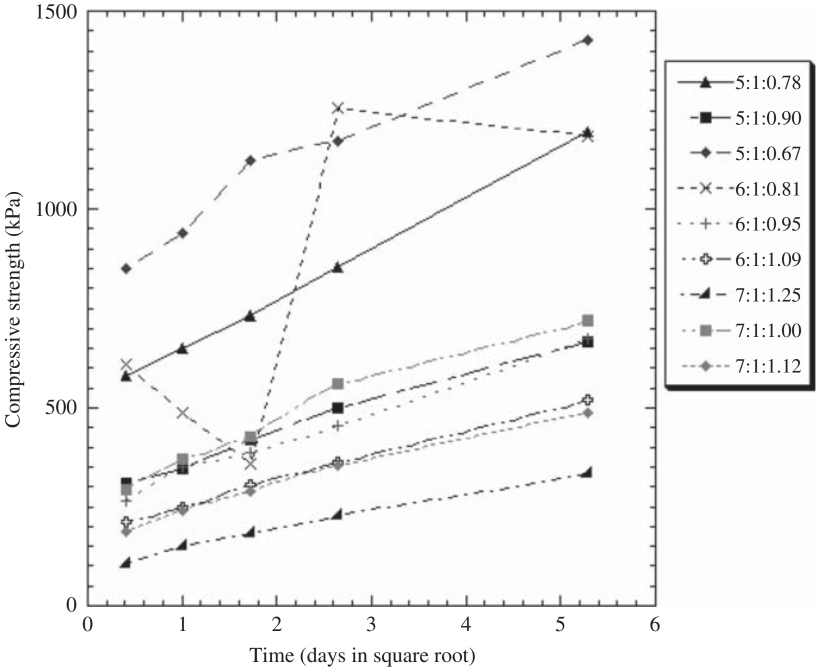


Figure 4.15. Strength development with time (shown in square root values) for mixtures with varying sand–fly ash–water ratios (by mass).

the water–fly ash ratios. The higher the water–fly ash ratios, the lower the strengths at different ages. For unknown reason(s), mixture 6:1:0.81 demonstrated abnormal strength variations with time.

Using the information obtained from the laboratory-prepared rapid-setting CLSM mixtures and keeping in mind the key attributes of the mixture (including rapid hardening and robustness of properties, as a function of water content), the research team selected two mixtures with sand:ash:water mass ratios of 5:1:0.75 and 6:1:0.91. The proportions and target modulus and velocity values (from SASW) of the two mixtures are shown in Table 4.16. The first mixture (5:1:0.75) was estimated to reach its target stiffness (ample for continuation of constructing bridge approach) in about 1 hour, with the second mixture estimated to require about 3 hours to reach a similar rigidity. These mixtures, referred to as “1-hour set” and “3-hour set,” were put forward as viable options for the field test, with the decision to be made by the contractor as to which of the two mixtures to use for the bridge approach repair.

Repair of Bridge Approaches

The two candidate CLSM mixtures selected by the research team were approved by TxDOT for the repair of the bridge approaches on Loop 1604. However, the contractor opted to use only one of the mixtures for the actual repair. The 1-hour set mixture was selected based on the faster setting time and increased speed of construction.

The repair of the bridge approaches was performed over a 10-day period, with construction taking place on 4 nights during this time period. The construction involved two separate bridges, each of which is a two-lane bridge. Each night, one lane on one of the bridges was closed from 8:00 p.m. to 6:00 a.m., allowing a total of 10 hours to excavate the original

Table 4.16. Mixture proportions recommended for bridge approach application and corresponding target modulus values.

Mixture	Sand:Ash:Water (by mass)	Sand (kg/m^3)	Ash (kg/m^3)	Water (kg/m^3)	Target Modulus (MPa)	Target Velocity (m/s)
1-hour set	5:1:0.75	1627	325.4	244	2529	1071
3-hour set	6:1:0.91	1658	276.4	252	1633	848

approach backfill, cast the new CLSM section, and pave over the newly cast CLSM section with hot-mix asphalt. For a given night, a single CLSM placement on one side of the bridge consisted of a 1.2 m deep section, 3.3 m in the longitudinal direction (in the direction of travel), and 6 m in the transverse direction.

There was no difficulty removing the original backfill from the bridge approaches. Figure 4.16(a) shows a typical section that was cleared of the original backfill, with the right side of the photo showing the repaired section from the previous evening. Careful examination of the CLSM placed 24 hours earlier did not reveal any visible cracks, large air voids, or "cold joints" in this massive block. A good bond appeared to have formed between the CLSM backfill and the hot-mix asphalt placed above it. The CLSM cast 24 hours prior was still warm to the touch, mainly attributed to the slow dissipation of the hydration heat in such a massive unit. Figure 4.16(b) shows the placing of the rapid-setting CLSM mixture into the bridge approach area. Note that the backfill was built up as thin layers. The mixture exhibited a flow value of 270 mm, which was sufficiently fluid for this application. The surface was bull-floated to achieve a horizontal surface to facilitate the paving with hot-mix asphalt.

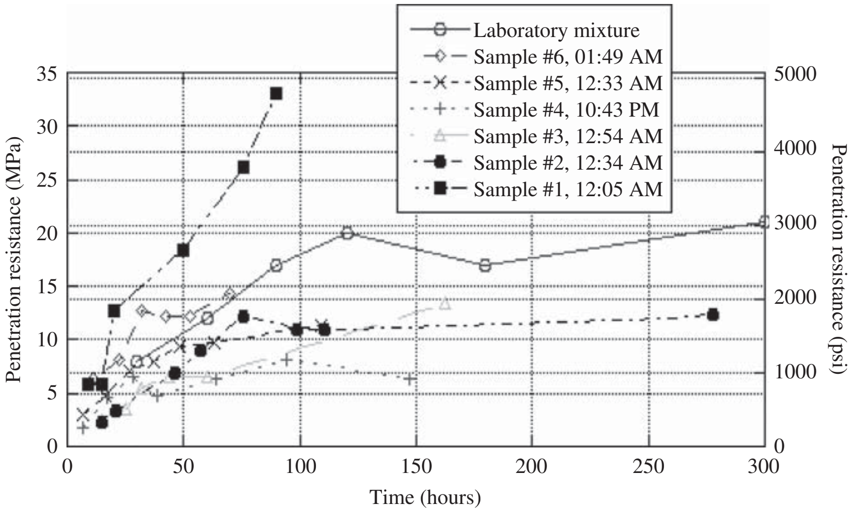
The research team visited the construction site on two separate nights to observe the CLSM placement and to obtain test cylinders (thirty 75 × 150 mm and six 150 × 300 mm) for subsequent testing. Specimens were also cast and tested on site for setting time following ASTM C 403. On each night, three trucks were sampled from the middle of each load. The penetration resistance results are shown in Figure 4.17. The setting characteristics from the different truck loads varied considerably, although a penetration resistance of approximately 7.0 MPa was obtained in about an hour for all samples. The differences in setting times between laboratory and actual field samples are mainly attributed to differences in temperature history, as well as differences in mixing action, moisture corrections, etc.

The Kelly ball (ASTM D 6024) was also used as a simple index to determine the early hardening characteristics of the CLSM for the bridge approach repair and to estimate when hot-mix paving could commence. Figure 4.18 shows the use of the Kelly ball on the surface of the finished backfill; typical results for two approaches are shown in Table 4.17. It should be emphasized that the ball drop method measures only properties of the surface layer of the CLSM fill. Even though the diameter of the indentation of the Kelly ball on the northbound approach was about 90 mm, the CLSM was deemed to be sufficiently stiff to accommodate the asphalt paving. The reason for proceeding with paving despite a relatively large indentation was that the top surface of the placement was moved around significantly to obtain the required grade. The research team's prior experience with the CLSM had shown that if the initial hydration is disturbed, the strength can be severely affected. Thus, the surface property of the fill likely did not truly represent the characteristics at deeper depths. In fact, except for the upper portion, the material beneath was in place for more than 2 hours because of the reloading of the volumetric mixers. In addition, this ball drop method is likely

(a)

(b)

Figure 4.16. Opening (a) and backfill (b) of bridge approaches.



Note: Samples 1 through 3 were from one night's construction, and samples 4 through 6 were from construction one week later, also at night.

Figure 4.17. Needle penetration values (ASTM C 403) for rapid-setting CLSM used in bridge approach repair.

quite severe for CLSM due to the 13.62 kg mass of the steel ball. When the CLSM was deemed to be strong enough to support heavy equipment, the asphalt paving commenced.

The two bridge approach backfills were instrumented with temperature-measuring devices (i-buttons) to monitor the temperature history on the second observation night. The i-buttons were placed near the center of the backfill. The reading was taken every 5 minutes for 7 days. The results are plotted in Figure 4.19. The southbound bridge approach reached its peak of 47°C 24 hours after placement, while the northbound peak temperature of 54°C was reached about 2 days after placement. The measured temperature rise for each field section was due to the massive volume of the backfill. These high temperatures were not detected in the 150 × 300 mm cylinders prepared in the laboratory.

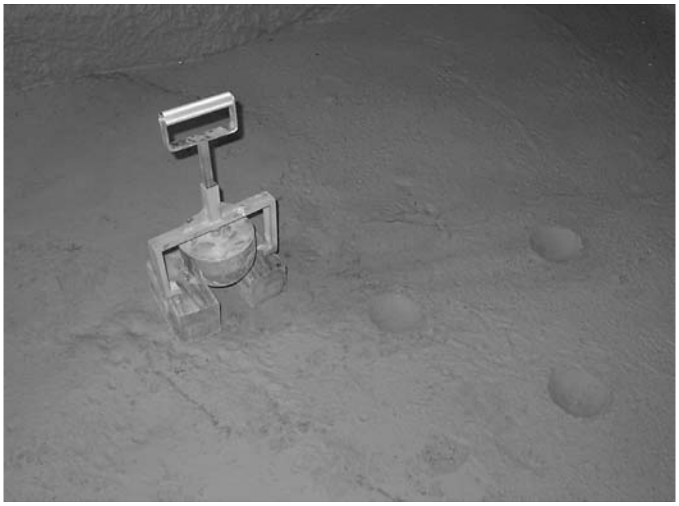


Figure 4.18. Use of Kelly ball to determine the proper timing of hot-mix asphalt paving.

Monitoring of Backfill Materials

As previously described, compressive cylinders (75 × 150 mm and 150 × 300 mm) were cast during the placement of the rapid-setting CLSM. Because of logistical challenges in securing and storing the cylinders in the field, they were transported back to the laboratory after an age of at least 3 hours, by which time the cylinders were strong enough to resist damage due to transport. The cylinders were then stored in a standard curing room (23°C and 100 percent RH) until the time of testing. The 75 × 150 mm cylinders were tested using unbonded pads (based on recommendations from Chapter 3) at ages of 1, 3, 7, 28, 90, and 180 days.

Figure 4.20 shows the strength development of cylinders sampled from different batches at the jobsite. The variation of strengths was relatively high, up to 20 percent, which can be attributed to the cylinders being obtained from different batches, variations in moisture content in sand, and inherent variability in site-cast mixtures. In addition, visual inspection of several cylinders after being tested to failure in compression revealed the presence of deposits or lumps of white powder in the mixture. This white powder was not analyzed, but the presence of this impurity, which may have been lime, likely had some effect on the setting and hardening properties of the mixtures. Two of the sampled CLSM batches exhibited strengths greater than 5.0 MPa at an age of 6 months, which may make future excavation quite difficult. However, the intention of this

Table 4.17. Typical results of Kelly ball tests (ASTM D 6024) in two bridge approach repairs.

Southbound		Northbound	
Time after placement (h:m)	Diameter of Kelly ball indentation (mm)	Time after placement (h:m)	Diameter of Kelly ball indentation (mm)
0:10	114	0:09	122
0:22	99	0:19	108
0:33	97	0:30	95
0:42	89	1:07	95
0:56	76	1:30	89

field test was not to produce excavatable CLSM but rather to develop a mixture that hardens quickly, allows for rapid construction and paving, and performs well over time, with little or no settlement.

Monitoring of Field Performance

Approximately 2 months after construction of the bridge approaches, a visual survey of the approaches was performed. No differential settlement of the bridge approach sections was visible and the sections were performing very well. The "bump at the end of the bridge" was essentially non-existent, which was a significant improvement over the condition of the bridge approach sections prior to repair. At the time of this inspection, a seismic pavement analyzer (SPA) was used to evaluate the in-situ moduli of the completed bridge approach sections. The SPA is an automated non-destructive device for conducting the SASW tests in less than 1 minute (Nazarian et al. 1993). In analyzing the SASW results, a thickness of 80 mm was assigned to the hot-mix asphalt layer. The upper CLSM fill was assumed to have a thickness of 600 mm. The remaining backfill above the native soil was the lower fill. Measurements were performed parallel with and perpendicular to the direction of travel on the roadway. The average moduli measured along the profile are shown in Figure 4.21. The modulus of the asphalt pavement was quite uniform. However, the modulus of the CLSM backfill varied significantly. This observation agrees with the measured variations in compressive strength quite well and supports the empirical relation typically used for conventional concrete, whereby the

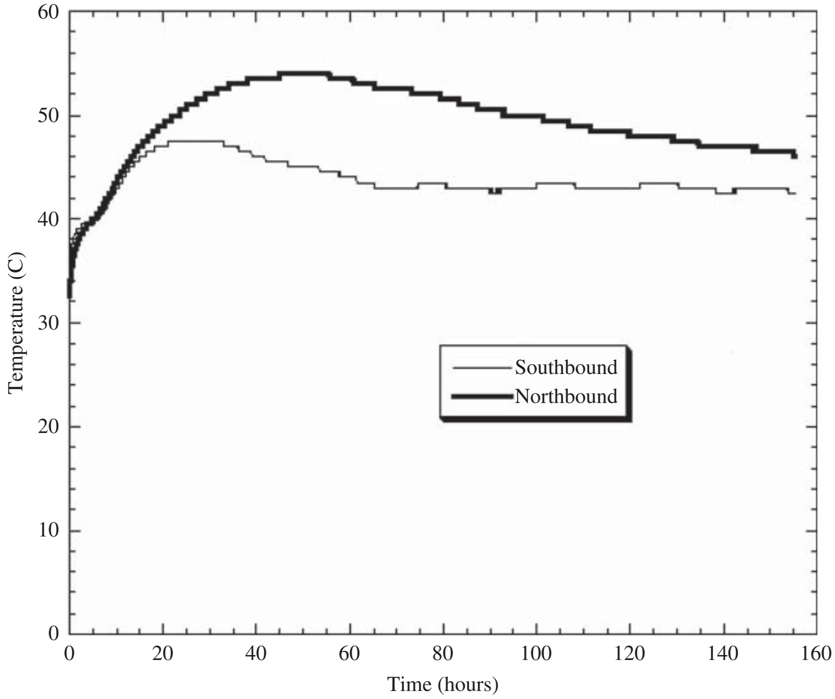


Figure 4.19. Heat generation in the center of rapid-setting CLSM bridge approach sections.

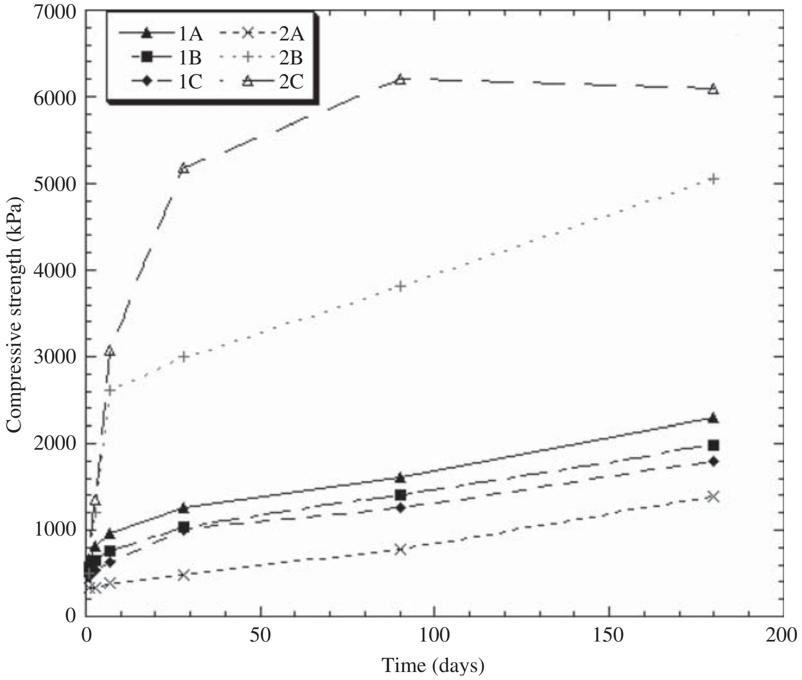


Figure 4.20. Unconfined compressive strength of cylinders from one night's construction (1A, 1B, and 1C) and from one week later (2A, 2B, and 2C).

elastic modulus is proportional to the square root of the compressive strength. One interesting result is that the upper 350 mm of the rapid-setting CLSM at bridge approach 2B was significantly softer than its lower fill, perhaps because of the addition of more water in the upper fill.

This section summarized a laboratory- and field-based evaluation of rapid-setting CLSM for use in bridge approach applications. The study was unique in that it first involved diagnosing the cause of a failed field application of the material and then used the information and experience gained in this exercise to design a mixture that was successfully used in an extensive field application. The overall experience shows that rapid-setting CLSM can be an extremely useful and versatile material for rapid construction, but also that care should be taken in designing and constructing field installations, with suitable quality control/quality assurance, to ensure long-term performance.

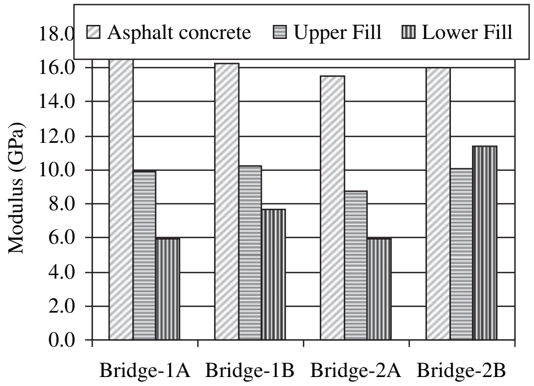


Figure 4.21. Average moduli of backfill and asphalt pavement measured in situ using SASW.

Field Test at Texas A&M University

Introduction

A comprehensive, long-term field test was performed at the National Geotechnical Experimentation Site located at the Texas A&M University Riverside Campus, which is about 12 km west of the main university campus in College Station, Texas. The objective of the field testing was to investigate the CLSM strength gain, excavatability of CLSM, and the long-term corrosion performance of ductile iron pipes and galvanized corrugated steel culverts backfilled with CLSM. It was recognized from the onset that because of the long-term nature of corrosion, long-term field data would be needed. Because the site is strategic to Texas A&M University (where all the laboratory corrosion testing was done, as described in Chapter 3) and the research team has unlimited access to the test location, the research team anticipates that it will continue to monitor the corrosion studies long after this NCHRP project has concluded. This site also was unique in that it allows for the controlled (and measured) application of chlorides to

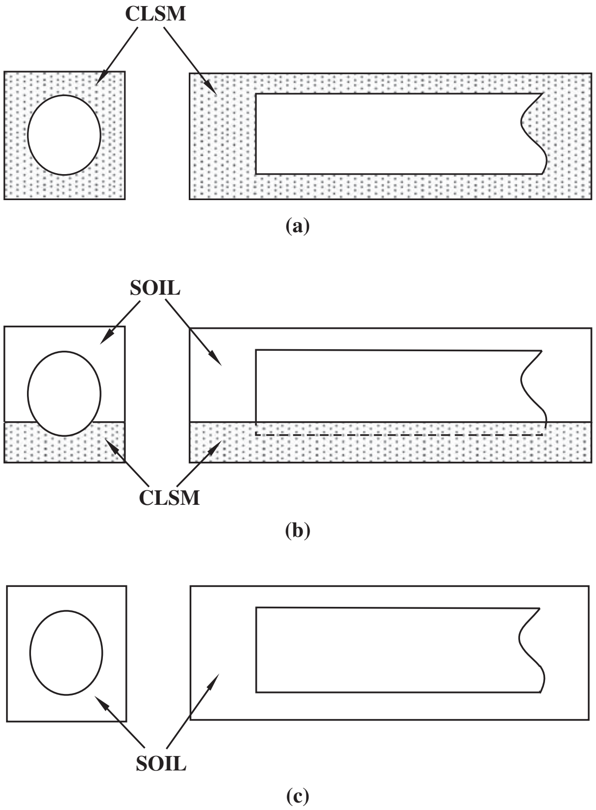


Figure 4.22. Three trench conditions used for the field test.

the site, which aims to replicate field conditions that lead to corrosion and to accelerate the rate of deterioration.

Site Layout and Construction

Two sites, a clay site and a sand site, were selected to observe the corrosion performance of embedded ductile iron pipes and galvanized corrugated steel culverts. Because the sites are part of the National Geotechnical Experimentation Site, the types of soils and clays at the sites have been well documented. For this project, test pits on both sites were excavated using a backhoe-mounted auger to collect and analyze the soil and clay. The clay site is underlain by four distinct layers. The surface layer is mottled red and gray clay. This clay layer is very uniform in thickness down to about 1.83 m below the surface. The plastic and liquid limits of the clay were 20.9 and 53.7 percent, respectively. The hydraulic conductivity coefficient was 4.99×10^{-3} m/year. The surface layer at the sand site is mottled red and tan silty sand. The percentage of fine particles was 17.4 percent, and the hydraulic conductivity coefficient was 5×10^{-2} m/year.

Metal pipes were placed in six trenches on each site using three different trench conditions. The trenches were 12.19 m long, 0.76 m deep, and 0.46 m wide. Figure 4.22 shows the three trench conditions used in the test:

- *Condition I:* Metallic pipes are completely embedded in CLSM (Figure 4.22(a)).
- *Condition II:* Metallic pipes are placed on a CLSM bedding and backfilled with soil from the site (Figure 4.22(b)).
- *Condition III:* Metallic pipes are completely embedded in soil (Figure 4.22(c)).

Commercially available ductile iron pipes and corrugated steel culverts were delivered to the site. Both types of pipe were cut into 0.76 m long pieces. The ductile iron pipes had an asphalt coating that was removed by sandblasting after soaking in lacquer thinner. Copper wires (2.32 mm diameter) were attached to each ductile iron and culvert sample to be used for corrosion observations later. After drilling and tapping the ductile iron pipe pieces, screws and washers were used to attach the wires as shown in Figure 4.23(a). Exposed wires and screws were coated with epoxy to prevent corrosion. Grounding clips

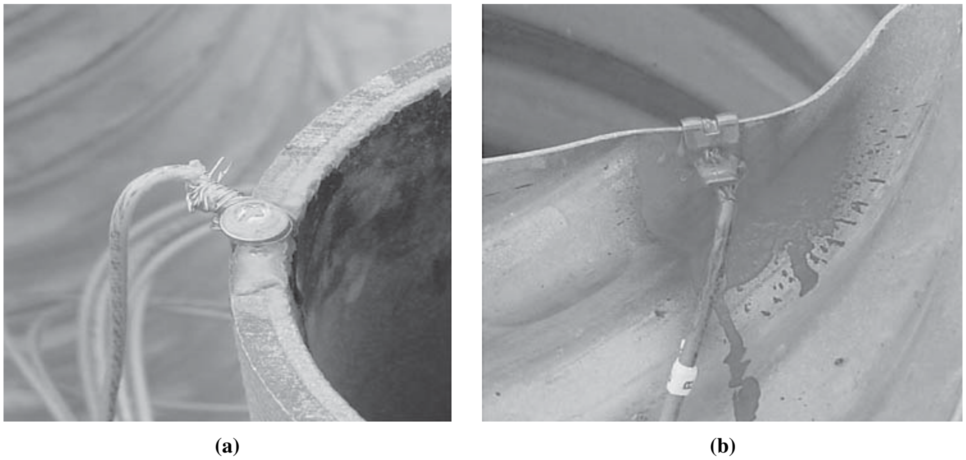

(a) (b)

Figure 4.23. Wiring of ductile iron pipes and corrugated steel culverts.

were used to attach wires to corrugated steel culvert pieces. After the wires were connected, the exposed sections of the wires and clips were coated with enamel. Epoxy was applied after the enamel was cured as shown in Figure 4.23(b).

Twelve of the cut ductile iron pipe samples and twelve of the cut corrugated culvert samples were painted with epoxy inside and outside leaving only a 0.15 m diameter circular area exposed. Counter electrodes for polarization studies were 0.15 × 0.15 m nickel-chromium wire mesh. Copper wires (2.32 mm diameter) with alligator clips were attached and soldered to the meshes. The alligator clips, the solder area, and exposed wires were coated with epoxy. These 24 pieces of pipes with limited exposure areas together with the counter electrodes can be used later for long-term corrosion rate measurements. Figure 4.24 shows three of the samples prepared for polarization testing.

The six trenches were excavated on each site in a 6 × 30.5 m rectangular area using a backhoe with a 0.46 m wide bucket. After the bottoms of the trenches were cleared, pipes were placed with 0.6 m space between them. Four ductile iron pipe samples and four corrugated steel culvert samples, including one of each with limited exposure areas, were placed in each trench. The pipe pieces were placed on steel chairs to allow free flow of CLSM mixture underneath the pipes. Each piece of pipe was also secured using four stakes, driven 1 foot into the ground to prevent lateral and vertical movement. Figure 4.25 shows a trench in the clay site with pipes.

The pipes prepared for polarization testing were placed at the two ends of the trenches. These pipes were placed with the exposed areas facing sideways so that when the trenches were backfilled they would be exposed to a CLSM and soil environment. Counter electrodes were placed adjacent to the exposed areas.

After the placement of the pipes, trenches were backfilled with a CLSM mixture provided by a local concrete supplier. The CLSM mixture contained 1483 kg/m^3 sand, 34 kg/m^3 cement, and 135 kg/m^3 fly ash. The water–cementitious material ratio was 0.8. The CLSM was delivered in ready-mixed concrete trucks and was placed into the trenches using a chute as shown in Figure 4.26.

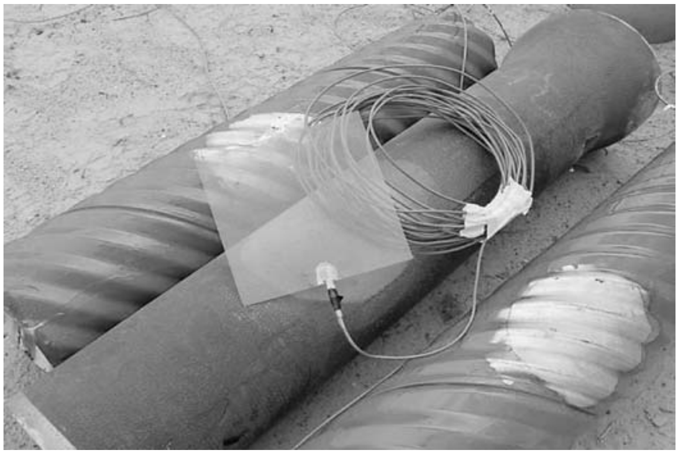


Figure 4.24. Metal pipes with 0.15 m diameter exposed surface and a counter electrode.

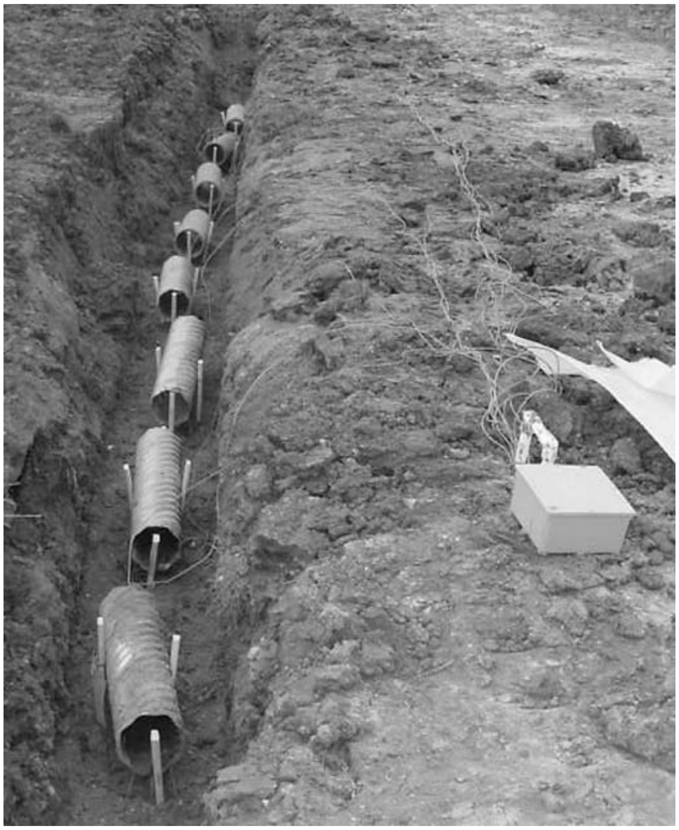


Figure 4.25. Clay site trench with pipes.

The average time to fill the condition I (completely filled with CLSM) trenches was 8 minutes. The truck was placed at one end at the trench and the trench was completely filled from this point (Figure 4.26(a)). The average time to fill the condition II (CLSM bedding and soil backfill) trenches was 11 minutes, and the truck had to be moved three times to ensure uniform thickness of bedding layer. Condition II and III trenches were filled with native soil after the setting of the CLSM backfill. The soil was placed into the trenches in layers with a backhoe and compacted with an average of three passes of a jumping jack compactor. The average time to compact an approximately 0.25 m thick by 12 m long layer of soil was approximately 5 minutes. This speed equals approximately 30 minutes for sample sized trenches filled with CLSM (3 to 4 times longer).

The wires connected to the pipe pieces in each trench ran along the bottom of the trenches and were collected in PVC boxes at the surface of each trench. The wires entered into the boxes through an inverted U-shaped conduit to prevent rainwater from entering into the boxes. A smaller box was placed inside each PVC box and wires were soldered to female con-


(a) (b)

Figure 4.26. Placement of CLSM into the trenches.

nectors attached to the lid of the smaller boxes for extra protection and ease of measurement. Connectors in each box are labeled with numbers 1 to 8. The connectors from 1 to 4 were attached to the galvanized corrugated steel culverts, starting from the closer end of the trench to the box and connectors 5 to 8 were connected to the ductile iron pipe samples. Connectors were attached to the counter electrodes of pipes 1 and 8. Figure 4.27 shows one of the PVC boxes and connectors.

Before the placement of the pipes, the research team planned to expose three of the six trenches on each site to chlorides. Therefore, to prevent the chlorides from flowing with rainwater to the trenches that were not supposed to be exposed to chlorides, the sites were graded with a motor grader to have a slope of 2 percent. Figure 4.28 shows the general site layout for one of the test sites.

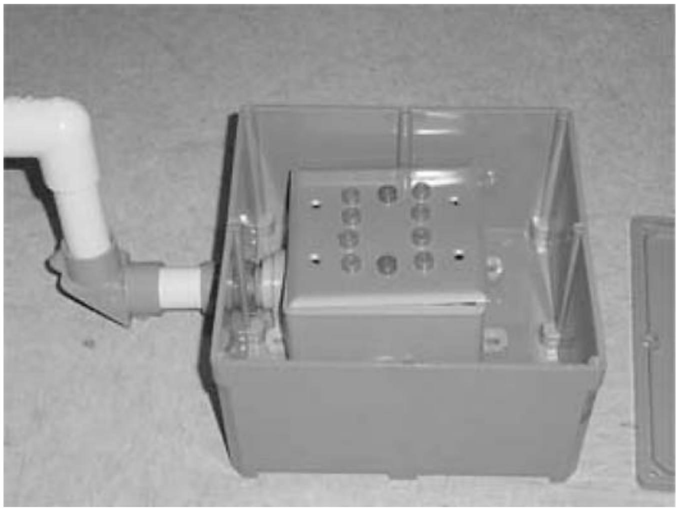


Figure 4.27. PVC connection box and connectors.

Testing Program

The flow (ASTM D 6103) and air content (ASTM C 231) of the CLSM delivered to the test site were measured prior to backfilling the trenches. Cylinders (100 × 150 mm) were cast to measure the compressive strength at 4, 7, and 28 days. Samples were capped with plastic lids after casting. One day after casting, cylinders were transported to a fog room (22°C and 98 percent RH) to be held until testing. Compressive strength testing was performed using neoprene pads and displacement-controlled testing equipment. The setting times of the CLSM mixture in the condition I trenches were measured using a needle penetrometer with a 6.45 mm^2 needle tip.

After backfilling was complete, the location of each piece of pipe was marked using flags. An average of 10.75 kg/m^2 sodium chloride was applied to the chloride sections of each site. After the application of chlorides to the backfilled testing sites, half-cell potentials were collected as an indicator of corrosion of the embedded metallic pipes. Half-cell potentials were collected using a copper–copper sulfate (Cu-CuSO$_4$) electrode and a high impedance multimeter. To measure the half-cell potential of a piece of embedded pipe, the electrode was placed on the soil or CLSM surface above the pipe sample, after the multimeter was connected to the corresponding connector in the PVC box. To be consistent, the electrode was placed next to the identifier flags on the surface identifying the location of

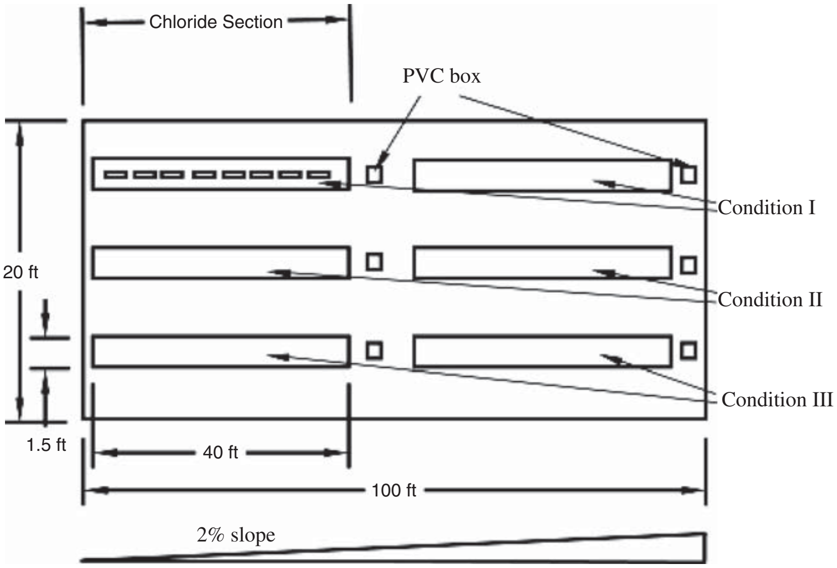


Figure 4.28. General site layout (not to scale).

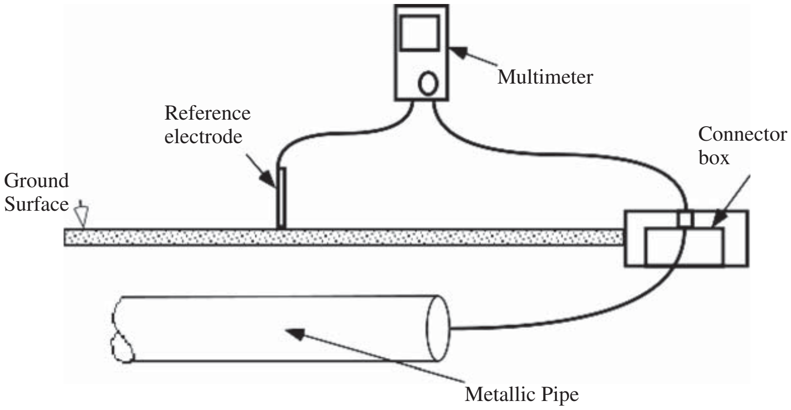


Figure 4.29. Half-cell potential reading connection.

pipe samples every time data was collected. If the surface was too dry, the surface was wetted to obtain a better electrical connection. Figure 4.29 shows the schematic of the half-cell potential test setup.

Test Results

Two CLSM samples were taken from each of the two ready-mix concrete trucks that delivered the material to the trenches, and the flow and air contents were quite uniform, with flows ranging from 225 to 240 mm and air contents ranging from 14 to 19 percent. The field penetrometer could not register any readings for about the first 11 to 12 hours after trench placement. The field penetrometer data are shown in Table 4.18. The particular CLSM mixture used in this study exhibited a sufficient set to support the weight of an average person about 15 hours after the completion of placement. The average strength of the CLSM, 24 hours after the placement, was about 345 kPa, measured by the penetrometer test. Figure 4.30 shows the compressive strength of the CLSM mixtures sampled from the two trucks at 4, 7, and 28 days.

Table 4.18. Field penetrometer results.

Time after placement (hours)	Penetrometer Results (kPa)					
	1	2	3	4	5	6
0	0	0	0	0	0	0
11	0	0	0	0	0	0
12	14	21	0	21	14	0
15	34	48	34	55	41	48
19	269	290	276	255	269	283
21	331	338	359	241	345	324
24	359	345	331	338	345	345

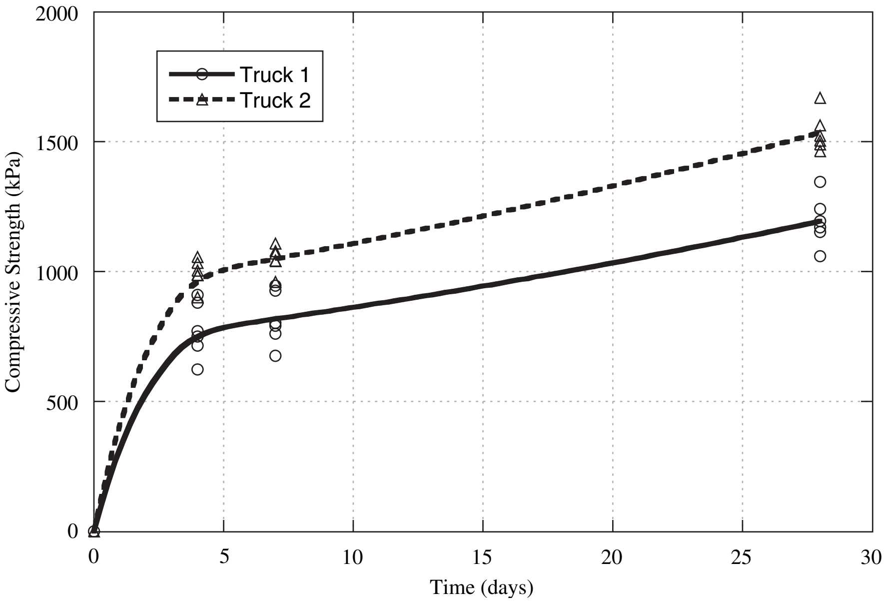


Figure 4.30. Compressive strength of laboratory-cured cylinders from TAMU field test.

Long-Term Corrosion Testing

As mentioned earlier in this section, a major thrust of this field test is to generate field data on the corrosion of metals imbedded in CLSM in the field. As was expected, the rate of corrosion under these field conditions has been quite low, and after more than 2 years of monitoring, little active corrosion has been measured. For completeness, a brief summary of the corrosion data (half-cell potential) is provided in Tables 4.19 and 4.20. These tables show the average half-cell potential measurement against the Cu-$CuSO_4$ reference electrode of the four galvanized steel or the four ductile iron pipes exposed to the same conditions. The half-cell potentials shown are time-weighted averages for the conditions shown.

The research team will continue to monitor this unique long-term corrosion site and hope that these data will prove useful in developing information about the service life of metals embedded in CLSM. Long-term excavatability studies also will be performed as part of these ongoing efforts.

Summary of Key Findings from Field Tests

This chapter has summarized the findings from six CLSM field tests performed throughout the United States. As previously mentioned, the main goals of this field testing program were to fill in the gaps in understanding CLSM behavior and

Table 4.19. Time-weighted average half-cell potentials for the clay site.

Soil Type	Environment	Condition	Pipe Type	Weighted Half-Cell Potential (V)
Clay	Chloride	CLSM	Galvanized	–0.7672
			Ductile	–1.0719
		CLSM/Soil	Galvanized	–0.7018
			Ductile	–1.0030
		Soil	Galvanized	–0.6850
			Ductile	–1.0135
	Non-chloride	CLSM	Galvanized	–0.6997
			Ductile	–0.8849
		CLSM/Soil	Galvanized	–0.6165
			Ductile	–0.8923
		Soil	Galvanized	–0.5585
			Ductile	–0.9236

Table 4.20. Time-weighted average half-cell potentials for the sand site.

Soil Type	Environment	Condition	Pipe Type	Weighted Half-Cell Potential (V)
Sand	Chloride	CLSM	Galvanized	–0.7006
			Ductile	–0.6169
		CLSM/Soil	Galvanized	–0.6340
			Ductile	–0.9711
		Soil	Galvanized	–0.4242
			Ductile	–0.5911
	Non-chloride	CLSM	Galvanized	–0.8330
			Ductile	–0.8708
		CLSM/Soil	Galvanized	–0.4646
			Ductile	–0.9200
		Soil	Galvanized	–0.3537
			Ductile	–0.9078

performance and to validate the test methods, specifications, and guidelines developed in the earlier stages of this project.

In general, the field tests proved to be quite successful and enlightening. *For the most part, the test methods, specifications, and guidelines developed under this project were found to be appropriate and effective.* Several specific technical issues were addressed in the course of these field tests, with an emphasis on aspects of CLSM behavior that could not be adequately evaluated in the laboratory, such issues as excavatability and corrosion. Although the relevant data from some long-term corrosion field tests were not collected under this project (because of the slow rate of corrosion in field installations), it is anticipated that these data will be collected in the future and presented to the appropriate AASHTO committees for consideration.

Some of the specific findings from this field testing program are briefly summarized below:

- The basic tests for CLSM, such as flow, air content, and unit weight, were found to be effective and easy to implement, and most jurisdictions involved in the field tests were already routinely using the tests in practice.
- The compressive strength of CLSM was measured in each field test using the testing methodology developed under this project. The approach for proper handling, curing, capping, and testing was validated throughout the process.
- The tests showed that strength measured on standard-cured cylinders can vary significantly from actual CLSM strength in field applications, mainly because of differences in time-temperature histories. This disconnect appears to be greatest when fly ash is used, and as such, users should be aware of this issue when considering long-term excavatability.
- There is no single property of CLSM (e.g., compressive strength) that can be used as a definitive index for excavatability. Compressive strength is the most commonly measured and reported CLSM property, and can be a reasonable index of excavatability in some cases. However, the disconnect between the strength of laboratory-cured cylinders and the actual long-term strength of CLSM in trenches, etc. makes full reliance on laboratory strengths when predicting excavatability difficult. Testing cylinders in the laboratory under conditions expected in field installations is recommended when excavatability is a concern.
- The removability modulus, originally developed by Hamilton County (Ohio) engineers, is a useful tool in attempting to predict excavatability. This method is an empirical approach to predicting excavatability using an equation featuring the unit weight and 28-day strength value of CLSM. This approach can be further improved upon by using field-cured strengths, thereby minimizing the disconnect with laboratory-cured cylinders, in the equation. The inclusion of unit weight is actually quite helpful as a parameter used in predicting excavatability because it tends to pick up the aggregate-related effects associated with excavatability. Specifically, in some field tests, the lack of aggregates in CLSM (e.g., mixtures with 95 percent Class F fly ash, 5 percent portland cement, and water added for desired fluidity) resulted in a mixture that was easier to excavate than would have been expected, based solely on the strength of the mixture.
- The DCP was found to be a particularly useful tool in monitoring early-strength gain of CLSM, as well as the long-term strength and excavatability of installations. This method is unique in that it allows for measuring the properties of CLSM as a function of depth, thereby avoiding a shortcoming of surface penetration tests (needle penetrometer, soil penetrometer) that only assess the near-surface behavior.
- Due to the high fluidity of CLSM mixtures, floating of pipes or unintentional shifting of utilities may result, and users should take precautions to avoid this behavior. Such precautions are addressed in the specifications and guidelines developed under this project for backfill applications.
- More long-term monitoring is essential for a true assessment of corrosion of metals in CLSM. Tests initiated under this project will continue to be monitored, and the relevant findings will be communicated to the appropriate AASHTO committees.

CHAPTER 5

Conclusions and Suggested Research

Conclusions

This report summarized the key findings of a multi-year research project on CLSM for use in backfill, utility bedding, void fill, and bridge approach applications. The research involved both a major laboratory component and field component. Through these efforts, several key deliverables have been produced, including a recommended suite of tests methods (Appendix B), specifications (Appendix C), recommended practices (Appendix D), and an implementation to drive these deliverables into practice (Appendix E).

Significant progress was made in this project to better understand the behavior of CLSM and to evaluate the properties that most impact performance. The following list presents some of the main overall findings from this project:

1. Suitable test methods exist or were developed under this project to measure most of the key CLSM properties affecting performance in the four target applications. Appendix B describes the tests recommended to evaluate relevant fresh, hardened, and durability properties of CLSM.
2. Predictive models were developed to predict the water demand and compressive strengths for a range of CLSM mixtures. This information can be helpful in designing mixtures for applications where strength may be a key limiting factor, such as in the use of excavatable CLSM.
3. The effects of temperature on strength gain of CLSM mixtures can be very pronounced, especially when using Class C fly ash. One should be aware of this increased strength gain, especially when CLSM is being used in a hot climate and when future excavatability may be required. Keeping this strong temperature dependence in mind and accounting for it in design and construction can help to effectively produce excavatable CLSM. Trial batching and testing at elevated temperatures help to gain insight into long-term strength gain in field applications, especially when fly ash or other supplementary cementitious materials are used.
4. There is no single parameter that adequately predicts excavatability. Compressive strength can serve as a useful surrogate value in some cases, but one should try to capture the long-term strength gain when applying strength as a predictive tool. Basing long-term strength gain on short-term laboratory testing can be problematic for some CLSM mixtures (especially those containing fly ash). Calculating a removability modulus shows promise in predicting excavatability. Lastly, the dynamic cone penetrometer was found to be a valuable method of assessing CLSM in the field and estimating ease of excavatability.
5. Significant research was performed on the corrosion of metallic pipe materials in CLSM. In general, CLSM was found to be beneficial in reducing corrosion (compared to typical compacted fill) when pipes are completely embedded in CLSM. The reduced permeability of CLSM can reduce the ingress of chlorides and the microstructure of CLSM can improve corrosion resistance through changes in the pH and resistivity of the pore solution. A potential for corrosion exists when pipes are embedded in both CLSM and surrounding soil or conventional fill, because a galvanic cell is set up that can increase corrosion activity. This case is similar in nature to metals embedded in dissimilar soils, and similar precautions can be taken to ensure the desired service life.
6. The by-product materials tested in this study were found to be non-toxic. However, a testing program was proposed to evaluate other by-product materials that might be more of a concern with regard to leaching and environmental impact. This method involves the testing of total heavy metals, possibly followed by TCLP (if the total heavy metals are above certain threshold values), and possibly followed by leachate testing from CLSM containing the subject material (if the TCLP values exceed certain thresholds).
7. Due to the high fluidity of CLSM mixtures, floating of pipes or unintentional shifting of utilities may occur during placement; users should take precautions to avoid this result.

Precautions are addressed in the specifications and guidelines developed under this project for backfill applications.

Suggested Research

As is the case for any research project, all of the important issues can not be studied, or at least not in the level of detail desired. This research made important gains in many of the technical areas relevant to CLSM, and the findings from this study have shed light on issues that require even more study. The following list presents some of the areas for suggested future research:

1. More long-term monitoring is essential in truly assessing the corrosion of metals in CLSM. Field tests initiated under this project will continue to be monitored, and the relevant findings will be communicated to the appropriate AASHTO committees.
2. Other data and information from field performance of metals in CLSM should be gathered and synthesized to better quantify the service life in various environments.
3. Other durability issues, such as frost heave (or other frost-related issues), should be studied in more detail to determine if long-term field performance can be assured in cold climates, with severe freeze-thaw cycles.
4. Information should be gathered on problems encountered in field applications related to excessive long-term strength gain that have hindered excavation. Information on materials, mixture proportions, and engineering properties (e.g., strength, unit weight, etc.) should be gathered in order to further elucidate the factors that most contribute to excavatability problems.
5. More detailed information on productivity and speed of CLSM, compared to conventional compacted fill, should be collected to better quantify the benefits of using CLSM in the four key applications studied in this project.

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APPENDIX A

Corrosion Study

This appendix is available on the TRB website as part of *NCHRP Web-Only Document 116* (www.trb.org/news/blurb_detail.asp?id=8714).

APPENDIX B

Recommended Test Methods for CLSM

Introduction

One of the most important outputs of this research project is the recommendation of a suite of tests to measure important CLSM properties. Currently, there are only five ASTM standard test methods and no AASHTO method for testing of CLSM mixtures. Further, some of the existing ASTM test methods may need to be modified to more accurately measure parameters that can better evaluate properties and characteristics of CLSM. In addition, tests currently used to assess CLSM vary significantly from one laboratory or agency to another. This general lack of suitable test methods intended specifically for CLSM was a major concern voiced by state DOTs in the survey distributed as part of NCHRP Project 24-12 and included in the Phase I Interim Report for that project.

This appendix describes a suite of test methods that can be used to measure CLSM properties of interest. Different CLSM applications will often require different CLSM properties to be measured. Only the properties that are deemed important for a given applications should be measured. This appendix represents the recommended test methods (existing, modified, or new) that are capable of measuring a range of CLSM properties.

Recommended Test Methods

Based on the findings from the laboratory and field testing programs, various test methods were identified as being appropriate for evaluating the characteristics and/or properties of CLSM mixtures. These test methods were divided into four groups (A through D), as characterized in the following list and shown in Table B-1.

A. **Existing** test methods that can be used directly to test CLSM properties
B. **Modifications** of existing test methods
C. **New** test methods proposed to evaluate CLSM
D. **Potential** test methods that could be applicable to CLSM but were not studied in enough detail to be recommended as a standard method or were beyond the scope of this study

For the purpose of this report, the tests listed in group A, which are existing methods, are referred to by their test designation (i.e., ASTM D 5971). If these methods are ultimately adopted as-is by AASHTO, it is recommended that a new AASHTO designation replace the existing ASTM designation. Tests shown in groups B and C (modified and new tests, respectively) are referred to throughout this report generically as AASHTO X 1, AASHTO X 2 . . . AASHTO X 10. Table B-1 shows both the temporary AASHTO designation and the ASTM method upon which the modified method was based. It is also recommended that these methods be given an original AASHTO designation if they are eventually adopted by AASHTO. Lastly, tests in group D are referred to in this report by their actual designations (ASTM, AASHTO, or other), except for tests for which no standard test methods exist, which is designated in Table B-1 as "No standard."

Tests shown in group D are methods that the research team believes may have potential as standard CLSM methods, but the methods were either not included in the investigation or were not studied in enough detail to give adequate guidance. For instance, the researchers performed only limited testing using CBR, resilient modulus, and triaxial shear methods. No significant problems were encountered with these methods, and the research team believes they are applicable for CLSM applications. Other examples of test methods that are recommended as potential tests for CLSM, but were either not assessed in detail or not assessed at all are the TCLP test, which was performed on several by-product materials in this project, and the American Nuclear Society leachate test (ANS 16.1), which was not performed on any materials in this study (because the materials all "passed" the TCLP test). Because of the minimal (or no) emphasis placed on these tests, the methods are not currently being proposed for consideration for AASHTO adoption as candidate tests for CLSM. Rather, they are being identified as potential tests, worthy of further evaluation.

Table B.1. Summary of CLSM test methods.

Group	Properties/Characteristics	Test Methods	Descriptions
A	Sampling	ASTM D 5971	Existing standard test methods
	Flow	ASTM D 6103	
B	Setting/hardening	AASHTO X 1 (modified ASTM C 403)	Modifications of existing standard test methods (except as noted). Modifications are described in this appendix.
	Unit weight and air content	AASHTO X 2 (modified ASTM C 231)	
	Compressive strength	AASHTO X 3 (modified ASTM D 4832)	
	pH of CLSM	AASHTO X 4 (modified ASTM G 51)	
	Resistivity	AASHTO X 5 (modified ASTM G 57)	
	Freezing and thawing	AASHTO X 6 (modified ASTM D 560)	
	Water permeability	AASHTO X 7 (modified ASTM D 5084)	
C	Corrosion	AASHTO X 8	Newly proposed (included in this appendix)
	Segregation	AASHTO X 9	
	Subsidence	AASHTO X 10	
D	Suitability for load application (ball drop)	ASTM D 6024	Potential methods for CLSM; Not experimentally studied or more testing needed
	Unit weight, yield, cement content, and air content (gravimetric)*	ASTM D 6023	
	California Bearing Ratio (CBR)	AASHTO T 193	
	Resilient modulus	AASHTO T 292	
	Triaxial shear strength	USACE EM 1110-2-1906	
	Dynamic cone penetrometer	No standard	
	Drying shrinkage	No standard	
	Direct shear*	ASTM D 3080	
	Thermal conductivity*	ASTM D 5334	
	Consolidation*	ASTM D 2435	
	Air/gas permeability*	ASTM D 4525	
	Total heavy metals in CLSM	EPA Method 610	
	Toxicity Characteristic Leaching Procedure (TCLP)	EPA Method 1311	
	Leachate test	ANS 16.1	

* Test methods not experimentally studied in research program

Group A Test Methods

Test methods in group A are recommended to be adopted by AASHTO directly from existing ASTM standard test methods. ASTM D 5971, “Standard Practice for Sampling Freshly Mixed Controlled Low-Strength Material,” specifies a procedure for obtaining a representative sample of freshly mixed CLSM for testing as delivered to the project site. This method was employed in the field testing program.

ASTM D 6103, “Standard Test Method for Flow Consistency of Controlled Low Strength Material (CLSM),” was used extensively throughout the project, and the results indicate that this method is applicable and provides a relative value for CLSM flow.

Group B Test Methods

Test methods in group B are existing standards that have been modified specifically for use with CLSM mixtures. The research team evaluated these methods, and necessary modifications were made to accomplish objective results for testing of CLSM mixtures. Following the same procedure used by AASHTO, modifications were made for each test. The format consists of a brief modification, in which the deletions, substitutions, or additions are highlighted, along with their section number within the existing method. This modification page would typically be followed by the standard test upon which it was based. For this report, the brief modifications are provided without the existing standard methods. The method proposed to measure the pH of CLSM was based in part on a similar ASTM method (ASTM G 51) but was modified for this research and written as a new method in AASHTO format. It is included in this group because it is a modified method, but it is written as a new method because of the substantial changes made to the method.

The modifications proposed for each test are provided next, proceeded by a brief discussion on the rationale for the modification(s) for each method.

Setting/Hardening

Both a standard needle penetrometer (ASTM C 403) and soil pocket penetrometer were investigated as part of the laboratory and field programs. Slight modifications to the needle penetrometer test are recommended, as described next.

Provisional Method of Test for

Setting and Hardening of Controlled Low Strength Material (CLSM) by Penetration Resistance

AASHTO Designation: X 1 (2008)
ASTM Designation: C 403/C 403M-95

AASHTO X 1 (2008) is identical to ASTM C 403/C 403M-95 except the following:

1. The word "concrete" or "mortar" shall be changed to "CLSM."
2. Sieving of CLSM is not necessary and does not need to be performed.
3. The times of initial and final setting are not determined in this procedure.
4. Practice ASTM C 173 shall be replaced by AASHTO X 2.
5. Add new Section 6.7 to ASTM C 403/C 403M to read as follows:
   "6.7 *Soil pocket penetrometer*—The soil pocket penetrometer is a device used to estimate the unconfined compressive strength of cohesive soil in the field. The accuracy is at least 0.5 kgf/cm^2. The penetration depth is approximately 6.3 mm."
6. No consolidation of CLSM mixture, as stated in Section 7.7, is needed.
7. Change Section 8.2 of ASTM C 403/C 403M to the following:
   "for determination of applying consequent constructions or opening to traffic, suitable field penetration apparatus shall be used (note).
   NOTE—Caution shall be taken when using long needles that may break during use."
8. Change the title of Section 9 of ASTM C 403/C 403M to the following:
   "**9 Procedure A**"
9. Add one sentence before the first sentence of Section 9.2 of ASTM C 403/C 403M as follows:
   "Penetration needles described in Section 6.2 shall be used."
10. The procedure in Section 9.3 of ASTM C 403/C 403M shall not be performed. The penetration resistance values of 500 psi and 4000 psi shall not be used for judgment of initial and final setting.
11. Change Section 9.5 of ASTM C 403/C 403M to the following:
    "Make at least six penetrations for each time of setting test with time intervals of such duration of 22 to 26 hours."
12. Change Section 10 of ASTM C 403/C 403M to the following:
    "**10 Procedure B**
    10.1 The same procedure as in Procedure A should be followed, except for the use of a different apparatus.
    10.2 The penetration depth is approximately 6.3 mm. Caution shall be taken to eliminate the influence of water and fines, which typically gather on the mixture surface because of bleeding and segregation, on the penetration depth reading.
    10.3 Shorter time intervals may be used than those specified in Procedure A as a result of shallower penetration."
13. Change Section 11.2.3 of ASTM C 403/C 403M to the following:
    "The penetration resistance values from Procedure A can be used to estimate the ultimate bearing capacity of hardening CLSM. The unconfined compressive strength values can be used to determine the opening to traffic or consequent operations."
14. Change Section 12 of ASTM C 403/C 403M to the following:
    "Precision and Bias are not currently available."

Air Content (Pressure Method)

Although there is an existing ASTM standard (D 6023, "Standard Test Method for Unit Weight, Yield, Cement Content, and Air Content (Gravimetric) of Controlled Low Strength Material (CLSM)"), the research team concluded from the laboratory testing phase that a method for evaluating the air content of CLSM using a pressure method approach is necessary. The proposed method is explained in the following paragraph.

A significant degree of technical difficulty occurs when ASTM D 6023 is used for CLSM mixtures. CLSM mixtures often include by-product and off-spec materials as mixture constituents. The physical properties, such as the specific gravity, of these materials are often difficult to measure, and variations in the physical properties are expected for some raw materials. Because calculations for determining the air content of CLSM require physical property values of the constituent materials, determining the air content following ASTM D 6023 is not practical for use as a quality control measure in the field. Thus, an alternative method using the pressure approach is proposed. This method is a modification of ASTM C 231 and was used throughout this research project.

Provisional Method of Test for

Air Content of Freshly Mixed Controlled Low-Strength Material (CLSM) by the Pressure Method

AASHTO Designation: X 2 (2008)
ASTM Designation: C 231-97

AASHTO X 2 (2008) is identical to ASTM C 231-97 except for the following:

1. Change Section 1.4 of ASTM C 231-97 to the following:
   "The values stated in SI units are to be regarded as the standard."
2. Change Section 7.1 of ASTM C 231-97 to the following:
   "Obtain the sample of freshly mixed CLSM mixture in accordance with applicable procedures of ASTM D 5971."
3. Change Section 8.1.1 to 8.1.3 of ASTM C 231-97 to the following:
   "Dampen the interior of the measuring bowl and place it on a flat, level, firm surface. Place a representative sample of the CLSM, prepared as described in ASTM D 5971, in the measuring bowl until it is completely full."

Compressive Strength

ASTM D 4832, "Standard Test Method for Preparation and Testing of Controlled Low Strength Material (CLSM) Test Cylinders," is often specified and used by researchers and engineers. But, as discussed in Chapter 3, some modifications are needed to measure compressive strength of CLSM specimens accurately and in a repeatable manner.

Provisional Method of Test for

Preparation and Testing of Controlled Low Strength Material (CLSM) Test Cylinders

AASHTO Designation: X 3 (2008)
ASTM Designation: D 4832-95

AASHTO X 3 (2008) is identical to ASTM D 4832-95 except for the following:

1. Change the last sentence of Section 5.3 of ASTM D 4832-95 to the following:
   "Other tests that can be used during construction for quality control of CLSM are Test Methods X 1, X 2, and X 3."
2. Change Section 6.1 of ASTM D 4832-95 to the following:
   "6.1 *Single-Use Cylindrical Molds*—Plastic single-use molds with the length to diameter ratio of 2 to 1 and with tight-fitting lids, conforming to ASTM C 470. Other sizes and types of molds may be used as long as the length to diameter ratio is 2. The plastic molds may be prepared by cutting the opposite sides from top to bottom and then using tape to bind the mold back to its original shape."
3. Change Section 6.2 of ASTM D 4832-95 to the following:
   "6.2 *Sampling and Mixing Receptacle*—The receptacle shall be a suitable heavy-gage container, wheelbarrow, etc. of sufficient capacity to allow easy sampling and mixing and to allow preparation of at least three cylinders and for other tests such as described in Test Methods X 1, X 2, and X 3."
4. Change Section 6.3 of ASTM D 4832-95 to the following:
   "6.3 *Testing Machine*—The testing machine shall meet the requirements as described in AASHTO T 22-97 or T 208-96."
5. Add the following note after Section 7.2.2 of ASTM D 4832-95:
   "Note: Lightly rotating the solidified sulfur cap from the CLSM samples is a suitable approach to release the sulfur cap from the capping plate."
6. Change the first sentence of Section 10.1 of ASTM D 4832-95 to the following:
   "After seven days of curing, the specimen shall be removed from the mold. Careful attention shall be paid such that specimens are not damaged. If leaching of hydration products from CLSM specimens is a potential problem, cylinders shall not be stripped until the day of testing. The samples should be kept moist until the time of testing. No drying time before testing is required."

7. Add the following note after Section 10.1.3 of ASTM D 4832-95:
   "Only elastomeric pads with a Shore A durometer hardness of 50 or less shall be used for testing CLSM cylinders. The pad material is not limited to neoprene type."
8. Change the second sentence of Section 11.2 of ASTM D 4832-95 to the following:
   "When a testing machine meeting requirements as described in AASHTO T 22-97 is used, apply the load at a constant rate such that the cylinder will fail in not less than 2 min. When a testing machine meeting requirements as described in AASHTO T 208-96 is used, apply the displacement at a constant rate of 0.25 to 0.64 mm/min."

Measuring pH values of CLSM

The pH of CLSM is one parameter used to evaluate the corrosion susceptibility of metal samples embedded in soil or CLSM. ASTM G 51, "Standard Test Method for Measuring pH of Soil for Use in Corrosion Testing," is the test method typically used for evaluating the pH of soils. Because CLSM requires special crushing prior to testing, a modified version of ASTM G 51 has been developed. The proposed AASHTO X 4 (2004) is a new method, mainly based on ASTM G 51.

Provisional Method of Test for

Measuring pH of Controlled Low Strength Material (CLSM) for Use in Corrosion Testing

AASHTO DESIGNATION: X 4 (2008)
ASTM Designation: ASTM G 51-95

1 Scope

1.1 This test method covers a procedure for determining the pH of a CLSM mixture for corrosion testing. The principal use of the method is to supplement other CLSM characteristics (resistivity, chloride concentration, etc.) to identify conditions under which the corrosion of metals embedded in CLSM may be accentuated.

1.2 This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.

2 Referenced Documents

2.1 *ASTM Standard*

A 674, "Standard Practice for Polyethylene Encasement for Ductile Iron Pipe for Water or Other Liquids"
E 177, "Practice for Use of the Terms Precision and Bias in ASTM Test Methods"
E 691, "Practice for Conducting an Interlaboratory Study to Determine the Precision of a Test Method"
G 57, "Standard Method for Field Measurement of Soil Resistivity Using the Wenner Four-Electrode Method"

2.2 *Other Standards*

ANSI/AWWA C 105/21.5 American National Standard for Polyethylene Encasement for Ductile Iron Pipe for Water or Other Liquids

3 Significance and Use

3.1 Information on the pH of CLSM can be used as an aid in evaluating the potential corrosivity of pipe in a CLSM mixture environment.

4 Apparatus

4.1 *pH Meter*—A portable, battery-powered pH meter is necessary for field measurements. Most instruments can also function as a high-impedance voltmeter. An LCD display is preferred for readability in a bright, outdoor environment. A portable or benchtop model can be used for laboratory determination of the pH.

4.2 *Calomel and Glass Electrodes*

4.2.1 Use a saturated calomel reference electrode or its equivalent to determine the pH of a CLSM. A few crystals of solid potassium chloride should always be present within the chamber surrounding the calomel to assure that the solution is saturated under the conditions of use. The design of the electrode must permit the formation of a fresh liquid junction between the solution of potassium chloride and the buffer or test specimen for each test and allow traces of the CLSM to be readily removed by washing.

4.2.2 A glass electrode of rugged construction is required. The performance of the glass electrode is satisfactory if it furnishes the correct pH value (± 0.1 pH unit) for standard buffered solutions.

4.2.3 A combination electrode consisting of a saturated calomel reference electrode and a glass electrode (4.2.1 and 4.2.2) combined as a single electrode is acceptable. However, the requirements outlined above are equally applicable to the electrodes used in this combination unit.

4.3 *Temperature Compensation*—Some pH electrodes have temperature compensation built in as part of the pH electrode. A thermometer of rugged construction is required if temperature compensation is not available as part of the pH electrode system. A stainless steel sheathed thermometer is preferred.

5 Reagents and Materials

5.1 During the calibration procedure for the pH meter, standard buffered solutions of known pH are necessary. These solutions, or tablets to make up these solutions, can be purchased from chemical supply companies or pH equipment manufacturers.

6 Sampling

6.1 By the nature of the measurement, pH is determined for a small volume of CLSM pore solution. Thus, it is important that at least three measurements from three different samples with the same mixture constituents and proportions and from the same batch be obtained and a simple average calculated.

7 Calibration and Standardization

7.1 *Test for Linearity*—Prior to field use, or periodically when used extensively in the field, test the pH measuring apparatus for linearity of response. This procedure is as follows:

7.1.1 Turn on the instrument, allow it to warm up thoroughly, and bring it to electrical balance in accordance with the manufacturer's instructions. Before use, clean and rinse the glass and calomel electrodes in distilled water.

7.1.2 At least two standard buffered pH solutions that span the anticipated CLSM pH to be measured are required. From practical experience, standard solutions of pH 4, 7, and 8 are recommended. For the test, the temperature of these solutions shall not differ from each other by more than 5°C. A laboratory thermometer can be used for these measurements.

7.1.3 Adjust the temperature-compensating dial on the pH meter to the standard solution temperature.

7.1.4 Immerse the electrodes in a small volume of the first known standard solution. Now adjust the pH meter to read this known pH.

7.1.5 Remove the electrodes from the first standard solution, and rinse in distilled water. Immerse the electrodes in the second known standard solution and read the pH value. Judge the system to be operating satisfactorily if the reading obtained for the second standard agrees within +/− 0.1 unit of the assigned pH.

7.2 *Calibration of pH Meter*—Calibrate the pH meter immediately before use. If a series of measurements are to be made, repeat the calibration procedure at intervals of about 30 min. Perform the pH meter calibration as follows:

7.2.1 Use a standard pH solution in the range of the pH of the CLSM to be tested, if such information is known beforehand. Otherwise, begin with a standard solution having a pH of 7. Stabilize the temperature of the solution so that it matches the temperature of the CLSM to within 10°C.

7.2.2 Immerse the electrodes in the known standard solution and calibrate the meter in accordance with the manufacturer's instructions.

8 Procedure

8.1 *Preparation for pH Determination of CLSM*

8.1.1 For evaluating the pH of in-place CLSM, the pH measurement should be made in the field with the glass electrode contacting the CLSM at the specific depth of interest. If the surface CLSM pH is desired, then the CLSM can be broken up so as to accept the electrodes. Existing loose material on the surface shall be removed from the surface and shall not be used for evaluating the pH. If a subsurface pH is desired, then a boring or an excavation must be done so that the electrode can be placed in the CLSM at the desired depth. After boring through the CLSM to the depth of interest, carefully break up the material at the desired reading depth with the boring tip. Then lower the probe into the cavity for testing.

8.1.2 The crushed CLSM sample can be brought to the surface with a boring tool or a post-hole digger, and the measurement made in the field on the CLSM obtained.

8.1.3 The least desirable pH measurement of CLSM is that which is based on a CLSM sample transported to a laboratory for evaluation. However, if the pH must be measured in the laboratory, then make the pH measurement as quickly as possible after the CLSM sample is taken from the field. Place the sample in a clean, airtight glass container or plastic bag so that the CLSM is not in contact with any metal. If the pH measurement is not made within 24 hours from the time the sample is obtained in the field, then it is recommended that the sample be packed in dry ice to retard any change in pH due to chemical or biological reactions. Make the pH measurement on the CLSM at room temperature and as received.

8.1.3.1 Depending on the moisture content of the sample, some water may have to be added to the sample obtained in the field.

8.1.3.2 If the CLSM sample is frozen, it must be allowed to thaw prior to making the measurement.

8.2 *Determination of pH of CLSM*

8.2.1 Complete the meter calibration procedure (7.2). The standard solution temperature must match the temperature of the CLSM within 10°C. The temperature of the CLSM can be determined by inserting a metal-sheathed thermometer into the crushed CLSM to the depth of interest.

8.2.2 Clean the electrode surface by washing it with distilled water.

8.2.3 Press the contact area of the glass electrode or combination electrode, as the case may be, against the CLSM at the location of interest. This step is important since poor contact or electrode movement can affect the stability of the measurement.

8.2.4 The reference electrode should be placed in contact with the crushed CLSM near the glass electrode (this step is not required when using a combination electrode). An electrode separation of about 300 mm (1 ft) is suggested for surface measurements. For subsurface readings, the reference electrode may be placed on the surface about 300 mm from the bore hole entry.

8.2.5 With the electrode(s) in place, set the meter to read pH, allowing 1 or 2 minutes for equilibrium to be established, then take the meter reading.

8.2.6 After approximately 1 min, repeat the reading. In general, the values will agree within 0.2 pH units. If the range of values is as large as 0.4, then repeat 8.1.1 and, if necessary, Section 7. If the problem persists, check your equipment to verify that it is operating properly, and check your measurement technique as described in Procedure, Section 8, in this test method.

9 Laboratory Procedure

9.1 Samples tested in the laboratory shall be crushed and placed in a non-conductive container. If the CLSM sample is dry, some water may be required to obtain a stable pH reading.

9.2 Follow the procedures outlined in sections 8.2.1, 8.2.2, 8.2.3, 8.2.5, and 8.2.6.

10 Keywords

10.1 corrosion of metals in CLSM, pH of CLSM, measurement of pH, test method for CLSM pH, field measurement of pH, CLSM pH for corrosion testing, underground corrosion.

Measuring Resistivity of CLSM Specimens

The resistivity is another parameter that may be used to evaluate the corrosion susceptibility of metal samples embedded in soil or CLSM. ASTM G 57, "Standard Test Method for Field Measurement of Soil Resistivity Using the Wenner Four-Electrode Method," is an adequate test method to evaluate the resistivity of CLSM. The only proposed change is to change all references to the soil from "soil" to "soil and CLSM."

Provisional Method of Test for

Field Measurement of Soil and Controlled Low-Strength Material (CLSM) Resistivity Using the Wenner Four-Electrode Method

AASHTO Designation: X 5 (2008)
ASTM Designation: G 57-95a

AASHTO X 5 (2008) is identical to ASTM G 57 except for the following:

1. Change the word "soil" to "soil and CLSM" throughout the test method.

Freezing and Thawing Testing

Because of the similarity of CLSM and compacted soil-cement mixtures, ASTM D 560, "Standard Test Methods for Freezing and Thawing Compacted Soil-Cement Mixtures," only requires slight modifications to estimate the behavior of CLSM specimens under freezing and thawing cycles. The research team proposes that ASTM D 560 be modified for evaluating the relative performance of CLSM when exposed to freezing and thawing cycles.

Provisional Method of Test for

Freezing and Thawing CLSM Mixtures

AASHTO Designation: X 6 (2008)
ASTM Designation: D 560-96

AASHTO X 6 (2008) is identical to ASTM D 560-96 except for the following:

1. Change Sections 4.1, 4.2, 4.3, 4.8, 4.10, 4.11, 4.12, 4.13, and 4.18 of ASTM D 560-96 to the following:
   "*Specimen*—Cylindrical CLSM specimens with a diameter of 102 mm and a height of 102 to 127 mm should be used in this testing."
2. Change title of Section 5 of ASTM D 560-96 to the following:
   "**Procedure**"
3. Change Sections 5.1 and 5.2 of ASTM D 560-96 to the following:
   "*Sampling*—Prepare specimens of size described in Section 4.1."
4. Change Section 5.3.1 of ASTM D 560-96 to the following:
   "At the end of the storage (7 days or 28 days) in the . . . and remove."
5. Change last sentence of Section 5.3.2 of ASTM D 560-96 to the following:
   "Weigh the specimen."
6. Ignore Sections 5.3.3 and 5.3.4 of ASTM D 560-96.
7. Ignore Note 4 of 560-96.
8. Ignore Section 5.3.6 ASTM D 560-96.
9. Ignore Section 5.3.8 ASTM D 560-96.
10. Ignore Section 6 of ASTM D 560-96.
11. Ignore Sections 7.1.1 to 7.1.3 of ASTM D 560-96.
12. Ignore Section 9 of ASTM D 560-96.

Water Permeability

Even though water permeability testing was performed for only six CLSM mixtures, the method was deemed to be applicable and the values obtained were compatible with those found in the literature. Thus, ASTM D 5084 is being recommended for adoption by AASHTO. When using this method, the typical practice of checking the B value (e.g., $B > 0.95$) for saturation is not applicable or recommended because CLSM specimens are usually stronger and less compressible than soil samples and act more like rock cores, where the B values may remain nearly unchanged after applications of high back pressures. The proposed recommended test method is presented below in AASHTO format.

Provisional Method of Test for

Measurement of Hydraulic Conductivity of Saturated CLSM Mixtures Using a Flexible Wall Permeameter

AASHTO Designation: X 7 (2008)
ASTM Designation: D 5084-96

AASHTO X 7 (2004) is identical to ASTM D 5084-96 except for the following:

1. Change Note 8 of Section 8.3.3.1 of ASTM D 5084-96 to the following:
   "Note 8—The *B* coefficient is defined for this type of test as the change in pore water pressure in the porous material divided by the change in confining pressure. Because CLSM is relatively incompressible, saturated materials have *B* values that are somewhat less than 1.0. The specimen is deemed as sufficiently saturated if the *B* values remain nearly unchanged with changes in confining pressure."

Group C Test Methods

The research conducted in this project resulted in the development of three new provisional test methods that can be used to evaluate CLSM. These methods, referred to by their temporary AASHTO designations, are listed below:

- AASHTO X 8, "Evaluating the Corrosion Performance of Samples Embedded in Controlled Low-Strength Material (CLSM) via Mass Loss Testing"
- AASHTO X 9, "Determining the Potential for Segregation in Controlled Low-Strength Material (CLSM) Mixtures"
- AASHTO X 10, "Evaluating the Subsidence of Controlled Low-Strength Material (CLSM) Mixtures"

Provisional Method of Test for

Evaluating the Corrosion Performance of Samples Embedded in Controlled Low Strength Material (CLSM) via Mass Loss Testing

AASHTO Designation: X 8 (2008).

1 Scope

1.1 This test method covers a procedure for determining the performance of metallic samples embedded in CLSM mixtures.

1.2 This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.

2 Referenced Documents

2.1 *ASTM Standards*

G 1, "Standard Practice for Preparing, Cleaning, and Evaluating Corrosion Test Specimens"
D 4832, "Standard Test Method for Preparation and Testing of Controlled Low Strength Material (CLSM) Test Cylinders"
C 192, "Standard Practice for Making and Curing Concrete Test Specimens in the Laboratory"
C 496, "Standard Test Method for Splitting Tensile Strength of Cylindrical Concrete Specimens"

2.2 *Other Standards*

3 Significance and Use

3.1 The environment in which the metallic sample is exposed directly impacts underground corrosion of metallic samples. This test method provides a method to compare the corrosion performance of metallic samples embedded in CLSM. A control sample made with locally available soil materials can be fabricated and tested for comparative purposes.

4 Apparatus

4.1 *Metallic Coupons*

4.1.1 The intent of this test is to determine the influence of the surrounding materials (i.e., different CLSM mixtures or soil) and environment on the corrosion performance of metallic coupons embedded in them. When comparing the influence of surrounding materials, metallic coupons shall be obtained from the same lot of material.

4.1.2 Metallic coupons shall be approximately 13 mm by 25 mm. The thickness of the coupon will depend on the type of metallic material.

4.1.3 A 2 mm hole shall be drilled through the coupon within 5 mm of the shorter edge and at the midpoint between the long edges.

4.1.4 The metallic coupons shall be cleaned and weighed (following ASTM G 1 test procedures) prior to placement into the CLSM (or control sample).

4.2 *Mold*

4.2.1 A single-use plastic cylindrical mold shall be used.

4.2.2 The mold shall be cut on opposite sides along the longitudinal axis from the top opening of the mold to the bottom of the mold. Do not cut the bottom of the mold.

4.2.3 Carefully align the mold back into its original shape and place tape around the outer cylinder circumference to hold the cylinder in its original shape. Additional tape may have to be placed along the cut lines to prevent leakage during casting.

4.3 *Sewing Thread*—Heavy-duty sewing thread will be used to suspend the coupons in the plastic cylindrical molds prior to testing. Threads shall be cut into lengths of approximately 200 mm.

4.4 *Testing Machine*—The testing machine shall conform to the specifications of ASTM C 39.

4.5 *Holding Tank*—The holding tank shall be non-metallic and shall be large enough to expose all samples from the study at the same time. The sides of the holding tank shall be high enough to ensure proper exposure conditions.

5 Reagents and Materials

5.1 Depending on the exposure conditions, several different types of chemicals may be used. Calcium chloride has been used to mimic chloride-containing soils.

6 Sampling

6.1 A minimum of three samples shall be cast per coupon type.

7 Sample Preparation

7.1 Suspend the metallic coupons in the plastic molds as shown in Figure B.1. Ensure that a cover of 38 mm is obtained (from the top of the metallic coupon to the top of the cylinder). The mass of the metallic coupons should be marked on the outer surface of the cylinder.

7.2 Mixing of the CLSM shall be performed according to ASTM D 4832.

7.3 Place the CLSM (or soil) into the mold, being careful to not move the metallic coupon from the center of the plastic mold. Corrosion performance may be dependent on the amount of cover and can significantly influence the corrosion susceptibility of the metallic coupon.

7.4 Follow the recommended procedure in ASTM C 192 to cure the samples immediately after casting. Soil samples do not require curing.

7.5 If sand or other soil types are being used as a control, approximately 25 holes shall be drilled around the perimeter of the plastic mold to ensure exposure of the soil to the solution environment. Holes should be covered with a semi-permeable material to allow solution to pass and to keep the soil in the mold.

8 Cylinder Exposure

8.1 After curing, remove the tape from the outside of the plastic mold and carefully separate the mold from the CLSM sample.

8.2 Place the sample into the test solution, ensuring that the solution depth is 100 mm (50 mm of exposed sample). This depth shall be maintained throughout the test period.

8.3 All samples being compared shall be placed in the same holding tank container to ensure similar exposure conditions and solutions.

8.4 Samples shall be exposed for a minimum of 180 days. Longer exposure periods are allowable, but all samples shall be evaluated for mass loss at the same exposure time.

9 Mass Loss Testing

9.1 After the exposure period has elapsed, the coupons can be removed from the CLSM by placing the CLSM specimen in a testing machine and loading similar to ASTM C 496.

9.2 Follow ASTM G 1 to clean the sample and obtain the mass loss.

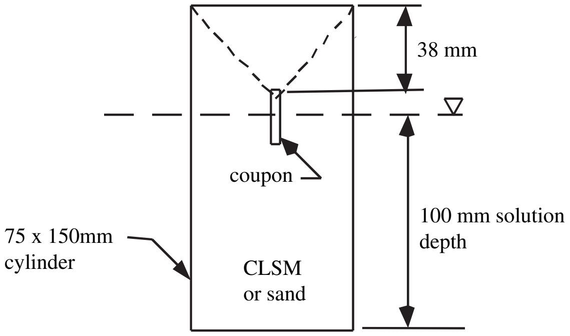


Figure B.1. Sample layout.

10 Reporting

10.1 Report the mass loss as a percentage of the original weight of the metallic coupon. The percent mass loss can be determined as follows:

$$Percent\ Mass\ Loss = \frac{M_{original} - M_{corroded}}{M_{original}} \cdot 100$$

where $M_{original}$ = the mass of the metallic coupon prior to embedment into the CLSM or soil sample.
$M_{corroded}$ = the mass of the metallic coupon after removal from the CLSM or soil sample.

NOTE—Corrosion damage may also be reported as corrosion rate by using the mass loss and the conversion formula provided in ASTM G 1.

10.2 Comparisons shall be made between the mass loss (corrosion rate) of the metallic coupon embedded in soil (the control sample) and between the coupons embedded in CLSM.

NOTE—In case galvanic corrosion of the metallic material is expected due to exposure of the metal partly to the tested CLSM mixture and partly to a soil, average percent mass loss of the metallic material exposed to soil should be expected to be approximately 25 and 35 times higher than the measured average percent mass loss for sands and clays, respectively.

11 Keywords

11.1 corrosion, CLSM.

Provisional Method of Test for

Determining the Potential for Segregation in Controlled Low-Strength Material (CLSM) Mixtures

AASHTO Designation: X 9 (2008)

1 Scope

1.1 This test method covers a procedure for determining the susceptibility of a CLSM mixture to segregate during hardening.

1.2 This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.

2 Referenced Documents

2.1 *ASTM Standards*
C 136, "Standard Test Method for Sieve Analysis of Fine and Coarse Aggregates"
D 4832, "Standard Test Method for Preparation and Testing of Controlled Low Strength Material (CLSM) Test Cylinders"

3 Significance and Use

3.1 Information on the potential segregation of CLSM mixtures can be determined. Segregation of CLSM may result in nonuniform properties and characteristics. It is not the objective of this proposed standard that all CLSM mixtures be tested for segregation. If unique requirements or materials are needed, segregation testing may be necessary.

4 Apparatus

4.1 *Segregation Mold*—A mold, as shown in Figure B.2, shall be used to determine the degree of segregation of CLSM mixtures.

4.2 *Tamping Rod*—A round, straight 10 mm diameter steel rod, 300 mm in length and having both ends rounded to a hemispherical tip of radius 5 mm.

4.3 A set of aggregate sieves, including sizes 9.5 mm, No. 4 (4.75 mm), No. 8 (2.36 mm), No. 16 (1.18 mm), No. 30 (600 µm), No. 50 (300 µm), and No. 100 (150 µm). If an aggregate with a maximum aggregate size (MAS) larger than 9.5 mm is used, include all sieves as specified in ASTM C 136 up to a size that is one size larger that the MAS for the mixture.

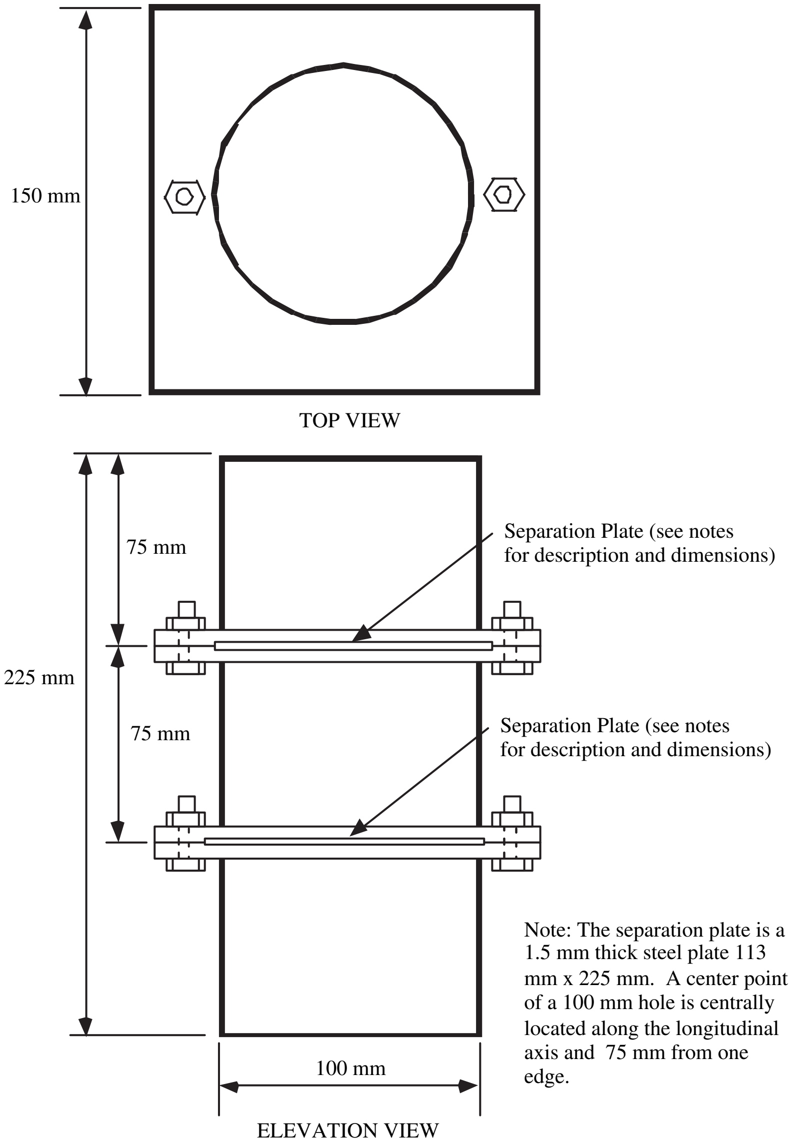


Figure B.2. Segregation mold.

5 Procedure

5.1 Both segregation plates on the segregation mold shall be placed such that the 100 mm hole is aligned with the inside diameter of the mold.

5.2 CLSM segregation samples shall be prepared following Sections 9.1 and 9.2 of ASTM D 4832.

5.3 Approximately 20 minutes prior to the initial set or 2 hours after placement (whichever is sooner), the segregation mold shall be separated into thirds. Force the segregation plates into and through the sample. Special care shall be taken that no material is lost during mold separation.

5.4 Order the sieves from maximum size on top to minimum size on bottom. The smallest sized sieve in the set shall be a No. 100 sieve.

5.5 Extract the fresh CLSM from the upper third of the mold into the maximum sized sieve. Ensure that all aggregate and paste is removed from the segregation mold by gently washing the sides of the mold into the sieve stack.

5.6 Continue to place water onto the CLSM in the upper sieve. After the aggregates have been washed and no additional aggregates are being washed through the top sieve, carefully remove the top sieve and its contents and begin placing water on the CLSM in the next sieve. Ensure that all aggregates are clean at this level and continue this process for each successive sieve. Care shall be taken to not spill any aggregate from the cleaned aggregates in the sieves. In addition, care shall be taken to not overload one sieve such that large amounts of aggregate and water are retained on the sieve. If too much aggregate is retained on one sieve, the washing water will overflow and material will be lost. To avoid such overflow, separate sieves intermittently and inspect for possible backup. If the aggregate and cement are inhibiting the flow of water through the sieve, remove the sieve and re-establish flow.

5.7 After all aggregate on each sieve has been cleaned, dry the aggregates and perform a sieve analysis for the upper third, center third, and lower third of the segregation mold.

6 Analysis

6.1 Plot the sieve analysis from CLSM retained in the upper, middle, and lower one-third of the segregation mold. The percentage retained (or passed) for each mold section can then be compared.

6.2 No recommendations are available yet on the potential change in material properties and/or characteristics resulting from segregation of CLSM.

7 Keywords

7.1 segregation, CLSM, sieve, mold.

Provisional Method of Test for

Evaluating the Subsidence of Controlled Low-Strength Materials (CLSM)

AASHTO Designation: X 10 (2008)

1 Scope

1.1 This test method covers a procedure for determining the subsidence of CLSM mixtures.

1.2 This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.

2 Referenced Documents

2.1 *ASTM Standards*
D 4832, “Standard Test Method for Preparation and Testing of Controlled Low Strength Material (CLSM) Test Cylinders”

3 Significance and Use

3.1 Subsidence of CLSM occurs when the fresh CLSM mixture loses water and entrapped air through bleeding and absorption into the surrounding soil. Significant subsidence may require additional labor and materials to offset its effects. Also, knowing the subsidence of a CLSM mixture can assist the contractor in placing the fresh CLSM such that after setting (i.e., after the subsidence has taken place), the material will be at the final required grade.

4 Apparatus

4.1 *Subsidence Mold*—The subsidence mold shall be a 100 mm diameter by 600 mm tall plastic cylinder. The cylinder shall be discarded after one use.

4.2 *Subsidence Gage*—The subsidence gage is used to measure the drop in the CLSM surface with respect to the top of the cylinder. Figure B.3 shows the subsidence gage.

5 Sample Preparation and Testing

5.1 Mix and cast the CLSM as specified in ASTM D 4832.

5.2 Immediately after filling the cylinder, strike off excess CLSM from the surface to obtain a flat even surface.

5.3 Prior to testing, place the gage on a flat surface and measure the distance, d_1, from the tip of the gage to the inside bottom of the subsidence gage.

5.4 Wait 15 minutes and place the subsidence gage on the top of the cylinder. Release the knurled nut and gently lower the pin to the surface of the CLSM. Tighten the knurled nut and measure the distance from the tip of the pin to the inside bottom of the subsidence gage, d_n, where n is the measurement number.

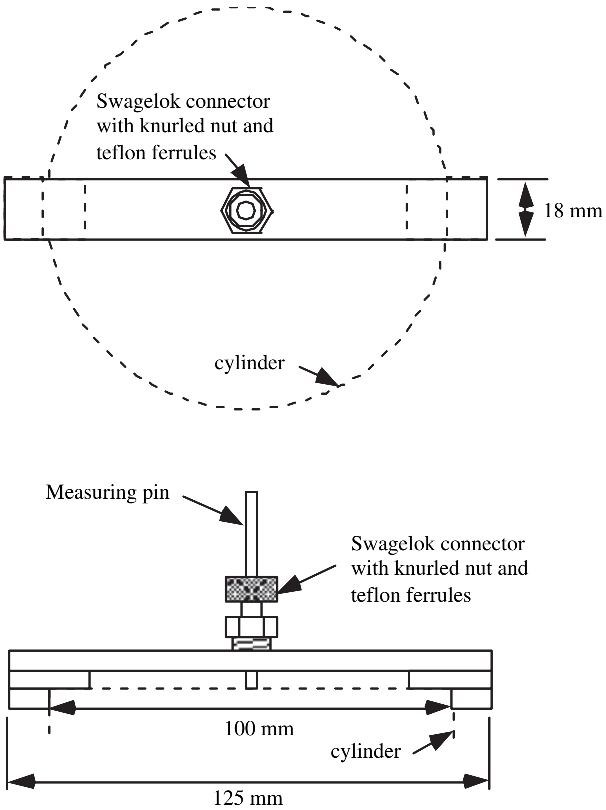


Figure B.3. Subsidence gage layout.

5.5 Measurements shall be made near the center of the sample away from the edges. Where heavy bleeding occurs, the bleed water shall be removed from the top surface using a large-tip transfer pipette prior to measurement. Maintain a record of the time after mixing.

5.6 Evaluate the sample every 15 minutes as discussed in Sections 5.4 and 5.5 until the sample has reached initial set.

6 Reporting

6.1 Report the maximum value of subsidence as follows:

$$\text{Subsidence} = \frac{d_n - d_1}{0.6 \text{ meters}}$$

Report the subsidence value with the mixture designation and mixture proportions.

7 Keywords

7.1 subsidence, CLSM.

Group D Test Methods

As previously mentioned, inclusion in this group does not indicate that these test methods are not important. Rather, such inclusion indicates only that these test methods were not investigated in this research project and/or more detailed research is needed before they can be adopted as AASHTO methods. The following subsections briefly discuss each method.

Suitability for Load Application

ASTM D 6024, “Standard Test Method for Ball Drop on Controlled Low Strength Material (CLSM) to Determine Suitability for Load Application,” has been used to some extent in CLSM construction. As this method is for field practice, it was not evaluated as part of the laboratory testing program. For many applications, determining the suitability of load applications is essential and will be included as part of the field testing plan. The research team attempted to correlate the diameter of indentation of ball drop with penetration values for different CLSM mixtures in selected field tests but was not successful. The influence of surface bleed water deserves additional attention to determine if it affects subsequent measurements. Field tests showed that this method was too demanding for CLSM mixtures to meet the 76 mm dent diameter requirement. Instead, a dent diameter of 90 mm was deemed acceptable.

Unit Weight, Yield, Cement Content, and Air Content

ASTM D 6023, "Standard Test Method for Unit Weight, Yield, Cement Content, and Air Content (Gravimetric) of Controlled Low Strength Material (CLSM)," was not incorporated into the laboratory testing program. Because of the complex calculations involved and the potential lack of desired inputs and values (e.g., specific gravity), the method is not likely to be adopted as an AASHTO method. Interested practitioners may use it as a check for the proposed pressure method, AASHTO X 2.

California Bearing Ratio

Specimens from only six CLSM mixtures were tested for CBR values at the age of 28 days according to slightly modified AASHTO test method T 193. In general, the test method was performed without difficulty. However, because CLSM mixtures are generally much stronger than soil, more research is needed to verify the suitability of this test method. Interested parties may refer to the testing and preliminary findings described in Chapter 3 of this report.

Resilient Modulus

AASHTO T 292, "Resilient Modulus of Subgrade Soils and Untreated Base/Subbase Materials," was used to evaluate six CLSM specimens. Because of the limited amount of testing, future research is needed to draw conclusions from this testing.

Triaxial Shear Strength

A testing procedure from the U.S. Army Corps of Engineers, EM 1110-2-1906, was used in this study to determine the cohesion and internal friction angles of six CLSM mixtures. This procedure was determined to be feasible for evaluating the triaxial properties of CLSM mixtures tested in the laboratory program, but its limited inclusion in the testing program makes recommending it as a standard test method difficult. The researchers expect this method, along with possibly CBR and resilient modulus test methods, may eventually be recommended for adoption by AASHTO.

Dynamic Cone Penetrometer

The dynamic cone penetrometer (DCP) was used in this project to estimate the excavatability of CLSM mixtures and appears to show promise for this application. The DCP is a modified and simplified version of the penetrometer used by the Country Roads Board, Victoria, Australia. It is used by geotechnical engineers to obtain an index of in-situ CBR and to estimate the strength of soil as a function of depth. The testing consists of dropping a hammer (8 kg in weight) from a height of 575 mm, which forces a steel rod with conical head into the CLSM or soil. The penetration depth per blow was recorded. The corresponding DCP index value can be used to estimate a soil strength value (CBR).

Drying Shrinkage

This test method was used to evaluate the drying shrinkage of CLSM mixtures and was adopted from European practice. The molds for this testing were specially made for this project and knowledge of this test method is limited within the United States. As a result of the lack of availability of the test molds and the lack of experience with this method, this method is not recommended for further testing. Interested readers may refer to Katz et al. (2002) for more information on this topic. Their research demonstrated the significant effect of the fineness, shape, surface structure, and relative content of the waste (e.g., dust from cement kiln and asphalt plants) on the volume changes, both at early age and later ages.

Direct Shear

Although direct shear testing was not experimentally evaluated in this program, it has been evaluated by other researchers. ASTM D 3080, "Standard Test Method for Direct Shear Test of Soils under Consolidated Drained Conditions," is often used for this purpose.

Thermal Conductivity

Thermal properties of CLSM mixtures may be important for underground piping applications such as pipes carrying hot water. Because of the limited scope of this research project, the thermal properties of CLSM were not evaluated. Related testing information can be found in ASTM D 5334, "Standard Test Method for Determination of Thermal

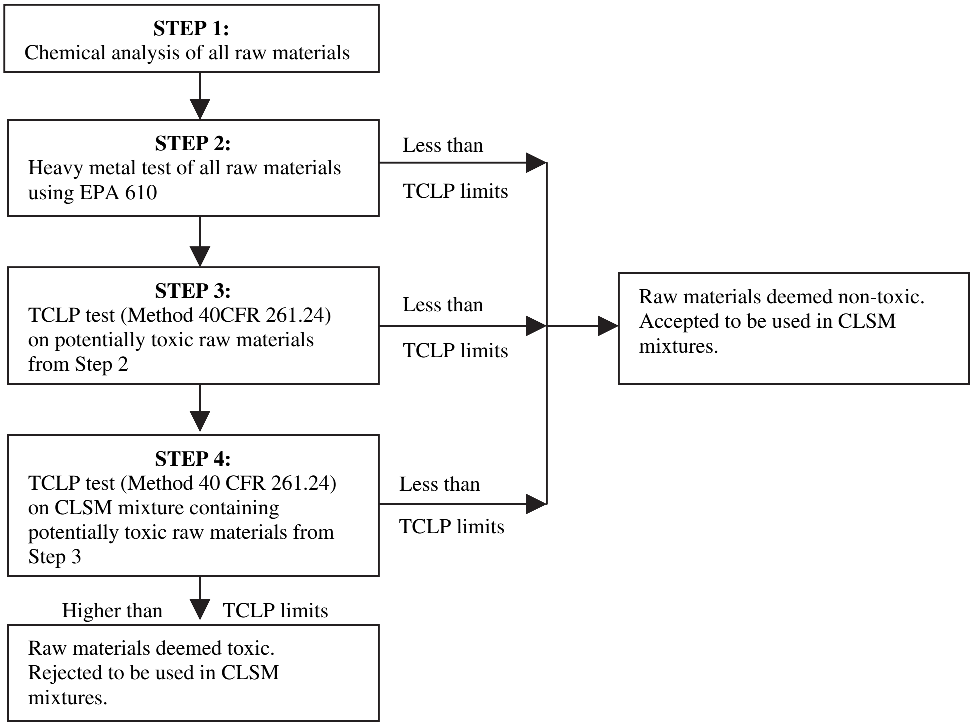


Figure B.4. Proposed flowchart to study toxicity of CLSM constituent materials.

Conductivity of Soil and Soft Rock by Thermal Needle Probe Procedure."

Consolidation

The consolidation of CLSM mixtures may be important for various applications, such as pavement base/subbase and bridge approach fill. ASTM D 2435, "Standard Test Method for One-Dimensional Consolidation Properties of Soils," can be consulted if deemed necessary for a specific application. Consolidation was not evaluated as part of this research project.

Air/Gas Permeability

Air/gas permeability of CLSM mixtures may be important for backfill applications, especially when natural gas pipes are embedded in the CLSM. If a pipe leaks, a CLSM mixture with low permeability could make detecting the location of the leak difficult. Based on the literature review, air permeability of CLSM mixtures can be evaluated using ASTM D 4525, "Standard Test Method for Permeability of Rocks by Flowing Air."

Leaching/Environmental Impact

An entire procedure, shown in Figure B.4, has been proposed to evaluate constituent raw materials for potential leaching of heavy metals. This approach can be used as a reference for engineers unfamiliar with toxicity testing.

Conclusion

This appendix provided guidance on various CLSM test methods. Selected methods described in this appendix were used in the field testing program. The test methods recommended should be evaluated by practitioners and their feedbacks may be included in the continuous development of these methods.

Reference

Katz, A., Kovler, K., and Schamban, I. (2002). "Early-Age Shrinkage and Cracking of Controlled Low-Strength Materials (CLSM)." *Early Age Cracking in Cementitious Systems,* RILEM Proceedings, PRO 23, pp. 373–381.

APPENDIX C

Recommended Specifications for CLSM

Introduction

This appendix includes proposed criteria, recommended specifications, and guidelines for the use of CLSM in the following applications:

- Backfill
- Utility Bedding
- Void Fill
- Bridge Approaches

For each of the above applications, a general description is provided for the application and issues (criteria) that are relevant to the application of CLSM. After this information, recommended specifications and guidelines are given for each application. The recommended specifications and guidelines are based on a survey of current practice, as well as on the findings of the laboratory and field tests. All proposed specifications are written in a format consistent with existing AASHTO specifications. Appendix D, Recommended Practice for CLSM, contains some of the same information and guidance that is contained in this appendix. This approach is intentional and is intended to allow each appendix to serve as a stand-alone product, albeit for a slightly different audience or end use.

For various CLSM parameters, the research team can provide only general guidance and recommended values and limits. In instances where selection of specific numeric values (i.e., maximum compressive strength) is difficult or impossible, the research team has enclosed the values in brackets, such as [1 MPa], in a format typically used by AASHTO that allows practitioners to input values of their choice. This capability is especially important for CLSM, where variations in local materials and practices make it difficult to impose single limits that are applicable to all areas and applications.

Backfill

This section provides a definition of backfill as used for this report, along with a figure representative of typical backfill conditions. The criteria that are important to backfill applications are then discussed, specifically in relation to the two types of backfills presented: trenches and walls.

Finally, a recommended specification for backfill is provided. It is presented in a manner consistent with the AASHTO *Guide Specifications for Highway Construction*—1998 in both format and language. The materials test methods discussed are found in Appendix B of this report.

Definition and Types of Backfill

Backfill as intended in this report and recommended specification relates to the infill material to cover pipes (in trench applications) up to a specified grade (usually equal to the grade of undisturbed earth on either side of a trench wall) or to the horizontal-reaction–providing infill adjacent to retaining walls and other wall structures. For the purposes of this report, the CLSM is the alternative of an infill material that is typically a compacted granular structural fill.

Backfill is not the same as utility bedding, although it can be contiguous with such bedding. Backfill also is not the same as void fill; the primary difference is that backfill is placed against a structure with the purpose of providing at least some structural resistance to loads.

Figure C.1 indicates common backfill applications.

Criteria for Backfill

Backfill generally must fill an open space of some sort, usually a space accessible from above, and it must provide some sort of structural support for the object that is being backfilled. In the case of a trench, the backfill may provide structural support for part of the pipe and the trench wall. For bridge abutments,

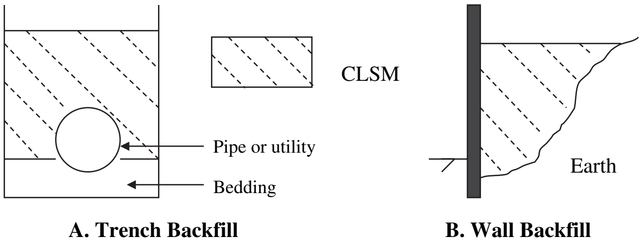


Figure C.1. Common backfill applications.

retaining walls, and other walls, the backfill is providing support for the wall, usually acting as a bridge between the wall and the area of unexcavated, natural earth.

Because of the various applications and needs for backfill, the criteria noted below have been deemed important. Criteria important to trench and/or wall applications are noted.

Flowability

This characteristic is important to both trench and wall applications. CLSM must flow from its point of delivery to a reasonable distance, such as along a trench floor or to the wall. A mixture that is too stiff will not allow the material to reach all necessary locations without the application of additional equipment and labor. A mixture that is too liquid (no severe segregation) is generally not a problem, if all other material properties discussed below are met. It is cautioned that a "runny" mixture may cause difficulties if there are small gaps in sandbag, bulkheads, or similar retaining structures.

A flow resulting in a circular-type spread with a diameter of [203 to 254 mm] as measured by ASTM D 6103 is considered an appropriate criterion for backfill applications.

Setting Time

Frequently, backfilling is an interim operation in construction. That is, additional construction activities are performed overtop or adjacent to the backfilled area. Accordingly, it is desirable that the CLSM mixture has a setting time consistent with the overall construction schedule. In the case of a trench under a roadway, a fast setting time may be desirable so that a pavement layer may be placed on top of it. In cases such as backfill for a wall, or in other trench applications, a general surrogate measurement as to whether the CLSM has sufficiently set is "walkability," this is, when a person of average weight and shoe size can walk on the surface of the CLSM without creating significant (greater than 3 mm) indents in the material. The CLSM mixture should set in such a time, consistent with walkability needs and other measurements, so that it does not unduly delay subsequent or concurrent construction practices.

In general, pavements can be placed over CLSM when the CLSM has reached a strength of [0.2] MPa or a penetration resistance of [2.8] MPa according to AASHTO X 1.

Long-Term Strength

Frequently, backfill may need to be removed later, such as when a pipe requires repair, or when additional future construction is performed. This need suggests that CLSM should have some predetermined maximum strength to ensure its future removability. For hot-weather construction, CLSM mixtures containing fly ash may obtain higher strength in the field than estimated in the laboratory. The actual value of that strength may depend on whether removal is anticipated using manual equipment or machinery.

Likewise, by its very nature, backfill must provide some structural resistance to loads. A minimum strength must be specified that is appropriate to whatever the structural needs (e.g., traffic loads) of the specific application may be.

Permeability

A concern among utility companies is that CLSM is perceived as being nearly impermeable to gas. This impermeability may lead to difficulty in locating gas leaks in pipelines. This concern applies only to trench backfill applications.

Water permeability, on the other hand, may be an issue to both trench backfill and to wall backfill. A barely permeable CLSM mixture may cause leaking water to travel along a pipe length until it reaches a suitable fissure in the CLSM. Thus, the location of evidence of water leakage (bubbling or ballooning of the ground surface, for example) may not coincide with the actual location of a pipe leak, causing difficulty in determining the exact location of the damaged pipe. For wall backfills, a nearly impermeable CLSM mixture may lead, depending on the application design, to excess water being unable to flow through or around the CLSM, which may lead to a buildup of water pressures against a wall or to washouts at the CLSM-soil interface. For applications where pipes are located near the foot of abutment walls, the locations of leaks may become difficult to ascertain in much the same way as they may be in trenches.

Accordingly, a minimum permeability is established based on the water permeability coefficient k. The minimum k should be [1×10^{-4} mm/s] unless permeability is deemed not to be an issue. The permeability coefficient can be measured using AASHTO X 7.

Air Content

Air content requirements are established to provide for the durability of backfill material in freeze-thaw conditions. A minimum air content of [6] percent is required unless otherwise specified or unless needs suggest a different limit.

Corrosivity

Corrosion issues come into play in trench applications when pipes run transversely through a backfilled area. The soil-CLSM interface can cause an electrochemical potential leading to corrosion of metallic pipe in this area. Whenever such an interface exists, it is important to specify either a cathodic protection scheme or a physical protection scheme, such as coating or covering the pipe with a protective layer in this interface region.

Subsidence

In cases where interim and final grades of construction materials are important, such as in a trench transverse to a roadway (where subsidence could cause a dip in the final roadway surface, or even worse, cracking in an asphalt or portland cement concrete surface or a chip seal because of uneven support conditions), it is important to limit or take into account the subsidence of CLSM. Typically, CLSM may "shrink" approximately 6 mm for every 300 mm of depth. Thus, layers above the CLSM, or an additional thin lift of CLSM, may be required after any initial subsidence. Because overfilling trenches is impractical (because the CLSM would simply run over the edges), proper planning related to subsidence must be undertaken.

Other Criteria

Other criteria may become important on a case-by-case basis. For example, the thermal properties of the CLSM backfill may be important for a utility application in which hot or cold water is being piped. For roadway-support related applications, the California Bearing Ratio (CBR) or resilient modulus (M_R) of the in-place CLSM may be critical. Performance criteria related to these and other items should be specified by the engineer, with the appropriate test methods indicated as discussed previously in this report.

Recommended Specification: Backfill

Section 2X2. CLSM Backfill

2X2.01 Description.

Furnish and install backfill to provide necessary structural support for utilities, trench walls, retaining walls, abutments, and other applications.

2X2.02 Material.

CLSM backfill composed of some or all of the following components:

Aggregate	AASHTO M 6 or as approved by the engineer
Water	Water used in mixing and curing of CLSM shall be subject to approval and shall be reasonably clean and free of oil, salt, acid, alkali, sugar, vegetable, or other substance injurious to the finished product. Water shall be in accordance with AASHTO T 26.
Color agent	ASTM C 979
Cement	AASHTO M 85
Mineral admixtures	AASHTO M 295 or as approved by the engineer.
Chemical admixtures	AASHTO M 194 or as approved by the engineer.

Backfill may not contain any material deemed toxic or hazardous. Material Safety Data Sheets (MSDS) must be available for any component of the mixture upon request. Backfill shall be compatible with bedding materials, electrochemically and otherwise if used as a metal pipe backfill application.

2X2.03 Mixture Proportions.

Proportioning of CLSM mixtures shall be the responsibility of the contractor or the contractor's supplier. The mixture may be rejected for failure to meet, or to sustain, the mixture's consistency and all properties specified herein.

2X2.04 Construction.

2X2.04.01 Batching, mixing, and transporting

CLSM may be produced on site or batched at a remote facility and appropriately mixed and transported to the site. If transported, an appropriate transit-mix truck shall be used. [End plugs or lower transport volumes shall be required for mixtures of extreme flowability or as required by the engineer.] Hauling and dumping using a conventional open-haul unit is allowed if approved by the engineer. No blade mixing shall be allowed.

2X2.04.02 Sampling and testing

All CLSM shall be accompanied by a batch ("delivery") ticket that certifies the content of the material and the data on the following items:

(a) Project designation
(b) Date
(c) Time
(d) Compressive strength, f'_c
(e) Yield and unit weight
(f) Flowability
(g) Removability modulus (optional)

In addition, the following tests shall be performed for each [100] cubic meters of material delivered and used on the project site.

Strength

Six (6) cylinders will be required, with three (3) cylinders tested according to AASHTO X 3 (2004) at 28 days and three (3) cylinders tested at 91 days. The contractor shall be responsible for the curing and protection of the cylinders until such time that they are ready to be tested or to be picked up by the testing agency.

Note: For any project using less than [100] cubic meters of material, three (3) cylinders will be required for every [50] cubic meters of material, with two (2) cylinders tested at 28 days as noted above and the third tested at 91 days.

Flowability

Three (3) samples shall be tested according to ASTM D 6103 on site prior to installation of the material as backfill. The material must provide a flow diameter of no less than 200 mm, unless specified by the engineer.

Air Content

For jobs where long-term freeze-thaw durability has been indicated as a concern, the air content of fresh CLSM will be determined using AASHTO X 2 prior to installation of the material as backfill. The CLSM must have an air content no less than [6] percent by volume.

2X2.04.03 Site Preparation

If utility bedding is not already present, excavate to line and grade shown on the plans or described in the specifications. Excavate rock, hardpan, and other unyielding material to [300] mm below the designed trench grade. If utility bedding is present, ensure that the bedding is not covered by rock, soil, or deleterious material.

Clear the trench or wall area of any deleterious material; soil clods; loose, sloughing, caving, or otherwise unsuitable soil; or other materials such that a reasonably clear and clean fill area is provided.

Cleanup and backfill of trenches for water mains shall begin immediately upon completion of the hydrostatic test (if necessary) or as directed by the engineer.

No placement of CLSM shall commence until all items have been inspected by the engineer and approved for backfilling. [Wait [7] days or meet a minimum compressive strength of [19] MPa before backfilling against newly constructed masonry or concrete structures.]

For trench applications, provide suitable vertical wall containment such as sandbag or soil bulkheads to limit the flow distance of the CLSM to no more than [20] m from the discharge location. For backfill applications, provide suitable vertical wall containment to ensure that the CLSM will not flow into areas beyond those specified on the plans. For steeply sloping trenches, provide bulkheads at intervals as approved by the engineer.

If standing water exists, CLSM may be poured if the standing water represents no more than approximately [4] percent of the volume of CLSM to be placed in a single lift. If more water than this limit is present, it must be removed through appropriate water control measures.

Ensure that all sheeting and bracing, temporary formwork, and other items assisting with the construction can be removed after completion of the CLSM placement.

Whenever excavation is made for structures across private property, the topsoil removed in the excavation shall be kept separate and replaced, as nearly as feasible, in its original position, and the entire area shall be restored to a condition acceptable to the engineer.

2X2.04.04 Placement

Placement of CLSM shall be completed no more than [90] minutes after the end of mixing. For fast-setting CLSM mixture, the material shall be mixed on site and placed immediately.

Place the CLSM directly in the trench or excavation.

Place the CLSM using pumps, chutes, or any other method as approved by the engineer. Place the CLSM in lifts such that the hydrostatic pressures developed will not compromise the integrity of bulkheads, formwork, trench or other soil walls, or other temporary or permanent structures.

Placement shall bring the material up uniformly to lines or limits as shown on plans.

For cases in which subsidence effects on the final grade are critical, place a final lift that will account for estimated subsidence or otherwise ensure that the final grades on the plans can be achieved and maintained.

The CLSM shall be applied in such a manner that no labor is required in the trench or excavation. No compaction or vibration equipment shall be allowed.

The CLSM must have a minimum temperature of [10] °C at the time of placement.

Place CLSM only in conditions where the ambient temperature is greater than [4] °C. Do not place CLSM in contact with frozen soil or other material. Once placed, keep the CLSM from freezing for a period of no less than [36] hours.

CLSM may not be placed in conditions of inclement weather (e.g., rain) unless approved by the engineer. [CLSM may be placed in conditions of inclement weather (e.g., rain), if any rainfall does not result in ponding on the surface of the in-place material and if the requirements for minimal standing water, noted above, are met.]

For projects in which no pipe bedding is in place, ensure and maintain the appropriate horizontal and vertical alignment of pipes and fixtures prior to and during the placement procedure, and until such time as the CLSM has set to sufficient strength to hold the pipes in place. Use straps, soil anchors, or other approved means of restraint.

Coat or protect pipes as needed when pipes traverse soil and CLSM.

Pipe or other items damaged by the contractor during construction shall be replaced at the contractor's expense or repaired to the satisfaction of the engineer.

2X2.05 Acceptance.

Material acceptance shall be based on all criteria specified herein, plus the following:

Strength: a 28-day compressive strength of no more than [0.7 MPa] and no less than [0.2 MPa].

Flowability: a diameter of no more than [225 mm] and no less than [175 mm].

Removability modulus: a value, calculated using in-situ density and [91-day] compressive strength, or as dictated by the anticipated removal methods and as specified by the engineer, or as based on documented local experiences of excavation as provided by the contractor.

2X2.06 Measurement.

Measurement shall be based on the payment lines indicated on the plans. Payment shall be based on the CLSM in its hardened state. No payment shall be made for additional material required by slips, slides, cave-ins, over-excavation, or other actions resulting from the elements or from construction activities. No payment shall be made for unused or wasted material.

2X2.07 Payment.

Payment shall be per cubic meter of in-place material including all costs for furnishing all materials, equipment, labor, and incidentals necessary to complete this item.

Utility Bedding

This section provides a definition of utility bedding as used for this report, along with a figure representative of typical utility bedding conditions. The criteria that are important to utility bedding applications are then discussed. Utilities could include pipe, electrical, telephone, and other types of conduits.

Finally, a recommended specification for utility is provided. It is presented in a manner consistent with the AASHTO *Guide Specifications for Highway Construction*–1998 in both format and language. The materials test methods discussed are found in Appendix B of this report.

Definition and Types of Utility Bedding

Utility bedding as intended in this report and recommended specification relates to the preplaced or infill material to provide support strength for utilities (usually underground). For the purposes of this report, CLSM is the alternative of a bedding material that is typically a compacted granular structural fill.

Utility bedding is not the same as backfill, although it can be contiguous with such backfill in the case of encasing the entire conduit. Utility bedding also is not the same as void fill, with the primary difference being that utility bedding is placed underneath the utility structure with the purpose of providing supporting strength to the utilities and distributing loads and reactions.

Figure C.2 shows common utility bedding applications.

Criteria for Utility Bedding

Utility bedding generally must provide enough support strength for the utilities, usually by influencing the load and reaction distribution and the resultant lateral pressures. In the case of bedding only, the bedding may provide structural support for the utility and distribute the reaction. For encasing the entire conduit, the application is providing support for the conduit, distributing the reaction, and transferring the load.

Because of the various applications and needs for backfill, the criteria noted below have been deemed important. Criteria important to trench and/or wall applications are noted. The criteria may not be inclusive for all applications.

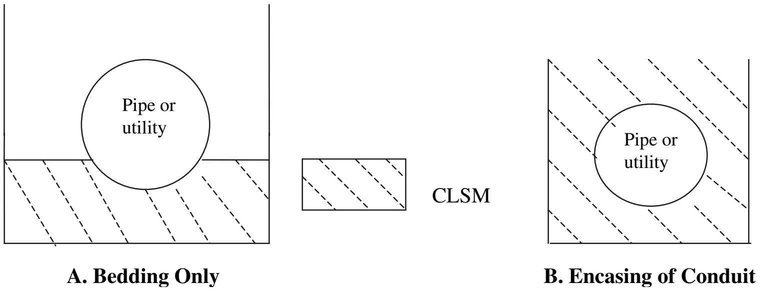


Figure C.2. Typical applications of CLSM in utility bedding.

Trench Width

When CLSM is used for utility bedding, the width of excavation shown on the plans may be changed so that the clear distance between the outside of the pipe and the side of the excavation, on each side of the pipe, is a minimum of [150 mm], except that [300 mm] shall be required for pipes of [1,050 mm] and greater in diameter or span when height of cover is greater than [6.1 m].

Structure Span

Because CLSM is in a liquid state during placing, it will exert floatation on structures. It is cautioned that such flotation force may cause damage to the structures, especially when the structures do not have adequate resistance. Generally, CLSM shall not be used with underground structures having a span greater than [6.1 m], unless otherwise approved by the engineer.

Flowability

This characteristic is important to both bedding and encasing applications. CLSM must flow from its point of delivery to a reasonable distance, such as along a trench floor. A mixture that is too stiff will not allow the material to reach all necessary locations and completely fill the space beneath the pipe without the application of additional equipment and labor. A mixture that is too liquid shall be treated with precautions and its tendency of subsidence shall be considered when encasing the entire conduit. It is cautioned that a "runny" mixture may cause difficulties if there are small gaps in sandbag bulkheads or similar.

A flow resulting in a circular-type spread with a diameter of [203 to 254 mm] as measured by ASTM D 6103 is considered an appropriate criterion.

Setting Time

Frequently, utility bedding is an interim operation in construction. That is, additional construction activities are performed overtop the bedding area. Accordingly, it is desirable that the CLSM mixture has a setting time consistent with the overall construction schedule. In the case of bedding for a trench under a roadway, a fast setting time may be desirable so that backfilling may be placed on top of it. In cases such as encasing the entire conduit, a general surrogate measurement as to whether the CLSM has sufficiently set is "walkability," that is, when a person of average weight and shoe size can walk on the surface of the CLSM without creating significant (greater than 3 mm) indents in the material. The CLSM mixture should set in such a time, consistent with walkability needs and other measurements, such as field needle penetrometer and pocket soil penetrometer, so that it does not unduly delay subsequent or concurrent construction practices.

In general, pavements can be placed over CLSM when the CLSM has reached a compressive strength of [0.2] MPa.

Strength

By its very nature, utility bedding must provide adequate structural support strength to conduits. A minimum strength must be specified that is appropriate to whatever the structural needs (e.g., traffic loads) of the specific application may be. Frequently, encasing may be removed later, such as when a pipe requires repair, or when additional future construction is performed. This suggests that the CLSM have some predetermined maximum strength to ensure its future removability. The actual value of that strength may depend on whether removal is anticipated using manual equipment or machinery.

Permeability

As for encasing entire conduit applications, a concern among utility companies is that CLSM is perceived as being impermeable to gas or liquids. This impermeability may lead to difficulties in locating leaks in pipelines.

Accordingly, a minimum permeability is established based on the water permeability coefficient *k*. The minimum *k* should be [1×10^{-4} mm/s] unless permeability is deemed not to be an issue.

Air Content

Air content requirements are established to provide for the durability of bedding material in freeze-thaw conditions. A minimum air content of [6] percent and a minimum strength of [0.35] MPa is required unless otherwise specified or unless needs suggest a different limit.

Corrosivity

Corrosion issues come into play in bedding applications when pipe cross sections run through CLSM and soil. The soil-CLSM interface can cause an electrochemical potential difference leading to corrosion of metallic pipe in this area. Whenever such an interface exists, it is important to specify either a cathodic protection scheme or a physical protection scheme, such as coating or covering the pipe with a protective layer in this interface region. Dielectric connection pipes can also be used.

When conduits are encased entirely in CLSM, this type of corrosion is unlikely.

Subsidence

In the case of encasing entire conduits, the requirements in "Backfill" may apply.

Other Criteria

Other criteria may become important on a case-by-case basis. For example, the thermal properties of the CLSM utility bedding may be important for a utility application in which hot or cold water is being piped. Drying shrinkage may be critical for the integrity of supported conduits. For roadway support–related applications, the California Bearing Ratio (CBR) or resilient modulus (M_R) of the in-place CLSM may be critical. Performance criteria related to these and other items shall be specified by the engineer, with the appropriate test methods indicated as discussed previously in this report.

Recommended Specification: Utility Bedding

Section 2X2. CLSM Utility Bedding

2X2.01 Description.

Furnish and install bedding to provide necessary structural support strength for utilities.

2X2.02 Material.

CLSM backfill composed of some or all of the following components:

Aggregate	AASHTO M 6 or as approved by the engineer.
Water	Water used in mixing and curing of CLSM shall be subject to approval and shall be reasonably clean and free of oil, salt, acid, alkali, sugar, vegetable, or other substance injurious to the finished project. Water shall be in accordance with AASHTO T 26.
Color agent	ASTM C 979
Cement	AASHTO M 85
Mineral admixtures	AASHTO M 295 or as approved by the engineer.
Chemical admixtures	AASHTO M 194 or as approved by the engineer.

Utility bedding may not contain any material deemed toxic or hazardous. Material Safety Data Sheets (MSDS) must be available for any component of the mixture upon request. Bedding materials shall be compatible with backfill materials, electrochemically and otherwise, if used in a metal conduit application.

2X2.03 Mixture Proportions.

Proportioning of CLSM mixtures shall be the responsibility of the contractor or the contractor's supplier. The mixture may be rejected for failure to meet, or to sustain, the mixture's consistency and all properties specified herein.

2X2.04 Construction.

2X2.04.01 Batching, mixing, and transportation

CLSM may be produced on site or batched at a remote facility and appropriately mixed and transported to the site. If transported, an appropriate transit-mix truck shall be used. [End plugs or lower transport volumes shall be required for mixtures of extreme flowability or as required by the engineer.] Hauling and dumping using a conventional open-haul unit is allowed if approved by the engineer. No blade mixing shall be allowed.

2X2.04.02 Sampling and testing

All CLSM shall be accompanied by a batch ("delivery") ticket that certifies the content of the material and the data on the following items:

(a) Project designation
(b) Date
(c) Time
(d) Compressive strength, f'_c, at 28 days, preferably 91 days
(e) Yield and unit weight
(f) Flowability
(g) Removability modulus (optional)

In addition, the following tests shall be performed for each [100] cubic meters of material delivered and used on the project site.

Strength

Six (6) cylinders will be required, with three (3) cylinders tested according to AASHTO X 3 at 28 days and three (3) cylinders tested at 91 days. The contractor shall be responsible for the curing and protection of the cylinders until such time that they are ready to be tested or to be picked up by the testing agency. A minimum strength of [0.35] MPa at 28 days shall be required if long-term freeze-thaw condition is expected.

Note: For any project using less than [100] cubic meters of material, three (3) cylinders will be required for every [50] cubic meters of material, with two (2) cylinders tested at 28 days as noted above and the third tested at 91 days.

Flowability

Three (3) samples shall be tested according to ASTM D 6103 on site prior to installation of the material as backfill. The material must provide a flow diameter of no less than 200 mm, unless specified by the engineer.

Air Content

For jobs where long-term freeze-thaw durability has been indicated as a concern, the air content of fresh CLSM will be determined using AASHTO X 2 prior to installation of the material as backfill. The CLSM must have an air content no less than [6] percent by volume.

2X2.04.03 Site Preparation

Excavate to line and grade shown on the plans or described in the specifications. Excavate rock, hardpan, and other unyielding material to [300] mm below the designed trench grade. Ensure that there is no loose rock, soil, or deleterious material that will fall during placing of CLSM.

Clear the trench or wall area of any deleterious material; soil clods; loose, sloughing, caving, or otherwise unsuitable soil; or other materials such that a reasonably clear and clean fill area is provided.

No placement of CLSM shall commence until all items have been inspected by the engineer and approved for utility bedding.

Adequate conduit anchorage shall be provided to ensure the movement of supported structure is within tolerance limits, as designated by the engineer.

For bedding applications, provide suitable vertical wall containment such as sandbag or soil bulkheads to limit the flow distance of the CLSM to no more than [20] m from the discharge location. For encasing applications, provide suitable vertical wall containment to ensure that the CLSM will not flow into areas beyond those specified on the plans. For steeply sloping trenches, provide bulkheads at intervals as approved by the engineer.

If standing water exists, it must be removed through appropriate water control measures. Soil shall be dried until suitable for placement of CLSM as approved by the engineer.

Ensure that all sheeting and bracing, temporary formwork, and other items assisting with the construction can be removed after completion of the CLSM placement.

Whenever excavation is made for structures across private property, the topsoil removed in the excavation shall be kept separate and replaced, as nearly as feasible, in its original position, and the entire area shall be restored to a condition acceptable to the engineer.

2X2.04.04 Placement

Placement of CLSM shall be completed no more than [30] minutes after the end of mixing.

Place the CLSM directly in the trench or excavation.

Place the CLSM using pumps, chutes, or any other method as approved by the engineer. Place the CLSM in lifts such that the hydrostatic pressures developed will not compromise the integrity of bulkheads, formwork, trench or other soil walls, or other temporary or permanent structures.

CLSM shall be carefully placed to fit the lower part of the conduit exterior for a width of at least 60 percent of the conduit breadth. Make sure no voids exist underneath the conduit. Placement shall bring the material up uniformly to lines or limits as shown on plans.

The CLSM shall be applied in such a manner that no labor is required in the trench or excavation. No compaction or vibration equipment shall be allowed.

The CLSM must have a minimum temperature of [10] °C at the time of placement.

Place CLSM only in conditions where the ambient temperature is greater than [4] °C. Do not place CLSM in contact with frozen soil or other material. Once placed, keep the CLSM from freezing for a period of no less than [36] hours.

CLSM may not be placed in conditions of inclement weather (e.g., rain), unless approved by the engineer. [CLSM may be placed in conditions of inclement weather (e.g., rain), if any rainfall does not result in ponding on the surface of the in-place material and that the requirements for minimal standing water, noted above, are met.]

Ensure and maintain the appropriate horizontal and vertical alignment of pipes and fixtures prior to and during the placement procedure, and until such time as the CLSM has set to sufficient strength to hold the pipes in place. Use straps, soil anchors, or other approved means of restraint if necessary.

Coat or protect pipes as needed when pipes traverse soil and CLSM.

Pipe or other items damaged by the contractor during construction shall be replaced at the contractor's expense or repaired to the satisfaction of the engineer.

Galvanic corrosion can occur at soil-CLSM interface. When CLSM is used as a bedding material, the backfill material also is recommended to be CLSM of similar constituents and mixture proportions.

2X2.05 Acceptance.

Material acceptance shall be based on all criteria specified herein, plus the following:

Strength: a 28-day compressive strength of no more than [0.7 MPa] and no less than [0.35.MPa].

Flowability: a diameter of no more than [225 mm] and no less than [178 mm].

Removability modulus: a value, calculated using in-situ density and [91-day] compressive strength, or as dictated by the anticipated removal methods and as specified by the engineer, or as based on documented local experiences of excavation as provided by the contractor

2X2.06 Measurement.

Measurement shall be based on the payment lines indicated on the plans. Payment shall be based on the CLSM in its hardened state. No payment shall be made for additional material required by slips, slides, cave-ins, over-excavation, or other actions resulting from the elements or from construction activities. No payment shall be made for unused or wasted material.

2X2.07 Payment.

Payment shall be per cubic meter of in-place material including all costs for furnishing all materials, equipment, labor, and incidentals necessary to complete this item.

Void Fill

This section provides a definition of void fill as used for this report, along with a figure representative of typical void fill conditions. The criteria that are important to void fill applications are then discussed.

Finally, a recommended specification for void fill is provided. It is presented in a manner consistent with the AASHTO *Guide Specifications for Highway Construction*–1998 in both format and language. The materials test methods discussed are found in Appendix B of this report.

Definition and Types of Void Fill

Void fill as intended in this report and specification relates to the infill material to occupy empty spaces created by erosion, construction, abandonment, and other activities. For the purposes of this report, the use of CLSM is a unique solution for void fills that are difficult, if not impossible, to fill with a compacted granular fill.

Void fill is not the same as utility backfill, although it can be similar. The primary difference is that void fill is generally placed to occupy empty spaces rather than to provide a sort of structural support.

Figure C.3 illustrates a typical void where CLSM can be applied.

Criteria for Void Fill

Void fill generally must fill an open or covered space of some sort, usually a space accessible from above, and it must occupy the space with minimum large voids left behind. Its application must not cause undesired movement or damage of adjacent structures.

Because of the various applications and needs for void fill, the criteria noted below have been deemed important.

Flowability

This characteristic is important to void fill applications. CLSM must flow from its point of delivery to a reasonable distance, such as reaching the other end of the void. A mixture that is too stiff will not allow the material to reach all necessary

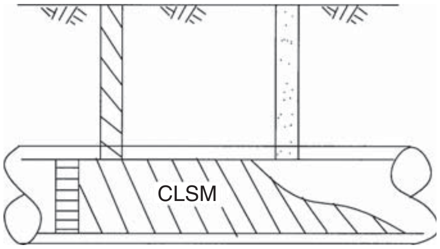


Figure C.3. Typical applications of CLSM in void fill.

locations without the use of additional equipment and labor. A mixture that is too liquid is generally not a problem, if all other material properties discussed below are met.

A flow resulting in a circular-type spread with a diameter of [203 to 254 mm] as measured by ASTM D 6103 is considered an appropriate criterion, or as decided by the engineer.

Subsidence

In cases where subsidence could cause a dip in the final surface, it is important to limit or take into account the subsidence of CLSM, if necessary. Typically, CLSM may "shrink" approximately 6 mm for every 300 mm of depth. Because overfilling voids is impractical (because the CLSM would simply run over the edges), proper planning related to subsidence must be undertaken.

Strength

If void fill must provide some structural resistance to loads, a minimum strength must be specified that is appropriate to whatever the structural needs of the specific application may be.

Other Criteria

Other criteria may become important on a case-by-case basis. For example, the weight of void fill may cause disturbance to foundations of adjacent structures. Performance criteria related to these and other items shall be specified by the engineer, with the appropriate test methods indicated as discussed previously in this report.

Recommended Specification: Void Fill

Section 2X2. CLSM Void Fill

2X2.01 Description.

Furnish and install void fill to occupy abandoned empty spaces.

2X2.02 Material.

CLSM backfill composed of some or all of the following components:

Aggregate	AASHTO M 6 or as approved by the engineer.
Water	Water used in mixing and curing of CLSM shall be subject to approval and shall be reasonably clean and free of oil, salt, acid, alkali, sugar, vegetable, or other substance injurious to the finished project. Water shall be in accordance with AASHTO T 26.
Color agent	ASTM C 979
Cement	AASHTO M 85
Mineral admixtures	AASHTO M 295 or as approved by the engineer.
Chemical admixtures	AASHTO M 194 or as approved by the engineer.

Void fill may not contain any material deemed toxic or hazardous. Material Safety Data Sheets (MSDS) must be available for any component of the mixture upon request.

2X2.03 Mixture Proportions.

Proportioning of CLSM mixtures shall be the responsibility of the contractor or the contractor's supplier. The mixture may be rejected for failure to meet, or to sustain, the mixture's consistency and all properties specified herein.

2X2.04 Construction.

2X2.04.01 Batching, mixing, and transporting

CLSM may be produced on site or batched at a remote facility and appropriately mixed and transported to the site. If transported, an appropriate transit-mix truck shall be used. [End plugs or lower transport volumes shall be required for mixtures of extreme flowability or as required by the engineer.] Hauling and dumping using a conventional open-haul unit is allowed if approved by the engineer. No blade mixing shall be allowed.

2X2.04.02 Sampling and testing

All CLSM shall be accompanied by a batch ("delivery") ticket that certifies the content of the material and the data on the following items:

(a) Project designation
(b) Date
(c) Time
(d) Compressive strength, f'_c
(e) Yield and unit weight
(f) Flowability

In addition, the following tests shall be performed for each [100] cubic meters of material delivered and used on the project site.

Strength

Six (6) cylinders will be required, with three (3) cylinders tested according to AASHTO X 3 at 28 days and three (3) cylinders tested at 91 days. The contractor shall be responsible for the curing and protection of the cylinders until such time that they are ready to be tested or to be picked up by the testing agency.

Note: For any project using less than [100] cubic meters of material, three (3) cylinders will be required for every [50] cubic meters of material, with two (2) cylinders tested at 28 days as noted above and the third tested at 91 days.

Flowability

Three (3) samples shall be tested according to ASTM D 6103 on site prior to installation of the material as void fill. The material must provide a flow diameter of no less than 200 mm.

2X2.04.03 Site Preparation

No cleanup of site is required.

Access holes shall be installed to ensure complete filling of voids.

Adjacent structures shall be appropriately prepared for the placement of CLSM. CLSM mixtures may exert lateral pressure on those structures.

2X2.04.04 Placement

Placement of CLSM shall be completed no more than [90] minutes after the end of mixing.

Place the CLSM directly in the voids. Appropriate measures shall be taken to ensure complete void fill.

Place the CLSM using pumps, chutes, or any other method as approved by the engineer.

Placement shall bring the material up uniformly to lines or limits as shown on plans.

For cases in which subsidence effects on the final grade are critical, place a final lift that will account for estimated subsidence or otherwise ensure that the final grades on the plans can be achieved and maintained.

The CLSM shall be applied in such a manner that no labor is required in the voids. No compaction or vibration equipment shall be allowed.

The CLSM must have a minimum temperature of [10] °C at the time of placement.

Place CLSM only in conditions where the ambient temperature is greater than [4] °C. Do not place CLSM in contact with frozen soil or other material. Once placed, keep the CLSM from freezing for a period of no less than [36] hours.

CLSM may not be placed in conditions of inclement weather (e.g., rain), unless approved by the engineer. [CLSM may be placed in conditions of inclement weather (e.g., rain), if any rainfall does not result in ponding on the surface of the in-place material and the requirements for minimal standing water, noted above, are met.]

2X2.05 Acceptance.

Material acceptance shall be based on all criteria specified herein, plus the following:

Strength: a 28-day compressive strength no less than [0.1 MPa] or as required by the engineer.

Flowability: a diameter of no more than [225 mm] and no less than [200 mm] or as required by the engineer.

2X2.06 Measurement.

Measurement shall be based on the payment lines indicated on the plans. Payment shall be based on the CLSM in its hardened state. No payment shall be made for additional material required by slips, slides, cave-ins, over-excavation, or other actions resulting from the elements or from construction activities. No payment shall be made for unused or wasted material.

2X2.07 Payment.

Payment shall be per cubic meter of in-place material including all costs for furnishing all materials, equipment, labor, and incidentals necessary to complete this item.

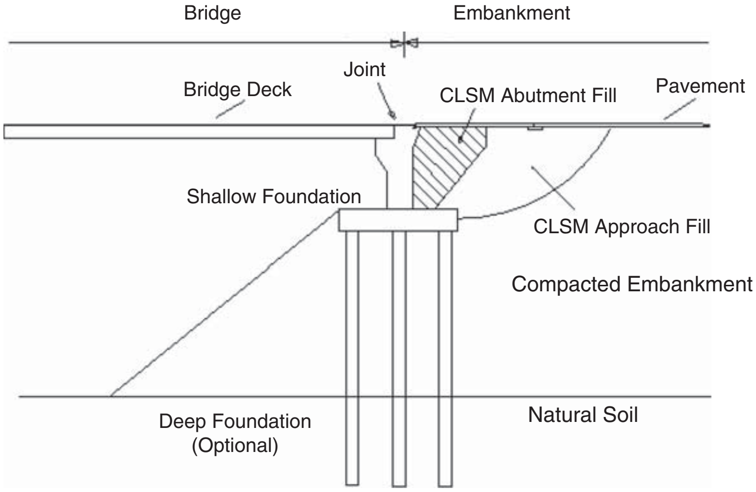
Bridge Approaches

This section provides a definition of bridge approach fill as used for this report, along with figures representative of typical bridge approach fill conditions. The criteria that are important to bridge approach fill applications are then discussed, specifically fill behind bridge abutments (embankment) and under bridge approach slabs.

Finally, a recommended specification for bridge approach fill is provided. It is presented in a manner consistent with the AASHTO *Guide Specifications for Highway Construction*–1998 in both format and language. The materials test methods discussed are found in Appendix B of this report.

Definition and Types of Bridge Approach Fill

Bridge approach fill as intended in this report and specification relates to the infill material to work as embankment (in fill behind bridge abutments applications) up to a specified grade (usually equal to the grade of pavement) or to the infill for bridge abutment. For the purposes of this report, the CLSM is the alternative of an infill material that is typically a compacted granular structural fill. Bridge approach fill is not the same as utility bedding, backfill, or void fill; the primary difference is that bridge approach fill is placed against a structure with the purpose of providing adequate structural resistance to loads. Figure C.4 indicates common bridge approach fill applications.



Source: Modified from Jean-Louis Briaud, Ray W. James, and Stacey B. Hoffman, *NCHRP Synthesis of Highway Practice 234: Settlement of Bridge Approaches (The Bump at the End of the Bridge)*, TRB, National Research Council, Washington, DC (1997), p. 4, Figure 1.

Figure C.4. Typical applications of CLSM in bridge approach construction.

Criteria for Bridge Approach Fill

Bridge approach fill generally must fill an open space of some sort, usually a space accessible from above, and it must provide adequate structural support or/and least density for least differential settlements of the bridge approach system. In the case of embankment fill, the fill may provide structural support for pavement above and distribute loads. For bridge abutments fill, the fill is providing support for the wall, usually acting as a bridge between the wall and the area of embankment.

Because of the various applications and needs for bridge approach fill, the criteria noted below have been deemed important. Criteria important to embankment and/or bridge abutments applications are noted. These criteria may not be inclusive for all applications

Flowability

This characteristic is important to both embankment and bridge abutments applications. CLSM must flow from its point of delivery to a reasonable distance, such as along an embankment floor or to the wall. A mixture that is too stiff will not allow the material to reach all necessary locations without the application of additional equipment and labor. A mixture that is too liquid may cause hydrostatic pressure that will build up during construction. It is cautioned that a "runny" mixture may result in containment difficulties if there are small gaps in sandbag bulkheads or similar.

A flow resulting in a circular-type spread with a diameter of 178 to 254 mm as measured by ASTM D 6103 is considered an appropriate criterion.

Setting Time

Frequently, bridge approach fill is an interim operation in construction. That is, additional construction activities are performed overtop or adjacent to the filled area. Accordingly, it is desirable that the CLSM mixture has a setting time consistent with the overall construction schedule. In both cases of embankment and bridge abutment applications, a fast setting time may be desirable so that a pavement layer may be placed on top of the CLSM. In these cases, a general surrogate measurement as to whether the CLSM has sufficiently set is "walkability," that is, when a person of average weight and shoe size can walk on the surface of the CLSM without creating significant (greater than 3 mm) indents in the material. The CLSM mixture should set in such a time, consistent with walkability needs and other measurements, so that it does not unduly delay subsequent or concurrent construction practices.

In general, pavements can be placed over CLSM when the CLSM has reached a compressive strength of [0.2] MPa.

Long-Term Strength

By its very nature, bridge approach fill must provide adequate structural resistance to loads. A minimum strength must be specified that is appropriate to whatever the structural needs (e.g., traffic loads) of the specific application may be.

In rare cases, bridge approach fill may be removed later, such as when additional future construction is performed. For this reason, a predetermined maximum strength is recommended to ensure the future removability of the CLSM.

The actual value of that strength may depend on whether removal is anticipated using manual equipment or machinery.

Permeability

Water permeability is an important issue for bridge approach fill. A very impermeable CLSM mixture may lead, depending on the application design, to excess water being unable to flow through or around the CLSM, which may lead to a buildup of pressures against the abutment, or to washouts at the CLSM-soil interface. The installation of appropriate drainage system shall be carefully evaluated.

Accordingly, a minimum water permeability is established based on the permeability coefficient *k*. The minimum *k* should be [1×10^{-4} mm/s] unless permeability is deemed not to be an issue.

Air Content

Air content requirements are established to provide for the durability in freeze-thaw conditions and/or density limitation of approach fill material. A minimum air content of [6] percent is required for freeze-thaw conditions unless otherwise specified or unless needs suggest a different limit.

Corrosivity

Corrosion is generally not a problem for bridge approach fill unless pipes are installed in the fill.

Corrosion issues come into play in applications when pipes run transversely through a filled area. The soil-CLSM interface can cause an electrochemical potential difference leading to corrosion of metallic pipe in this area. Whenever such an interface exists, it is important to specify either a cathodic protection scheme or a physical protection scheme, such as coating or covering the pipe with a protective layer in this interface region.

Subsidence

Both interim and final grades of construction materials are important for bridge approach fill. It is important to limit or take into account the subsidence of CLSM. Typically, CLSM may "shrink" approximately 6 mm for every 300 mm of depth. Thus, layers above the CLSM, or an additional thin lift of CLSM, may be required after any initial subsidence. It is essential that the proper planning related to subsidence be undertaken.

Other Criteria

Other criteria may become important on a case-by-case basis. The California Bearing Ratio (CBR) or resilient modulus (M_R) of the in-place CLSM may be critical. Performance criteria related to these and other items shall be specified by the engineer, with the appropriate test methods indicated as discussed previously in this report.

Recommended Specification: Bridge Approach Fill

Section 2X2. CLSM Bridge Approach Fill

2X2.01 Description.

Furnish and install bridge approach fill to provide adequate structural support and less settlement bridge approaches.

2X2.02 Material.

CLSM backfill composed of some or all of the following components:

Aggregate	AASHTO M 6 or as approved by the engineer.
Water	Water used in mixing and curing of CLSM shall be subject to approval and shall be reasonably clean and free of oil, salt, acid, alkali, sugar, vegetable, or other substance injurious to the finished project. Water shall be in accordance with AASHTO T 26.
Color agent	ASTM C 979
Cement	AASHTO M 85
Mineral admixtures	AASHTO M 295 or as approved by the engineer.
Chemical admixtures	AASHTO M 194 or as approved by the engineer.

Bridge approach fill may not contain any material deemed toxic or hazardous. Material Safety Data Sheets (MSDS) must be available for any component of the mixture upon request. Bridge approach fill shall be compatible with instruments embedded in it.

2X2.03 Mixture Proportions.

Proportioning of CLSM mixtures shall be the responsibility of the contractor or the contractor's supplier. The mixture may be rejected for failure to meet, or to sustain, the mixture's consistency and all properties specified herein.

2X2.04 Construction.

2X2.04.01 Batching, mixing, and transporting

CLSM may be produced on site or batched at a remote facility and appropriately mixed and transported to the site. If transported, an appropriate transit-mix truck shall be used. [End plugs or lower transport volumes shall be required for mixtures of extreme flowability or as required by the engineer.] Hauling and dumping using a conventional open-haul unit is allowed if approved by the engineer. No blade mixing shall be allowed.

2X2.04.02 Sampling and testing

All CLSM shall be accompanied by a batch ("delivery") ticket that certifies the content of the material and the data on the following items:

(a) Project designation
(b) Date
(c) Time
(d) Compressive strength, f'_c, at 28 days, preferably 91 days
(e) Yield and unit weight
(f) Flowability
(g) Removability modulus (optional)

In addition, the following tests shall be performed for each [100] cubic meters of material delivered and used on the project site.

Strength

Six (6) cylinders will be required, with three (3) cylinders tested according to AASHTO X 3 at 28 days and three (3) cylinders tested at 91 days. The contractor shall be responsible for the curing and protection of the cylinders until such time that they are ready to be tested or to be picked up by the testing agency.

Note: For any project using less than [100] cubic meters of material, three (3) cylinders will be required for every [50] cubic meters of material, with two (2) cylinders tested at 28 days as noted above and the third tested at 91 days.

Flowability

Three (3) samples shall be tested according to ASTM D 6103 on site prior to installation of the material as backfill. The material must provide a flow diameter of no less than [200 mm].

Air Content

For jobs where long-term freeze-thaw durability has been indicated as a concern, the air content of fresh CLSM will be determined using AASHTO X 2 prior to installation of the material as backfill. The CLSM must have an air content no less than [6] percent by volume.

2X2.04.03 Site Preparation

Clear the space to be filled of any deleterious material; soil clods; loose, sloughing, caving, or otherwise unsuitable soil; or other materials such that a reasonably clear and clean fill area is provided.

No placement of CLSM shall commence until all items have been inspected by the engineer and approved for bridge approach filling. [Wait [7] days or meet a minimum compressive strength of [19] MPa before backfilling against newly constructed masonry or concrete abutments.]

For embankment or abutment applications, provide suitable containment to ensure that the CLSM will not flow into areas beyond those specified on the plans.

If standing water exists, it must be removed through appropriate water control measures. Soil shall be allowed to dry until suitable for placement of CLSM as approved by the engineer.

Ensure that all sheeting and bracing, temporary formwork, and other items assisting with the construction can be removed after completion of the CLSM placement.

2X2.04.04 Placement

Placement of CLSM shall be completed no more than [30] minutes after the end of mixing.

Place the CLSM directly in the contained space in or behind the bridge abutments.

Place the CLSM using pumps, chutes, or any other method as approved by the engineer. Place the CLSM in lifts such that the hydrostatic pressures developed will not compromise the integrity of bulkheads, formwork, trench or other soil walls, or other temporary or permanent structures.

Placement shall bring the material up uniformly to lines or limits as shown on plans.

For cases in which subsidence effects on the final grade are critical, place a final lift that will account for estimated subsidence or otherwise ensure that the final grades on the plans can be achieved and maintained.

The CLSM shall be applied in such a manner that no labor is required in the trench or excavation. No compaction or vibration equipment shall be allowed.

The CLSM must have a minimum temperature of [10] °C at the time of placement.

Place CLSM only in conditions where the ambient temperature is greater than [4] °C. Do not place CLSM in contact with frozen soil or other material. Once placed, keep the CLSM from freezing for a period of no less than [36] hours.

CLSM may not be placed in conditions of inclement weather (e.g., rain) unless approved by the engineer. [CLSM may be placed in conditions of inclement weather (e.g., rain), if any rainfall does not result in ponding on the surface of the in-place material and the requirements for minimal standing water, noted above, are met.]

For bridge abutment fill, ensure and maintain the appropriate horizontal and vertical alignment of abutment walls prior to and during the placement procedure, and until such time as the CLSM has set to sufficient stiffness to exert minimum forces on the walls. Use soil counter fill or other approved means of restraint.

Coat or protect pipes as needed when pipes traverse soil and CLSM.

Pipe or other items damaged by the contractor during construction shall be replaced at the contractor's expense or repaired to the satisfaction of the engineer.

2X2.05 Acceptance.

Material acceptance shall be based on all criteria specified herein, plus the following:

Strength: a 28-day compressive strength of no more than [8.4 MPa] and no less than [0.35 MPa].

Flowability: a diameter of no more than [225 mm] and no less than [178 mm].

Removability modulus: a value, calculated using in-situ density and [91-day] compressive strength, or as dictated by the anticipated removal methods and as specified by the engineer, if future excavation is expected, or as based on documented local experiences of excavation as provided by the contractor.

2X2.06 Measurement.

Measurement shall be based on the payment lines indicated on the plans. Payment shall be based on the CLSM in its hardened state. No payment shall be made for additional material required by slips, slides, cave-ins, over-excavation, or other actions resulting from the elements or from construction activities. No payment shall be made for unused or wasted material.

2X2.07 Payment.

Payment shall be per cubic meter of in-place material including all costs for furnishing all materials, equipment, labor, and incidentals necessary to complete this item.

APPENDIX D

Recommended Practice for CLSM

1. **SCOPE**
   1.1. This Recommended Practice is focused on criteria, specifications, and guidelines for the use of controlled low-strength material (CLSM) for backfill, utility bedding, void fill, and bridge approach applications.
   1.2. The Recommended Practice describes methods, limits, and issues related to the successful application of CLSM.
   1.3. The Recommended Practice is based on the research results described in the Final Report for NCHRP Project 24-12(01), including the content of the appendices. It should be used in conjunction with the findings, test methods, and specifications described therein.
2. **PREAMBLE**
   2.1. Transportation agencies face challenges related to the use of traditional backfill material (soil) or higher strength cementitious materials with respect to the combination of timely construction, ease of construction, quality control, and ease of removal, if required.
      2.1.1. CLSM has attributes that make it a potentially effective option for state departments of transportations (DOTs) and other agencies involved with backfilling or void-filling operations.
      2.1.2. CLSM is a material with variable properties that can result in poorer than expected performance without proper guidance for the user.
   2.2. Careful consideration of CLSM constituent materials, mixture proportioning, testing, handling, and excavation is required for CLSM to be an optimal alternative to the use of traditional materials.
   2.3. Where guidance related to properties, specifications, or other items cannot be specific, ranges of values are shown. Where appropriate ranges have not yet been identified, no values are shown. Anywhere that brackets [] are indicated, the user is cautioned to make a reasoned judgment as to values to be included. The use of ranges in this Recommended Practice is not meant to indicate the appropriateness of those ranges for all applications.
3. **USAGE DECISIONS AND PREPARATIONS FOR CLSM**
   3.1. As noted in the sections that follow, CLSM serves as a substitute primarily for structural fill. Thus, CLSM should be considered for projects where its advantages (e.g., flowability and related construction time savings) outweigh any potential disadvantages (e.g., additional materials costs).
   3.2. Agencies should consider preparing or recommending training to contractors who may undertake CLSM projects in their jurisdiction.
      3.2.1. CLSM, as a material that differs notably from structural fill and ready-mixed concrete, requires familiarity with its purposes, mixture design, testing, and installation to help ensure a quality project. A project with a contractor who takes on a first CLSM job with inadequate preparation may result in loss of anticipated advantages of the CLSM and in concerns about future uses of the material.
4. **APPLICATIONS AND RELATED GUIDANCE**
   4.1. BACKFILL
      4.1.1. Definitions and Types
         4.1.1.1. Backfill as intended in this Recommended Practice relates to the infill material to cover pipes (in trench applications) up to a specified grade (usually equal to the grade of undisturbed earth on either side of a trench wall) or to the horizontal-reaction–providing infill adjacent to retaining walls and other wall

structures. The CLSM is the alternative to the infill material that is typically a compacted granular structural fill.

4.1.1.2. Backfill is not the same as utility bedding, although it can be contiguous with such bedding. Backfill also is not the same as void fill; the primary difference is that backfill is placed against a structure with the purpose of providing at least some structural resistance to loads.

4.1.1.3. Figure D.1 indicates two common backfill applications for which CLSM may be a candidate.

4.1.2. Criteria of Importance

4.1.2.1. Backfill generally must fill an open space of some sort, usually a space accessible from above, and it must provide some sort of structural support for the object that is being backfilled. In the case of a trench, the backfill may provide structural support for part of the pipe and the trench wall. For bridge abutments, retaining walls, and other walls, the backfill is providing support for the wall, usually acting as a bridge between the wall and the area of unexcavated, natural earth.

4.1.2.2. Flowability is important to both trench and wall applications. CLSM must flow from its point of delivery to a reasonable distance, such as along a trench floor or to the wall. A mixture that is too stiff will not allow the material to reach all necessary locations without the application of additional equipment and labor. A mixture that is too liquid (no severe segregation) is generally not a problem, if all other material properties discussed below are met. “Runny” mixtures may cause difficulties if there are small gaps in sandbag, bulkheads, or similar retaining structures.

4.1.2.2.1. A flow resulting in a circular-type spread with a diameter of [175 to 250 mm] as measured by ASTM D 6103 is considered an appropriate criterion for backfill applications.

4.1.2.3. The CLSM mixture should have a setting time consistent with the overall construction schedule, because backfilling is an interim operation in construction.

4.1.2.3.1. For trenches under roadways or similar applications, fast setting times may be desirable so that a pavement layer may be placed on top of it.

4.1.2.3.2. For wall backfill, or in other trench applications, a general surrogate measurement as to whether the CLSM has sufficiently set is “walkability,” that is, when a person of average weight and shoe size can walk on the surface of the CLSM without creating significant (greater than 3 mm) indents in the material. The CLSM mixture should set in such a time, consistent with walkability needs and other measurements, so that it does not unduly delay subsequent or concurrent construction practices.

4.1.2.3.3. Pavements generally can be placed over CLSM when the CLSM has reached a strength of [0.2] MPa or a penetration resistance of [2.8] MPa according to the recommended test method in Appendix B.

4.1.2.4. Long-term strength issues should be considered, so that backfill may be removed later, such as when a pipe requires repair, or when additional future construction is performed.

4.1.2.4.1. CLSM should have some predetermined maximum strength to ensure its future removability.

4.1.2.4.1.1. Laboratory-cured samples behave differently than field applications. Field curing test samples may be useful, especially if the application will occur at high temperatures and/or will include fly ash.

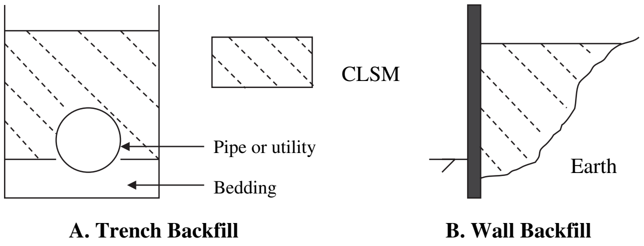


Figure D.1. Common backfill applications.

- 4.1.2.4.2. For hot-weather construction, CLSM mixtures containing fly ash may obtain higher strength in the field than estimated in the laboratory. The actual value of that strength may depend on whether removal is anticipated using manual equipment or machinery.
  - 4.1.2.4.2.1. The use of a dynamic cone penetrometer (DCP) test on site prior to excavation may allow for obtaining different equipment than originally anticipated if the actual in-situ strength is higher than anticipated.
  - 4.1.2.4.2.2. Including aggregates in CLSM mixtures will generally result in more difficult excavation (than CLSM without aggregates). Most CLSM does contain fine aggregate, and, in rare instances, CLSM can also contain coarse aggregate. For CLSM mixtures with similar compressive strengths, CLSM without aggregate is easier to excavate than CLSM containing fine aggregate, which is easier to excavate than CLSM containing coarse aggregate (with or without fine aggregate).
  - 4.1.2.4.2.3. Correlation tests for CLSM mixtures and their excavatability may be useful to anticipate long-term strength gain for future excavation.
  - 4.1.2.4.2.4. The removability modulus predictor (as developed by Hamilton County, Ohio), when used in conjunction with unit weight values, provides good estimates of excavatability.
  - 4.1.2.4.2.5. If feasible, core cylinders should be kept at the site (perhaps buried in a nearby area) and then tested shortly before an excavation operation. This test may provide the best measure of excavatability of the actual application.
- 4.1.2.4.3. Backfill must provide some structural resistance to loads. A minimum strength must be specified that is appropriate to whatever the structural needs (e.g., traffic loads) of the specific application may be.

4.1.2.5. Impermeability of CLSM may lead to difficulty in locating gas leaks in pipelines (when using typical leak detection equipment used for conventional backfill). This concern applies only to trench backfill applications.

4.1.2.6. Water permeability may be an issue to both trench backfill and to wall backfill. A barely permeable CLSM mixture may cause leaking water to travel along a pipe length until it reaches a suitable fissure in the CLSM. Thus, the location of evidence of water leakage (bubbling or ballooning of the ground surface, for example) may not coincide with the actual location of a pipe leak, causing difficulty in determining the exact location of the damaged pipe. For wall backfills, a nearly impermeable CLSM mixture may lead, depending on the application design, to excess water being unable to flow through or around the CLSM, which may lead to a buildup of water pressures against a wall or to washouts at the CLSM-soil interface. For applications where pipes are located near the foot of abutment walls, the locations of leaks may become difficult to ascertain in much the same way as they may be in trenches.

- 4.1.2.6.1. A minimum permeability is established based on the water permeability coefficient *k*. The minimum *k* should be [1×10^{-4} mm/s] unless permeability is deemed not to be an issue. The permeability coefficient can be measured using the recommended test method in Appendix B.

4.1.2.7. Proper air content will provide for the durability of backfill material in freeze-thaw conditions. A minimum air content of [6] percent is required unless otherwise specified or unless needs suggest a different limit. Also, for a given CLSM mixture, the higher the strength, the better the resistance to frost-induced damage.

4.1.2.8. Corrosion issues should be considered for trench applications when pipes run transversely through a backfilled area. The soil-CLSM interface can cause an electrochemical potential leading to corrosion of metallic pipe in this area (this potential can occur when different soils interface without the presence of CLSM also). CLSM generally is a better environment than soil backfill with respect to corrosion problems.

- 4.1.2.8.1. Wrapping or coating pipe in the interface region may be an effective corrosion mitigation approach.
- 4.1.2.8.2. Whenever such an interface exists, it is important to specify either a cathodic protection scheme or a physical protection scheme, such as coating or covering the pipe with a protective layer in this interface region.

4.1.2.9. Where interim and final grades of construction materials are important, such as in a trench transverse to a roadway (where subsidence could cause a dip in the final roadway surface or cracking in an asphalt or portland cement concrete or chip-seal surface because of uneven support conditions), it is important to limit or take into account the subsidence of CLSM. Typically, CLSM may "shrink" approximately 6 mm for every 300 mm of depth. Thus, layers above the CLSM, or an additional thin lift of CLSM, may be required after any initial subsidence. Because overfilling trenches is impractical (because the CLSM would simply run over the edges), the proper planning related to subsidence must be undertaken.

4.1.2.10. Because pipes may exhibit buoyancy ("pipe floating"), weighting or securing of pipes in CLSM applications may be required.

4.1.2.11. Case-by-case analyses of special conditions requiring special criteria should be conducted.

4.1.2.11.1. Thermal properties of the CLSM backfill may be important for a utility application in which hot or cold water is being piped.

4.1.2.11.2. For roadway support–related applications, the California Bearing Ratio (CBR) or resilient modulus (M_R) of the in-place CLSM may be critical. Performance criteria related to these and other items should be specified by the engineer, with the appropriate test methods indicated as described in Appendix B.

4.1.3. Specifications Issues

4.1.3.1. Agency construction and other documents should consider appropriate descriptions when specifying CLSM as backfill.

4.1.3.2. A sample work description could state: "Furnish and install backfill to provide necessary structural support for utilities, trench walls, retaining walls, abutments, and other applications."

Material specifications should note that CLSM may be composed of some or all of the following components and their associated specification or test method:

Aggregate	AASHTO M 6 or as approved by the engineer.
Water	Water used in mixing and curing of CLSM shall be subject to approval and shall be reasonably clean and free of oil, salt, acid, alkali, sugar, vegetable, or other substance injurious to the finished product. Water shall be in accordance with AASHTO T 26.
Color agent	ASTM C 979
Cement	AASHTO M 85
Mineral admixtures	AASHTO M 295 or as approved by the engineer.
Chemical admixtures	AASHTO M 194 or as approved by the engineer.

4.1.3.3. Backfill should not contain any material deemed toxic or hazardous. Material Safety Data Sheets (MSDS) must be available for any component of the mixture upon request. Backfill shall be compatible with bedding materials, electrochemically and otherwise if used as a metal pipe backfill application.

4.1.3.4. Proportioning of CLSM mixtures should be the responsibility of the contractor or the contractor's supplier. The mixture should be rejectable for failure to meet, or to sustain, the mixture's consistency and all properties specified herein.

4.1.3.5. Construction specifications should include guidance on batching, mixing, and transportation, such as the following: CLSM may be produced on site or batched at a remote facility and appropriately mixed and transported to the site. If transported, an appropriate transit-mix truck shall be used. [End plugs or lower transport volumes shall be required for mixtures of extreme flowability or as required by the engineer.] Hauling and dumping using a conventional open-haul unit is allowed if approved by the engineer. No blade mixing shall be allowed.

4.1.3.6. Guidance on sampling and testing should be included in project specifications, such as the following: All CLSM shall be accompanied by a batch ("delivery") ticket that certifies the content of the material and the data on the following items: (a) project designation; (b) date; (c) time; (d) compressive strength, f'_c; (e) yield and unit weight; (f) flowability; and (g) removability modulus (optional).

4.1.3.6.1. The following tests should be performed for each [100] cubic meters of material delivered and used on the project site.

Strength

Six (6) cylinders will be required, with three (3) cylinders tested according to the test method in Appendix B at 28 days and three (3) cylinders tested at 91 days. The contractor shall be responsible for the curing and protection of the cylinders until such time that they are ready to be tested or to be picked up by the testing agency.

Note: For any project using less than [100] cubic meters of material, three (3) cylinders will be required for every [50] cubic meters of material, with two (2) cylinders tested at 28 days as noted above and the third tested at 91 days.

Flowability

Three (3) samples shall be tested according to ASTM D 6103 on site prior to installation of the material as backfill. The material must provide a flow diameter of no less than 200 mm, unless specified by the engineer.

Air Content

For jobs where long-term freeze-thaw durability has been indicated as a concern, the air content of fresh CLSM will be determined using the test method in Appendix B prior to installation of the material as backfill. The CLSM must have an air content no less than [6] percent by volume.

4.1.3.6.2. Site preparation guidance should consider inclusion of the following language.

4.1.3.6.2.1. If utility bedding is not already present, excavate to line and grade shown on the plans or described in the specifications. Excavate rock, hardpan, and other unyielding material to [300] mm below the designed trench grade. If utility bedding is present, ensure that the bedding is not covered by rock, soil, or deleterious material.

4.1.3.6.2.2. Clear the trench or wall area of any deleterious material; soil clods; loose, sloughing, caving, or otherwise unsuitable soil; or other materials such that a reasonably clear and clean fill area is provided.

4.1.3.6.2.3. Cleanup and backfill of trenches for water mains shall begin immediately upon completion of the hydrostatic test (if necessary) or as directed by the engineer.

4.1.3.6.2.4. No placement of CLSM shall commence until all items have been inspected by the engineer and approved for backfilling. [Wait [7] days or meet a minimum compressive strength of [19] MPa before backfilling against newly constructed masonry or concrete structures.]

4.1.3.6.2.5. For trench applications, provide suitable vertical wall containment such as sandbag or soil bulkheads to limit the flow distance of the CLSM to no more than [20] m from the discharge location. For backfill applications, provide suitable vertical wall containment to ensure that the CLSM will not flow into areas beyond those specified on the plans. For steeply sloping trenches, provide bulkheads at intervals as approved by the engineer.

4.1.3.6.2.6. If standing water exists, CLSM may be poured if the standing water represents no more than approximately [4] percent of the volume of CLSM to be placed in a single lift. If more water than this limit is present, it must be removed through appropriate water control measures.

4.1.3.6.2.7. Ensure that all sheeting and bracing, temporary formwork, and other items assisting with the construction can be removed after completion of the CLSM placement.

- 4.1.3.6.2.8. Whenever excavation is made for structures across private property, the topsoil removed in the excavation shall be kept separate and replaced, as nearly as feasible, in its original position, and the entire area shall be restored to a condition acceptable to the engineer.

4.1.3.6.3. Placement guidance should include consideration of the following language:

- 4.1.3.6.3.1. Placement of CLSM shall be completed no more than [90] minutes after the end of mixing. For fast-setting CLSM mixture, the material shall be mixed on site and placed immediately.
- 4.1.3.6.3.2. Place the CLSM directly in the trench or excavation.
- 4.1.3.6.3.3. Place the CLSM using pumps, chutes, or any other method as approved by the engineer. Place the CLSM in lifts such that the hydrostatic pressures developed will not compromise the integrity of bulkheads, formwork, trench or other soil walls, or other temporary or permanent structures.
- 4.1.3.6.3.4. Placement shall bring the material up uniformly to lines or limits as shown on plans.
- 4.1.3.6.3.5. For cases in which subsidence effects on the final grade are critical, place a final lift that will account for estimated subsidence or otherwise ensure that the final grades on the plans can be achieved and maintained.
- 4.1.3.6.3.6. The CLSM shall be applied in such a manner that no labor is required in the trench or excavation. No compaction or vibration equipment shall be allowed.
- 4.1.3.6.3.7. The CLSM must have a minimum temperature of [10] °C at the time of placement.
- 4.1.3.6.3.8. Place CLSM only in conditions where the ambient temperature is greater than [4] °C. Do not place CLSM in contact with frozen soil or other material. Once placed, keep the CLSM from freezing for a period of no less than [36] hours.
- 4.1.3.6.3.9. CLSM may not be placed in conditions of inclement weather (e.g., rain) unless approved by the engineer. [CLSM may be placed in conditions of inclement weather (e.g., rain) as long as any rainfall does not result in ponding on the surface of the in-place material and that the requirements for minimal standing water, noted above, are met.]
- 4.1.3.6.3.10. For projects in which no pipe bedding is in place, ensure and maintain the appropriate horizontal and vertical alignment of pipes and fixtures prior to and during the placement procedure, and until such time as the CLSM has set to sufficient strength to hold the pipes in place. Use straps, soil anchors, or other approved means of restraint.
- 4.1.3.6.3.11. Pipe or other items damaged by the contractor during construction shall be replaced at the contractor's expense or repaired to the satisfaction of the engineer.

4.1.3.6.4. Material acceptance guidance should consider inclusion of the following language:

- 4.1.3.6.4.1. Material acceptance shall be based on all criteria specified, plus local experience with excavatability, including the following:
  - 4.1.3.6.4.1.1. Strength: a 28-day compressive strength of no more than [1 MPa] and no less than [0.2 MPa].
  - 4.1.3.6.4.1.2. Flowability: a diameter of no more than [250 mm] and no less than [175 mm].
  - 4.1.3.6.4.1.3. Removability modulus: a value, calculated using in-situ density and [91-day] compressive strength, or as dictated by the anticipated removal methods and as specified by the engineer.

4.1.3.6.5. Material measurement guidance should consider inclusion of the following language:

- 4.1.3.6.5.1. Measurement shall be based on the payment lines indicated on the plans. Payment shall be based on the CLSM in its hardened state. No payment shall be made for additional material required by slips, slides, cave-ins, over-excavation, or other actions resulting from the elements or from construction activities. No payment shall be made for unused or wasted material.

4.1.3.6.5.2. Material payment guidance should consider inclusion of the following language:

4.1.3.6.5.2.1. Payment shall be per cubic meter of in-place material including all costs for furnishing all materials, equipment, labor, and incidentals necessary to complete this item.

4.2. UTILITY BEDDING

4.2.1. Definitions and Types

4.2.1.1. Utilities could include pipe, electrical, telephone, and other types of conduits.

4.2.1.2. Utility bedding relates to the preplaced or infill material to provide support strength for utilities (usually underground). CLSM is the alternative to a bedding material that is typically a compacted granular structural fill.

4.2.1.3. Utility bedding is not the same as backfill, although it can be contiguous with such backfill in the case of encasing the entire conduit. Utility bedding also is not the same as void fill; the primary difference is that utility bedding is placed underneath the utility structure with the purpose of providing supporting strength to the utilities and distributing loads and reactions.

4.2.1.4. Figure D.2 indicates two common utility bedding applications for CLSM.

4.2.2. Criteria of Importance

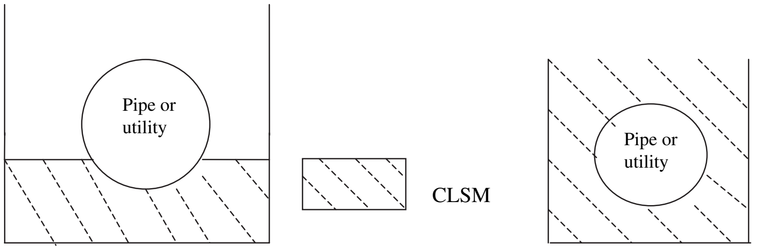
4.2.2.1. Utility bedding generally must provide enough support strength for the utilities, usually by influencing the load and reaction distribution and the resultant lateral pressures. In the case of bedding only, the bedding may provide structural support for the utility and distribute the reaction. For encasing the entire conduit, the application is providing support for the conduit, distributing the reaction, and transferring the load.

4.2.2.2. When CLSM is used for utility bedding, the width of excavation ("trench width") shown on the plans may need to be changed so that the clear distance between the outside of the pipe and the side of the excavation, on each side of the pipe, is a minimum of [150 mm], except that [300 mm] should be required for pipes of [1,050 mm] and greater in diameter or span when height of cover is greater than [6.1 m].

4.2.2.3. Because CLSM is in a liquid state during placing, it will exert flotation on structures. It is cautioned that such flotation force may cause damage to the structures, especially when the structures do not have adequate resistance. Generally, CLSM shall not be used with underground structures having a span greater than [6.1 m], unless otherwise approved by the engineer.

4.2.2.4. The criteria for backfill noted previously that are also applicable to utility bedding include the following, with the same guidance on tests and specification limits:

4.2.2.4.1. Flowability (so that the material may flow along a trench floor and fill all spaces beneath the conduit that it is supporting)
4.2.2.4.2. Subsidence (such that conduit that is entirely encased does not lose support)
4.2.2.4.3. Setting time
4.2.2.4.4. Strength
4.2.2.4.5. Permeability
4.2.2.4.6. Air content



A. Bedding Only

B. Encasing of Conduit

Figure D.2. Typical applications of CLSM in utility bedding.

- 4.2.2.4.7. Corrosion (with the understanding that conduits entirely encased in CLSM are unlikely to exhibit corrosion resulting from electrochemical potential differences)
- 4.2.2.4.8. Thermal properties
- 4.2.2.4.9. Roadway support properties

4.2.3. Specifications Issues
  - 4.2.3.1. Specifications, construction, materials, measurement, and payment guidance for backfill should be considered, plus the following issues:
    - 4.2.3.1.1. No placement of CLSM shall commence until all items have been inspected by the engineer and approved for utility bedding.
    - 4.2.3.1.2. Adequate conduit anchorage shall be provided to ensure the movement of supported structure is within tolerance limits, as designated by the engineer.
    - 4.2.3.1.3. For bedding applications, provide suitable vertical wall containment such as sandbag or soil bulkheads to limit the flow distance of the CLSM to no more than [20] m from the discharge location. For encasing applications, provide suitable vertical wall containment to ensure that the CLSM will not flow into areas beyond those specified on the plans. For steeply sloping trenches, provide bulkheads at intervals as approved by the engineer.
    - 4.2.3.1.4. The time limit for placement of CLSM should be no more than [30] minutes after the end of mixing.
    - 4.2.3.1.5. CLSM should be carefully placed to fit the lower part of the conduit exterior for a width of at least 60 percent of the conduit breadth. Make sure no voids exist underneath the conduit. Placement should bring the material up uniformly to lines or limits as shown on plans.

4.3. VOID FILL

4.3.1. Definition and Types
  - 4.3.1.1. Void fill relates to the infill material to occupy empty spaces created by erosion, construction, abandonment, and other activities.
  - 4.3.1.2. The use of CLSM is a unique solution for void fills that are difficult, if not impossible, to fill with a compacted granular fill.
  - 4.3.1.3. Void fill is not the same as utility backfill, although it can be similar. The primary difference is that void fill is generally placed to occupy empty spaces rather than to provide a sort of structural support.
  - 4.3.1.4. Figure D.3 illustrates a typical void where CLSM can be applied.

4.3.2. Criteria of Importance
  - 4.3.2.1. Void fill generally must fill an open or covered space of some sort, usually a space accessible from above, and it must occupy the space with minimum large voids left behind.
  - 4.3.2.2. Its application must not cause undesired movement or damage of adjacent structures.
  - 4.3.2.3. Flowability must be considered. CLSM must flow from its point of delivery to a reasonable distance, such as reaching the other end of the void. A mixture that is too stiff will not allow the material to reach all necessary locations without the use of additional equipment and labor. A mixture that is too liquid is generally not a problem, if all other material properties discussed below are met.
    - 4.3.2.3.1. A flow resulting in a circular-type spread with a diameter of [175 to 250 mm] as measured by ASTM D 6103 is considered an appropriate criterion, or as decided by the engineer.

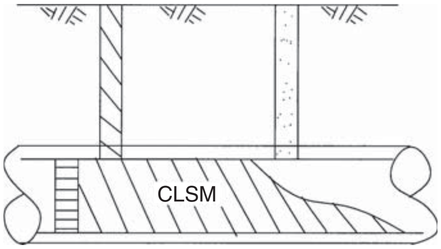


Figure D.3. Typical applications of CLSM in void fill.

4.3.2.4. In cases where subsidence could cause a dip in the final surface, it is important to limit or take into account the subsidence of CLSM, if necessary. Typically, CLSM may "shrink" approximately 6 mm for every 300 mm of depth. Because overfilling voids is impractical (because the CLSM would simply run over the edges), proper planning related to subsidence must be undertaken.

4.3.2.5. If void fill must provide some structural resistance to loads, a minimum strength must be specified that is appropriate to whatever the structural needs of the specific application may be.

4.3.2.6. If the weight of void fill may cause disturbance to foundations of adjacent structures, appropriate considerations to unit weight, air content, or other issues are essential. Performance criteria related to these and other items should be specified by the engineer, with appropriate test methods indicated.

4.3.2.7. The criteria for backfill noted previously are also applicable to void fill, with the same guidance on tests and specification limits.

4.3.3. Specifications Issues

4.3.3.1. Specifications, construction, materials, measurement, and payment guidance issues noted for backfill should also be considered for void fill, as appropriate.

4.4. BRIDGE APPROACHES

4.4.1. Definition and Types

4.4.1.1. Bridge approach fill relates to the infill material to work as embankment (in fill behind bridge abutments applications) up to a specified grade (usually equal to the grade of pavement) or to the infill for bridge abutment.

4.4.1.2. CLSM is the alternative of an infill material that is typically a compacted granular structural fill.

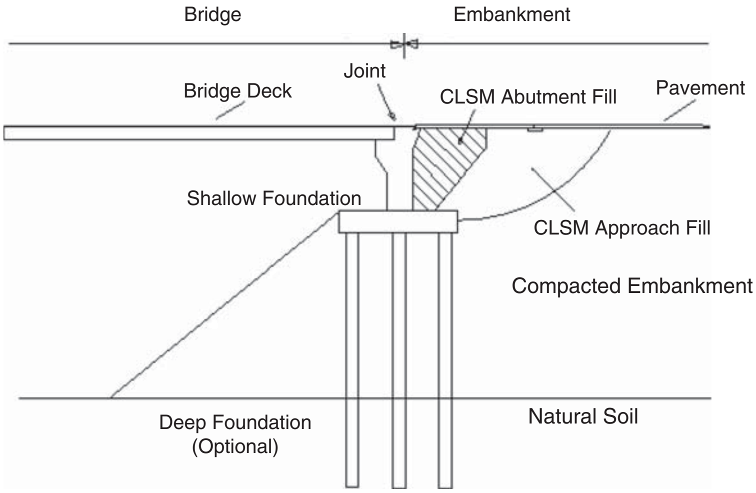
4.4.1.3. Bridge approach fill is not the same as utility bedding, backfill, or void fill; the primary difference is that bridge approach fill is placed against a structure with the purpose of providing adequate structural resistance to loads.

4.4.1.4. Figure D.4 indicates common bridge approach fill applications.

4.4.2. Criteria of Importance

4.4.2.1. Bridge approach fill generally must fill an open space of some sort, usually a space accessible from above, and it must provide adequate structural support or/and least density for least differential settlements of the bridge approach system.

4.4.2.2. In the case of embankment fill, the fill may provide structural support for pavement above and distribute loads.



Source: Modified from Jean-Louis Briaud, Ray W. James, and Stacey B. Hoffman, *NCHRP Synthesis of Highway Practice 234: Settlement of Bridge Approaches (The Bump at the End of the Bridge)*, TRB, National Research Council, Washington, DC (1997), p. 4, Figure 1.

Figure D.4. Typical applications of CLSM in bridge approach construction.

4.4.2.3. For bridge abutment fill, the fill is providing support for the wall, usually acting as a bridge between the wall and the area of embankment.

4.4.2.4. Because of the varying nature of the bridge approach, not all criteria below may be important for all applications.

4.4.2.5. The criteria for backfill noted previously that are also applicable to utility bedding include the following, with the same guidance on tests and specification limits:

4.4.2.5.1. Flowability

4.4.2.5.2. Subsidence

4.4.2.5.2.1. Both interim and final grades of construction materials are important for bridge approach fill.

4.4.2.5.3. Setting time

4.4.2.5.4. Strength (By its very nature, bridge approach fill must provide adequate structural resistance to loads. A minimum strength must be specified that is appropriate to whatever the structural needs (e.g., traffic loads) of the specific application may be. In rare cases, bridge approach fill may be removed later, such as when additional future construction is performed. For this reason, a predetermined maximum strength is recommended to ensure future removability of the CLSM. The actual value of that strength may depend on whether removal is anticipated using manual equipment or machinery.)

4.4.2.5.5. Permeability

4.4.2.5.5.1. Water permeability is an important issue for bridge approach fill. A very impermeable CLSM mixture may lead, depending on the application design, to excess water being unable to flow through or around the CLSM, which may lead to a buildup of water pressures against the abutment or to washouts at the CLSM-soil interface. The installation of appropriate drainage system shall be carefully evaluated.

4.4.2.5.5.2. Minimum water permeability is established based on the permeability coefficient k. The minimum k should be [1×10^{-4} mm/s] unless permeability is deemed not to be an issue.

4.4.2.5.6. Air Content

4.4.2.5.7. Corrosion (only if pipes or other metallic components are installed in the fill)

4.4.2.5.8. Thermal properties

4.4.2.5.9. Roadway support properties

4.4.3. Specifications Issues

4.4.4. Specifications, construction, materials, measurement, and payment guidance similar to that of backfill are appropriate for bridge approach applications, with some revisions.

4.4.4.1. For bridge abutment fill, ensure and maintain the appropriate horizontal and vertical alignment of abutment walls prior to and during the placement procedure, and until such time as the CLSM has set to sufficient stiffness to exert minimum forces on the walls. Use soil counter fill or other approved means of restraint.

4.4.4.2. A 28-day compressive strength of no more than [8.4 MPa] and no less than [0.35 MPa] should be considered.

4.4.4.3. A flowability test diameter of no more than [225 mm] and no less than [178 mm] should be considered.

5. METHODS FOR LONG-TERM IMPROVEMENT OF PRACTICE

5.1. CLSM is a product whose future performance is best predicted by past performance in similar situations for similar mixtures. Accordingly, where practical, efforts should be made to include samples for short- and long-term testing of CLSM material for every job.

5.2. As noted previously, where practical, specimens of the CLSM should be buried adjacent to the project site, in as similar conditions as possible, so that long-term properties of the CLSM can be tested. The performance of CLSM is highly dependent on the curing, climatic, and local field conditions, and such specimens will allow for both better prediction of properties under those conditions, and for the specific probable excavatability of the CLSM at that site should it be required.

5.2.1. Such test cylinders should be tested for excavatability prior to establishing the contract documents and schedule for a follow-up project, because of the likelihood of the test results indicating long-term strength gains that may differ from anticipated ones.

5.3. Agencies should consider developing performance-tracking methods for CLSM applications. Relevant material and project information should be recorded, including mixture design, constituent materials (and their sources), specified test methods (and their results), and actual follow-up performance data where available.

  5.3.1. Follow-up performance data should include any site observations made by maintenance or construction crews. For example, on a trench fill application in a roadway, if noticeable subsidence of the CLSM occurs that results in roadway damage, note should be taken. If excavation of a utility trench backfill requires more powerful equipment than was anticipated based on the original project material and construction specification (e.g., if the removability was designed for hand tools and requires power equipment), it should be noted.

5.4. Corrosion activity for utility or other applications should be tracked at sites that undergo later excavation. Because corrosion tends to be a longer term phenomenon, laboratory or short-term predictive tests can provide only limited guidance.

5.5. Where actual field performance of CLSM differs dramatically from the specified or predicted performance, efforts should be made to engage forensic studies of the site by appropriate experts, either in house or under contract. Results of such studies should be shared both among all applicable portions of the agency and with the industry at large to help provide better understanding of the causes of variable CLSM performance.

  5.5.1. Agencies should consider noting the major "repositories" of information related to CLSM, such as the American Concrete Institute Committee 229, the National Ready-Mixed Concrete Association, and others, so that all appropriate information can be shared with those groups.

APPENDIX E

Implementation Plan

This appendix is available on the TRB website as part of *NCHRP Web-Only Document 116* (www.trb.org/news/blurb_detail.asp?id=8714).

Abbreviations and acronyms used without definitions in TRB publications:

AAAE	American Association of Airport Executives
AASHO	American Association of State Highway Officials
AASHTO	American Association of State Highway and Transportation Officials
ACI–NA	Airports Council International–North America
ACRP	Airport Cooperative Research Program
ADA	Americans with Disabilities Act
APTA	American Public Transportation Association
ASCE	American Society of Civil Engineers
ASME	American Society of Mechanical Engineers
ASTM	American Society for Testing and Materials
ATA	Air Transport Association
ATA	American Trucking Associations
CTAA	Community Transportation Association of America
CTBSSP	Commercial Truck and Bus Safety Synthesis Program
DHS	Department of Homeland Security
DOE	Department of Energy
EPA	Environmental Protection Agency
FAA	Federal Aviation Administration
FHWA	Federal Highway Administration
FMCSA	Federal Motor Carrier Safety Administration
FRA	Federal Railroad Administration
FTA	Federal Transit Administration
IEEE	Institute of Electrical and Electronics Engineers
ISTEA	Intermodal Surface Transportation Efficiency Act of 1991
ITE	Institute of Transportation Engineers
NASA	National Aeronautics and Space Administration
NASAO	National Association of State Aviation Officials
NCFRP	National Cooperative Freight Research Program
NCHRP	National Cooperative Highway Research Program
NHTSA	National Highway Traffic Safety Administration
NTSB	National Transportation Safety Board
SAE	Society of Automotive Engineers
SAFETEA-LU	Safe, Accountable, Flexible, Efficient Transportation Equity Act: A Legacy for Users (2005)
TCRP	Transit Cooperative Research Program
TEA-21	Transportation Equity Act for the 21st Century (1998)
TRB	Transportation Research Board
TSA	Transportation Security Administration
U.S.DOT	United States Department of Transportation