A Novel Abutment Construction Technique for Rapid Bridge Construction: CLSM with Full-Height Concrete Panels

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16. Abstract

One of the major obstacles facing rapid bridge construction for typical span type bridges is the time required to construct bridge abutments and foundations. This can be remedied by using the controlled low strength materials (CLSM) bridge abutment. The CLSM bridge abutment comprises full-height precast concrete panels attached to a CLSM backfill via epoxy-coated steel anchors. The main objective of this study is to examine the application of the CLSM bridge system in typical span type bridges used in railroad and highway situations. To do so, an instrumented, large-scale laboratory test was performed on a CLSM bridge abutment to investigate its performance due to the application of a monotonically increasing sill (foundation) pressure. The test results show that the CLSM bridge abutment, with a relatively short cure time of 7 days, is capable of carrying bridge loads with a reasonably large safety margin, and with minimal deformations.

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EXECUTIVE SUMMARY

A Novel Abutment Construction Technique for Rapid Bridge Construction: Controlled Low Strength Materials (CLSM) with Full-Height Concrete Panels

PROBLEM STATEMENT

Rapid construction/replacement methods for railroad and highway bridges are essential to maintaining freight movement with minimal adverse economic effects. Prefabricated bridge components, including bridge girders, bridge decks, and segmental piers, have been used successfully in the U.S. and abroad for rapid bridge construction, and adequate information is currently available for the use of such bridge components; however, there is a major obstacle facing rapid bridge construction for "typical" span type bridges used in railroad and highway applications: constructing bridge abutments and their deep foundations (piles) is very time-consuming, thereby rendering any rapid bridge construction method less effective. Therefore, there is an urgent need to develop and use a novel method of accelerated construction for bridge abutments and foundations.

RESEARCH OBJECTIVES

To reduce the time required to construct bridge abutments, a "controlled low strength materials (CLSM) bridge abutment" can be used. The CLSM bridge abutment comprises full-height precast concrete panels attached to a CLSM backfill via epoxy-coated steel anchors. The main objective of this study is to examine the application of the CLSM bridge system in typical span type bridges used in railroad and highway situations. To do so, an instrumented, large-scale laboratory test is performed on a CLSM bridge abutment to investigate its performance due to the application of a monotonically increasing sill (foundation) pressure.

BACKGROUND

The proposed CLSM bridge abutment provides a load-bearing mechanism for the bridge sill, thereby eliminating the need for piling, and the abutment does not require the use of a deep foundation, even if the underlying soil is weak. The CLSM abutment can be used in railroad applications as well as highways. Because of system flexibility and lack of piling, the long-term settlement of the sill is likely to occur at the same rate of the settlement of the roadway bed thus reducing the differential settlement and the associated "bumps" at the ends of the bridge.

CLSM bridge abutments can be constructed in a very short time because they do not require heavy machinery for excavation and compaction, and, most importantly, they do not require the use of piles and piling equipment. It is anticipated that with the CLSM bridge system a complete bridge can be constructed in less than a week compared with a typical construction time of several months for a conventional bridge of the same size. In our large-scale laboratory test performed as part of this research, we applied very high foundation loads on the seventh day after placing the CLSM fill; shorter waiting times are also possible.

It is noteworthy that CLSM has been used by several state DOTs as self-leveling backfill behind conventional pile-supported bridge abutments to alleviate the "bump" at the end of the bridge (i.e., approach settlements). In the proposed CLSM abutment, however, the CLSM abutment itself will provide the bearing mechanism for the bridge sill. This unique approach has never been attempted previously, but it has the potential to profoundly reduce the cost and construction time of bridge abutments. The large-scale laboratory test provided in-depth understanding of the behavior of the proposed CLSM abutment and showed that it can carry bridge loads with a large safety margin (FS>3) and with minimal deformations (<0.25 inch).

Controlled Low Strength Materials (CLSM)

CLSM (aka: flowable fill) is defined as self-compacting cementitious material that is in a flowable state at the time of placement and has a specified compressive strength of 1200 psi or less at 28 days, but is defined as excavatable if the compressive strength is 300 psi or less at 28 days (ACI 1999). CLSM contains water, cement, fly ash, admixtures, and aggregates. ACI (1999) reports that the wet density of CLSM ranges between 85 and 145 pcf, but the dry density is substantially less than the wet density due to water loss.

CLSM is durable, excavatable, erosion-resistant, self-leveling; it cures rapidly and is incompressible after curing, and flowable around confined spaces. It also can reduce possible cave-ins, and it uses environmentally impacted materials such as fly ash within its mix. When flowable fill is used the need for compaction is eliminated, thereby reducing equipment needs, labor costs, and the amount of inspection. CLSM also can be placed all in one pour.

CLSM Bridge Abutment

The proposed CLSM bridge abutment comprises full-height precast concrete panels attached to a CLSM backfill via epoxy-coated steel anchors. The CLSM bridge abutment provides a load-bearing mechanism for the bridge sill, thereby eliminating the need for piling, and the CLSM abutment itself does not require the use of a deep foundation, even if the underlying soil is weak. If the foundation soil is found unacceptable, a flowable fill foundation may be used to provide a stronger platform for the construction. The flowable fill foundation may involve removing about a 3-ft thick layer of the foundation soil and simply replacing it with a flowable fill.

The interlocking full-height concrete panels provide a form that contains the newly poured CLSM backfill until setting. The theory behind CLSM bridge abutments is that the epoxy-coated steel anchors make the CLSM mass and the full-height concrete panels behave as a single unit. The concrete facing panels and the reinforced CLSM mass are then treated as one unit and analyzed as a large gravity wall, which must be analyzed for stability in sliding and overturning. In addition, the number of epoxy-coated steel anchors required and their spacing must be determined based on internal stability. The internal stability of the CLSM wall must be ensured, as well. Rupture occurs when excessive forces exceed the ultimate tensile strength of the epoxy-coated steel anchors. Slippage of reinforcement in the CLSM-reinforcement composite can occur when the interface friction (bond) is insufficient. Finally, the bearing pressure of such a large gravity wall must be checked to ensure that it does not exceed the allowable bearing capacity of the soil.

Construction Procedure For CLSM Abutments

The construction sequence of a CLSM bridge abutment is very simple and involves the following steps:

1. Level the foundation soil and place a precast concrete leveling pad for the precast concrete panels.
2. Install interlocking full-height concrete panels (Example: 18-ft high panels) with temporary lateral supports.
3. Place a 6-ft thick layer of CLSM (flowable fill).
4. Install the first row of epoxy-coated ¾-inch diameter steel anchors (insert through the opening from outside). This can be done even before the flowable fill is set since the guide hole in the concrete panel will keep the anchor in a horizontal position.
5. Place the second 6-ft thick layer of flowable fill.
6. Install the second row of epoxy-coated ¾-inch diameter steel anchors.
7. Place the last 6-ft thick layer of flowable fill.
8. Wait for the flowable fill to set (usually 24-48 hours) then remove lateral supports.
9. Place the precast concrete bridge sill, place the approach fill behind the sill, and place the precast concrete bridge on elastomeric pads (or the equivalent) affixed to the sill.

The bridge does not need to have an approach slab, as road base material can be compacted directly behind the bridge sill to form the approach way and to create a gradual transition from the roadway to the bridge. Asphalt pavement can then be placed on the bridge and approach without a conventional joint system (approach slab) at the bridge ends. The intent is to allow the bridge and the adjacent road to settle together, providing a smooth, bump-free ride for drivers traveling on and off the bridge.

WORK PERFORMED

Numerous CLSM mixes were tested for mechanical properties including compressive strength (1 day, 7 days, and 28 days), flow consistency, and pullout strength of rebars embedded in CLSM (Chapter 2). The selection criteria for a final mix was based on its excavatability as well as its relative high early strength. The selected CLSM mixture has a flow of 14 inches according to the Standard Test Method for Flow Consistency of CLSM (ASTM D 6103) and has a seven-day compressive strength of 55 psi.

In Chapter 3, the application of a CLSM bridge abutment in normal-span bridges is examined through a full-scale laboratory test. An instrumented CLSM bridge abutment (8.8 ft × 8.8 ft in plan, and 9 ft in height) with full-height prefabricated concrete panels was constructed to investigate the performance of the abutment due to application of a monotonically increasing sill pressure. Full-height precast concrete panels were attached to the CLSM backfill via steel anchors. The objectives of the test were: (1) to determine the constructability of the proposed CLSM bridge abutment, and (2) to determine the behavior of CLSM bridge abutments, in terms of load carrying capacity and deformations, after 7 days of CLSM setting time. The latter objective is of great interest since it will provide evidence about the behavior of the CLSM abutment shortly after the CLSM was poured--a critical issue with respect to rapid construction of the abutment.

The CLSM bridge abutment and the concrete sill were instrumented to measure their behavior during construction and upon application of bridge loads. Instrumentation included load cells, pressure cells, strain gauges, LVDTs and high-resolution digital video cameras. Of particular interest was the displacement of the sill and the lateral pressure and displacement of the facing wall. Also, because of the three-dimensional behavior of the abutment, the wing walls were instrumented to measure their lateral displacements.

Up to 175 kips of vertical load was applied to the CLSM abutment without any failure or damage in the system. This load is equivalent to an expected reaction force in a 100-ft-long single-span highway bridge. The average final settlement of the bridge sill was about 0.25 inches.

The maximum lateral displacement of the front facing panel occurred at the top of the panel and was about 0.12 inches. The lateral displacement at the middle and the bottom of the panel were considerably smaller. Lateral displacements of the wing walls were negligible with the maximum value of 0.04 inches at the top.

The lateral pressure of backfill against the front facing panel was monitored during and after the placement of the CLSM material as well as during the loading stage of the experiment. It is known that a freshly placed concrete behaves temporarily like a fluid, producing a hydrostatic pressure that acts laterally on a wall. For flowable fills, Schmitz et al. (2004) concluded that the lateral pressure on a wall after the curing stage is negligible. However, during the placement of CLSM, the structure must be designed to temporarily support the fluid pressures. Our measured data indicated that the fresh flowable fill resulted in smaller lateral pressure on the abutment than that from normal fluid pressure. The maximum lateral pressure of about 3.5 psi was measured at the bottom of the facing panel initially but it was gradually reduced to about 1 psi.

During the application of bridge loading, the lateral pressures were very small in general with the maximum value of 4 psi recorded near the middle of the panel. Upon applying the bridge load, the lateral pressure at the top of the panel was unchanged in the beginning and then started to increase approaching about 1.5 psi at 175 kips load. The pressure at the bottom of the panel remained unchanged. It is interesting to note the pressures elsewhere consistently decreased as the bridge load increased. This may be attributed to the lateral (outside) deflection of the facing panel.

Several strain gauges were used to measure the strains at the top and bottom sides of several steel anchors at their points of attachment with the facing panels. The two gauges, one at the top and one at the bottom side of the anchor, are necessary to calculate the axial force in the anchors. The measured strains indicated that steel anchors installed at higher elevations experienced both axial and bending loads while those at the lower elevation experienced mainly axial loads.

SUMMARY AND CONCLUSIONS

One of the major obstacles facing rapid bridge construction for typical span type bridges is the time required to construct bridge abutments and foundations. This can be remedied by using the controlled low strength materials (CLSM) bridge abutment.

A suitable CLSM mixture with optimum strength and flowability was designed by performing a series of unconfined compression, flowability, and pull-out tests. Using the selected CLSM mix, an instrumented, large-scale CLSM bridge abutment with full-height concrete panels was constructed to test its performance due to the application of a gradually increasing bridge load.

The measured lateral pressure against the abutment wall panels was very small in general, and was higher in the mid-height layers of the flowable fill during the curing time due to limited shrinkage that could have taken place in such regions. After curing, the lateral pressure decreased to negligible levels due to shrinkage. It was found that it is easy to remove the CLSM material after the test was done, indicating that the selected CLSM mix was indeed excavatable.

The test results show that the CLSM bridge abutment, with a relatively short cure time of 7 days, is capable of carrying bridge loads with a reasonably large safety margin, and with minimal deformations. The CLSM bridge abutment in this study resisted 175 kips of static load without any failure and with minimal settlement (0.25 inches) of the bridge superstructure. This load corresponds to an applied pressure of 77.6 psi on the bridge sill. In contrast, an average sill pressure of 13.5 psi is calculated from the dead load of a large single-span bridge of 80 ft length and 35 ft width supported by a 35 ft × 5 ft bridge sill. This sill pressure is nearly six times smaller than the pressure applied in the laboratory test. Such a small pressure will cause extremely small sill settlements.

RECOMMENDATIONS FOR FUTURE RESEARCH

The research team suggests a full-scale field construction of a CLSM bridge system to demonstrate its feasibility as a rapid bridge construction method. In addition to showing the short- and long-term performance of the CLSM bridge system, the field work will also enable bridge engineers and geotechnical engineers to gain experience and become familiar with the proposed rapid construction method. The work will also improved current understanding of the behavior of CLSM bridge abutments carrying realistic bridge loads.

CHAPTER 1
INTRODUCTION

1. PROBLEM STATEMENT

Rapid construction/replacement methods for railroad and highway bridges are essential to maintaining freight movement with minimal adverse economic effects. Prefabricated bridge components, including bridge girders, bridge decks, and segmental piers, have been used successfully in the U.S. and abroad for rapid bridge construction, and adequate information is currently available for the use of such bridge components; however, there is a major obstacle facing rapid bridge construction for "typical" span type bridges used in railroad and highway applications: constructing bridge abutments and their deep foundations (piles) is very time-consuming, thereby rendering any rapid bridge construction method less effective. Therefore, <u>there is an urgent need to develop and use a novel method of accelerated construction for bridge abutments and foundations</u>.

2. RESEARCH OBJECTIVES

To reduce the time required to construct bridge abutments, a "controlled low strength materials (CLSM) bridge abutment" can be used. The CLSM bridge abutment comprises full-height precast concrete panels attached to a CLSM backfill via epoxy-coated steel anchors. The main objective of this study is to examine the application of the CLSM bridge system in typical span type bridges used in railroad and highway situations. To do so, an instrumented, large-scale laboratory test is performed on a CLSM bridge abutment to investigate its performance due to the application of a monotonically increasing sill (foundation) pressure.

3. BACKGROUND

As indicated in the figure 1.1, the proposed CLSM bridge abutment provides a load-bearing mechanism for the bridge sill, thereby eliminating the need for piling, and the abutment does not require the use of a deep foundation, even if the underlying soil is weak. The CLSM abutment can be used in railroad applications as well as highways.

Because of system flexibility and lack of piling, the long-term settlement of the sill is likely to occur at the same rate of the settlement of the roadway bed thus reducing the differential settlement and the associated "bumps" at the edges of the bridge.

CLSM bridge abutments can be constructed in a very short time because they do not require heavy machinery for excavation and compaction, and, most importantly, they do not require the use of piles and piling equipment. It is anticipated that with the CLSM bridge system a complete bridge can be constructed in less than a week compared with a typical construction time of several months for a conventional bridge of the same size. In our large-scale laboratory test performed as part of this research, we applied very high foundation loads on the seventh day after placing the CLSM fill; shorter waiting times are also possible.

It is noteworthy that CLSM has been used by several state DOTs as self-leveling backfill behind conventional pile-supported bridge abutments to alleviate the "bump" at the end of the bridge (i.e., approach settlements). In the proposed CLSM abutment, however, the CLSM abutment itself will provide the bearing mechanism for the bridge sill. This unique approach has never been attempted previously, but it has the potential to profoundly reduce the cost and construction time of bridge abutments. The large-scale laboratory test provided in-depth understanding of the behavior of the proposed CLSM abutment and showed that it can carry bridge loads with a large safety margin (FS>3) and with minimal deformations (<0.2 inch).

3.1 What is CLSM?

CLSM (flowable fill) is defined as self-compacting cementitious material that is in a flowable state at the time of placement and has a specified compressive strength of 1200 psi or less at 28 days, but is defined as excavatable if the compressive strength is 300 psi or less at 28 days (ACI 1999). CLSM contains water, cement, fly ash, admixtures, and aggregates. ACI (1999) reports that the wet density of CLSM ranges between 85 and 145 pcf, but the dry density is substantially less than the wet density due to water loss.

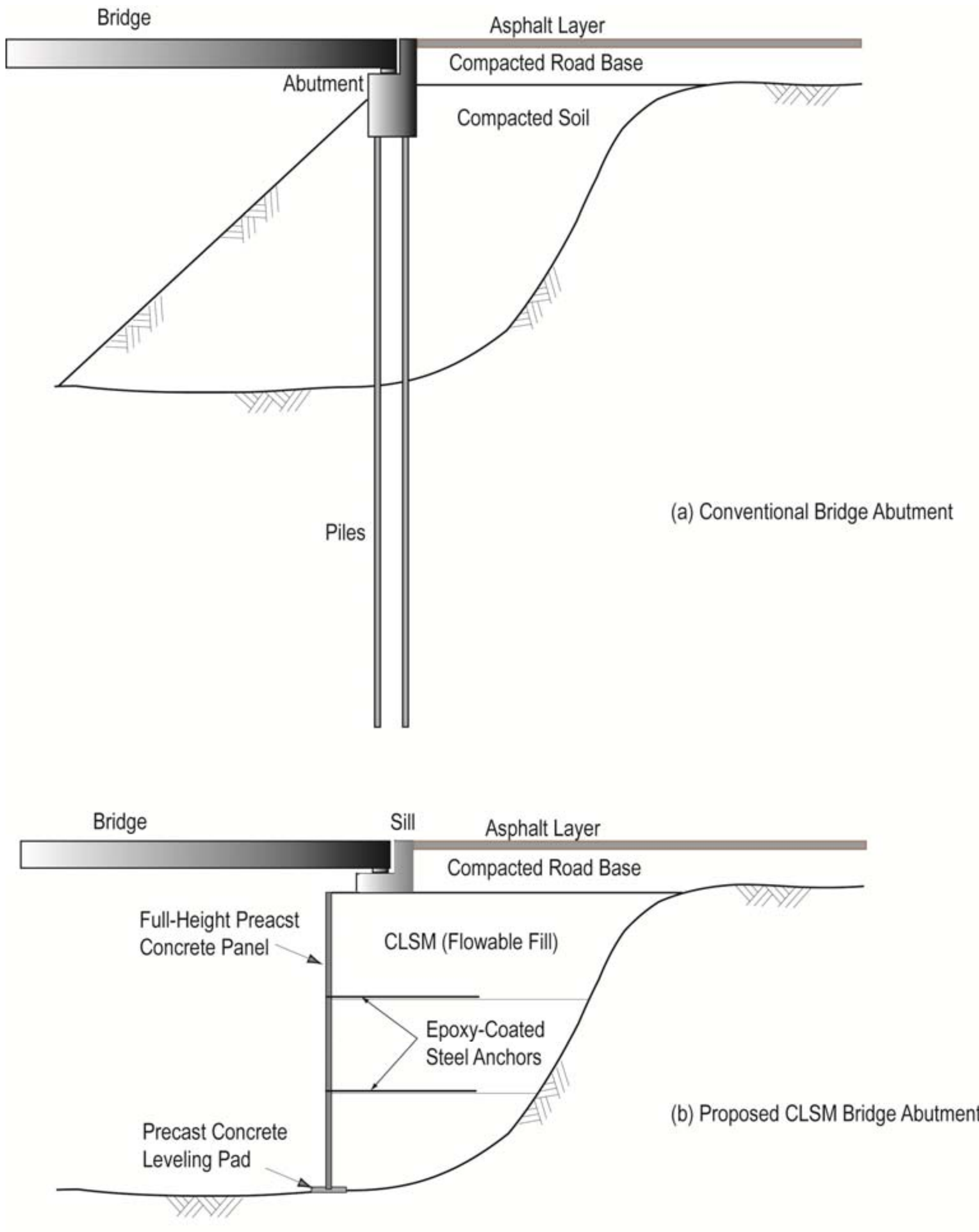

Figure 1.1: Comparison between Conventional and CLSM Bridge Abutments

CLSM is durable, excavatable, erosion-resistant, self-leveling; it cures rapidly and is incompressible after curing, and flowable around confined spaces. It also can reduce possible cave-ins, and it uses environmentally impacted materials such as fly ash within its mix (Trejo et al., 2004; Hajafi and Tia 2004; and Newman et al., 1993). Hajafi and Tia (2004) noted that when flowable fill is used the need for compaction is eliminated, thereby reducing equipment needs, labor costs, and the amount of inspection. CLSM also can be placed all in one pour.

Regarding the lateral earth pressures against the abutment, Schmitz et al. (2004) concluded such pressure after curing is negligible, but during placement of CLSM the structure must be designed to temporarily support fluid pressures. Snethen et al. (1997) found that the lateral earth pressure was higher in the center layer of the flowable fill at curing due to the speed of hydration and the length of the drainage path. At the center, water could not dissipate or evaporate as fast as points near the surface.

Some disadvantages of CLSM include shrinkage, frost susceptibility, drainage, bleeding, earth pressure during its fluid state, and the requirement of forms (Hajafi and Tia 2004; Newman et al., 1993, Schmitz et al., 2004). If this material is expected to be excavated, a trial mix is recommended due to the sensitivity of compressive strength. ACI (1999) noted that blockage of pumping equipment can result if there is segregation of particles, high fines content, or improper mixing. Also, the final grade level after placement is likely to be lower than during placement because of the reduced volume of the material as water is released. ACI (1999) has reported that settlement equal to 1/8 to 1/4 inches per foot of depth is typical and that designers need to consider subsidence in their quantities and in plan preparation.

Overall, the performance of CLSM has been good when used as self-leveling backfill behind conventional pile-supported bridge abutments. A survey by Trejo et al. (2004) indicated that 42 out of 44 state DOTs have specifications for CLSM. A study of 177 bridges in Oklahoma compared different backfills behind conventional bridge abutments (Snethen and Benson, 1998; and Snethen et al., 1997), and the results of the CLSM approaches showed very little movement prior to placement of the pavement. In addition, a WisDOT study (Wilson 1999) found that rideability over approaches with CLSM was better than approaches with granular backfill (both fills were used behind conventional pile-supported abutments).

3.2 What is a CLSM Bridge Abutment?

Figure 1.1(b) shows a schematic diagram of a typical CLSM bridge abutment with full-height precast concrete panel facing; in contrast, Figure 1.1(a) shows a schematic diagram of a conventional bridge abutment with pile foundation. As indicated in Figure 1.1(b), the CLSM bridge abutment provides a load-bearing mechanism for the bridge sill, thereby eliminating the need for piling, and the CLSM abutment itself does not require the use of a deep foundation, even if the underlying soil is weak. If the foundation soil is found unacceptable, a flowable fill foundation may be used to provide a stronger platform for the construction. The flowable fill foundation may involve removing about a 3-ft thick layer of the foundation soil and simply replacing it with a flowable fill. The sill can be precast or cast-in-place reinforced concrete.

The interlocking full-height concrete panels provide a form that contains the newly poured CLSM backfill until setting. The theory behind CLSM bridge abutments is that the epoxy-coated steel anchors make the CLSM mass and the full-height concrete panels behave as a single unit. The concrete facing panels and the reinforced CLSM mass are then treated as one unit and analyzed as a large gravity wall, which must be analyzed for stability in sliding and overturning. In addition, the number of epoxy-coated steel anchors required and their spacing must be determined. Finally, the bearing pressure of such a large gravity wall must be checked to ensure that it does not exceed the allowable bearing capacity of the soil. The internal stability of the CLSM wall must be ensured, as well. Rupture occurs when excessive forces exceed the ultimate tensile strength of the epoxy-coated steel anchors. Slippage of reinforcement in the CLSM-reinforcement composite can occur when the interface friction (bond) is insufficient.

The proposed CLSM bridge abutments have great promise in terms of ductility, flexibility, constructability, and costs. One major advantage of CLSM abutments is that they can be constructed rapidly without the need for compaction, piling, and heavy machinery.

4. CONSTRUCTION PROCEDURE FOR CLSM ABUTMENTS

The construction sequence of a CLSM bridge abutment is very simple and involves the following steps (see Figure 1.2):

1. Level the foundation soil and place a precast concrete leveling pad for the precast concrete panels.
2. Install interlocking full-height concrete panels (Example: 18-ft high panels) with temporary lateral supports.
3. Place a 6-ft thick layer of CLSM (flowable fill).
4. Install the first row of epoxy-coated ¾-inch diameter steel anchors (insert through the opening from outside). This can be done even before the flowable fill is set since the guide hole in the concrete panel will keep the anchor in a horizontal position.
5. Place the second 6-ft thick layer of flowable fill.
6. Install the second row of epoxy-coated ¾-inch diameter steel anchors.
7. Place the last 6-ft thick layer of flowable fill.
8. Wait for the flowable fill to set (usually 24-48 hours) then remove lateral supports.
9. Place the precast concrete bridge sill, place the approach fill behind the sill, and place the precast concrete bridge on elastomeric pads (or the equivalent) affixed to the sill.

The bridge does not need to have an approach slab, as road base material can be compacted directly behind the bridge sill to form the approach way and to create a gradual transition from the roadway to the bridge. Asphalt pavement can then be placed on the bridge and approach without a conventional joint system (approach slab) at the bridge ends. The intent is to allow the bridge and the adjacent road to settle together, providing a smooth, bump-free ride for drivers traveling on and off the bridge.

The CLSM bridge system does not use piles and is more suited for single-span bridges in critical crossings. Single-span bridges are more tolerant of settlement than multi-span structures, and the CLSM bridge system is designed to compensate for post-construction settlement; the bridge, abutment, and approach are supported on the same foundation system. The bridge is designed for uniform settlement
between the sub- and superstructures.

5. RECOMMENDATIONS FOR FUTURE RESEARCH

The research team suggests a full-scale field construction of a CLSM bridge system (Figure 1.3) to demonstrate its feasibility as a rapid bridge construction method. In addition to showing the short- and long-term performance of the CLSM bridge system, the field work will also enable bridge engineers and geotechnical engineers to gain experience and become familiar with the proposed rapid construction method. The work will also improved current understanding of the behavior of CLSM bridge abutments carrying realistic bridge loads.

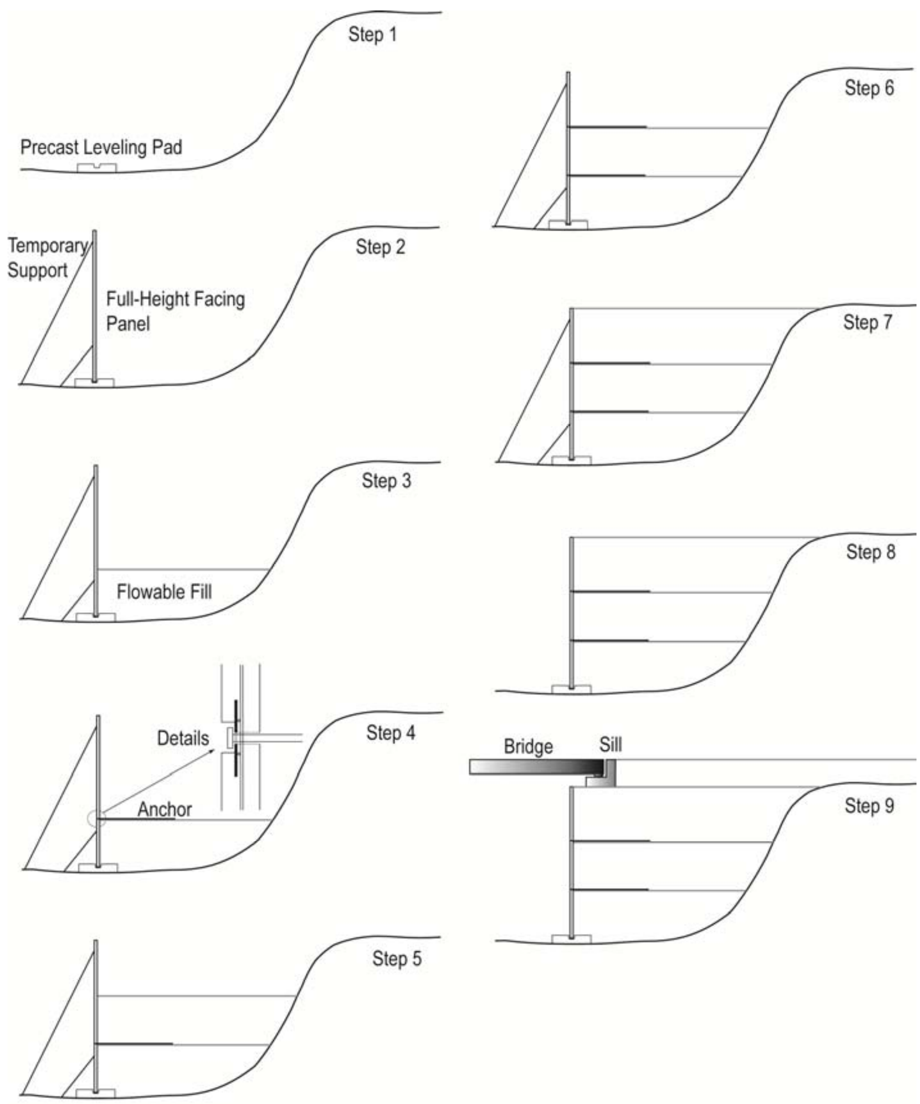

Figure 1.2: Construction Sequence

The CLSM bridge abutments, the concrete slab (deck), and the bridge girders can be instrumented, as shown in Figure 1.3, with strain gauges, pressure cells, displacement gauges, and surveying points to measure their behavior during construction and upon application of construction and service loads. Measurements should continue for several years after completion of the construction to investigate the long-term behavior of the prefabricated bridge elements and the CLSM abutments. Of particular interest is the vertical displacement of the bridge and the lateral displacement of the full-height facing panels. An extensive array of displacement gauges and surveying targets can be used to measure horizontal and vertical displacements of the bridge, the approach fill, and the abutment facing. The displacement gauges can be mounted on a reference steel frame supported by two piles driven near the bridge abutment (not shown in the figure). A pavement profiler can be used to quantify approach settlements. Also, because of the three-dimensional nature of the proposed construction, the wing walls should be instrumented with surveying targets to measure their lateral displacements. Based on the results of the field testing and monitoring, an updated design guide can be developed.

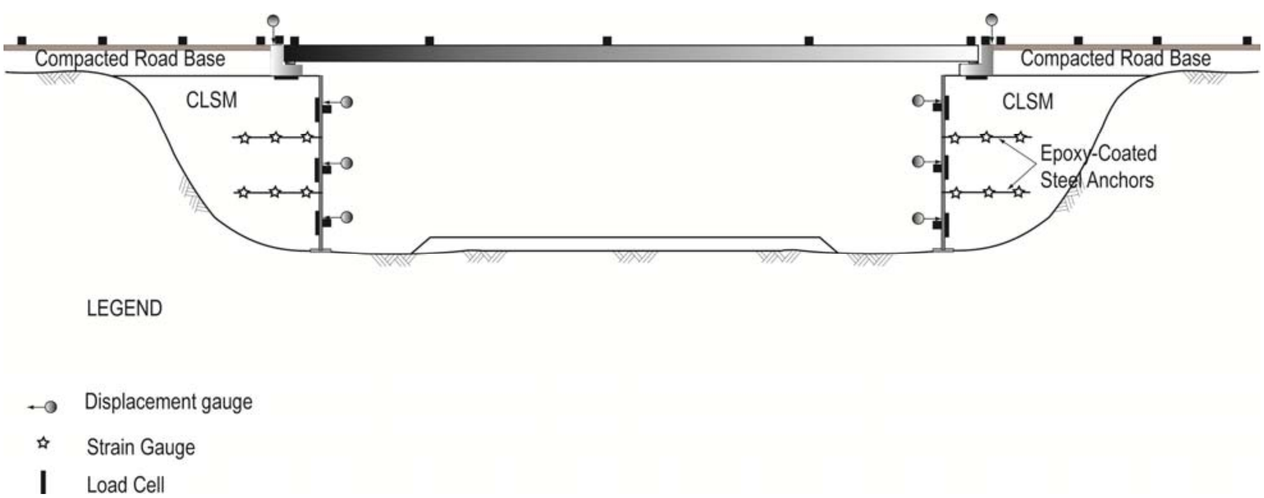

Figure 1.3: Proposed Field Test with CLSM Bridge Abutments

CHAPTER 2

SELECTION OF A CONTROLLED LOW STRENGTH MATERIALS (CLSM) MIXTURE FOR RAPID CONSTRUCTION OF BRIDGE ABUTMENTS

1. INTRODUCTION

Recently the use of Controlled low strength material (CLSM) as a new cost and time efficient substitute of compacted fills has grown considerably. CLSM is a mixture of soil or aggregate, cementitious material, fly ash, water and sometimes chemical admixtures that hardens into a material with a higher strength than the soil. CLSM, also known as flowable fill, is defined by the ACI Committee 229 (1999) as flowable self-compacting cementitious material that has a specified 28 days compressive strength of 8.3 MPa (1200 psi) or less. CLSM is defined as excavatable if 28 days compressive strength is 2.1 MPa (300 psi) or less. CLSM can be used as a replacement for compacted backfill and typically has strengths of 0.3 to 0.7 MPa (50 to 100 psi) for most applications (ASTM D 6103).

CLSM is a fill material with several inherent advantages which allows for construction. A number of these advantages over conventional earthfill materials that require controlled compaction in layers include the following (Dockter, 1998):

- Ease of mixing and placement,
- Ability to flow into hard-to-reach places,
- Self-leveling characteristics,
- Cures rapidly,
- Incompressible after curing,
- Can be excavatable, and
- Environmentally-friendly utilization of by-product materials such as fly ash or foundry sand in the mix, thereby reducing the demands on landfills (Trejo et al., 2004; Najafi and Tia 2004; and Newman et al., 1993).

Najafi and Tia (2004) noted that when flowable fill is used the need for compaction is eliminated. This reduces equipment needs, labor costs and the associated inspections. Although CLSM mixtures provide numerous advantages, there are some technical challenges. The major challenge in application of CLSM is that this material behaves like a compacted soil. Therefore, much of the available knowledge and publications on its applications had fallen between the concrete materials engineering and geotechnical engineering and it is often not given the level of attention it deserves by either group (Javed et al., 2002).

Some disadvantages of CLSM hindering extensive use of this material, include (Najafi and Tia 2004; Newman et al., 1993, Schmitz et al., 2004):

- Susceptibility to segregation and bleeding,
- High lateral pressures during placement,
- High shrinkage,
- Potential leaching of constituent materials, and
- Reduced durability of CLSM subjected to freezing and thawing cycles.

Investigation using trial mix is often recommended especially if CLSM is expected to be excavated in the future. Excessive long-term strength gain makes it difficult to excavate CLSM at later stages. ACI Committee 229 (1999) noted that segregation of particles, high fines content, or improper mixing may result in blockage of pumping equipment. Halmen et al. (2005) believes that the major challenge in implementation of the use of CLSM is the lack of knowledge on the corrosion performance of steel pipe materials embedded in CLSM.

CLSM is a multipurpose construction material that has been used in a wide variety of applications that are well documented in the literature. The primary application of CLSM is as a backfill in place of compacted soil. Among the many applications of CLSM, the following are the most important (ACI Committee 229, 1999 and NRMCA, 1989):

- Backfill for sewer trenches, conduit trenches, utility trenches, building excavations, bridge abutments and retaining walls;

- Structural fill for foundation footings, sub footings, floor slab bases, road bases, subbases, subgrades, and utility bedding;
- Void-filling for underground storage tanks, abandoned sewers, abandoned utility, voids under pavement, basements or other underground structures;
- Bridge approaches; either as a subbase for the bridge approach slab or as backfill with other elements.

Utility bedding applications involve the use of CLSM as a bedding material for pipes, electrical and other types of utilities, and conduits. Because it resists erosion better than many other fill materials, CLSM can be used for erosion control in embankments and slopes, and to fill voids under culverts, pavements, sidewalks, bridges and other structures where natural soil or noncohesive granular fill has eroded away (ACI Committee 229, 1999). It was also indicated that appropriate CLSM mixtures can be designed as anti corrosion fill, thermal and isolation fill (Brewer, 1994). The use of CLSM for encapsulation of contaminated soil was also documented in the literature (Melton, 2005). CLSM is used in nuclear facilities for conventional applications because it decreases personnel exposure to radiation (ACI Committee 229, 1999).

2. EXPERIMENTAL PROGRAM

Material specification tests were conducted to design the appropriate CLSM mix for rapid construction of bridge abutments (CLSM Abutments), and to obtain required engineering properties of the mixtures for future numerical analysis. The engineering properties investigated include flowability, density, unconfined compressive strength and stress–strain behavior. The CLSM bridge abutment comprises full-height precast concrete panels that are attached to a CLSM backfill via steel anchors, Figure 2.1. Therefore, the bond capacity of steel anchors embedded in the CLSM was also investigated.

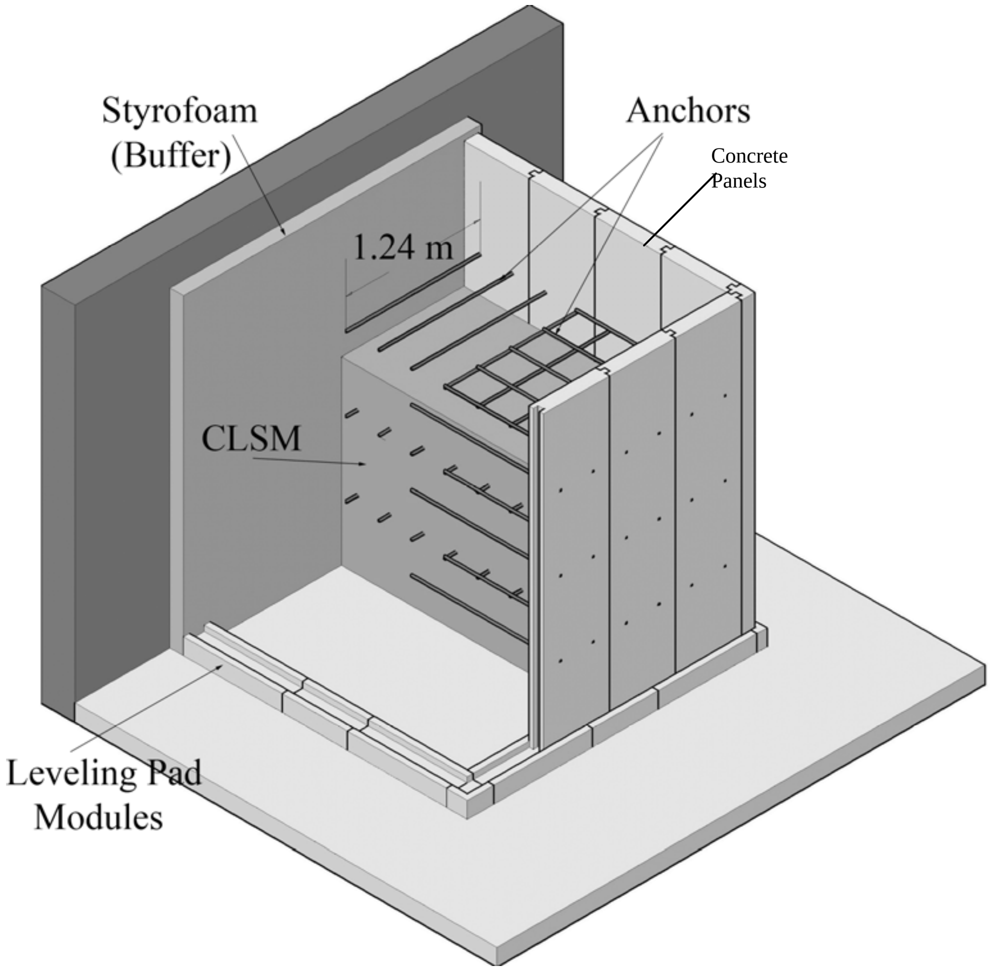

Figure 2.1: Embedded Anchors in CLSM Backfilled Abutment

2.1 Materials

The selected materials include Type I Portland cement, Class F fly ash, fine aggregates and water. Selection of materials for CLSM should be based on availability, cost, specific application and the necessary characteristics of the mixture including flowability, strength, excavatablity, density, etc (ACI Committee 229, 1999).

The Type I Portland cement used in this research meets all applicable chemical and physical requirements of ASTM C 150, “Standard Specification for Portland Cement” and is manufactured by Lafarge Cement Co. Fly ash is one of the by-products generated from the coal combustion in electric power generating plants. Fly ash used in this research was Class F type from We Energies, the Elm Road Generating Station (ERGS), located along the shore of Lake Michigan near the existing Oak Creek Power Plant (OCPP), Wisconsin.

Concrete sand was used as fine aggregates. This sand was in the laboratory at a room temperature; the moisture content was 1.16%. Potable tap water at approximate room temperature of 23 ºC (75 ºF) was used as mixing water for production of the flowable fill mixtures.

2.2 Mixture Proportioning

CLSM mixtures are usually designed based on development of compressive strength. Digioia and Brenda (1992) noted that the appropriate control of strength in flowable fill is a main criterion in a mix design. To design CLSM mix, it is not just required to meet minimal strengths to maintain and provide suitable structural support, but also the ultimate strength must be controlled to allow for future excavation (Lovencin et al., 2006).

Due to the sensitivity of compressive strength and other properties, trial and error process has been recommended for proportioning of flowable fill mixtures (FHWA, 1997). When a CLSM mixture is designed, a number of engineering parameters must be evaluated prior to, during, and after placement in the field (Javed et al., 2002). Depending on specific application of flowable fill in this project, the following criteria were set for CLSM mixture:

- Strength development;
- Time of set;
- Flowability; and
- Bond behavior between the rebar and CLSM

Initial mixtures were tested for flowability and compressive strength to identify the key components and compositions of CLSM which can reach the target strength and flowability. Trial mixtures were evaluated and then adjusted to achieve the target properties (ACI Committee 229, 1999).

Initially, excavatable and nonexcavatable mixtures were examined. The selection criteria favored the mix with high early strength and with 28 days strength not exceeding 8.3 MPa (1200 psi). Besides, it was desired to obtain the mixture proportions with lower ultimate strength to allow for future excavatable construction option. Finally, 20 different CLSM mixtures with different levels of cement content, fly ash dosage and water to cement (w/c) ratios were produced.

In this study, 100 × 200 mm (4 × 8 in.) cylindrical molds were used to cast the specimens for the determination of compressive strength (ASTM D 4832). The specimens were cured for varying periods, 1 day, 7 days and 28 days, before the compressive strength tests. For each curing period, three cylindrical samples, so totally nine specimens were produced and tested per each mix. Therefore, for the whole research study, 180 cylindrical CLSM specimens were cast.

2.3 Preparation of CLSM Mixtures

The test cylinder molds were always properly cleaned and greased with mineral oil before preparation of CLSM mixtures. All constituent materials, cement, fly ash and sand were carefully weighed and placed into buckets with sealed lids.

The batching sequence was to place the sand into the mixer and it was mixed for ½ minute to make the sand uniform, and then most of the mixing water was added followed by the addition of cement and fly ash. After placement of the materials into the mixer, the mixer was kept rotating for three minutes, then the remaining mixing water was added. The mixing was resumed for 2½ additional minutes.

Immediately after mixing, flowable fill was poured into a large container ready to cast the prepared specimen molds. Prior to pouring into specimen molds, a sample of the fresh mix was tested to measure plastic properties including unit weight (ASTM D 6023) and flowability (ASTM D 6103). Each specimen was properly marked and labeled for identification and testing purposes.

Because of the self-leveling characteristic of CLSM, casting the cylinder molds did not require densification as is normally needed for concrete samples. After specimens were cast, they were cured at room temperature. Specimens were kept in the molds until the testing age.

2.4 Test Methods

2.4.1 Flowability Tests

Flowability tests had to be conducted in order to assure the CLSM ability to fill the whole abutment in one lift and to prevent blockage of pumping equipment. Flowability of mixtures was measured according to the "Standard Test Method for Flow Consistency of CLSM" (ASTM D 6103) and the desired flowability was 350 mm (14 in.), see Figure 2.2.

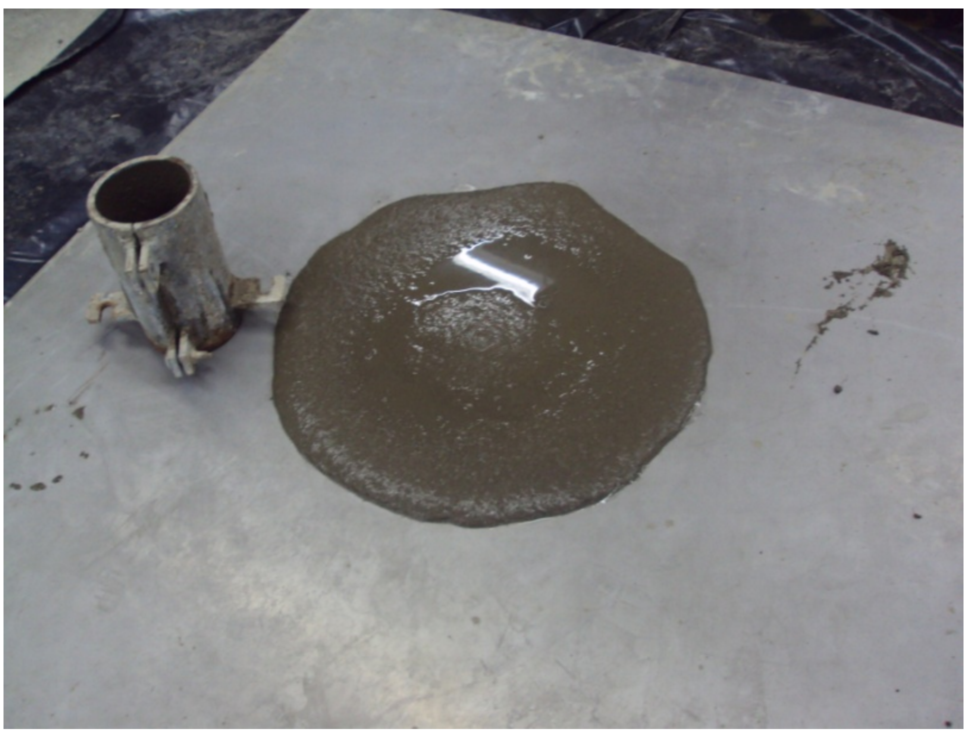

Figure 2.2: Standard Test Method for Flow Consistency of CLSM

2.4.2 Compressive Strength

Cylindrical specimens were tested to determine the compressive strength of the material (Figures 2.3 and 2.4). Removing the specimen from the mold involved careful handling due to its low strength (as compared to hardened concrete cylinders). The cylinders were then tested to obtain the compressive strengths (ASTM D 4832). Three 100 × 200 mm (4 × 8 in.) cylindrical specimens from each batch were tested at 1, 7 and 28 days except when obstructed by cylinder damage from demolding. The compression tests were performed using a relatively low-load capacity computerized testing machine with load control loading. Table 2.1 shows different CLSM mixture proportions tested in this research study, flowability and compressive strength results for 1, 3 and 28 days age.

Table 2.1: Mixture proportions and performance of investigated CLSM

Mix #	Cement, kg/m^3, (lb/yd^3)	Fly ash, kg/m^3, (lb/yd^3)	Sand, kg/m^3, (lb/yd^3)	Water, kg/m^3, (lb/yd^3)	Plasticizer (ml)	Flow, mm (in.)	Density kg/m^3, (lb/ft^3)	w/cm	Compressive Strength, MPa (psi)		
									1 day	**7 days**	**28 days**
1	82	20	1498	210	-	159	1810	2.05	-	0.2±0.03	0.51±0.05
	(138)	(35)	(2525)	(354)		(6.25)	(113)			(29±4.4)	(74±7.5)
2	79	20	1458	452	-	241	2009	4.60	-	0.16±0.04	0.39±0.02
	(133)	(33)	(2458)	(762)		(9.5)	(125.4)			(23.2±5.9)	(56±2.9)
3	123	31	1215	706	-	140	2074	4.58	-	0.24±0.02	0.59±0.05
	(208)	(52)	(2047)	(1189)		(5.5)	(129.5)			(35±3.6)	(86±7.4)
4	92	23	1355	527	-	178	1996	4.60	-	0.21±0.03	0.56±0.04
	(154)	(39)	(2284)	(888)		(7)	(124.6)			(30.3±4.3)	(81±6.1)
5	50	270	1569	245	-	210	2134	0.76	0.16±0.06	0.21±0.05	-
	(85)	(455)	(2644)	(413)		(8.25)	(133.2)		(22.7±8.7)	(31±7.5)	
5R	50	269	1562	259	-	210	2140	0.81	0.20±0.02	0.27±0.02	1.89±0.29
	(84)	(453)	(2633)	(437)		(8.25)	(133.6)		(29.4±2.5)	(39.4±2.4)	(274±42)
6	50	260	1514	303	-	432	2127	0.99	0.10±0.01	0.56±0.07	1.48±0.11
	(84)	(439)	(2552)	(510)		(17)	(132.8)		(15.1±1.4)	(81±10.2)	(214±16)
7	274	51	1594	229	135	210	2148	0.71	0.41±0.05	4.28±0.19	9.76±0.32
	(462)	(86)	(2686)	(387)		(8.25)	(134.1)		(59.3±6.6)	(621±27.1)	(1416±47)
8	268	50	1556	268	50	203	2142	0.84	1.87±0.04	13.29±0.29	-
	(451)	(84)	(2623)	(451)		(8)	(133.7)		(271±6.3)	(1927±42)	
9	279	465	1115	297	12.5	241	2156	0.40	1.28±0.07	16.26±4.18	-
	(470)	(783)	(1880)	(501)		(9.5)	(134.6)		(186±9.8)	(2358±606)	

10	172	576	1122	299	12.5	222	2169	0.40	0.29±0.02	6.46±0.22	9.11±0.88
	(290)	(971)	(1891)	(504)		(8.75)	(135.4)		(42.3±2.7)	(937±31.3)	(1322±127)
11	47	268	1579	221	12.5	191	2116	0.70	0.14±0.03	1.00±0.12	2.09±0.10
	(80)	(452)	(2662)	(373)		(7.5)	(132.1)		(20.2±4.9)	(145±17.8)	(303±15)
12	56	319	1501	263	19	267	2139	0.70	0.13±0.00	1.02±0.04	2.14±0.13
	(95)	(538)	(2529)	(443)		(10.5)	(133.5)		(18.3±0.5)	(148±6.2)	(311±19)
13	75	300	1499	267	19	267	2142	0.71	0.12±0.01	1.49±0.03	2.85±0.08
	(126)	(505)	(2527)	(451)		(10.5)	(133.7)		(17.9±2)	(216±4.8)	(414±12)
14	45	258	1516	303	-	356	2122	1.00	0.08±0.00	0.38±0.01	0.85±0.09
	(77)	(434)	(2555)	(511)		(14)	(132.5)		(11±0.6)	(55±1.8)	(124±13)
15	76	497	1338	287	21	330	2198	0.50	0.19±0.01	1.97±0.02	4.39±0.69
	(129)	(838)	(2255)	(483)		(13)	(137.2)		(27.6±1.2)	(285±2.9)	(636±100)
16	95	572	1240	267	25	305	2175	0.40	0.42±0.00	3.68±0.21	8.20±0.18
	(161)	(965)	(2091)	(450)		(12)	(135.8)		(60.5±0.7)	(534±30.5)	(1190±26)
17	87	299	1545	251	12.5	229	2182	0.65	0.44±0.01	1.92±0.04	3.90±0.32
	(146)	(504)	(2603)	(423)		(9)	(136.2)		(63.4±2.1)	(279±6.1)	(565±47)
18	57	323	1521	266	12.5	330	2167	0.70	0.16±0.01	0.94±0.06	1.88±0.02
	(96)	(545)	(2564)	(449)		(13)	(135.3)		(23.5±1.3)	(136±8)	(272±3.1)
19	58	331	1557	234	12.5	191	2180	0.60	0.30±0.00	1.41±0.07	2.87±0.27
	(98)	(558)	(2625)	(394)		(7.5)	(136.1)		(43.3±0.7)	(205±10.7)	(417±39)

Note: R in mixture number = mixtures that were replicated.

w/cm = water/cementitious materials

Strength is the main parameter to design a concrete and flowable fill mixture. Figure 2.5 shows that the ratio of water to cementitious material (cement and fly ash) is an important factor affecting the strength of flowable fill (like concrete). The plot illustrates that as the water to cementitious ratio (w/cm) increases, strength of CLSM decreases. The other important factor in determining bearing strength is cement content. Figure 2.6 indicates that CLSM mixtures with the same levels of w/cm, gain higher strength when cement content is increased. Also strength of CLSM improves by adding fly ash to a mix (Figure 2.7). In addition to strength, it was noted through visual observation that the mixes containing higher fly ash content have less bleeding and segregation.

Figure 2.3: Unconfined Compression Test Apparatus

Figure 2.4: Crushed CLSM Specimen

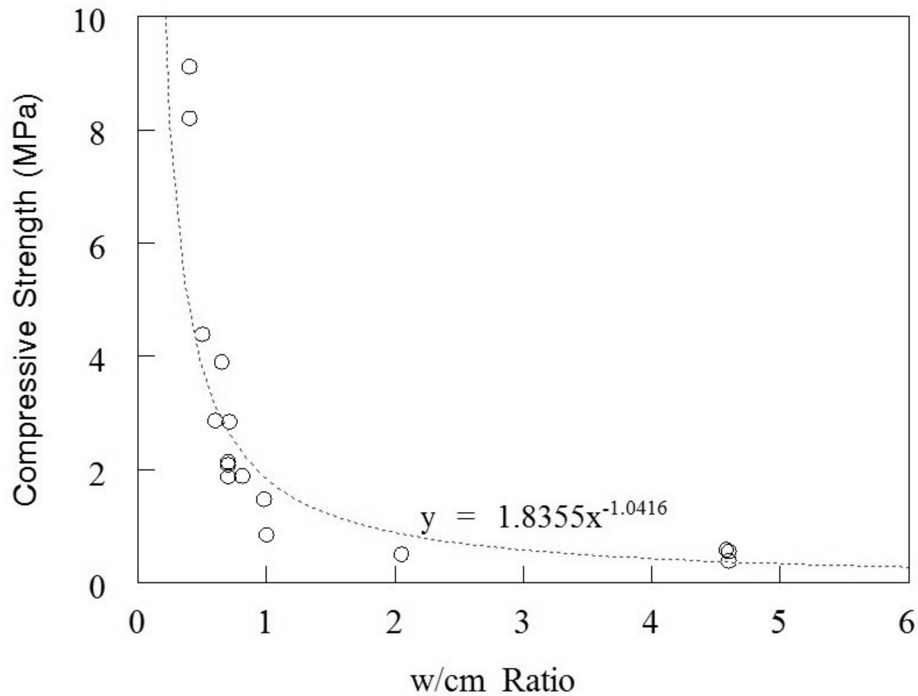

Figure 2.5: Relationship between 28-day compressive strength and w/cm ratio

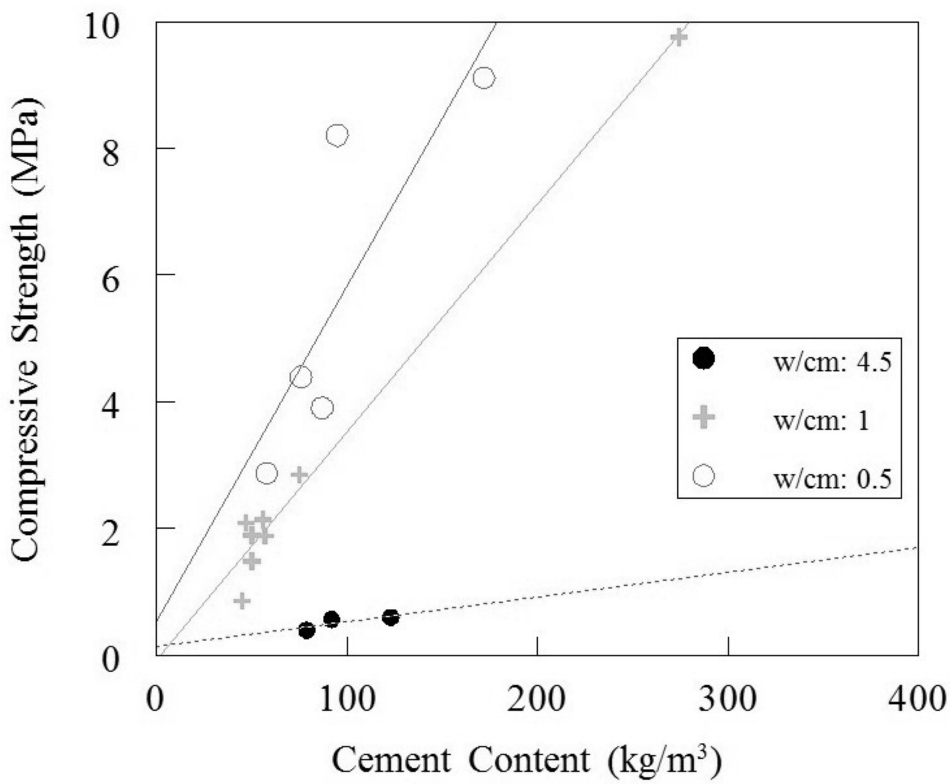

Figure 2.6: Relationship between 28-day compressive strength and cement content at given w/cm

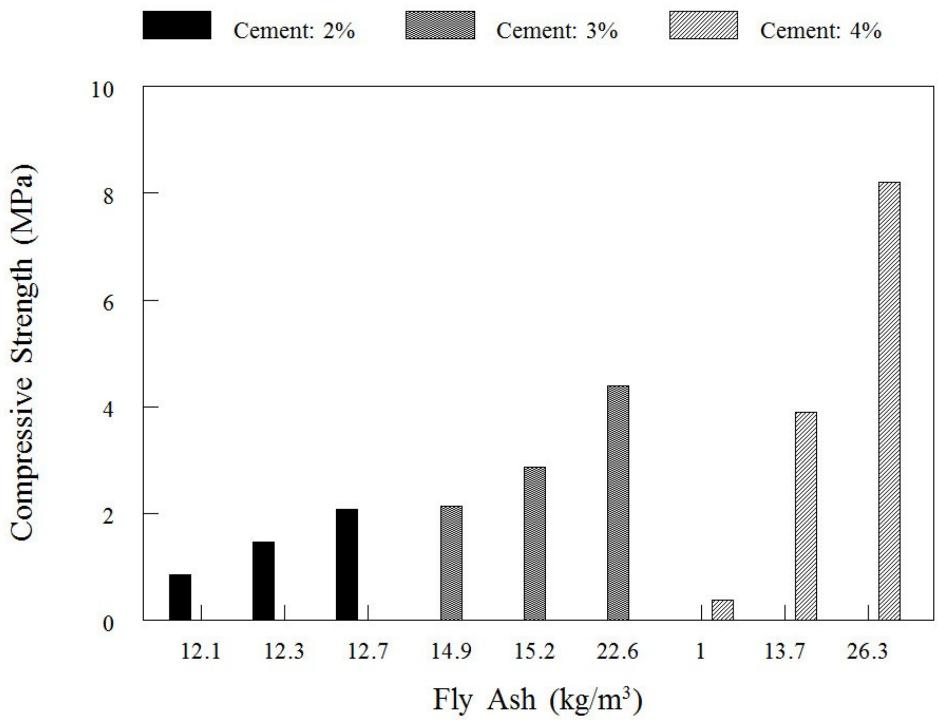

Figure 2.7: Relationship between 28-day compressive strength and fly ash content

Initially six mixtures were selected based on strength and flowability. Compressive strength of these mixtures was ranged from a low strength of 0.85 MPa (124 psi) to a high strength of 8.2 MPa (1190 psi). Figure 2.8 demonstrates the development of compressive strength with the curing age of the selected mixtures.

In addition to compressive strength, the stress-strain response of all cylinders was obtained. A typical behavior of all tested mixtures was a changing stress-strain response with the curing time. Early-age CLSM cylinders showed more ductile response like soil samples, but with age, CLSM behaved more like concrete with higher strength and lower ductility. This behavior is illustrated in Figure 2.9 for mixture #14. This change in stress-strain behavior is also noted by Folliard et al (1999). Stress-strain curve would also provide the elastic modules of the mixtures which is useful in the finite element analysis.

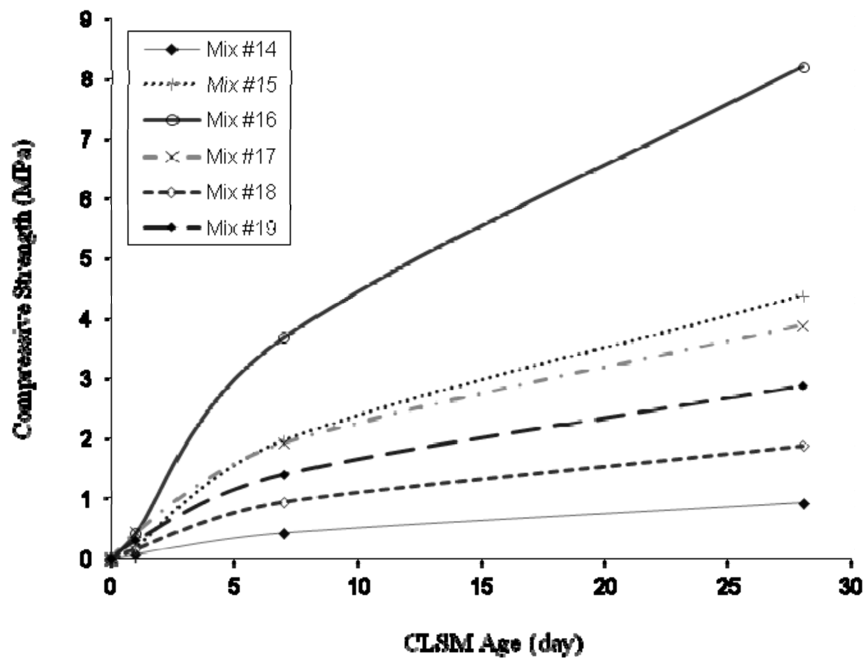

Figure 2.8: Compressive strength development for selected CLSM mixtures

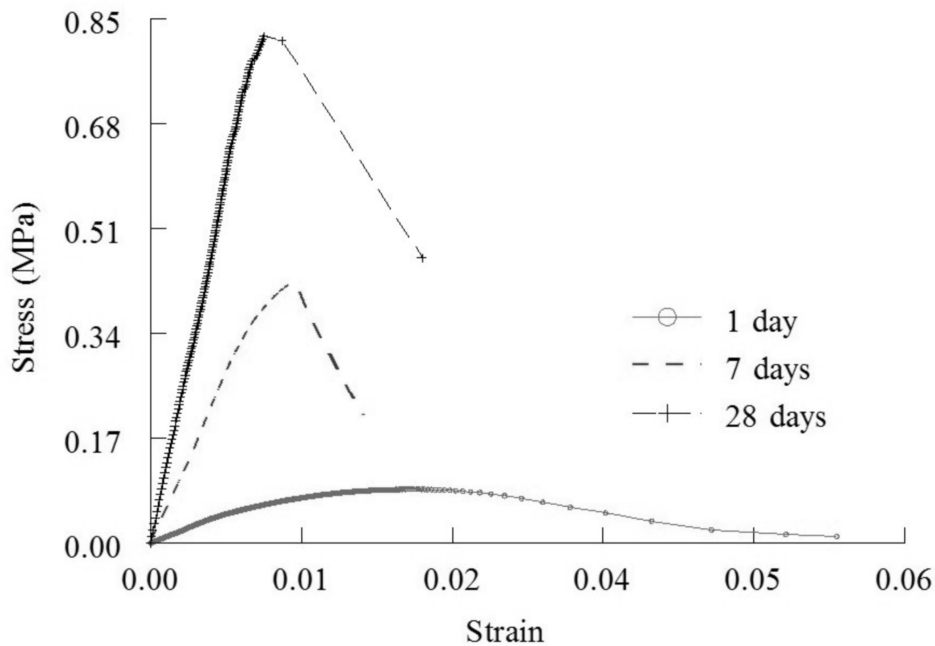

Figure 2.9: Stress-strain responses for mix #14 at 1, 7 and 28 days

2.4.3 Bond behavior between steel rebar and CLSM

Due to the special design of the CLSM bridge abutment, steel rebar anchors are in contact with CLSM, as illustrated by Figure 2.1. Pull-out tests of the steel anchors were conducted to ensure the internal stability of the CLSM abutment. Slippage of reinforcement in the CLSM-steel composite can occur when the interface friction (bond) is insufficient. The results of these tests would also be used to obtain the interface parameters needed for the finite element analysis.

Due to the importance of the bonding strength, three different pull-out test set-ups were implemented to achieve reliable results.

2.4.3.1 Pull-out test type 1

From the six selected mixtures, two mixtures, #14 and #16, were tested. Mix #16 has a high compressive strength equal to 8.2 MPa (1190 psi) to make a strong backfill and could be used if excavation is not intended. Mix # 14 has the average strength of 0.85 MPa (124 psi) which is within the range of excavatable CLSM.

In order to measure the pullout resistance of a steel bar embedded in the CLSM mixtures a special set-up was made and attached to the Instron machine, see Figures 2.10-2.12. Cylindrical CLSM samples, 100 × 200 mm (4 × 8 in.), with ribbed steel bar, 12.7 mm diameter and 27.9 cm length, placed in the center, were cast and cured for 1, 7 and 28 days. For each curing period 3 pull-out tests were performed for each. Pull-out load versus slip of the rebar for both mixtures is illustrated in Figure 2.13. Table 2.2 provides the average pull-out resistance results at each curing period for both mixtures. In this test, the failure of the sample was clearly affected by the boundaries (Figure 2.12), which indicates that prior to the slip failure of the rebar, the cylinder in fact had failed. This inaccuracy presented the need for another pull-out test set-up which can implement CLSM specimens with larger cross sectional area.

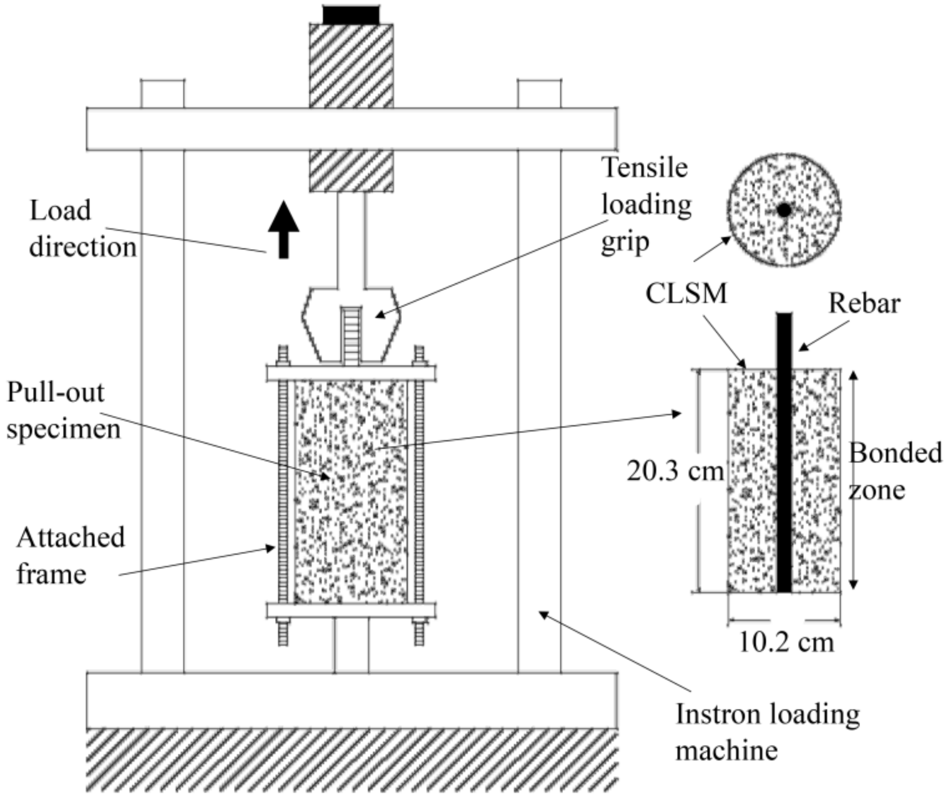

Figure 2.10: Set-up for pull-out test type 1 and associated specimen geometry

Figure 2.11: Pullout Test Type 1

Figure 2.12: Effect of Pullout on CLSM Specimen

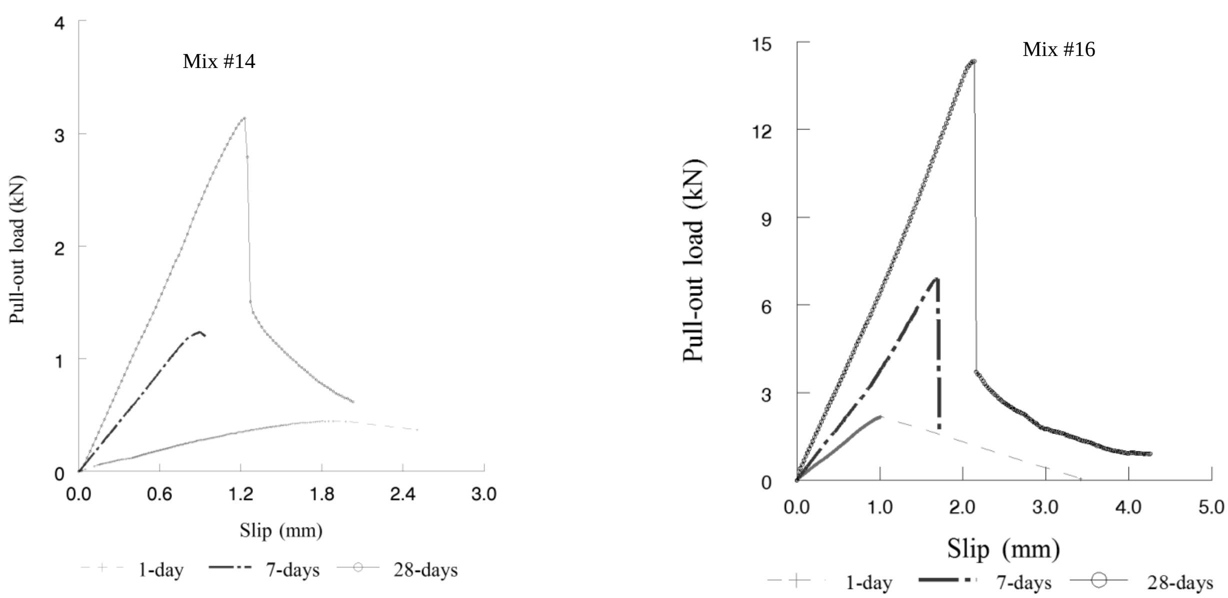

Figure 2.13: Pull-out load vs. slip for mix #14 and #16 (pull-out test 1)

Table 2. Results of pull-out test 1

Mix #	Pullout resistance, 1- day, kN, (lb)	Pullout resistance, 7-days, kN, (lb)	Pullout resistance, 28-days, kN, (lb)
14	0.45 (101)	1.35 (304)	2.7 (606)
16	1.57 (352)	6.48 (1457)	14.18 (3187)

2.4.3.2 Pull-out test type 2

The excavatable mixture, mix #14, was further investigated for large-scale testing. A wooden box of 0.61 m × 0.61 m × 0.91 m (2 ft × 2 ft × 3 ft) was made and divided into four equal partitions. Four ribbed rebars, 12.7 mm (0.5 in.) diameter and 1.1 m (3.5 ft) length, were placed and secured in the center of each partition, Figure 2.14 and 2.15. The box was filled with CLSM while some cylindrical molds were filled and placed in the center of the box for compression test. It was intended to compare the strength of the material inside the mass backfill with the known compressive strength of the mixture.

A frame was made over the box to set up the loading device and instrumentations, see Figure 2.16. A hydraulic jack was used for the loading. After 7 days curing, the tension load was applied gradually to each rebar and the slip was measured. Figure 2.15 shows the condition of the CLSM after a pullout test. Figure 2.17 illustrates the typical result of the tests. The average pull-out load for slip failure of the rebars was 21.3 kN (4800 lb) (with the coefficient of variation of 6.28%). After the pull-out tests, the cylinders embedded inside the box were retrieved to measure their compressive strength. The average compressive strength of the samples at 7 days was about 75 psi which is more than the strength found through standard sampling for compression test. This might be due to the temperature, drainage and coverage condition inside of the fill.

Figure 2.14: Pullout Test Type 2

Figure 2.15: CLSM Specimen After Pullout

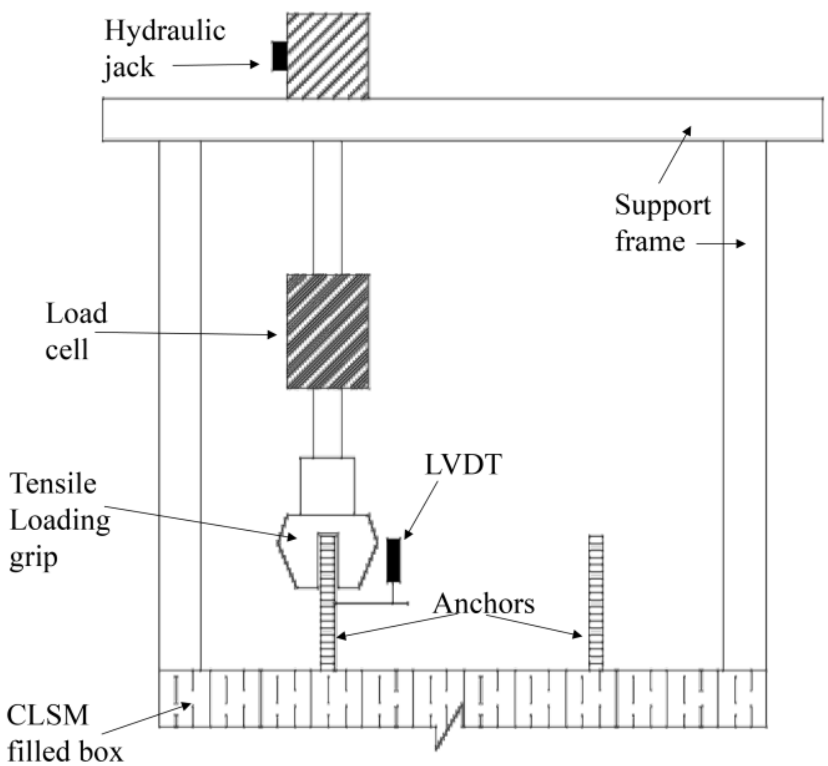

Figure 2.16: Set-up for Pull-out test type 2

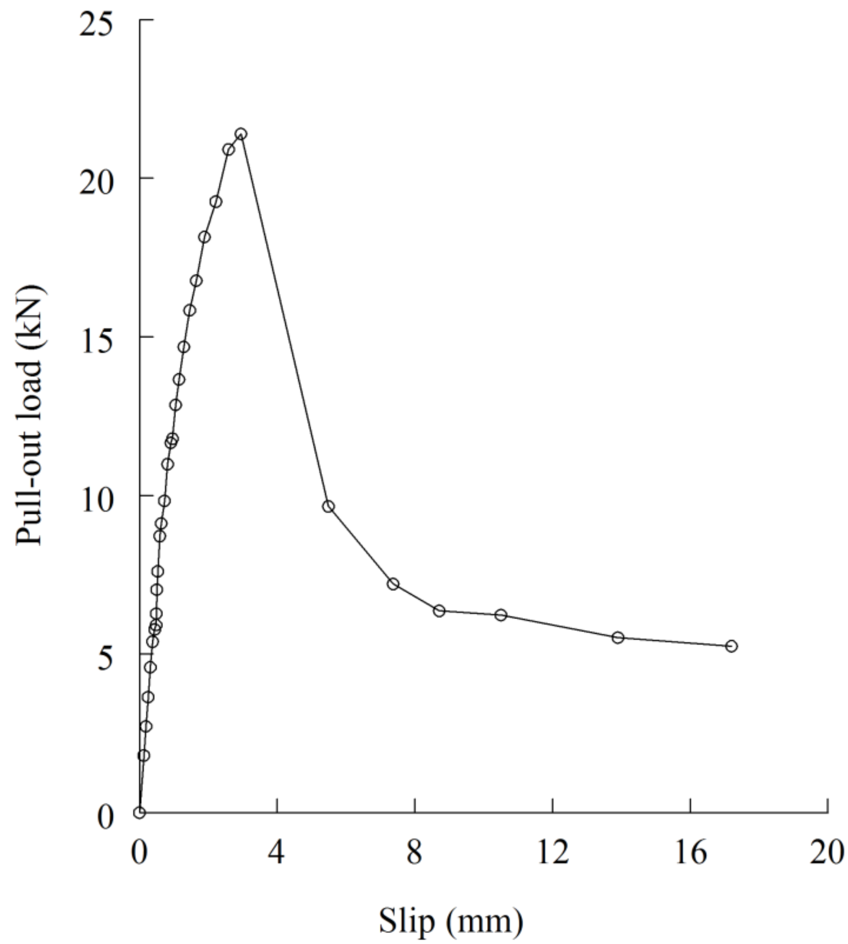

Figure 2.17: Pull-out load *vs.* slip (pull-out test type 2)

2.4.3.3 Pull-out test type 3

In order to verify the results of the last pull-out test set-up, it was decided to perform a real scale pull-out test with the same length of embedment as the steel anchors in the large-scale CLSM bridge abutment test. Two extra steel anchors, 12.7 mm (0.5 in.) diameter and 1.25 m (49 in.) length, were placed inside the abutment at wing walls through drilled holes in the concrete panels. These anchors were long enough to extend beyond the concrete face to allow the attachment of required testing equipment for the pull-out test.

Seven days after CLSM placement (mix #14) behind the testing abutment and prior to the main test, a hydraulic jack loading device, a load cell and a Linear Variable Differential Transformer (LVDT) were attached to the anchors (Figure 2.18 and 2.19) and the tension load was monotonically increased until the pull-out rupture occurred. The measured pull-out load versus slip of the steel anchor is shown in Figure 2.20. The average load for pull-out rupture of the rebars was about 21.8 kN (4900 lbs).

It was anticipated to get more pull-out load for this real-scale test because the length of embedment of steel bars was larger. The reason is that even though a ready mix concrete was asked to make mix #14, the collected samples during the placement, revealed that the batched mix had less 7-days compressive strength.

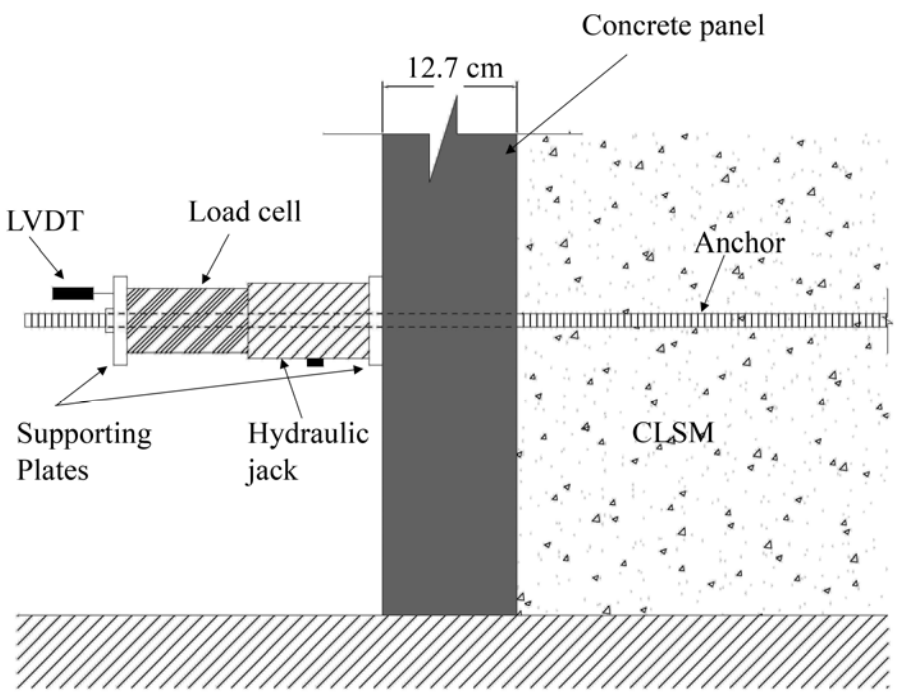

Figure 2.18: Set-up for pull-out test type 3

Figure 2.19: Pullout Test Type 3

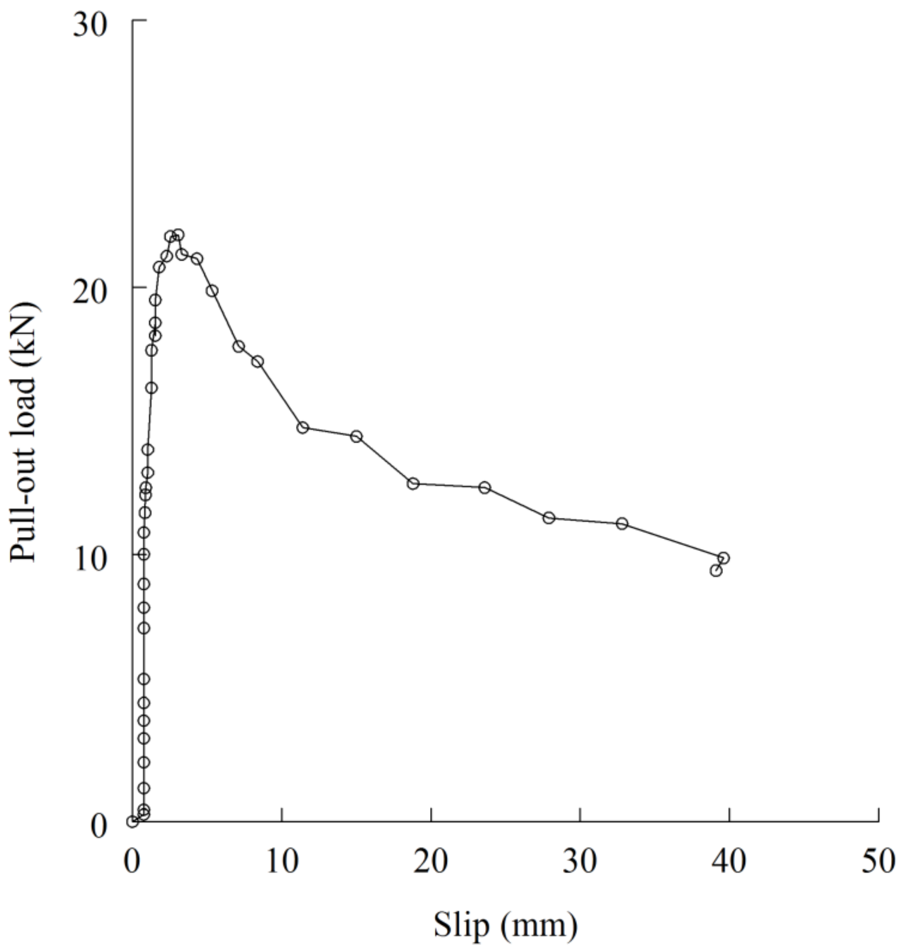

Figure 2.20: Pull-out load *vs.* slip (pull-out test type 3)

Comparison of the pull-out test results:

Results of the pull-out tests can be compared for mix #14 at an early age of 7 days after cast. In order to achieve a better assessment, the bond stress evaluation was made by using the equation below:

$$\tau = \frac{F}{\pi . \varphi . l_d}$$

Where, F is the pull-out load (at failure), ϕ is the steel bar diameter and l_d is the embedment length. Table 2.3 shows the comparison of the embedment length, compressive strength of the mixtures at 7 days and the evaluated bond stress. As it is mentioned before, pull-out test type 1 presented a small bond stress because the failure had reached the boundaries of the specimen. As it can be seen from the table, the higher strength of the mixture provides the higher bond stress between the steel bar and CLSM.

Table 2.3: Comparison of the bond stress in pull-out tests for mix #14.

Pull-out Test type	l_d, m, (in.)	f_c, MPa, (psi)	τ, MPa, (psi)
1	0.2, (8)	61, (0.42)	24.2, (0.17)
2	0.91, (36)	61, (0.42)	84.9, (0.58)
3	1.24, (49)	26, (0.18)	63.7, (0.44)

Note: f_c = Compressive strength at 7 days

CHAPTER 3
A LARGE-SCALE LABORATORY TEST FOR RAPID CONSTRUCTION OF CLSM BRIDGE ABUTMENTS

1. INTRODUCTION

Aging bridges with growing traffic demands has presented an increasing need for rapid construction/replacement of bridges to accommodate traffic flow and maintain freight movement with least adverse economic impact. According to the National Bridge Inspection Standards (NBIS), most bridges in the U.S. are inspected at least once every two years following the federal guidelines. In the December 2010 bridge inspection report by the U.S. Department of Transportation, it is stated that a quarter of the bridges in the U.S. are classified as deficient. Or, of the 604,474 bridges in the United States, 146,633 are classified as deficient, including 69,223 identified as structurally deficient and 77,410 as functionally obsolete bridges. Although all deficient bridges are not unsafe for travel, the numbers reveal the potential for many bridge replacement projects in the forthcoming years. The traveling public demands that these construction and replacement projects be completed more quickly to reduce congestion and to improve safety (Okumus, 2008).

Conventional cast in place construction of the foundation, substructure, superstructure components and other elements of bridges, demands a substantial amount of time as it requires the sequential labor-intensive processes of forming, placing and curing time to complete the project. This may cause disruption to the freight movement, and inconvenience to the traveling public during the construction period.

To mitigate the traffic congestion problems, it has been shown that the use of precast concrete components in bridges, including bridge girders, bridge decks, and segmental piers, could be a good solution. Since these components can be fabricated off-site, the number of labor and time consuming construction tasks that must be fulfilled on-site is reduced significantly. In addition to accelerated construction, the use of prefabricated bridge systems can allow for better in-plant quality control, improved durability, reduced life-cycle costs, use of innovative materials, better work-zone safety and minimum impact to the environment (Cheng and Capers, 2009).

The concept of using prefabricated elements in modern bridge construction has long been researched and has produced ample volume of information. Normally, most of the bridge construction duration is controlled by the construction of the substructure that consists typically of reinforced concrete abutments and piers with pile foundations. As such, utilizing rapid construction of only the bridge superstructure can only result in minor time saving. Hence, there is a vital need for developing and utilizing a novel method of accelerated construction for bridge substructures including bridge abutments.

2. CONTROLLED LOW STRENGTH MATERIAL (CLSM) BRIDGE ABUTMENT

Effective rapid bridge construction may be achieved by using the "controlled low strength materials (CLSM) bridge abutment". The CLSM bridge abutment construction is defined as using full-height precast concrete panels that are attached to a CLSM backfill via steel anchors. The CLSM bridge abutment provides a load-bearing support for the bridge sill, thus eliminating the need for piling systems. CLSM bridge abutments can be constructed in a shorter time because they do not require heavy machinery for excavation, compaction, and piling equipment. Depending on the project size, it is anticipated that several weeks or even months may be saved with the construction of CLSM integrated bridge system as compared with the construction of a conventional bridge abutment.

Figures 3.1(a) and 3.1(b) show schematic diagrams of a conventional bridge abutment with pile foundation and a typical CLSM bridge abutment with full-height precast concrete panel facing elements, respectively. As shown in Figure 3.1(b), the CLSM bridge abutment provides a load-bearing support for the bridge sill, thus eliminating the need for pile foundations. It should be noted that the CLSM abutment does not require the use of a deep foundation, even if the underlying soil is relatively weak. If the underlying soil is weak, a flowable fill foundation may be used to provide a stronger platform for the construction. The flowable fill foundation may involve removing about a 1-m (3-ft) thick layer of the foundation soil and simply replacing it with a flowable fill.

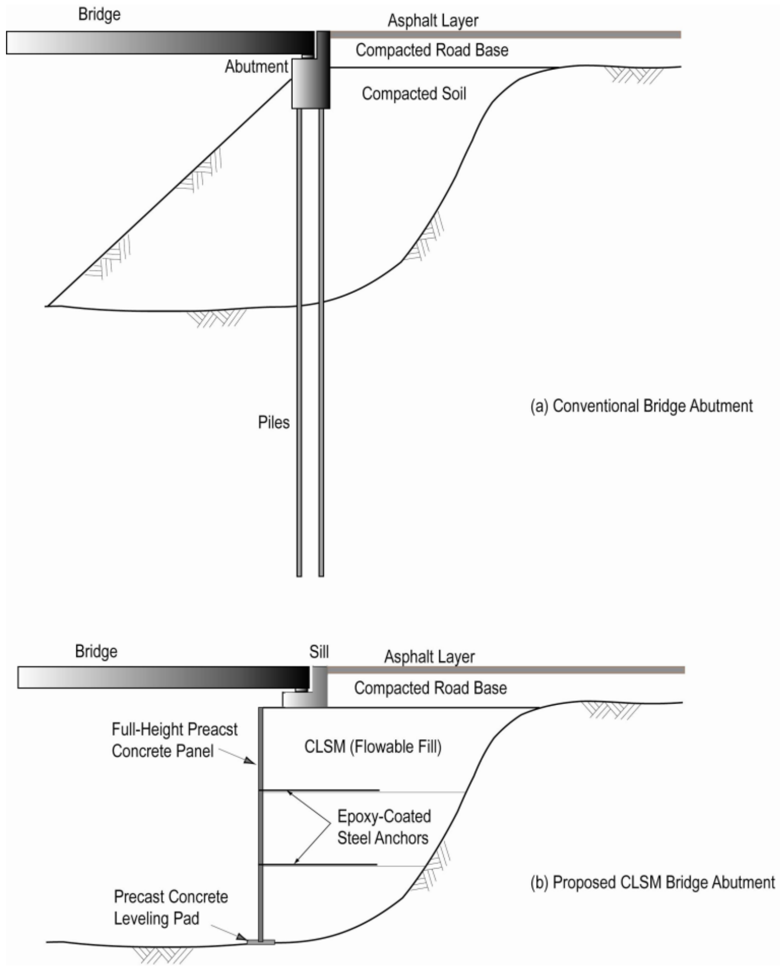

Figure 3.1: Comparison Between (a) Conventional Bridge Abutment and (b) CLSM Bridge Abutment

The interlocking full-height precast concrete panels serve as formwork that hold the newly poured CLSM backfill in place until the setting of the backfill materials is complete. The concept behind the favorable behavior of CLSM bridge abutment is based on having the CLSM mass, the steel anchors, and the full-height concrete panels act as a monolith. Accordingly, the concrete facing panels and the reinforced CLSM mass are then treated as one unit and analyzed as a large gravity wall. The required analysis includes the effects of strength, and stability in sliding and overturning. There are external and internal stability requirements for the CLSM bridge abutment. External stability of the CLSM abutment with bridge loading must be statisfied in terms of sliding, overturning, and bearing capacity of the underlying soil. Internal stability under bridge loading must be satisfied as well. Internal stability is based on the tie-back concept in which the steel anchors are theoretically holding in place the concrete panels and the CLSM wedge (behind the concrete panels) that is on the verge of active failure (i.e., the wedge is sliding towards the panels). Due to internal stability requirements, the anchors are designed to (1) resist yielding with a pre-specified safety factor, and (2) resist pullout with a pre-specified safety factor.

CLSM abutments have a number of distinct advantages over the conventional reinforced concrete abutments, including: (1) Construction of CLSM abutments is fast and requires only simple construction equipment, (2) When properly designed and constructed, CLSM abutments can withstand bridge loads with minimal deformations, (3) When properly designed and constructed, CLSM abutments can alleviate differential settlements at bridge approaches, and (4) CLSM abutments do not require embedment into the foundation soil to achieve stability. This is advantageous in terms of speedy construction and when involving contaminated soil.

Najafi and Tia (2004) noted that when a flowable fill is used the need for compaction is eliminated. This reduces additional equipment needs, labor costs and the amount of inspection. It has been shown that CLSM materials have performed well when used as self-leveling backfill behind conventional pile-supported bridge abutments. A survey by Trejo et al. (2004) indicated that 42 out of 44 state DOTs have standard specifications for the use of CLSM as backfill materials. A study of 177 bridges in Oklahoma compared different backfill materials behind conventional bridge abutments and the results indicated little movement at the CLSM approaches prior to the placement of the roadway pavement (Snethen and Benson, 1998; and Snethen et al., 1997). In addition, a Wisconsin Department of Transportation (WisDOT) study found that rideability over approaches with CLSM was better than approaches with granular backfill when used behind the conventional pile-supported abutments (Wilson 1999).

3. CONTROLLED LOW STRENGTH MATERIALS (CLSM)

CLSM (or flowable fill) is defined as self-compacting cementitious material that is in a flowable state at the time of placement and has a specified compressive strength of 8.3 MPa (1200 psi) or less at 28 days. It is also defined as able to be excavatable if the compressive strength is 2.1 MPa (300 psi) or less at 28 days. CLSM contains water, cement, fly ash, other admixtures, and aggregates. The American Concrete Institute Committee 229 requires that the wet density of CLSM should range between 1360 and 2320 kg/m^3 (85 and 145 pcf), but the dry density is expected to be substantially less than the wet density due to water loss. CLSM is durable, self-leveling, incompressible after curing, flowable around confined spaces and can be excavated and cures rapidly. CLSM makes use of environmentally impacted materials such as fly ash within its mix thereby reducing the demands on landfills, where these materials might otherwise be deposited (Trejo et al., 2004; Najafi and Tia 2004; and Newman et al., 1993).

Some disadvantages of CLSM include shrinkage, frost susceptibility, drainage, bleeding, and earth pressure during its fluid state (Najafi and Tia 2004; Newman et al., 1993, Schmitz et al., 2004). ACI Committee 229 (1999) noted that blockage of pumping equipment can result if there is segregation of particles, high fine materials content, or improper mixing. Also, the final grade level after placement will likely be lower than during the placement stage because of the reduction in the volume of the material as water is released. ACI Committee 229 (1999) has reported that a settlement equal to 3 to 6 mm (1/8 to 1/4 in.) per ft of depth is typical and that designers need to consider subsidence in their quantities and in plan preparation.

In this study, several CLSM mixes were tested for mechanical properties including compressive strength (1 day, 7 days, and 28 days), flow consistency, and pullout strength of rebars embedded in CLSM. The selection criteria for a final mix was based on a mixed being able to be excavated as well as relatively high early strength. The selected CLSM mixture has a flow of 350 mm (14 in.) according to the Standard Test Method for Flow

Consistency of CLSM (ASTM D 6103) and has a compressive strength of 0.38 MPa (55 psi) after seven days as shown in Table 3.1.

Table 3.1: Selected CLSM Mix

Cement, kg/m^3 (lb/yd^3)	46 (78)
Fly Ash (type F), kg/m^3 (lb/yd^3)	261 (440)
Sand, kg/m^3 (lb/yd^3)	1535 (2588)
Water, kg/m^3 (lb/yd^3)	307 (518)
Compressive strength at 1 day, MPa (psi)	0.08 (11)
Compressive strength at 7 days, MPa (psi)	0.4 (55)
Compressive strength at 28 days, MPa (psi)	0.8 (124)

4. LARGE SCALE CLSM BRIDGE ABUTMENT TEST

In this paper, the application of a CLSM bridge abutment in normal-span bridges is examined through a full-scale laboratory test. An instrumented CLSM bridge abutment (2.7 m (8.8 ft) x 2.7 m (8.8 ft) in plan, and 2.75 m (9 ft) in height) with full-height prefabricated concrete panels was constructed to investigate the performance of the abutment due to application of a monotonically increasing sill pressure (Figure 3.2). Full-height precast concrete panels were attached to the CLSM backfill via steel anchors (Figure 3.2(b)). Figure 3.3 shows design details of the reinforced concrete panel and the corner unit. The objectives of the test were: (1) to determine the constructability of the proposed CLSM bridge abutment, and (2) to determine the behavior of CLSM bridge abutments, in terms of load carrying capacity and deformations, after 7 days of CLSM setting time. The latter objective is of great interest since it will provide evidence about the behavior of the CLSM abutment shortly after the CLSM was poured--a critical issue with respect to rapid construction of the abutment.

The CLSM bridge abutment and the concrete sill were instrumented, as shown in Figures 3.2(a) and 2(c), to measure their behavior during construction and upon application of bridge loads. Instrumentation included load cells, pressure cells (Figure 3.4), strain gauges (Figure 3.5), LVDTs and high-resolution digital video cameras. Of particular interest was the displacement of the sill and the lateral pressure and displacement of the facing wall. Also, because of the three-dimensional behavior of the abutment, the wing walls were also instrumented to measure their lateral displacements. In addition, one LVDT was installed on the base leveling pad at the front facing wall to measure the settlement of the 20-cm-thick (8 in.) foundation soil.

The construction sequence of the CLSM bridge abutment was as follow:

Step 1; Prefabrication: Reinforced concrete panels and corner units with tongue-and-groove connection type, Figures 3.3 and 3.6, were designed to withstand the fluid pressure of the CLSM material and the lateral pressure due to the bridge load. Each panel had six openings to accommodate the installation of threaded steel bar anchors prior to the placement of the CLSM material (Figure 3.2 (b)). Matching nuts were cast in the panels at the position of the openings (Figure 3.7). The system is designed in a way that the anchors can be installed from outside the abutment during the gradual pouring of CLSM. Additional components included concrete leveling pad modules and a 30-cm (1-ft) thick reinforced concrete bridge sill.

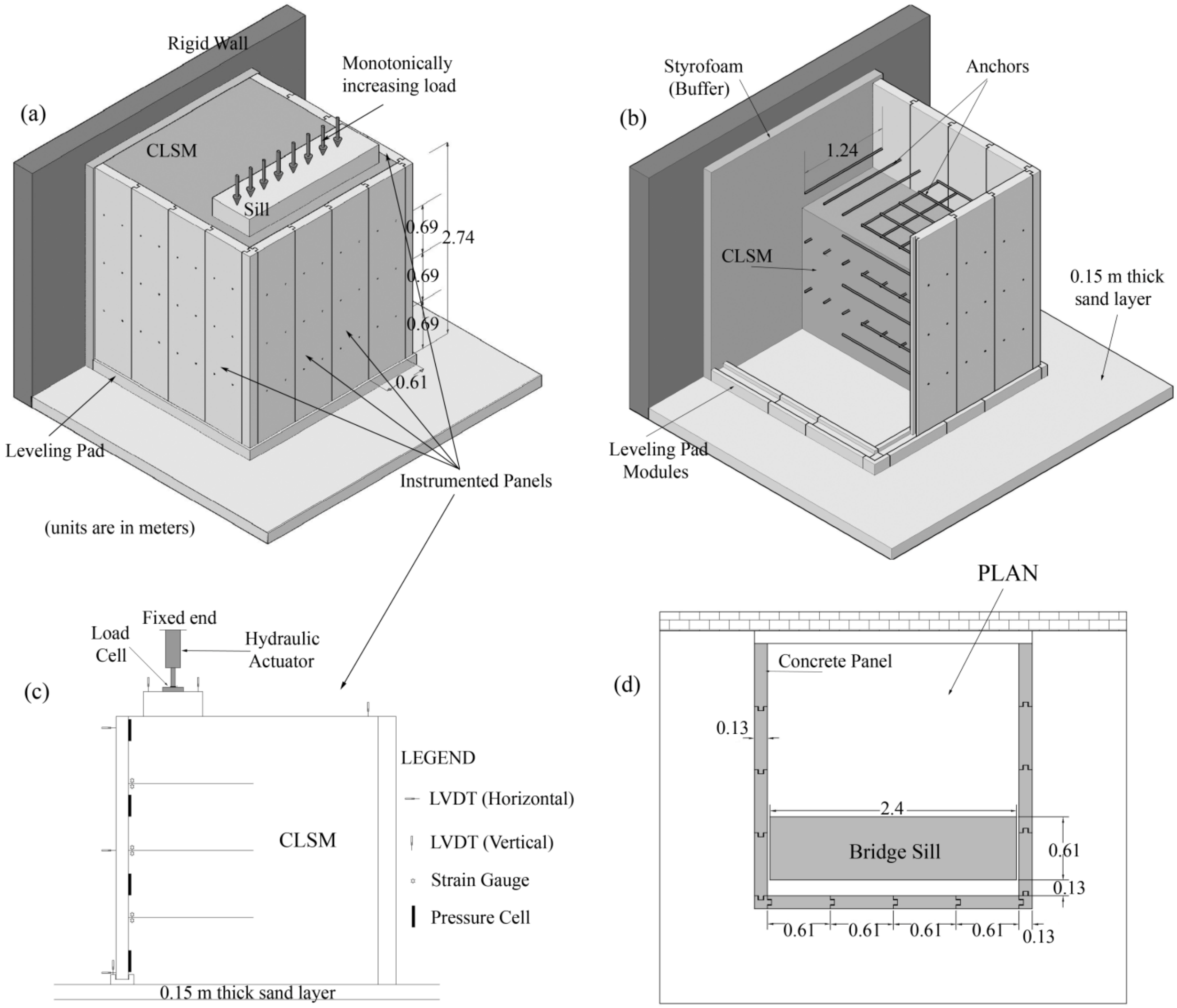

Figure 3.2: Configuration of the CLSM Bridge Abutment Test

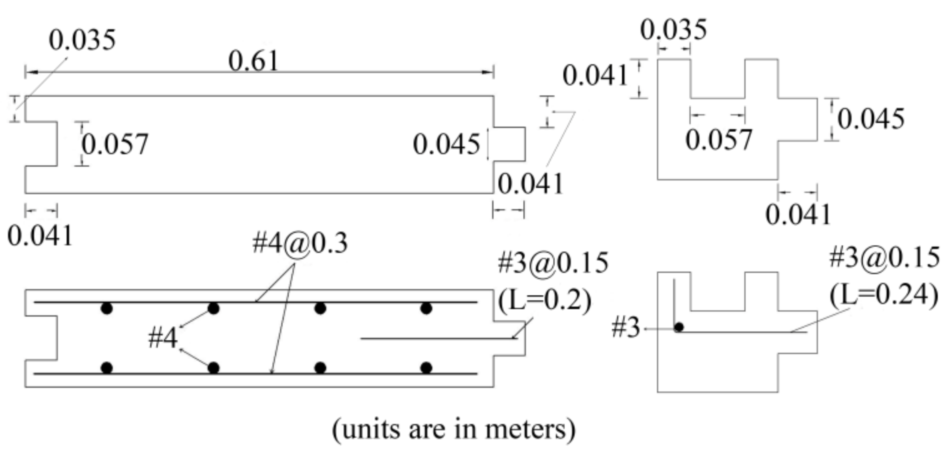

Figure 3.3: Reinforced Concrete Panel and Corner Unit Detail

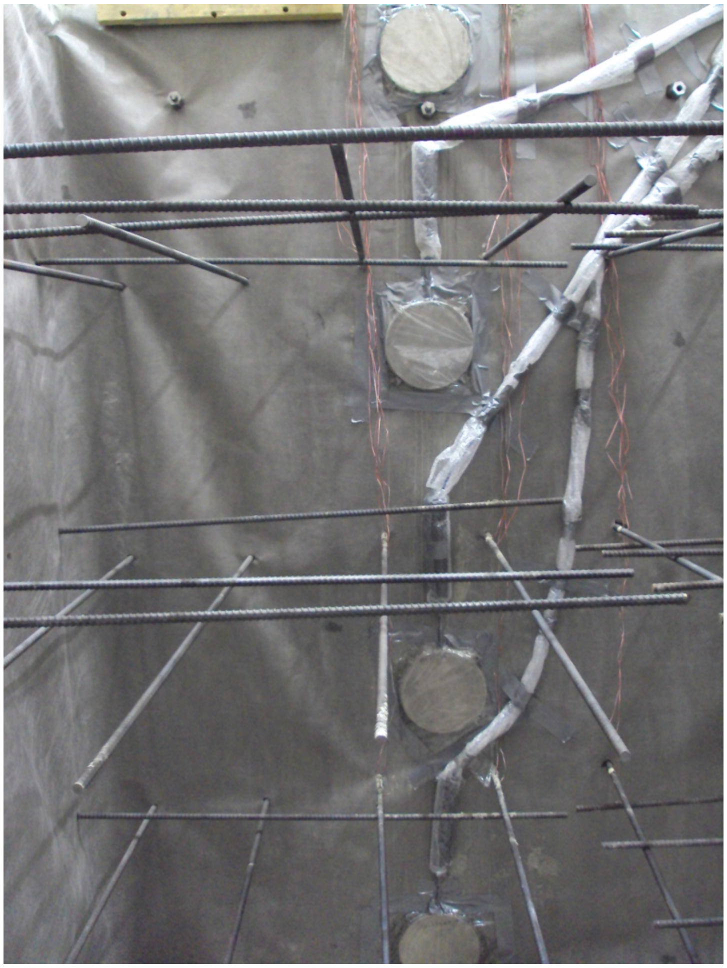
Figure 3.4: Pressure Cells

Step 2; Base Preparation: A 20-cm (8-in.) thick layer of compacted soil was placed on the laboratory's strong floor to serve as the base for the CLSM abutment (Figure 3.8). A layer of geomembrane was installed prior to the installation of the soil layer, as shown in the same figure, to ensure a water-tight testing environment. The leveling pad was then installed on top of the soil layer as shown in Figure 3.9.

Step 3; Panels Installation: The facing panels were assembled using the laboratory's overhead crane (Figures 3.10 and 3.11). A temporary bracing system was used to support the panels laterally, as shown in Figure 3.12, to ensure a safe working environment. After all the panels were installed, a geotextile layer (Typar 3301) was installed as a filter in one-piece cover for the interior side of the abutment to let the water drain and keep the fine grained materials of the backfill (Figure 3.5).

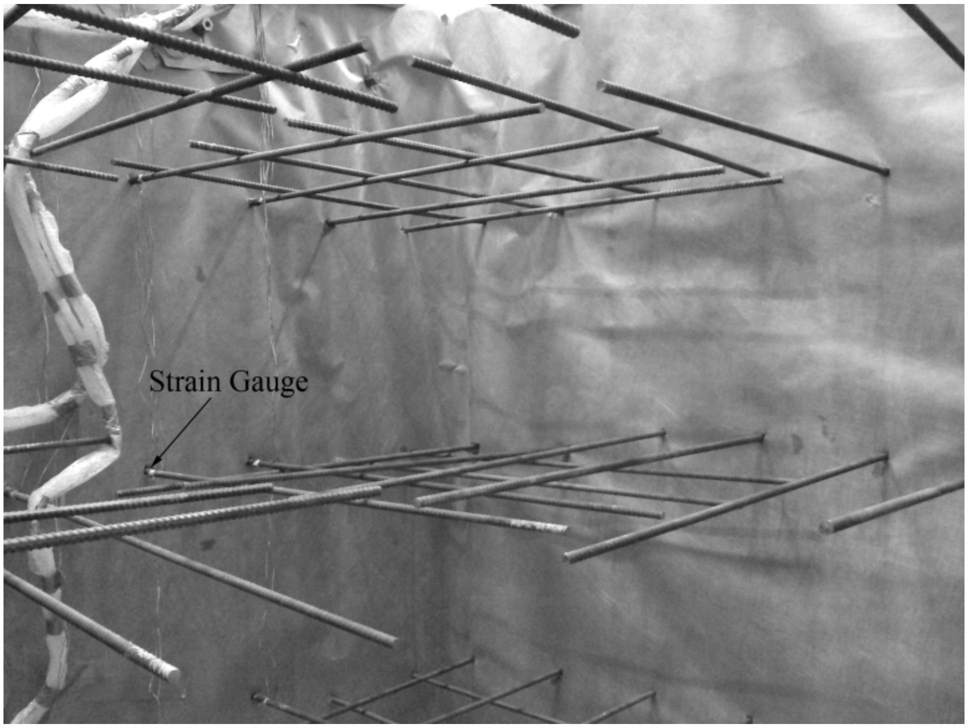

Figure 3.5: Strain Gauges mounted on Steel Anchors

Step 4; Anchor Installation: As shown in Figure 3.5, steel anchors were threaded through the nuts in the panels from the outside of the abutment.

Step 5; CLSM Placement: The entire abutment was backfilled in one continuous pour by pumping of the CLSM material as shown in Figures 3.13 and 3.14. Samples were collected during the placement of the CLSM material to compare the strength with that from the designed mix. Unconfined compression strengths of the samples were 0.2 MPa (30 psi) and 0.4 MPa (58 psi) at 7 days and 28 days, respectively. Flowability of the mix was controlled frequently in order to be kept around 350 mm (14 in.) according to the Standard Test Method for Flow Consistency of CLSM (ASTM D 6103). The excess water of the placed CLSM was released through anchor openings of the panels (Figure 3.15).

Step 6; Loading Frame: A loading frame was assembled using steel columns and beams. Two hydraulic jacks were mounted under the frame to allow application of load to the bridge sill, see Figures 3.16 and 3.17.

Step 7; Bridge Sill Placement: After six days from the time of the placement of the CLSM material, the precast concrete bridge sill was installed on top of the CLSM abutment as shown in Figure 3.16. LVDTs were mounted on the four corners of the sill to measure its settlement, and also on the front face and wing walls to measure their lateral displacements. A wooden frame was used as a reference base against which all LVDTs were mounted (Figure 3.18). Positions of the LVDTs are shown in Figure 2(c).

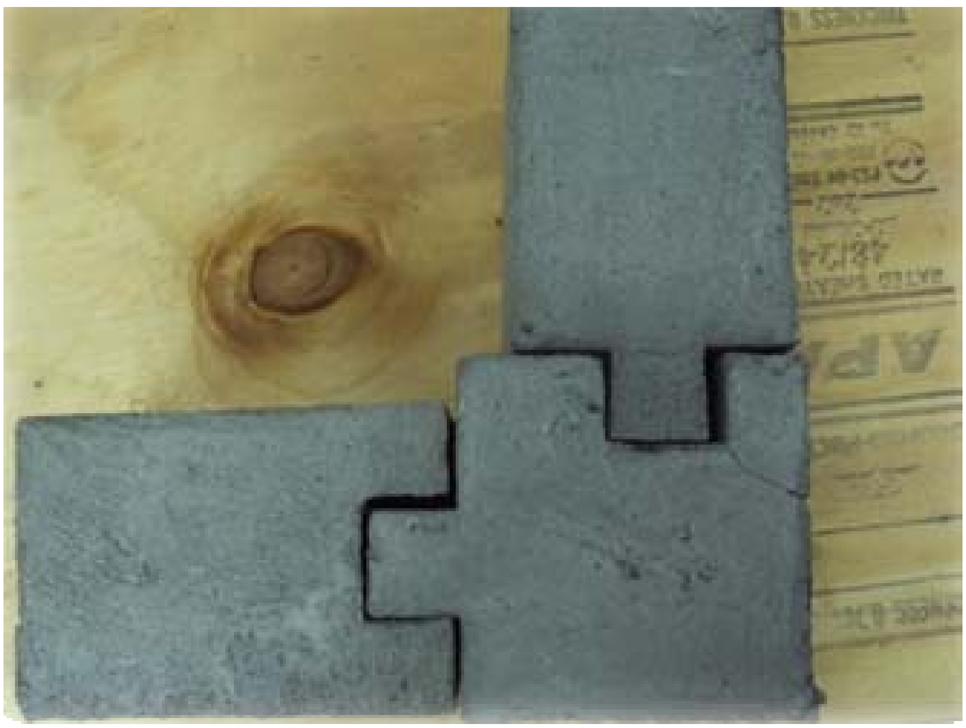

Figure 3.6: Reinforced Concrete Panels and a Corner Unit

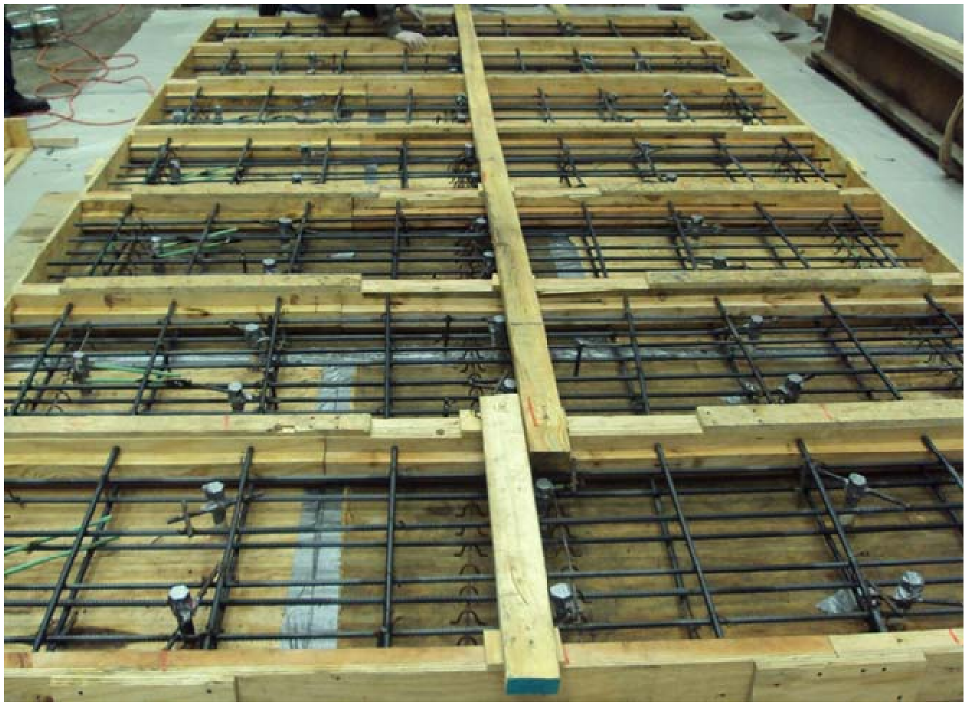

Figure 3.7: Reinforced Concrete Panels Form Work

Figure 3.8: Compaction of the Base Soil Layer

Figure 3.9: Leveling Pads

Figure 3.10: Panel Installation

Figure 3.11: Panel Installation

Figure 3.12: Temporary Lateral Support of Concrete Panels

Figure 3.13: CLSM Pouring

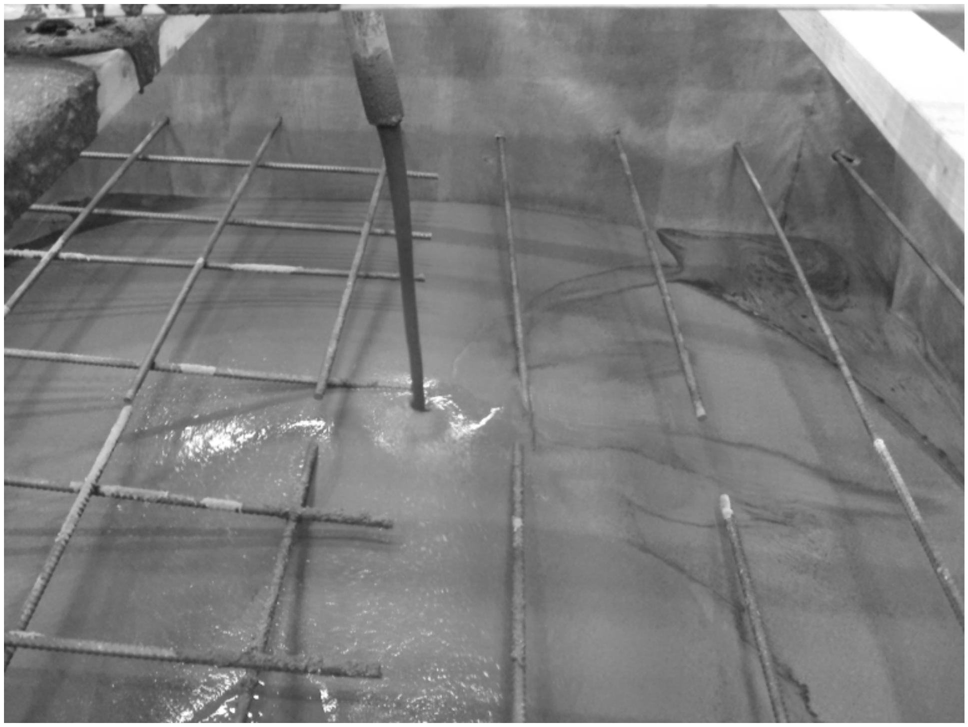

Figure 3.14: Continuous Pouring of CLSM

Figure 3.15: Released Water through Holes in the Panels

Figure 3.16: Reinforced Concrete Sill Placement

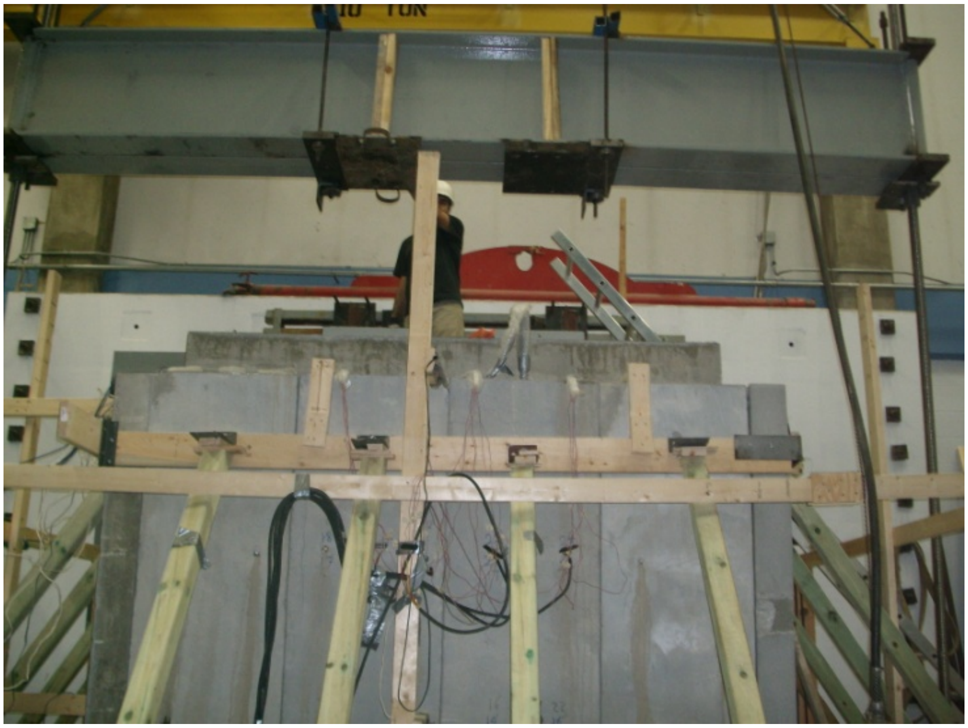

Figure 3.17: Loading Frame

Step 8; Application of Load: Seven days after the installation of the CLSM material, the lateral supports were removed from the abutment panels. Figure 3.18 shows the CLSM abutment just prior to the loading test. Static loads were applied to the bridge sill in steps using hydraulic jacks. All measurements including applied loads, lateral pressures on panels, displacements and strains were recorded using a data acquisition system. Dial displacement gauges were recorded manually.

Step 9; Excavation: After completing the test, the panels were detached, and the backfill was easily excavated because of the low strength of the CLSM, see Figure 3.19.

5. RESULTS AND DISCUSSION

Up to 780 kN (175 kips) of vertical load was applied to the CLSM abutment without any failure or damage in the system. This load is equivalent to an expected reaction force in a single-span highway bridge of 30 m (100 ft). Settlements at the four corners of the sill are shown in Figure 3.20. The observed small variation in settlements is possibly due to the initial gap(s) between the sill and the top surface of CLSM. The average final settlement of the bridge sill was about 6 mm (1/4 in.). Also the data from the LVDT on the leveling pad, as illustrated in Figure 3.21, shows that the underlying soil experienced only negligible settlement, as small as 0.4 mm (0.017 in.).

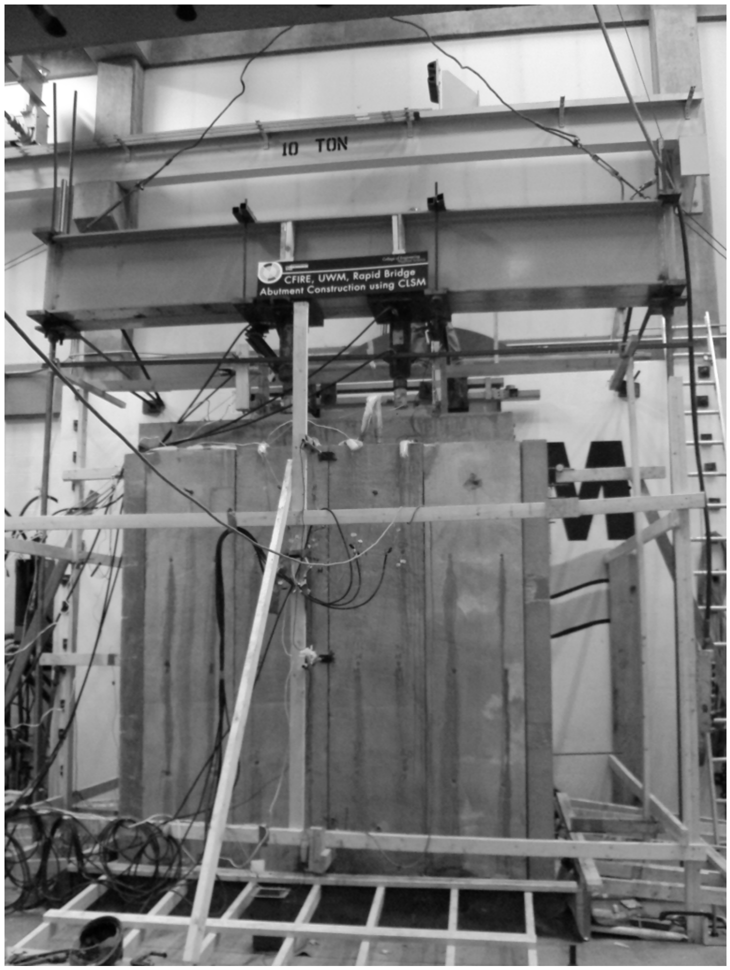

Figure 3.18: Large Scale CLSM Bridge Abutment Prior to Test

Figure 3.19: Excavation of the CLSM Backfill

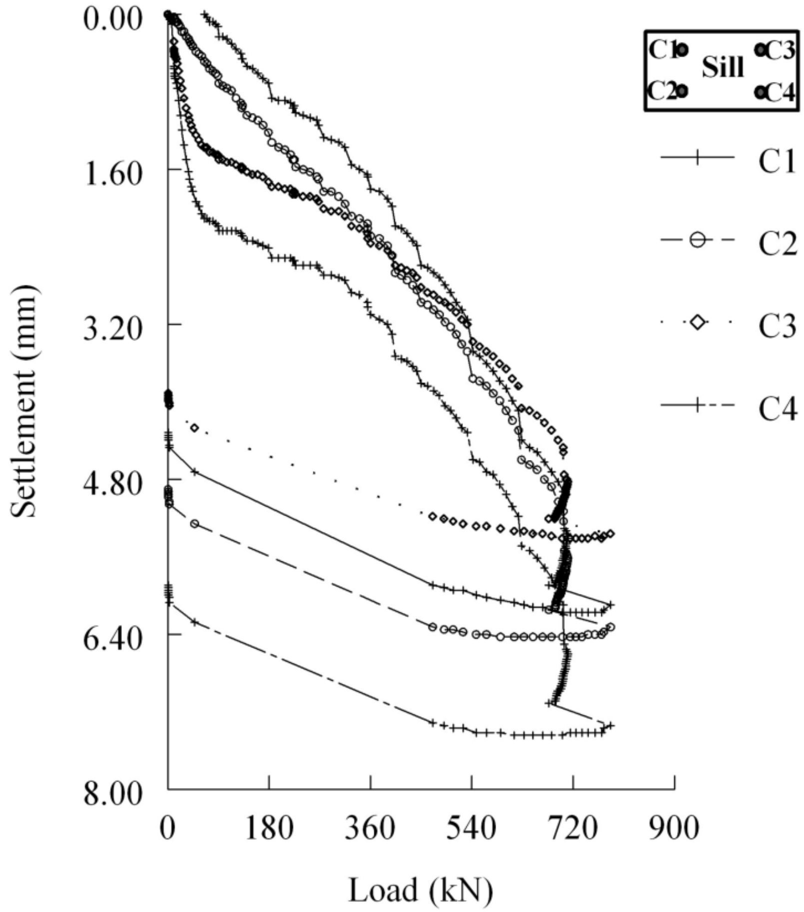

Figure 3.20: Settlement of the Bridge sill at Corners

The maximum lateral displacement of the front facing panel occurred at the top of the panel and was about 3 mm (0.12 in.) as shown in Figure 3.22. The lateral displacement at the middle and the bottom of the panel were considerably smaller as shown in the same figure. Lateral displacements of the wing walls were negligible with the maximum value of 1 mm (0.04 in.) at the top.

While the CLSM material cured, the pressure at the mid-height of the panel increased to 24 kPa (3.5 psi), see Figures 3.23 and 3.24. This higher lateral pressure at the mid-height areas is due to the speed of hydration and bleed water seepage at areas closer to the top and bottom of the abutment. This was verified by the large volume of drained water observed at the base of the test abutment. Past studies have also shown that at the mid-height regions of CLSM abutments, water cannot dissipate or evaporate as fast as regions near the surface (Snethen et al. 1997).

The lateral pressure of backfill against the front facing panel was monitored during and after the placement of the CLSM material as well as during the loading stage of the experiment. It is known that a freshly placed concrete behaves temporarily like a fluid, producing a hydrostatic pressure that acts laterally on a wall. For flowable fills, Schmitz et al. (2004) concluded that the lateral pressure on a wall after the curing stage is negligible. However, during the placement of CLSM, the structure must be designed to temporarily support the fluid pressures. The varying profile of the measured lateral pressure of the CSLM material as a function of age against the abutment panels is shown in Figure 3.23 and compared with the hydrostatic pressure. As it can be seen, fresh flowable fill results in smaller lateral pressure on the abutment than that from normal fluid pressure. The maximum lateral pressure of about 24 kPa (3.5 psi) was measured at the bottom of the facing panel initially but it was gradually reduced to about 7 kPa (1 psi).

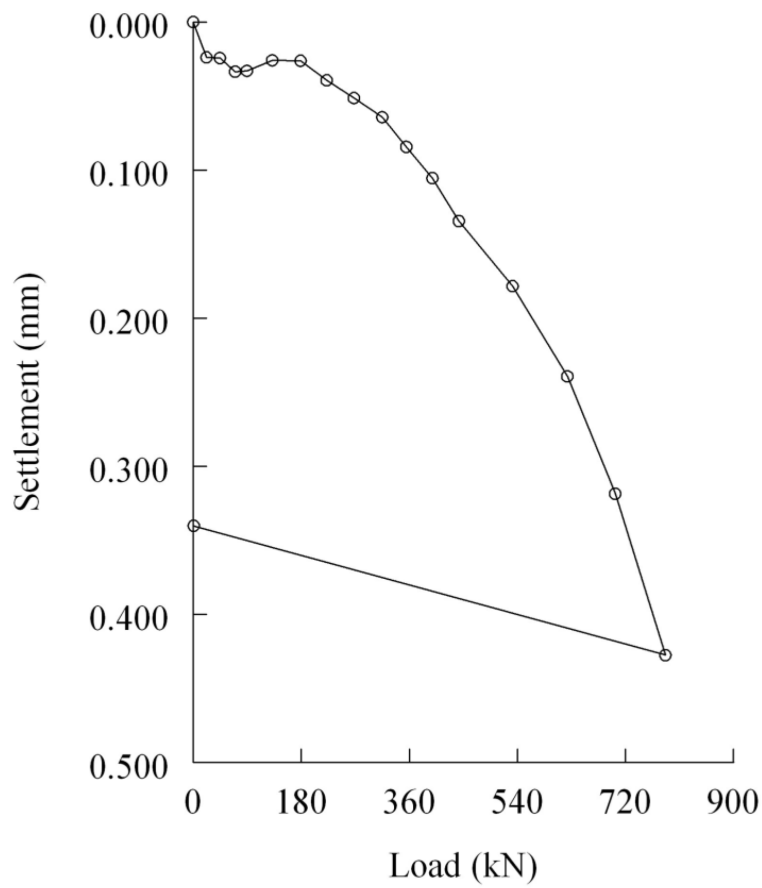

Figure 3.21: Settlement of the Foundation Soil

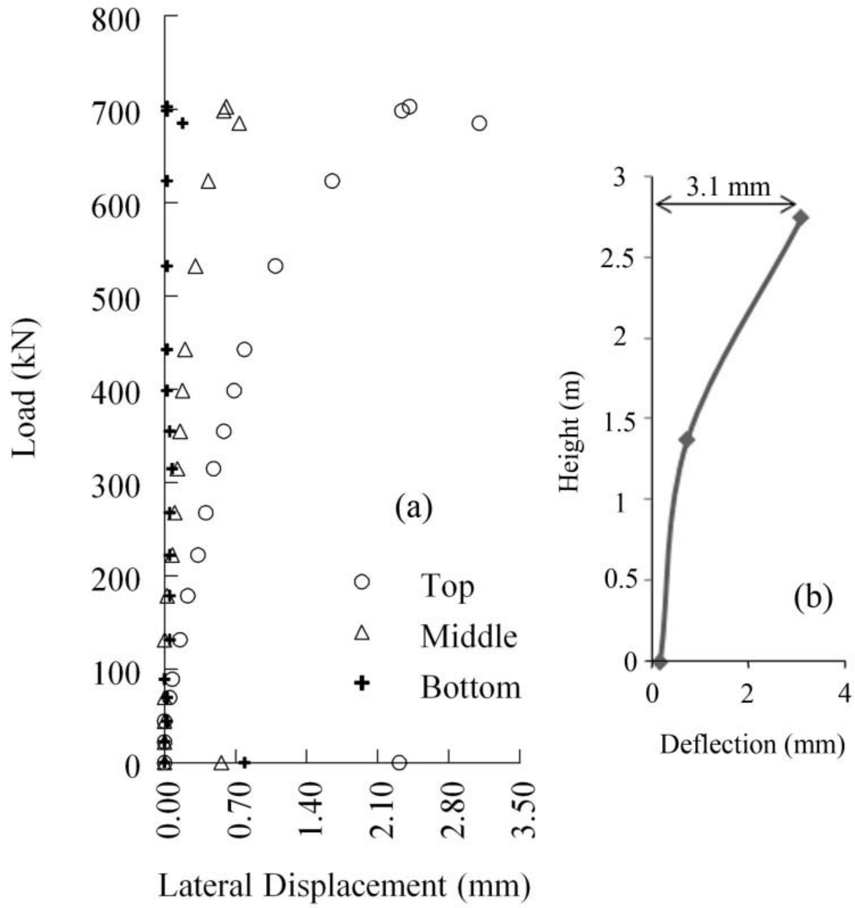

Figure 3.22: (a) Lateral Deflection of the Front Facing Wall, (b) Deflection Profile of the Panel

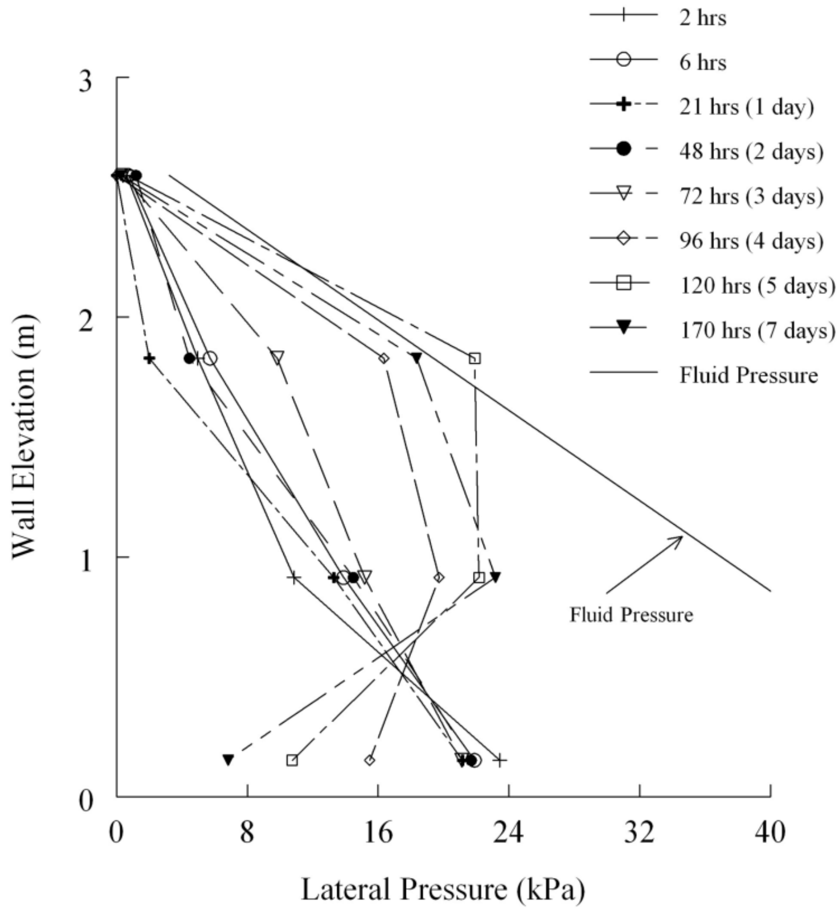

Figure 3.23: Lateral Pressure Against Abutment with CLSM Age

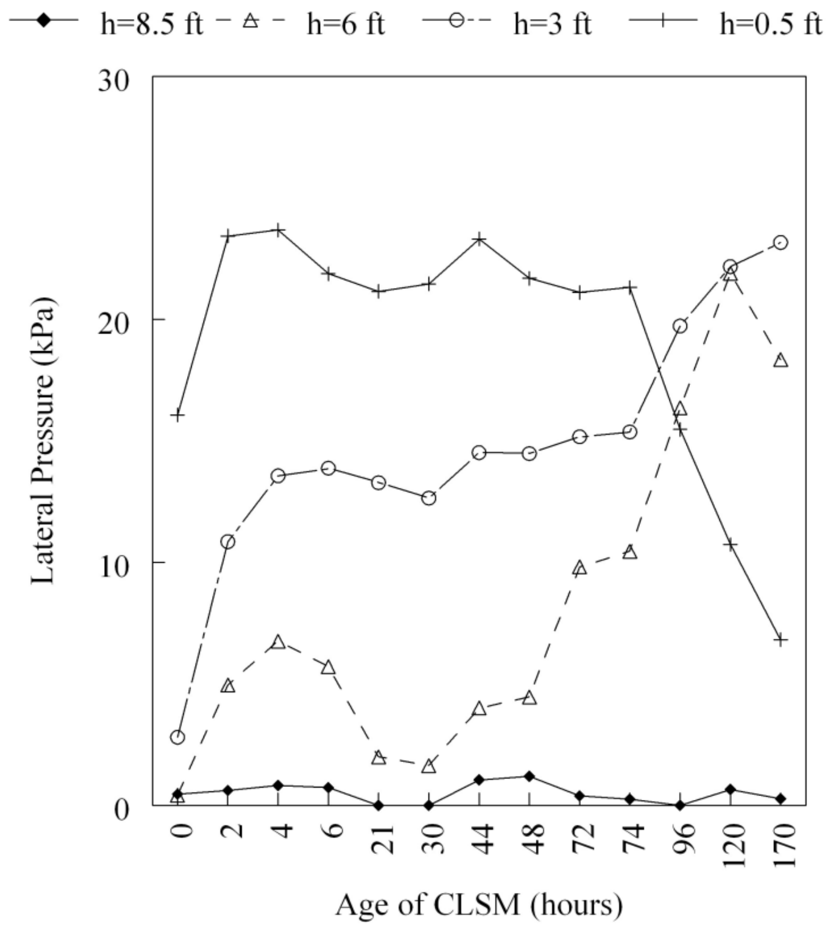

Figure 3.24: Lateral Pressure at Different Heights with CLSM Age

Figure 3.25 shows the lateral pressure on the front panel during the application of bridge loading. The figure shows that the lateral pressures are very small in general with the maximum value of 30 kPa (4 psi) recorded near the middle of the panel. As illustrated in Figure 3.25, upon applying the bridge load, the lateral pressure at the top of the panel was unchanged in the beginning and then started to increase approaching about 10 kPa (1.5 psi) at 790 kN (177 kips) load. The pressure at the bottom of the panel remained unchanged. It is interesting to note the pressures elsewhere consistently decreased as the bridge load increased. This may be attributed to the lateral (outside) deflection of the facing panel.

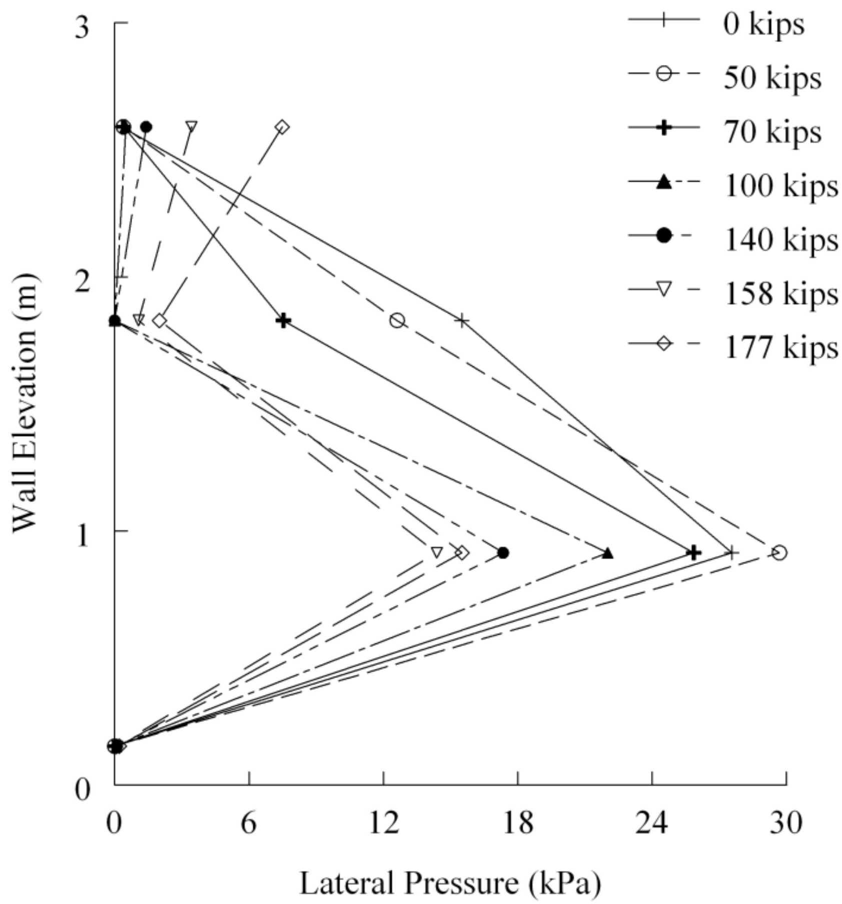

Figure 3.25: Lateral Pressure on the Front Wall with Applied Load

Several strain gauges were used to measure the strains at the top and bottom sides of several steel anchors at their points of attachment with the facing panels (Figure 3.26). The two gauges, one at the top and one at the bottom side of the anchor, are necessary to calculate the axial force in the anchors. The measured strains indicated that steel anchors installed at higher elevations experienced both axial and bending loads while those at the lower elevation experienced mainly axial loads. Figure 3.26 shows the measured strains, as function of the applied bridge load, in the steel anchors installed at different heights of the facing panel.

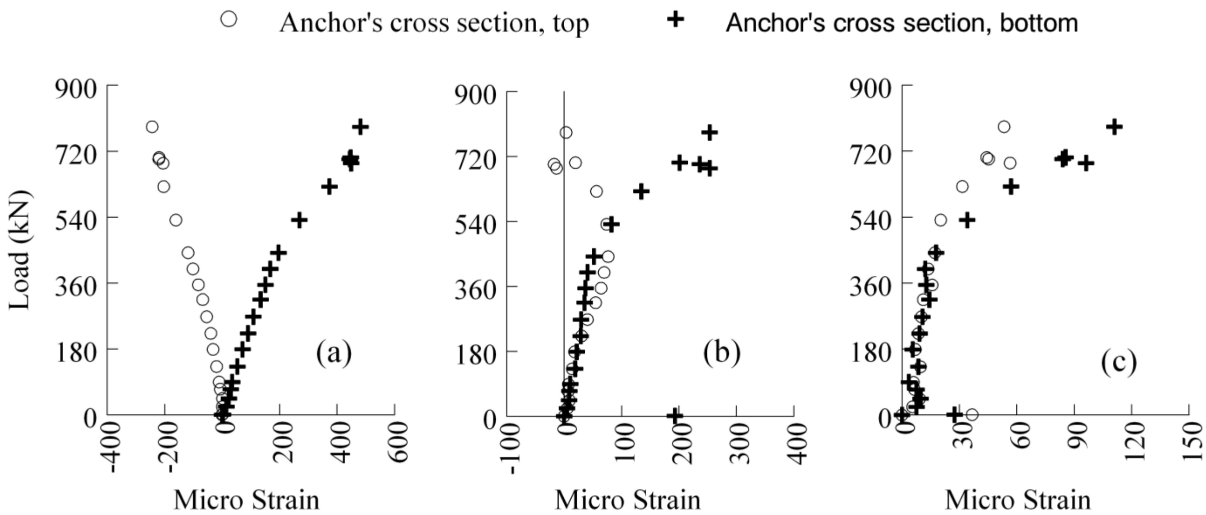

Figure 3.26: Measured strains at the Anchors Installed at (a) top, (b) middle and (c) bottom of the Front Wall Panel

6. SUMMARY AND CONCLUSIONS

One of the major obstacles facing rapid bridge construction for typical span type bridges is the time required to construct bridge abutments and foundations. This can be remedied by using the controlled low strength materials (CLSM) bridge abutment.

A suitable CLSM mixture with optimum strength and flowability was designed by performing a series of unconfined compression, flowability, and pull-out tests. Using the selected CLSM mix, an instrumented, large-scale CLSM bridge abutment with full-height concrete panels was constructed to test its performance due to the application of a gradually increasing bridge load.

The measured lateral pressure against the abutment wall panels was very small in general, and was higher in the mid-height layers of the flowable fill during the curing time due to limited shrinkage that could have taken place in such regions. After curing, the lateral pressure decreased to negligible levels due to shrinkage. It was found that it is easy to remove the CLSM material after the test was done, indicating that the selected CLSM mix was indeed excavatable.

The test results show that the CLSM bridge abutment, with a relatively short cure time of 7 days, is capable of carrying bridge loads with a reasonably large safety margin, and with minimal deformations. The CLSM bridge abutment in this study resisted 780 kN (175 kips) of static load without any failure and with minimal settlement (6 mm) of the bridge superstructure. This load corresponds to an applied pressure of 535 kPa (77.6 psi) on the bridge sill. In contrast, an average sill pressure of 93 kPa (13.5 psi) is calculated from the dead load of a large single-span bridge of 24 m (80 ft) length and 11 m (35 ft) width supported by a 11 m × 1.5 m (35 ft ×5 ft) bridge sill. This sill pressure is nearly six times smaller than the pressure applied in the laboratory test. Such a small pressure will cause extremely small sill settlements.

ACKNOWLEDGMENT

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REFERENCES

1. Adaska, W. S. (1997). “Controlled Low Strength Materials” Concrete International, Vol. 19, No. 4, pp. 41–43.
2. American Concrete Institute (ACI) Committee 229. (1999). “ACI 229R-99 report in controlled low-strength materials (CLSMs).” *American Concrete Inst*.
3. Brewer, W.E., 1994. "Durability Factors Affecting CLSM," Controlled Low-Strength Materials, ACI SP 150, W.S. Adaska, ed., American Concrete Institute, Detroit, MI, 113 pp.
4. Cheng, H., Capers, H. (2009). “Overnight Delivery – New Jersey DOT Rapid Bridge Replacement.” *Proc., 25th US-Japan Bridge Engineering Workshop*, Tsukuba, Japan, 163-172.
5. Digioia, Jr., A. M., and Brenda, G. F., Fly Ash Design Manual for Road and Site Applications, Vol. 2: Slurried Placement, EPRI Report Tr-100472, Electric and Power Research Institute, Palo Alto, CA, 1992.
6. Dockter, B.A., “Comparison of Dry Scrubber And Class C Fly Ash in Controlled Low-Strength Materials (CLSM) Applications,” The Design and Application of Controlled Low-Strength Materials (Flowable Fill), ASTM STP 1331, A. K. Howard and J. L. Hitch, eds., American Society for Testing and Materials, West Conshohocken, PA, 1998.
7. Federal Highway Administration (1997). “User Guidelines for Waste and By-Product Materials in Pavement Construction,” Report No. FHWA-RD-97-148.
8. Federal Highway Administration (FHWA). (2004). "National Bridge Inspection Standards (NBIS)." < http:// www.fhwa.dot.gov/bridge/nbis.htm>
9. Folliard, K. J., Trejo, D., Sabol, S. A., and Du., L., (1999). Controlled Low-Strength Material for Backfill, Utility Bedding, Void Fill, and Bridge Approaches, NCHRP Phase I Interim Report, Delaware Transportation Institute, University of Delaware, Newark.
10. Halmen, C, Trejo, D., Folliard, K.J., and Du, L. (2005), “Corrosion of Metallic Materials in Controlled Low-Strength Materials- Part 3,” *American Concrete Institute (ACI) Materials Journal*, Volume 102, Issue 6, pp. 429-437.

11. Hitch, J. L., “Test Methods for Controlled Low-Strength Material (CLSM): Past, Present, and Future,” The Design and Application of Controlled Low-Strength Materials (Flowable Fill), ASTM STP 1331, A. K. Howard and J. L. Hitch, eds., American Society for Testing and Materials, West Conshohocken, PA, 1998.
12. Javed, A., Lovencin, W., and Najafi, F.T., “Current Status of Accelerated Flowable Fill in the Pavement Section,” Proceedings, Canadian Society for Civil Engineering 20th Annual Conference, Montreal, Quebec, Canada, June 5-9, 2002.
13. Lovencin, W., Najafi, F.T., and Chaudhry, H. (2006). “Assessment of Flowable Fill Strength in Pavement Construction.” Journal of the TRB 1979, National Academies, NRC, Washington, DC, 84-92.
14. Melton, J. S., Nourse, W. A., Gardner, K. H., and Seager, T. P., 2005, "A Rational Mix Design for Flowable Fill Containing Contaminated Sediment." Third International Conference on Remediation of Contaminated Sediments, Jan. 24-27, New Orleans, LA.
15. Najafi, F.T, and Tia, M. (2004). “Use of Accelerated Flowable Fill in pavement Section.” *Final Report*, *Volume 1*, Florida Department of Transportation, Tallahassee, 124 pp.
16. Newman, F.B., Rojas-Gonzalez, L.F., and Knott, D.L. (1993). “Implementation Plan for Design and Use of Flowable Backfills by PennDOT for Highway and Bridge Construction.” *Report No. FHWA-PA-91-007+90-12*, FHWA, Washington, D.C. and Pennsylvania Department of Transportation, Harrisburg, 9 pp.
17. NRMCA, 1989, “What, Why, and How? Flowable Fill Materials,” Concrete in Practice No. 17, National Ready Mixed Concrete Association, Silver Spring, MD.
18. Okumus, Pinar. (2008). “Rapid Bridge Construction Technology: Precast Elements for Substructures.” M.S. thesis. Univ. of Wisconsin-Madison, Madison, WI.
19. Schmitz, M.E., Parsons, R.L., Ramierz, G., Zhao, Y. (2004). “Use of Controlled Low-Strength Material as Abutment Backfill.” *Report No. K-TRAN: KU-02-6,* Kansas Department of Transportation, Topeka, 76 pp.
20. Snethen, D.R. and Benson, J.M. (1998). “Construction of CLSM Approach Embankment to Minimize the Bump at the End of the Bridge.” *The Design and*

Application of Controlled Low-Strength Materials (Flowable Fill), American Society of Testing Materials (ASTM), STP 1331, pp. 165-179.

21. Snethen, D.R., Schwidder, A.J., Benson, J.M., and Koening, S.A. (1997). "Performance of Experimental Approach Embankments at Slat River Bridges on U.S. 177- Final Rept. Jul 93-Jun 97." *Final Report FHWA/OK-97(04)*, Oklahoma Department of Transportation, Oklahoma City, 240 pp.
22. Trejo, D., Folliard, K.J, and Du, L. (2004). "Sustainable Development Using Controlled Low-Strength Material." *Proceedings of International Workshop on Sustainable Development and Concrete Technology*, Beijing, China, 231-250.
23. Wilson, J. (1999). "Flowable Fill as Backfill for Bridge Abutments." *Report No. WI-16-99*, Wisconsin Department of Transportation, Madison, 26 pp.

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