DESIGN OF CONTROLLED LOW STRENGTH MATERIAL FOR BEDDING AND BACKFILLING USING HIGH PLASTICITY CLAY

by

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ABSTRACT

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Flowable fill or Controlled Low Strength Material (CLSM) is a self-compacted cementitious material used in the field in the place of compacted fill. It is also known as unshrinkable fill, controlled density fill, flowable mortar, plastic-soil cement, soil-cement slurry, and others. The advantages of this material include lesser soil settlements, elimination of compaction, and lower costs when compared to chemically treated and compacted subsoils. CLSMs have a wide range of applications such as using them as a backfill, bedding material, trench filling material, void filling material, bridge abutment and embankment materials and also in pavement bases.

Current research is aimed at the design of CLSMs using native soils that can be used as bedding and backfilling materials to support a large pipeline project. Native soils were selected as fine material mainly due to excavation in the site will lead to large amounts of excavated fills and hence any reuse of this material will enhance sustainability components of the projects. This will also result in significant cost savings to the construction project. Several mix designs using native high plasticity clays were attempted to establish the optimum quantities of binders and water. Set accelerator was also used to lower the setting time of some of the mix designs. All these mix designs were evaluated for their flowability, density, compressive strength and setting time properties as per the available ASTM standards.

Finally, six mix designs were formulated with setting time as limitation based on the property specifications for their use as a pipeline fill material at different zones. Test results and analysis indicates that high plasticity clay can be successfully used as aggregate in CLSM mixes. Further recommendations were made to study the durability of strengths achieved.

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CHAPTER 1

INTRODUCTION

1.1 General

Disposal of excavated trench material from a pipeline project is becoming a major concern in terms of sustainability and overall cost. The material excavated has to be transported several miles before it could be dumped into landfills and new material which satisfies the requirements as backfill material has to be borrowed to fill the pipeline trenches; all these make a big impact on environment by means of traffic pollution and are also major contribution factors for increasing the overall cost of the construction project (Karduri, 2011). Though part of the excavated material can be used as a backfill, the remaining material is typically dumped in landfills and landfilling is not always cost effective or an ecofriendly option. Effective reuse of the excavated material can address both the aforementioned concerns.

Haunch material in pipeline construction has its own significance in distributing the loads from the pipelines. It should be strong enough and should stay intact with the pipe structure and should be able to absorb the stresses with the bedding materials. Failure in the aforementioned properties of haunch material results in induction of large stresses at the contact points between pipe and bedding zone which eventually results in the development of tension cracks in the pipe’s inner section. Compaction of haunch material is also not an easy task as it may result in the damage of pipe.

CLSM is an effective option to satisfy the aforementioned needs for haunch material. Therefore, Controlled Low Strength Material (CLSM) is often used as a bedding material and is also used as a backfilling material for pipeline construction as this material can be used to easily fill the voids without compaction and meets the strength requirements to bear the pipe load or to transfer the load to surrounding soil. CLSM is generally made of binders such as cement, cement kiln dust, fly ash, dry scrubber ash, wood ash, phosphogypsum and aggregates that may include both not limited to concrete sand, foundry sand, recycled glass, scrap tire rubber and others. Sometimes chemical additives are also found as components which are often used to enhance some target CLSM properties.

This research attempts to replace the conventional aggregates with the native high plasticity soil and to formulate a CLSM mix design that meets the specified properties for an effective backfilling material. This in turn can reduce the overall costs of the project; can reduce the environmental impacts that are caused by dumping of excavated trench material in landfills and also can enhance the reuse of excavated material.

1.2 Project Details and Research Objectives

The Integrated Pipeline (IPL) project involves the design and installation of a 147 mile pipeline that will bring additional water supplies to Dallas/Fort worth metroplex. Water is collected from lakes such as Richland Chambers, Cedar creek and Lake Palestine and is transferred to metroplex through this pipeline. Large amounts of trench material have to be excavated and to be dumped as landfill (Karduri, 2011).

Using native soil in the place of conventional aggregate will greatly reduce the overall project costs and will enhance the sustainability of the project as it eliminates dumping of excavated material. But the CLSM made of native soil should possess the major target properties such as flowability, compressive strength, density and setting time.

The main objective of this thesis research is to formulate the mix design of CLSM that meets the four target properties by using locally available high plasticity soil from Eagle Ford geological formation. High plasticity soil from Eagle Ford formation is selected as an initial step in using the native soil in CLSM, because if CLSM made of this soil satisfies the CLSM usage requirements, then it can lead to use of these mixing in most construction projects that are built on clayey soils. Various tasks involved in addressing the above mentioned research objective are listed below:

1. Establish the water content required for flowability for all the mix designs that are to be evaluated for other CLSM properties.
2. Evaluate densities of each mix design proposed which can affect the excavatability of the CLSM for future repairs of the pipeline.

3. Evaluate the compressive strengths of all the proposed mixes and screen out the mixes whose compressive strengths are within the specified range.
4. Perform setting time tests in order to evaluate the hardening time required for each mix and also lowering the setting time by using set accelerator.
5. Evaluate the performance of proposed CLSM mix designs along with set accelerator and screen the final mixes that satisfy all the property requirements.

1.3 Thesis organization and Summary

Chapter 2 presents the available literature on history and development of CLSMs from the past four decades. Advantages of CLSMs over other conventional methods of backfilling, bedding, and bridge approach repairs are listed. Application areas of CLSMs are briefly discussed. Moreover, these application areas are supported by case studies made by numerous researchers. Components of CLSMs such as cement, cement kiln dust, fly ash, lime, concrete sand, foundry sand; chemical additives are presented in detail. Typical properties of CLSMs are also discussed.

Chapter 3 explains the criteria followed here for the selection of soils and research variables. It also illustrates the mix design procedures followed along with soil specimen preparation. Various test procedures involved in testing the native soil and also in determining the properties of CLSM are explained.

Chapter 4 includes the test results obtained on native soil and on CLSM mix designs. Water contents required for various mix designs are determined. Compressive strengths of formulated mixes are analyzed followed by density measurements and setting time measurements for all the mixes. Variations in properties with respect to set accelerator are also analyzed.

Chapter 5 presents the summary and conclusions of the observations and findings obtained from the research study. Also, recommendations are provided for future study.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

This chapter provides comprehensive literature review of Controlled Low Strength Material (CLSM) including its historical development, material composition, proportions, various application areas and advantages over other conventional materials. Background and literature review presented in this chapter is based on the reports from American Concrete Institute (ACI), National Cooperative Highway Research Program (NCHRP) as well as by conventional library and materials journals, ASTM special publication and Transportation Research Record (TRB).

2.2 Historical Background

In the early 1970’s, during the initial construction of the Enrico Fermi II Nuclear station in Monroe, Michigan, engineers from the Detroit Edison Company and Kuhlman corporation in Toledo, Ohio, tried to incorporate large amount of fly ash possible in concrete in order to reduce their stock piling in each concrete mix which lead to the discovery of low strength materials (Brewer, 1994). The University of Toledo in collaboration with these two companies performed a series of laboratory tests to confirm that appropriate and economical low-strength materials could be produced with fly ash as additive (Folliard et al. 2002).

CLSM was in use for the past four decades identified with various terms including flowable fill, unshrinkable fill, controlled density fill, flowable mortar, plastic-soil cement, soil-cement slurry, and K-Krete® (Folliard et al. 2008). The term "controlled low strength material or CLSM" is approved by the ACI Committee 229 in 1984 and this term is often used in the literature. Standard components of CLSMs are Portland cement, Fly ash, fine aggregates, and water. These typically develop compressive strengths around 0.7 MPa (100 psi) after 28 days of curing. Most of the current CLSM applications such as back fills, conduit bedding, erosion control, void filling require unconfined compressive strengths of 300 psi or less (ACI 229R-99). This lower strength requirement is necessary to allow for future excavations such as repairing a pipeline backfilled with CLSM (ACI 229R-99). Some the applications of the CLSM materials are discussed in the following section.

2.3 Advantages and Limitations of CLSM

CLSM is a self-compacted, cementitious material, used primarily as a backfill in lieu of compacted fill (ACI 229R-99). The advantages of using controlled low strength material in the place of concrete material as per ACI 229R-99 are presented in the following:

1. Using locally available materials, ready mixed concrete suppliers can produce CLSMs to meet most project specifications which make it readily available.
2. Depending on type and location of void to be filled, CLSM can be placed by chute, conveyor, pump or bucket, because CLSM is self-leveling, it needs little or no spreading or compacting. This speeds the construction and reduces the labor requirements.
3. CLSM mixtures can be adjusted to meet specific fill requirements. Mixes can be adjusted to improve flowability property. More cement or fly ash can be added to increase strength. Admixtures can be added to adjust setting times and other performance characteristics. Adding foaming agents to CLSM produces lightweight, insulating fill which shows the versatile nature of CLSM.
4. Load-carrying capacities of CLSM are typically higher than those of compacted soil or granular fill. CLSM is also less permeable, thus more resistant to erosion.
5. CLSM sets quickly and supports the traffic within several hours; downtime for pavement repairs is minimal.
6. This material exhibits low settlement properties.
7. CLSM reduces the excavation costs by allowing narrow trenches and in turn eliminates the compaction equipment required in conventional backfilling methods.

8. Use of CLSM improves workers safety as the workers do not have to get in to the trenches to place the material.
9. CLSM having the compressive strengths of 0.3 to 0.7 MPa (50 to 100 psi) is easily excavated using conventional digging equipment, yet is strong enough for most backfilling needs.
10. CLSM containing fly ash benefits environment by making use of this industrial by-product generated by power plans that burn coal to generate electricity.

Few limitations of this material are presented in the following (Collins et al. 1991):

1. The CLSMs need anchorage to hold the light-weight pipes to avoid floating during construction.
2. CLSMs need confinement before setting.
3. Mixtures having high strength are difficult to excavate.
4. They exert lateral pressure on structures while in fluid condition.

2.4 Applications of CLSM

CLSM has wide range of applications in construction works that include road cut backfill, utility embedment, pipe bedding, bridge abutment and embankment, void filling, seawall backfill, erosion control and pavement bases. Regarding the application areas, a survey was conducted by Folliard et al. in 1998 to all the states in which forty-four states specified their application areas and six were not responded. Figure 2.1 shows the application areas by each state in 1998 (Folliard et al. 2008). It can be observed that major applications were backfill and bedding material.

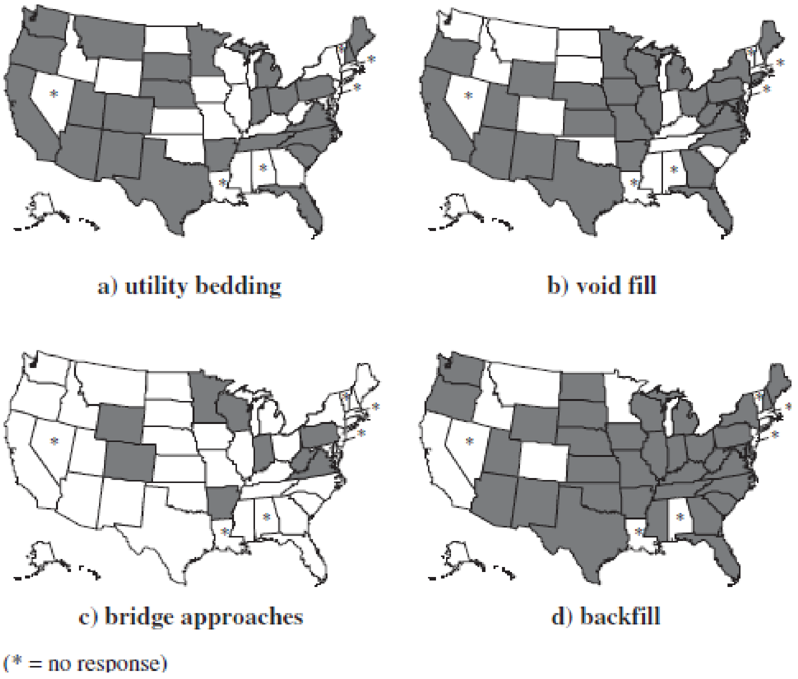


Figure 2.1 Applications of CLSM by state in 1998 (Folliard et al. 2008)

Another survey was carried out by Riggs and Keck (1998) by contacting Departments of Transportation (DOTs) to assess application areas of CLSM in southeastern states. The results of this survey are summarized in Table 2.1. It can be observed from this table that most states in the southeast USA are using CLSM primarily as a backfill or bedding alternatives to conventional backfill.

Table 2.1 Applications of CLSM by various state DOTs (Riggs and Keck, 1998)

State	Applications
Alabama	Backfill for drainage structures and cuts
Florida	Beddings; encasements; closures for tanks, pipes; trench backfill
Georgia	Beddings; encasements; closures for tanks, pipes; trench and abutment backfill
N. Carolina	Filling underground storage pipes and pipe culverts; backfilling culverts, bridges
S. Carolina	Backfilling under foundations, abandoned pipelines, culverts, tanks, utility trenches
Virginia	In lieu of compacted soil or aggregate backfill

The following sections present information on various applications of CLSMs in a variety of civil engineering projects with case studies as applicable.

2.4.1 *Bridge Approach Repairs*

Approach slab of a bridge is often subjected to settlements leading to the bump at the end of the bridge causing riding discomforts to travelers. Approach slab issues are mainly due to settlements in the compacted fill. Due to its low settlement potential and ease of handling, CLSM can serve as a desirable alternative for conventional compacted fills (Folliard et al. 1999).

In a case study reported by Du et al. (2006), Texas Department of Transportation (TxDOT) with the collaboration of NCHRP Project 24-12(1) research team, developed a suitable mixture to repair severe settlement of two bridge approaches, located at the Branch Sala Trillo on Loop 1604 between I-10 and I-35 in San Antonio (Du et al. 2006) Locally available concrete sand was used as aggregate whereas Class C fly ash was used as binder. The uniqueness of this mix used by the researchers was that they did not use any Portland cement as fly ash alone met the hardening and early strength requirement because of its high calcium oxide (CaO) content. Three mix proportions with sand-fly ash ratios of 5,6, and 7 by mass were formulated and two mixtures with sand:flyash:water mass ratios of 5:1:0.75 and 6:1:0.91 having 1 hour and 3 hour set times were selected for field implementation based on optimum values of flowability, strength and resilient modulus. Earlier mix was only used when there was insufficient time for the 3-hour set mixture to harden adequately for subsequent hot-mixing asphalt paving in order to open the traffic. Figure 2.2 shows the backfilling of bridge approach at San Antonio.

Figure 2.2 Placing rapid-setting CLSM for bridge approach (Du et al. 2006)

In another case study reported by Snethen et al. (1998), Oklahoma Department of transportation (ODOT) adopted five different construction methods to mitigate bump at five different approaches of bridges which was caused by the consolidation of soil underneath the approach slab. These methods include control soil, geotextile reinforced wall, controlled low strength material, dynamically compacted granular backfill, and vibrated granular backfill. Out of which CLSM was found to be a simple and reasonably cost effective material to reduce the potential for developing bump at the end of the bridge. The lateral earth pressures and settlements of an approach slab of a bridge system were less than the other options studied. Table 2.2 compares the equipment, construction time, and cost of the five approach embankments involved in these research. Figure 2.3 shows the excavation of backfill area for placing CLSM.

Figure 2.3 Excavation of backfill area at CLSM approach embankment (Snethen et al. 1998)

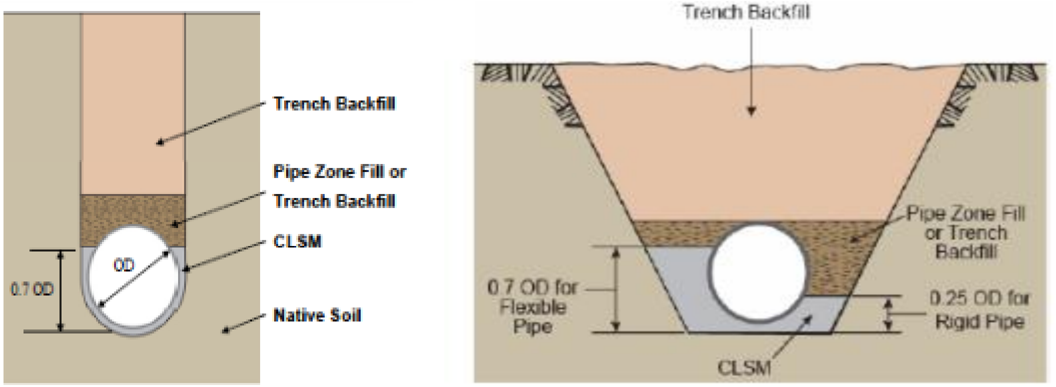
Table 2.2 Cost comparison of five approach embankments (Snethen et al. 1998)

Approach Embankment	**Quantities**	**Estimated Cost ($)**	**Construction Days**	**Equipment Required**
Unclassified Borrow (Control)	229 m^3	1500	4	Loader, pad vibrator
Geotextile Reinforced Wall	287 m^3	25000	5	Loader, pad vibrator, concrete spreaders, water truck
CLSM	159 m^3	14560	2	Concrete trucks, concrete vibrator
Dynamically Compacted Granular Fill	234 m^3	15000	5	Crane, concrete block, pad vibrator, water truck
Flooded and Vibrated Granular Fill	234 m^3	16000	2	Water truck, concrete vibrator

2.4.2 *Pipeline Applications*

With pipeline applications, CLSM can function in two ways: Gap fill or Trench fill (Howard, 1996). *Gap fill* applications use a U-shaped trench with narrow gap (<12 inches) between the pipeline and trench wall as shown in Figure 2.3a. In this case, pipe loads pass through CLSM zone in to the native soil. This can be attributed to the low thickness of the CLSM zone in *Gap fill* applications (Howard, 1996).

In *Trench fill* applications, the gap between the pipe and the trench wall at spring line is greater (>0.5D, where D is the outside diameter of the pipe) as shown in Figure 2.3b (Finney et al. 2008). The greater width of the CLSM zone allows this material to support the pipe loads, rather than transferring them to native soil (Howard, 1996).



(a) (b)

Figure 2.4: Types of fills (a) Gap fill (b) Trench fill (Finney et al. 2008)

Howard and Bowles (2008) reported a case study regarding the field performance of CLSM as an embedment and backfill material. Corrugated metal pipe (CMP) was installed using flowable fill. The pipe was then backfilled with 40 ft of cover. Flowable fill was selected as the embedment material because of speed of installation and to limit potential excessive deflection of the flexible CMP pipe. Flowable fill gives a higher resistance to deflection than compacted soil. Pipe diameter measurements were made after the flowable fill was placed and before backfilling to check circularity and to evaluate using flowable fill under high fills.

In 2007, 4.5 years after installation, the pipe diameters were again measured to verify the circularity and to see how the flowable fill had performed. The 2007 measurements showed that very little deflection or change in pipe shape had occurred in the CMP pipe. The installation was part of the Ridges Basin Inlet Conduit of the Animas-La Plata Project, a pumped storage system being built by the U. S. Bureau of Reclamation (Howard and Bowles, 2008). Figure 2.5 shows the hardened CLSM after removing casings.

Figure 2.5 End view of pipeline with CLSM (Howard and Bowles, 2008)

In a case study reported by Finney et al. (2008), the City of West Sacramento, California used CLSM as a bedding material and also as backfill to a point above the pipe crown for the construction of 6.4 km (4 mi.) pipeline. In this case, CLSM was used as trench fill application all along the pipeline. Two types of CLSM mixes were used in this application, the CLSM made with conventional aggregates is used up to the springline of pipeline and the portion above it is filled with CLSM made with the native soil which consisted of clay and sandy silt. They observed that the cost of construction was greatly reduced when compared to similar projects without CLSM applications. A picture showing the placement of CLSM at test section is shown in Figure 2.6

Figure 2.6 Placing of CLSM at test section (Finney et al. 2008)

In another case study reported by Gardner (1998), two types of quick setting CLSM mixtures were used by Seattle Public Utilities, Washington to replace an old 914-mm water main that was located under numerous train tracks in downtown Seattle. Since the time allotted to complete the project was very short, CLSM was chosen as fill material due to its quick setting nature. The strength of CLSM mixtures varied from 0.34 to 0.83 MPa. The work beneath each track was completed in short time of half a day, with the use of quick setting CLSM, this clearly shows the potential of CLSM in reducing the project time and advancing construction (Finney et al. 2008).

2.4.3 *Void Filling*

Voids are formed due to the continuous erosion of fill material mainly due to run off water in case of approach slabs or due to tidal currents in case of seawalls. Conventional granular backfill material is almost impossible to install and compact in these kinds of situations. CLSM was found to be viable option as it needs no compaction and easy to operate in voids when compared to other conventional methods.

According to the case study referred by Mason (1998), The United States Navy at Rough & Ready Island, Stockton, CA, installed a number of wharfs along the San Joaquin River side. During the installation works, it was noticed that there was a large void under the slab, running its entire length (183 m). The US Navy used controlled density fill (CDF) material to fill the void. A visual inspection showed that there was no settlement of the material. The total costs were reduced by more than 80% of the amount estimated for placing and compacting conventional granular backfill.

The U.S. Army Corps of Engineer Waterways Experiment Station (WES) used CLSM in a microtunneling application on a trial basis (Green et al. 1998). The CLSM mixture consists of Class C fly ash and water. A fly ash based CLSM without aggregate is easier to pump on the microtunneling machine. During the microtunneling field material, CLSM was used to stabilize a tunnel excavation while retracting the microtunneling machine through unstable, flooded, running sand (Green et al. 1998). The void left by the retracted tunnel machine was filled with the CLSM to provide continuous support to the excavation and avoid settlement of the ground surface. Reentry of the microtunneling machine was easy due to low strength development of CLSM.

2.5 CLSM-Components

The components of controlled low strength material differ depending on the availability of component materials as wells as on requirements and application area of CLSM. The main components of CLSM are aggregates (fine and coarse), cement, fly ash, lime and water. Admixtures are also used to enhance or retard some of the desirable properties such as setting time and density depending on the requirement. All these components are discussed individually in the following sections.

2.5.1 *Binders*

2.5.1.1 Cement

Although any type of Portland cement can be used in CLSM. ASTM C150 Type I is the most commonly used (Folliard et al. 2008). Portland cement predominantly consists of calcium silicate, which reacts with water to form hard material. Cement is generally used in small proportions of less than 4% of the total weight of CLSM mixture (ACI 1999). Cement is a hydraulic material that sets and hardens after reacting with water, through hydration reactions. The end product will be a solidified mass with enhanced strength. Cement is often the binding material used in flowable fills to achieve sufficient cohesion and strength to the mix material (ACI 229R-99).

Water-cement ratio plays an important part in controlling strength and flowability (Pierce et al. 2002). A higher water-cement ratio improves the flow properties but reduces the strength. As the water content of the mix increases, the strength of the material decreases with constant proportion of cement and vice-versa (Folliard et al. 2002). Curing temperature is another factor which affects the strength development of Portland cement-based CLSM materials. Generally, higher curing temperatures tend to increase the early strength due to hydration property of the cementitious material, but tend to affect long term strength adversely (Folliard et al. 2003). Sufficient amount of cement reduces segregation of CLSM materials, due to its binding property.

2.5.1.2 Cement Kiln Dust (CKD)

Cement kiln dust (CKD) is a by-product from cement manufacturing. CKD is a fine powdery material and appears like Portland cement. It is collected at electrostatic precipitators during the production of cement klinker (Siddique, 2009). The chemical composition of CKD depends on the raw material used to produce the clinker (Siddique, 2009).

Large amounts of CKD are being produced every year which is either stockpiled or landfilled (Pierce et al. 2003). Land filling is disadvantageous in many aspects since accumulation of heavy metals can leach out, which in turn causes environmental problems. Stock piling is associated with problems like transport, storage and disposal and also erosion due to wind and water (Pierce et al. 2003). Since CKD reacts with atmospheric moisture, it forms a hard crust on the surface, which can be an expensive problem to handle while disposal (Pierce et al. 2003).

Some of the known applications of CKD include: used as a stabilizing agent to treat soft or wet soils (Davis and Hoods, 1974) and loose sands (Baghdadi et al. 1995), and as filler in pavements (Zhu et al. 1999). The use of CKD in CLSM may be considered one such application. Since the CKD imparts low strength when compared to Portland cement, the CKD provides suitable substitute for Portland cement in producing a CLSM which can be easily excavated in the future. Another advantage is that the reduction of overall material cost since it can replace certain percentage of fly ash additive (Pierce et al. 2003). The only concern is Katz et al. (2004) found that use of finer CKD particles results in higher water demand and also the durability aspects of using CKD in CLSM have not been studied in detail and further work may be needed.

2.5.1.3 Lime

The use of lime stabilization of clay in construction is 5000 years old (Khattab et al. 2006). The pyramids of shersi in Tibet were built using a compacted mixture of clay and lime (Greaves, 1996). Lime used for soil treatment can be in the form of quick lime (calcium oxide, CaO), hydrated lime (calcium hydroxide, $Ca\ [OH]_2$ or lime slurry (Lime manual, 2004). Quicklime is manufactured by chemically transforming calcium carbonate (lime stone, $CaCO_3$) into calcium oxide.

Lime reacts with clay minerals and complex chemical reactions or pozzolanic reactions take place forming cementitious products in the form of a water insoluble gel of calcium silicate hydrates. With time, the gel gradually crystallizes into cementing agents such as calcium silicate hydrates (CSH) (tobermorite and hillebrandite) and calcium aluminate hydrates (CAH) (Galvao et al. 2004; Lime manual 2004). CSH and CAH are cementitious products similar to those formed in Portland cement. The reaction occurs only when the water is present and it carries calcium and hydroxyl ions to the clay surface (Galvao et al. 2004). This process results in soil stabilization improving strength of soil significantly besides altering various other properties of soil like swelling, shrinkage, permeability etc.

2.5.1.4 Fly Ash

Fly ash is a by-product of coal combustion and has found uses in wide range of construction applications, including flowable fill. Though fly ash has established itself as an important construction material, approximately 70-75% of the fly ash generated annually, is land filled (FHWA, 1998). ASTM C 618 defines fly ash as “the finely divided residue that results from the combustion of ground or powdered coal and is transported by the flue gases”. This does not include the residue from burning of municipal refuse.

As per ASTM fly ash is a pozzolanic material. A pozzolan is defined as “a siliceous or siliceous and aluminous material which itself possesses little or no cementitious value but which, in finely divided or powdered form, and in the presence of moisture, chemically reacts with calcium hydroxide at ordinary temperatures to form compounds that possess cementitious properties".

Formation of cementitious material by the reaction of free lime (CaO) with pozzolans (AlO_3, SiO_2, Fe_2O_3) in the presence of water is known as hydration reaction. The major reaction that takes place is between the reactive silica of the pozzolan and calcium hydroxide producing calcium silicate hydrate (CSH). The alumina in the pozzolan may also react with the calcium hydroxide and other components in the mixture to form other cementing products (CAH). The hydrated calcium silicate gel (C_2S) or calcium aluminate gel (C_3A) binds inert material together which lead to increase the strength of treated material. Fly ash plays a major role in flowable mixes to improve workability and strength (ACI 229R-94). It also minimizes bleeding, shrinkage and permeability of the flowable fill mix. When used in large proportions in flowable mixes, fly ash helps in producing low densities as compared to mixes with high aggregate contents (Krell, 1989). The following section describes different types of fly ashes used in CLSM applications.

Class C and Class F fly ashes are the two commonly used fly ash types in flowable fill mixes (ACI 229R-94, Collins et al. 1993, Krell, 1989). Class F fly ash is produced by burning anthracite or bituminous coal (Collins et al. 1993, ASTM C 618). Class F ash contains silica, aluminum and iron in combinations greater than 70%. Class F fly ash possess moderate pozzolanic properties due to low amounts of calcium ions present in these materials. Class C fly ash is produced from the burning of ignite or subbituminous coal. Class C fly ash generally contains more calcium and less iron with its lime (CaO) content in the range of 15% to 30% (Collins et al. 1993, ASTM C 618). This makes the Class C fly ash more cementitious and pozzolanic. Hence, Class C fly ash use in CLSMs imparts high strength to the material when compared to Class F fly ash in the same material (Trejo et al. 2003).

2.5.1.5 Dry Scrubber Ash

Dry scrubber ash is the ash collected from a combustion system that burns sub-bituminous coal and injects a lime absorbent in the form of crushed limestone to remove SO_2 emissions (Dockter et al. 1998). The physical and chemical properties of both this chemicals make it acceptable for their use in Portland cement concrete (Dockter et al. 1998). However, when compared with Class C fly ash, the mixtures prepared with dry scrubber ash showed more cementitious and less pozzolanic properties than Class C fly ash mixtures (Dockter et al. 1998). Hence, the use of this ash eliminates the use of cement in the CLSM mixtures. The mixtures with dry scrubber ash also showed early high strengths i.e., faster setting time (Dockter et al. 1998). This property allows the CLSM material to be subjected to overburden loads soon after their placement. The major advantage of using dry scrubber ash is that, though it fails to meet the specifications for the use in concrete, it can be used in CLSM mixtures.

2.5.1.6 Wood Ash

Wood ash is the residue generated due to combustion of wood and wood products (chips, saw dust, bark, etc.) (Naik et al. 2003) This by-product is largely produced in the US mainly to generate electricity and/or steam and is landfilled or applied on land as a soil supplement. Naik et al. (2003) reported the use of wood ash and other ashes generated form the fore mentioned supplemental fuels in CLSM. Their experimental results showed that the use of CFA reduced the density of CLSM material. The strength results were compatible to other CLSM mixtures with Class C or Class F fly ash. Another significant finding was that the permeability values of CLSM mixtures with CFA were lower than those observed for compacted clays due to the improvement of microstructure of these CLSM mixtures.

2.5.2 *Phosphogypsum (PG)*

Phosphogypsum is another by-product from the production of phosphoric acid, which is used in fertilizer industry. Previous literature mentioned that for every ton of phosphoric acid produced, about 5 tons of PG is produced as by-product (Borris and Boody, 1980). These high amounts of production of PG as a by-product have led to studies involving potential uses of this material.

The chemical composition of PG is $CaSO_4.2H_2O$, calcium sulfate dihydrite. There is an inherent presence of Radium-226 in PG and hence, the use of it is prohibited in applications involving ground water and agricultural purposes (Gandham et al. 1996). This CLSM material is used in applications like void filling and backfilling, where the contact of new member with the mixture is minimum at best. This PG is acceptable to be used as a substitute to cement provided it meets local environmental regulations. Gandham et al. (1996) provided results of CLSM with the use of PG as a substitute to cement. Their findings showed that the PG content did not significantly affect flowability properties of mix. However, some of the mixtures produced high strength (2 to 4 MPa), which would prove difficult to be excavated in the future. This property may be attributed to the rapid hydration of the readily available free lime present in Class C fly ash.

2.5.3 *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.

2.5.4 *Coarse Aggregates*

Aggregates make up major portion (72%) of a typical CLSM mixture. Most CLSMs contain fine aggregate alone, only a small percentage of CLSMs used in practice contain coarse aggregate.

Gravel is common coarse aggregate used and is expensive when compared to fine aggregates such as sand. Performance of gravel based mixtures is similar to those with sand (Fox, 1989). It was noted by Fox (1989) that the use of coarse aggregates reduces the water content of the CLSM mix. Typical gravel sizes of 3/8 in. 1 in. are considered in flowable fill works. Gravels with specific gravity of 2.68 were used in CLSM to obtain 28 day strength of 150 psi (Fox, 1989).

2.5.5 *Conventional Fine Aggregates*

Fine aggregates should comply with the ASTM C 33 standard. Sand is the most commonly used fine aggregate in the CLSM mixtures. The ACI 229R-99 has mentioned that well graded sand has proven to be very effective as a fine aggregate and also it improves the workability of the CLSM material. Rounded sand aggregates enhance flowable properties when compared to angular sand aggregates (Folliard et al. 2002). The use of non-standard material such as readily available native material is acceptable for the CLSM mixes, as long as the quality of such material is ensured (Tikalsky et al. 2000; Crouch et al. 1998). However, such CLSM materials should be tested prior to using them in the projects (ACI 229R-99).

By products and recycled materials such as concrete sand, foundry sand, bottom ash, high fines limestone screenings, recycled glass and scrap tire rubber, gravel and crushed stone can also be used as fine aggregates in the CLSM. These materials and their use in CLSM applications are briefly described in the following sections.

Fine aggregates like cement foundry sand or foundry sand, concrete sand are the most commonly used aggregates for CLSM and they are standardized components of CLSM as per ASTM C 33. Rounded sand aggregates enhance flowable properties when compared to angular sand aggregates. It is also reported that use of native soils with clayey fines as fine aggregates exhibit problems such as excess water demand, stickiness of the mix, incomplete mixing (Folliard et al. 2002). So, sand is preferred as fine aggregate in CLSM mix. A brief discussion on different types of conventional fine aggregates was done in the following sections.

2.5.5.1 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. Sand that does not meet ASTM C 33 requirements (e.g., gradation) can be often times used in CLSM production, provided that the specified flowability and constructability requirements are satisfied.

2.5.5.2 Foundry Sand

Foundry sand, a by-product of metal casting industry is becoming more viable candidate for use in CLSM because of its lower cost, increasing availability and satisfactory performance (Bhat and Lovell, 1996; Tikalsky et al. 1998). Production of these by-products in large amounts leads to disposal and environmental problems (Naik and Tarun, 1997). It is estimated that for every one ton of metal castings produced and shipped that a typical foundry generates approximately one ton of waste sand. The U.S. Environmental Protection Agency has also recognized foundry sand, along with fly ash, as suitable materials for CLSM (EPA, 1998). The effective use of these by-products in construction works involving large volumes of materials will reduce disposal costs, replace expensive virgin materials, and saves valuable landfill space.

Foundry sand consists primarily of clean, uniformly sized, high-quality silica sand or lake sand that is bonded to form molds for ferrous (iron and steel) and nonferrous (copper, aluminum, brass) metal castings (Collins et al. 1994). These sands, though clean before use, can be contaminated with metals from the casting process, which are known as spent foundry sands (Collins et al. 1994). Therefore, ferrous foundry sands are more commonly used in CLSMs because of the concerns over the potential leaching of phenols and heavy metals such as cadmium, lead, copper, nickel, and zinc (EPA, 1998) in nonferrous foundry sands.

Two general types of binder systems used in metal castings are clay-bonded systems (green sand) and chemically-bonded systems (Tikalsky, 2000; Tikalsky, 1998). Both types of sands are suitable for use in CLSMs. However, they have different physical and environmental characteristics (Tikalsky, 1998). Most of sand cast molds used in ferrous castings are of the green sand type, which consists of high-quality silica sand, 4 to 10 percent of bentonite clay as binder, 2 to 5 percent of water about 5 percent of carbonaceous additive to improve the casting surface finish (Tikalsky, 2000). Chemically bonded sand cast systems involve 97 percent of foundry sand along with organic binders and catalysts (Tikalsky, 2000).

Clean and used foundry sands can be used effectively as a replacement to fly ash additive in the manufacture of flowable slurry mixtures (Naik and Singh, 1997). Bleeding of water was noticed to increase with an increase in the foundry sand content. Voids created due to presence of coarser particles in the foundry sand are attributed to this bleeding (Naik and Singh, 1997). The results showed that excavatable flowable slurry with a 28-day strength range between 40 and 90 psi (0.28 and 0.62 MPa) and such materials can be manufactured with the replacement of fly ash by 85% of foundry sand (Naik and Singh, 1997).

Experiments performed by Duritsch (1993) involved the use of CLSM mixtures containing three different types of sands including virgin sand, spent clay-bonded sand and chemically bonded foundry sands. Results showed that the clay-bonded sand mixture required additional water to achieve the required flowablity. These materials produced low density mixtures due to low specific gravity of aggregates and increased moisture content. Foundry sand mixtures in CLSMs produce lower compressive strengths facilitating excavatability of the material and also a faster setting time than the virgin sand mixtures (Bhatt and Lovell, 1996).

Tikalsky et al. (1998) conducted research on both clay-bonded and chemically-bonded spent casting sands to be used as CLSM aggregates. Their analysis suggested that spent clay-bonded casting sands have to be blended with rounded siliceous sands to acquire better fluidity that those blended with coarse crushed limestone.

2.5.6 *Alternative Fine Aggregates*

Use of conventional aggregates is may not be always the viable option as it becomes costly for large projects. This necessitated the need of alternative options that can reduce the project cost and can replace the conventional aggregates effectively. Recycled materials such as scrap tire rubber, recycled glass were found to be cost effective and can survive the purpose effectively. Following are some of the alternatives for conventional aggregates that are found in literature.

2.5.6.1 Scrap Tire Rubber

The United States produces nearly 266 million of scrap tires per year, of which 24% are landfilled or dumped as stockpiles (EPA, 1999). Only 4% are beneficially used in civil engineering projects (Pierce et al. 2002). This calls for innovative methods of recycling waste tire rubber. In the field of civil engineering, the applications of recycled tire rubber provide benefits including the development of a low density and high ductility material (Pierce et al. 2002). Typical density of flowable fills with sand as fine aggregate range between 115 and 145 pcf (ACI 229R-99). However, in many construction applications, the use of a light weight material is preferred which will reduce the applied stress in both horizontal and vertical directions and thereby controls the settlement of underlying soils.

Scrap tire can be finely ground to produce crumb rubber, which exhibits a granular texture and ranges in size from very fine powder to sand sized particles. Due to its low specific gravity, crumb rubber can be considered as a light weight aggregate in flowable fills resulting in density range of 73 to 98 pcf (1.2 to 1.6 g/cm^3) (Pierce et al. 2002). The crumb rubber produces a fill material with a density of 80 pcf (1.3 g/cm^3), as compared to a typical CLSM with an average density of 130 pcf (2.1 g/cm^3) (Pierce et al. 2002). The strength properties of crumb rubber tire based CLSM are similar to those of standard flowable fill mixtures.

2.5.6.2 Recycled Glass

The colored glass material that cannot be used by local bottle manufacturers is crushed in to 1/2 in. material and is used in various construction projects (Ohlheiser, 1998). Ohlheiser (1998) used this recycled glass material in the place of virgin aggregates of CLSM. Field tests conducted on this CLSM proved that the glass composed CLSM performed better than or equal to the standard flowable fill material in terms of strength properties. This recycled glass is considered to be a better option in Colorado for both due to economic benefits and for recycling efforts (Ohlheiser 1998; Hook and Clem, 1998).

2.5.6.3 Native Soil

CLSM has mostly evolved using only conventional materials as aggregates. However, use of native soils in place of conventional aggregates is the cheapest viable alternative for large projects as it greatly reduces the dumping of excavated material which eventually saves land space and transportation cost. However, the CLSM mixed with the soil has to pass the workability and constructability properties. CLSM should possess the following properties.

1. When first mixed, it should be flowable (>10” slump)
2. When cured, it should have a minimum strength greater than the soil it is replacing (>100 kPa [15 psi] for most soils)
3. Its final strength should be low enough to allow it to be excavated (<2,000 kPa [300 psi][ACI, 2005])

These specifications changes with the requirement and area of application of CLSM. Reasonable strength range for CLSM is 28 day strength minimum of 350 kPa (50 psi) and maximum of 1,000 kPa (150 psi) to allow for some variation in actual reported test results(Finney et al. 2008). The lower-bound unconfined strength of 350 kPa (50 psi) is similar to the undrained shear strength of very stiff clay. The typical upper limit of 1,000 kPa (150 psi) is similar to the unconfined strength of hard clay (Crouch et al.1998).

When CLSM is manufactured from the native soil, one concern is the consistent strength of the mixture. Native soil will have more varied grain size distribution than processed sand which necessitates the need of varying mix design with variation in soil type. Duritsch (1993) conducted experiments using clay-bonded sand which resulted in higher water content to achieve required fluidity. However, greater water content may cause aggregate segregation, bleeding increase, and strength reduction (Wu et al. 2005). Therefore, the selection of a suitable water content making the material exhibit the best engineering performance is the first priority for the mix design. Use of native soil has been successfully implemented for the West Sacramento Force Main (WSFM) project, part of Lower North West Interceptor program, included construction of 6.4 km (4 mi.) through urban portions of the City of West Sacramento, California. Mostly, the advantages of using trench-side soil outweigh the disadvantages as long as the variability of native soil materials is understood and strict attention to the quality control is maintained (Finney et al. 2008)

2.5.7 *Chemical Admixtures*

Chemical admixtures are the materials that are added either before or during mixing to enhance or retard its properties, such as flowability, setting time, strength, water content, density of the mix (ACI 229R-99). Air-entraining agents (AEAs) are the most commonly used chemical admixture in CLSM. Some of the other admixtures used are water-reducing admixtures, set retarders or accelerators, and super plasticizers (Pons et al. 1998; ACI 229R-

94). However, when used in high quantities, these admixtures may cause segregation problems (ACI 229R-99).

AEAs have been used to improve flowability. It also enhances insulating characteristics. Air-modified CLSMs typically contains 15 to 35% air by volume. Higher air contents impart greater workability of the mixture. This condition leads to reduction in water contents, which in turn minimizes segregation and bleeding problems (Hoopes, 1998). Air volumes help in lowering the cost of CLSM by 10 to 30% (Riggs and Keck, 1998). ACI 229R-99 mentions that the air contents in excess of 6% may increase segregation in the mixtures. Water-reducing admixtures can be used in CLSM mixtures with low fines content, which increase the overall compressive strength, accelerate hardening and decrease subsidence or settlement properties (ACI 229R-99).

2.6 CLSM - Properties

This section provides information on the properties of CLSM that most affect its performance in key applications. According to Folliard et al. (2008), fresh properties of CLSM are flowability, segregation, bleeding, hardening time and subsidence while hardened CLSM properties include compressive strength, excavatability, permeability, shear strength, resilient modulus, consolidation, shrinkage and thermal conductivity. In case of pipeline applications properties such as flowability, setting time, compressive strength and density are of major importance. Hence, this literature search mainly focused on gathering information on these four fundamental properties of CLSM and how these properties are determined and are described briefly in the following sections.

2.6.1 *Flowability*

One of the most important properties of CLSM is its ability to flow easily into confined areas, without the need for conventional placing and compacting equipment. Its self-leveling property greatly reduces the labor and also increases the speed of construction. ASTM D 6103, “Flow Consistency of Controlled Low Strength Material” is the most commonly accepted test procedure. A plastic cylinder with dimensions 150 mm (6 in.) and 76 mm (3 in.) inside diameter 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 203 mm (8 in.) or higher is the typical value of a flowable mixture.

2.6.2 *Setting time*

Setting time is the approximate period of time required for CLSM to gain sufficient strength to support the weight of a person (ACI 229R-99). The setting time of CLSM material is affected by several parameters, including mixture proportions, climatic conditions and drainage conditions. ASTM C 403, “Time of Setting of Concrete Mixtures by penetration Resistance”) is the commonly used test in procedure in the Laboratory. Other techniques such as dynamic cone penetrometer and Kelly ball are also used for CLSM.

2.6.3 *Unconfined Compressive Strength*

Unconfined compressive strength is the significant property measured and is most commonly found in state DOT specifications. CLSM compressive strength values are often used as an index for excavatability or digibility, 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.

The development of CSLM 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 non-particulate component of strength results from the cementitious reaction of cement and fly ash with water, whereas the particulate component of strength is similar in the nature to that of granular soil. Water-cement ratio plays an important role in the development of unconfined compressive strength (Bhat and Lovell, 1996).

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 characteristic low strength of CLSM creates problems in testing cylinders because the many load frames used by researchers are in the range of 1,300 to 2,200 KN (Folliard et al. 1999). But, for these cylinders with compressive strength of 1.0 MPa, the maximum load at failure is only about 18 KN, approximately 1 percent of the load frame capacity which makes the precision of the load frame doubtful (Folliard et al. 2008). This problem can be eliminated when smaller diameter of cylinders is used (Folliard et al. 2008).

2.6.4 *Density and Excavatability*

Density of the CLSM mix mostly depends on the type of aggregate used. High density CLSMs are hard to excavate at the time of repair of pipes when used as backfill. Low density CLSMs are preferred to facilitate ease of excavation. Typical density of flowable fills reported in the literature ranged between 115 and 145 pcf (Pierce et al. 2002). Hamilton County developed an empirical approach to predict the long term strength or excavatability of CLSMs (Hamilton County, 1996; Du et al. 2002) which is both the function of 28-day uncompressive strength and density of CLSM in the field. If the calculated value of removability modulus is less than 1.0, the specific CLSM is considered to be removable.

2.7 Summary

This chapter explains a brief history and development of CLSM materials. The ingredients of CLSM and their proportions along with their advantages and disadvantages are described. Numerous applications of CLSMs along with their case studies are discussed briefly. It was shown that CLSMs were used with reasonable success in the past and can be used in future applications. Some of the application areas of CLSM discussed here include pipelines, bridge approaches, void filling.

Different types of materials that could be used in CLSM mixes are also discussed in detail. Several conventional as well as alternative fine aggregates that were used in successful CLSM applications were discussed. Successive use of native soil as an alternative for conventional aggregates is synthesized from this literature review. Non-standard materials including native and/or recycled materials and their significance in CLSMs are discussed. Fresh and hardened properties and their significance are studied in detail.

CHAPTER 3

LABORATORY TESTING PROGRAM

3.1 Introduction

The key objectives of this research study were to develop the CLSM mix design using native soils selected from Eagle ford geological formation such that the mix developed satisfies the four target properties including flowability, unconfined compressive strength, density and setting time and also to understand the impact of material and mixture proportions on CLSM characteristics. In order to achieve this, various CLSM mix proportions have to be designed and evaluated for their properties in the laboratory.

This chapter describes details of tests performed on native soil and CLSM. The test equipment used and procedures followed in soil-binder mixing and sample preparation are discussed. The research variables and mix proportions that are studied are also discussed in detail. Also, all the engineering tests performed here are in compliance with the American Society of Testing and Materials (ASTM) standards.

3.2 Selection of soils

The pipeline project under review involves design and installation of a 147 mile pipeline which has varying geology and includes several geological formations.

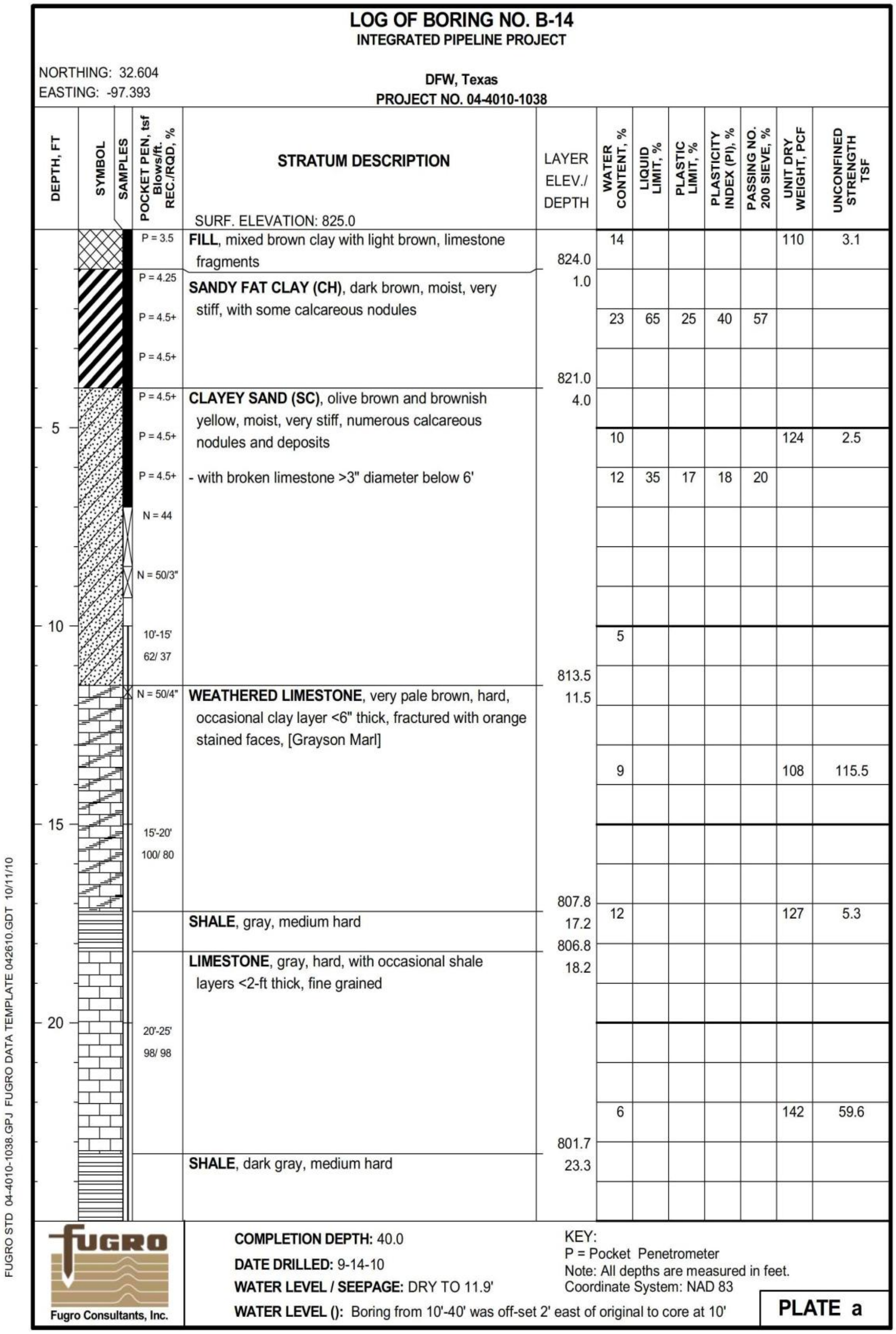
The first phase of this project was conducted by Karduri (2011) and focused on the selection and sampling of soils from multiple locations along the pipeline alignment to assess the reusability potential of these materials as bedding and backfill materials for the pipeline. Basic and advanced soil tests were performed on soil samples from each boring location to address their reusability as bedding zone or backfill materials (Karduri. 2011).

Based on the studies conducted by Karduri (2011) along the pipeline alignment, two different locations (B14 and B15) were selected for use as fine aggregate in CLSM mixes for this research. B14 soil consisted of low plastic clay material from Grayson Marl geological formation while B15 soil consisted of high plastic clay material from Eagle Ford geological formation. The main focus of this study is to use the high plastic clayey soil from Eagle Ford formation in CLSM mixes. Later, the Grayson Marl soil which is predominantly low plasticity clay was also used in combination with Eagle Ford clayey soil to improve the CLSM mix workability. The reason behind selecting Eagle Ford clay formation for CLSM mixes is that, if the CLSM mix can be designed using this high plastic clayey soil formation, then it can be designed with all other clay formations along the pipeline alignment (which exhibit lesser soil plasticity) as the Eagle Ford clay is a high plastic material with low workability characteristics.

Figure 3.1 shows the selected soil borings along the proposed pipeline alignment in red boxes. Locations are denoted with the letter B followed by a number; the B stands for Boring and the number provides a directional key.

The samples were collected with the help from Tarrant Regional Water District (TRWD) and Fugro consultants Inc. These samples were obtained from depths of 10 to 15 ft. Bore logs of B14 and B15 soils are shown in Figures 3.2 and 3.3.

Figure 3.1 Selected boring locations



LOG OF BORING NO. B-14

INTEGRATED PIPELINE PROJECT

NORTHING: 32.604
EASTING: -97.393

DFW, Texas

PROJECT NO. 04-4010-1038

SURF. ELEVATION: 825.0

DEPTH, FT	POCKET PEN, tsf Blows/ft. REC./RQD, %	STRATUM DESCRIPTION	LAYER ELEV./ DEPTH	WATER CONTENT, %	LIQUID LIMIT, %	PLASTIC LIMIT, %	PLASTICITY INDEX (PI), %	PASSING NO. 200 SIEVE, %	UNIT DRY WEIGHT, PCF	UNCONFINED STRENGTH TSF
	P = 3.5	**FILL**, mixed brown clay with light brown, limestone fragments	824.0 1.0	14					110	3.1
	P = 4.25	**SANDY FAT CLAY (CH)**, dark brown, moist, very stiff, with some calcareous nodules								
	P = 4.5+			23	65	25	40	57		
	P = 4.5+		821.0 4.0							
	P = 4.5+	**CLAYEY SAND (SC)**, olive brown and brownish yellow, moist, very stiff, numerous calcareous nodules and deposits								
5	P = 4.5+			10					124	2.5
	P = 4.5+	- with broken limestone >3" diameter below 6'		12	35	17	18	20		
	N = 44									
	N = 50/3"									
10	10'-15' 62/ 37		813.5 11.5	5						
	N = 50/4"	**WEATHERED LIMESTONE**, very pale brown, hard, occasional clay layer <6" thick, fractured with orange stained faces, [Grayson Marl]								
				9					108	115.5
15	15'-20' 100/ 80		807.8 17.2							
		SHALE, gray, medium hard	806.8 18.2	12					127	5.3
		LIMESTONE, gray, hard, with occasional shale layers <2-ft thick, fine grained								
20	20'-25' 98/ 98									
			801.7 23.3	6					142	59.6
		SHALE, dark gray, medium hard								

Fugro Consultants, Inc.

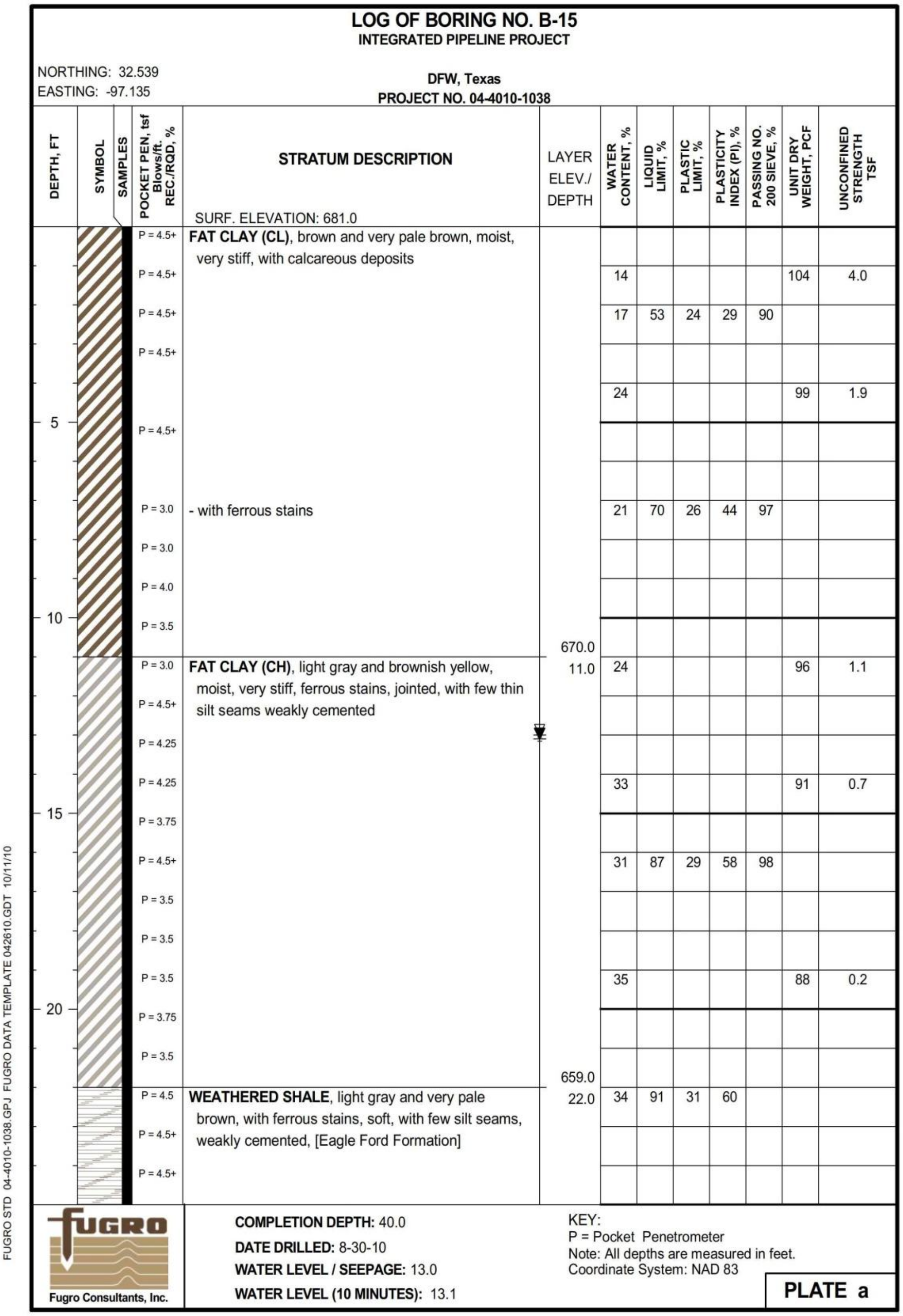
COMPLETION DEPTH: 40.0
DATE DRILLED: 9-14-10
WATER LEVEL / SEEPAGE: DRY TO 11.9'
WATER LEVEL (): Boring from 10'-40' was off-set 2' east of original to core at 10'

KEY:
P = Pocket Penetrometer
Note: All depths are measured in feet.
Coordinate System: NAD 83

PLATE a

FUGRO STD 04-4010-1038.GPJ FUGRO DATA TEMPLATE 042610.GDT 10/11/10

Figure 3.2 B14 Bore log



LOG OF BORING NO. B-15

INTEGRATED PIPELINE PROJECT

NORTHING: 32.539
EASTING: -97.135

DFW, Texas
PROJECT NO. 04-4010-1038

DEPTH, FT	SYMBOL	SAMPLES	POCKET PEN, tsf Blows/ft. REC./RQD, %	STRATUM DESCRIPTION SURF. ELEVATION: 681.0	LAYER ELEV./ DEPTH	WATER CONTENT, %	LIQUID LIMIT, %	PLASTIC LIMIT, %	PLASTICITY INDEX (PI), %	PASSING NO. 200 SIEVE, %	UNIT DRY WEIGHT, PCF	UNCONFINED STRENGTH TSF
			P = 4.5+	**FAT CLAY (CL)**, brown and very pale brown, moist, very stiff, with calcareous deposits								
			P = 4.5+			14					104	4.0
			P = 4.5+			17	53	24	29	90		
			P = 4.5+									
						24					99	1.9
5			P = 4.5+									
			P = 3.0	- with ferrous stains		21	70	26	44	97		
			P = 3.0									
			P = 4.0									
10			P = 3.5		670.0							
			P = 3.0	**FAT CLAY (CH)**, light gray and brownish yellow, moist, very stiff, ferrous stains, jointed, with few thin silt seams weakly cemented	11.0	24					96	1.1
			P = 4.5+									
			P = 4.25		▼							
			P = 4.25			33					91	0.7
15			P = 3.75									
			P = 4.5+			31	87	29	58	98		
			P = 3.5									
			P = 3.5									
			P = 3.5			35					88	0.2
20			P = 3.75									
			P = 3.5		659.0							
			P = 4.5	**WEATHERED SHALE**, light gray and very pale brown, with ferrous stains, soft, with few silt seams, weakly cemented, [Eagle Ford Formation]	22.0	34	91	31	60			
			P = 4.5+									
			P = 4.5+									

Fugro Consultants, Inc.

COMPLETION DEPTH: 40.0
DATE DRILLED: 8-30-10
WATER LEVEL / SEEPAGE: 13.0
WATER LEVEL (10 MINUTES): 13.1

KEY:
P = Pocket Penetrometer
Note: All depths are measured in feet.
Coordinate System: NAD 83

PLATE a

FUGRO STD 04-4010-1038.GPJ FUGRO DATA TEMPLATE 042610.GDT 10/11/10

Figure 3.3 B15 Bore log

3.3 Research variables

The strength, flowability and setting time of CLSM mixtures strongly depends on various factors that are described in chapter 2. Based on the literature review performed, variables such as aggregate type, binder type, binder proportions, curing period, curing conditions and water-binder ratio are considered as the primary variables affecting the flowability, strength and setting time properties of the CLSM. Table 3.1 presents the ranges of these variables studied in current investigation.

Table 3.1 Research variables considered in this study

Variable description	**Range**
Soil mixes based on CH and CL proportions (CH:CL)	2 [100:0, 50:50]
Binder dosage for each soil proportion	5 [10%, 15%, 20%,25%, 30%]
Binder proportions for each soil proportion C:F C:L	 4[100:0,100:0,20:80,0:100] 4 [33:67, 25:75, 20:80,0:100]
Curing time	2 [7 and 28 days]
Water binder ratio	Varied with the mix to reach flowability
Curing conditions	1 [1 week counter top, 3weeks: 100% relative humidity, 20±3 ^{o}C]

These properties are self-contradictory such as increase in flowability results in decrease in strength and also increase in setting time. To achieve optimum performance of all these properties, it is necessary to study various possible mix proportions though it is hard to compare the results. The final mix design should be optimized with all these variables to best suit in field implementation.

3.4 CLSM Mix Design

Before arriving at the above mentioned ranges for binder dosage, the current research determined the optimum binder values for cement by trial and error process. Samples were tested for compressive strengths at 3% (50 kg/m^3), 6% (100 kg/m^3) and 10% (167 kg/m^3) cement until the minimum strength requirement (70 to 150 psi) (as per TRWD specifications) was achieved. Quantities for lime and fly ash were estimated by doubling their quantities and these replace the cement quantity. For example, 5% of cement quantity was replaced by 10% of lime or fly ash.

Water quantity was established based on trial and error procedure until the required CLSM flowability (8-12 in.) was achieved. The test started from the liquid limit of the corresponding soil for each mix proportion. Density test was performed after finalizing the mix design which satisfied the flowability requirements. Samples for compressive strength tests and for setting time tests were prepared with the water content established for flow test.

The flow chart in Figure 3.4 depicts the detailed laboratory mix design carried out in this research.

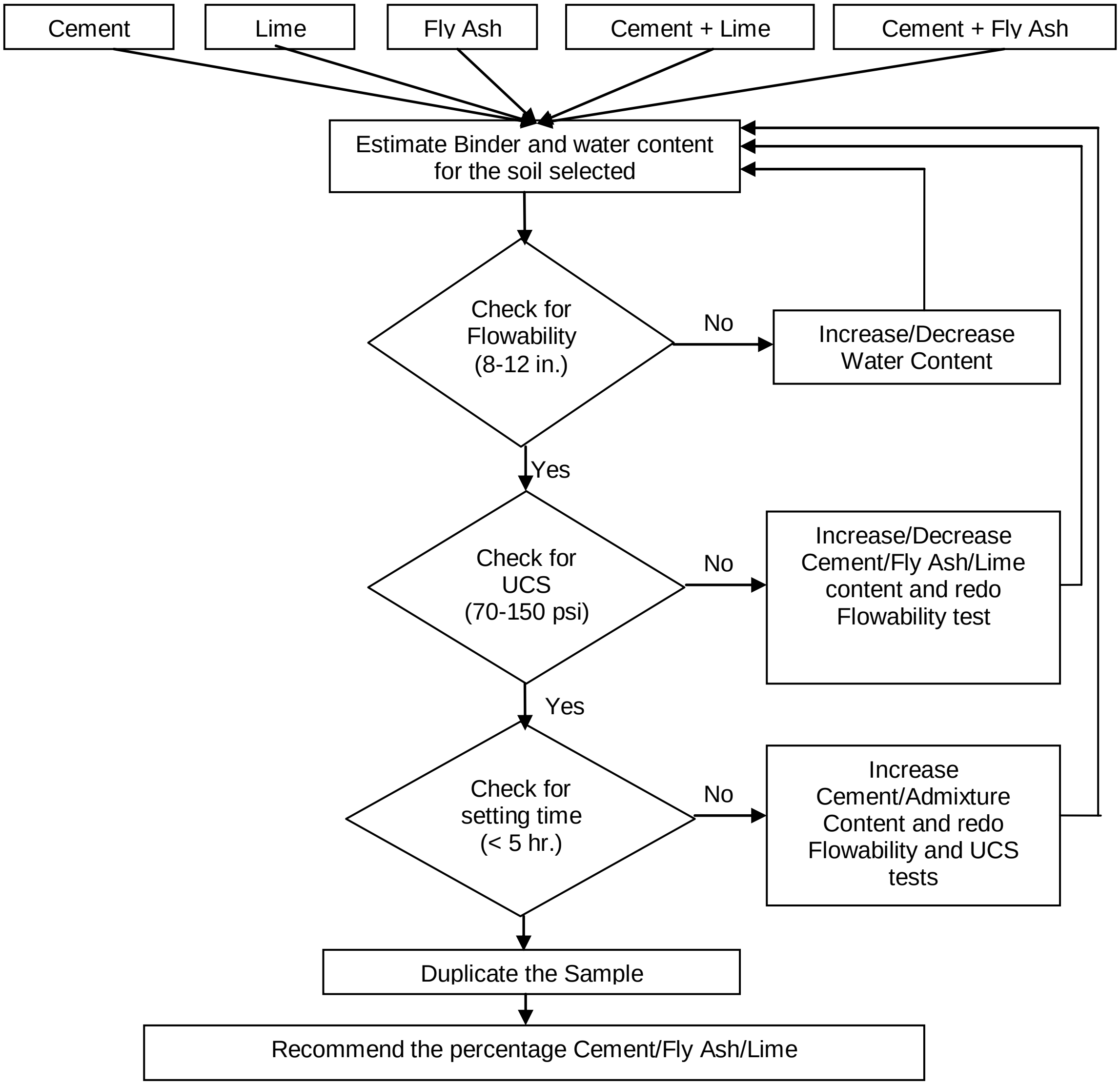


Figure 3.4 Flow chart of Laboratory mix design procedure for native soil based CLSM

3.5 Sample preparation

As there was no standardized method is established for preparing the soil samples, test procedure adopted by Folliard et al. (2008) was closely followed for preparing samples for flowability, density, compressive strength and setting time. Most of the preparation procedure discussed below was extracted from Folliard et al. (2008). This procedure is particularly applicable for medium stiff to stiff clayey soils. In order to obtain a uniform soil-binder mixture, the bulk and undisturbed soil samples were first oven dried (at 60^{o}C) and pulverized to obtain fraction passing through US Sieve 40 (0.425 mm). The natural water content was added separately to the soil along with the weight of water from mix proportion at the time of mixing.

Procedure followed for soil-binder mixing and specimen preparation is explained in following steps. Approximate quantity of representative pulverized soil required for preparing desired number of soil samples was obtained. Appropriate amount of binders (cement, lime and fly ash) were determined and weighed. The total water content which includes the insitu water content and the amount of water from designed mix proportion was determined.

The quantities of cement and/or fly ash or lime were mixed in dry conditions separately and then this mix was added and mixed to the soil in dry state prior to the addition of water in a commercially available dough mixer. The mixing rate of the outer spindle was at 60 rpm and inner spindle was rotated at 152 rpm. These rates were arrived at by a trial and error process to facilitate sufficient mixing time without forming soil binder lumps.

Water content established was slowly introduced in to the soil-binder mix. Flexible spatula was used to avoid the soil from sticking to the sides and bottom of the mixing bowl to ensure that there were no soil-binder lumps. Trial mixings were made to establish particular mixing time that yields uniform soil-binder mixture. The total mixing time in this study based on experience is 8 to 10 minutes. Finally, the soil binder mixture was transferred in to the bowl for flow, strength and setting time tests. Figure 3.5 shows the apparatus used for preparing CLSM mix.

Figure 3.5 Soil-binder mixer

UCS samples were then casted for 7 day and 28 day strength tests and both the samples were left countertop for the first week and then only 28 day samples were moved to 100% relative humidity room and were brought outside the humidity room at the time of testing while seven (7) day samples were left countertop until the time of testing. Humidity controlled curing was not performed on 7 day samples as they were still in wet condition. Hence countertop curing was considered and this method is similar to the one outlined in NCHRP report 597 by Folliard et al. in 2007.

3.6 Tests Conducted on Native Soil

3.6.1 *Sieve Analysis*

This test was conducted to obtain the grain-size distribution of soils for the two samples. The test was conducted according to ASTM D 422 method. A soil sample representative of the region from which it was collected was passed through No. 200 sieve using water. The distribution of particle size of the sample portion retained on No. 200 sieve was determined by sieve analysis, while the sample portion passed through No. 200 sieve was determined by hydrometer analysis. Sieve analysis establishes the percentage of the coarse fraction of the soil (Gravel and Sand) while hydrometer analysis establishes the percentage of fine fraction in the soil specimens (Silt and Clay).

3.6.2 *Hydrometer Analysis*

Hydrometer Analysis was carried out to study the micro level distribution of silt and clay fraction present in the field soil. This test was performed as per ASTM D 422. The procedure involved taking 50 g of the oven dried portion that passed No. 200 sieve (explained in previous section) and mixed with a solution containing a 4% deflocculating agent (Sodium Hexametaphosphate) and soaking for about 8 to 12 hours. The prepared soil was thoroughly mixed in a mixer cup and all the soil solids inside the mixing cup were transferred to a 1000 cc graduated cylinder and filled to mark using distilled water.

The hydrometer readings were recorded at cumulative time of 0.25 min., 0.5 min., 2 min. 4 min., 8 min., 15 min., 20 min., 2 hr., 4 hr., 8 hr., 12 hr., 24 hr., 48 hr., and 72 hr. After taking the readings initially for the first 2 minutes, the hydrometer was taken out and kept in another cylinder filled with distilled water. Necessary temperature corrections, zero corrections and meniscus corrections were made to the hydrometer readings as per procedure. Photographs of sieve analysis and hydrometer analysis are presented in Figure 3.6.

(a) (b)

Figure 3.6: Basic soil tests (a) Sieve analysis and (b) Hydrometer analysis

3.6.3 *Atterberg Limits*

If the soil is steadily dried, depending on its moisture content, it will behave like a plastic, semisolid, or solid material. To determine the water content boundaries between these states, it is important to perform Atterberg limits. These boundaries are known as shrinkage limit (SL), plastic limit (PL) and liquid limit (LL); they divide the soil states in the following order: dry, semi-solid, plastic, and liquid. Of the three states, LL and PL are the most crucial factors; the mathematical difference in these values is known as plasticity index (PI). PI characterizes the plasticity of soil numerically. The higher the PI, the more plastic the soil is.

Cassagrande developed a liquid limit device in which the liquid limit cup lifts and drops 10mm on a hard rubber plastic base (ASTM D 4318). The number of blows, the goal is 25 blows, is counted until the groove, made by a grooving tool, closes a distance of 13mm (1/2in.); this determines the moisture content within the soil. Typically the test is performed 2 to 3 times, as 25 blows is hard to achieve the first time. Therefore one point above and below is found and the moisture content is interpolated at 25 blows. The test to determine the PL is subjective to the user in that it requires practice for consistent results. It is defined as the moisture content at which the soil crumbles when rolled into a thread of 3.18mm (1/8in.) in diameter. ASTM D 4318 provides a detailed procedure.

3.7 Tests Conducted on CLSM Mixes

3.7.1 *Density Test*

Density test was performed, when the CLSM was in wet state. Details of test procedure are presented in the following sections.

The apparatus include a balance, filling apparatus, sampling and mixing receptacle, measure, strike-off plate and calibration equipment. The balance used was accurate enough to measure 0.01 lb of weight. A mixing receptacle and a pail of sufficient capacity were used to facilitate filling of the measure. The container was water-tight and sufficiently rigid to retain its form. The dimension of the measure was such that the height was approximately equal to the diameter. ASTM D 6023-94 specifies that the height of the measure shall neither be less than 80% nor greater than 150% of the diameter of the measure. Figure 3.7 shows the steel measure used in this research. The capacity of the measure was calibrated according to ASTM C 29.

Figure 3.7. Steel measure for density measurement

The measure was placed on a level, rigid and horizontal surface free from vibration and other disturbances. The CLSM material was thoroughly mixed in the receptacle. The center portion of the material was scooped through the filling apparatus and then poured in to the measure. After filling, the strike off plate was used to produce a smooth surface of the material. After removing the excess material from the exterior of the measure, the mass of the CLSM in the measure was determined close to 0.01 lb. The density was obtained by taking the weight over calibrated volume for the measure.

3.7.2 *Flow Test*

Flow test was conducted to determine the workability of the CLSM material and its ability to flow in to confined areas. This test method is intended to provide the user with a procedure to determine the fluidity of CLSM mixtures for use as a backfill or a structural fill. The testing procedure is detailed in the following section.

The apparatus used for flow test include flow cylinder, sampling and mixing receptacle, filling apparatus, nonporous surface, straight edge and a measuring tape. A plastic cylinder with dimensions 150 mm (6 in.) height and 76 mm (3 in.) inside diameter was used as the flow cylinder. The cylinder interior had a smooth surface and it was open at both ends. A 0.6 m (2 ft) square, acrylic plate was used to allow the spread of the CLSM from the flow cylinder.

A mixing receptacle and a pail of sufficient capacity were used to facilitate filling of the measure. A stiff metal straightedge of a convenient length was used to level the surface of the material in the flow cylinder. A plastic tape was used to measure the flow diameter of the CLSM patty. Figure 3.8 shows the acrylic plate and the flow cylinder used for the flow test.

The acrylic plate was placed on a flat, level surface. The flow cylinder was damped with water and placed on the acrylic plate and was held firmly while filling the material. The center portion of the CLSM material in the receptacle was scooped and poured into the flow cylinder until full. The excess of the material on the surface of the cylinder was removed using the straight edge. The cylinder was then raised quickly in a vertical direction by 15 cm (6 in.) within 5 seconds of filling and strike off. The entire test of filling through removal of flow cylinder without interruption was completed within a time of 1 minutes, as mentioned by ASTM standard. Two diameters perpendicular to each other of the patty were measured. The average of the two was considered as the flow diameter of the CLSM material.

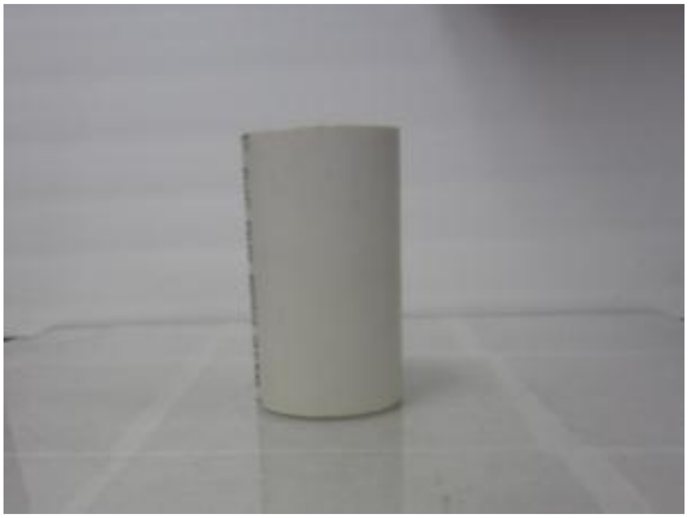


Figure 3.8 Acrylic plate with the flow cylinder

3.7.3 *Setting Time*

Setting time of the CLSM mix prepared was conducted to determine the time required for CLSM to resist 25 mm penetration of Vicat’s needle. Details of the test procedure involved are discussed in the following section.

The apparatus include plastic conical mold, plastic plate, sampling and mixing receptacle, filling apparatus, plunger, penetration needle, and a pipette. A plastic conical mould of 70 mm bottom diameter, 60 mm top and 40 mm high was used as the container. The mold was non-absorptive, rigid and watertight. A plunger which can apply 1 psi stress along with the needle was used as a penetration needle.

The conical plate and plastic plate assembly was placed on a flat level surface and the components were held together firmly while filling the material. The CLSM material was thoroughly mixed in the receptacle. The center portion of the material was scooped and then poured in to the conical mold until full and the excess material was removed by using a straightedge.

Just prior to making the penetration test, bleeded water from the surface was removed with the help of pipette. Needle assembly was brought just in contact with the test specimen and was released. Readings were taken until the depth of penetration retarded to 25 mm from surface of the mold by avoiding the areas where the CLSM has been disturbed by previous trails, as mentioned by the ASTM standard. Time required for 25 mm penetration was considered as the setting time of the CLSM material. Figure 3.9 shows the Vicat’s apparatus used for this test.

Figure 3.9 Vicat's apparatus

3.7.4 *Unconfined Compressive Strength Test*

After curing the samples for corresponding time periods, Unconfined Compressive Strength (UCS) tests were conducted as per ASTM D 2166. This test was conducted on the soil samples under unconfined conditions. The test was conducted on casted soil specimens of 3.0 inches in diameter and 6 inches in height. The soil specimen was first placed on a platform and then raised at a constant strain rate using the controls of the UCS setup until it came in contact with top plate. Figure 3.10 shows the unconfined compressive strength test setup and the computer system used for data acquisition.

Figure 3.10 UCS test setup with Data Acquisition System

Once the specimen was intact, it was loaded at a constant strain rate and as the load approached the ultimate load, failure cracks began to appear on the surface of the specimen. Both deformation and corresponding axial loads on the specimen were recorded using a Data Acquisition System (DAS). The data retrieved contained load (Q) and deformation ( ) data and the same were analyzed to determine the maximum unconfined compressive strength ( ) in psi. The following expressions show the computation of stress ( ) and strain ( ) corresponding to the load-deformation data recorded during a test.

– — —

Where, = change in length, = total length of specimen, = corrected area of cross section of the specimen and = initial area of cross section. Figure 3.11 shows the 28 days UCS sample casted with 10 % cement.

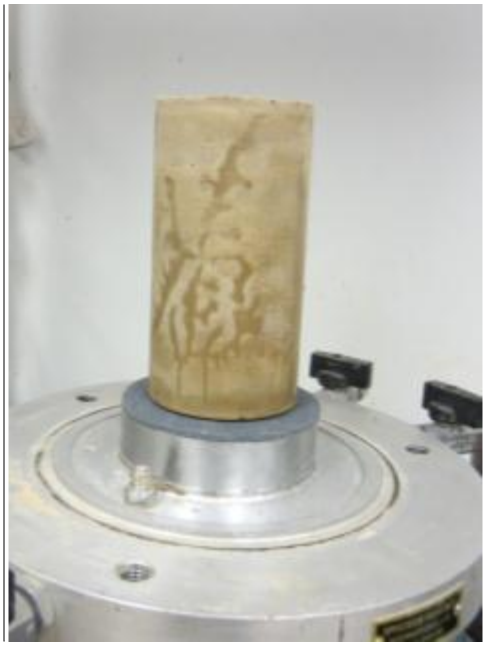


Figure 3.11 Typical 28 day UCS sample before testing

3.8 Summary

This chapter explains the criteria for selection of B14 and B15 soils as constituents for the mix design and also the locations of these soils along the pipeline. Various research variables involved in design of mix proportion were briefly discussed. Procedures adopted for formulation of mix designs and factors affecting the target properties are discussed. Procedures involved in determining the Index properties and results obtained for control soils were tabulated. Engineering tests performed to reach the target properties are also discussed in detail and the quantities needed to reach the target properties such as water content and binder proportions for various proposed mix designs are obtained. Sample preparation for flowability, compressive strength, density and setting time is also discussed in detail.

CHAPTER 4

RESULTS AND DISCUSSION OF LABORATORY CLSM MIX DESIGN

4.1 Introduction

This chapter presents comprehensive analysis of results obtained from laboratory tests on selected soils and different CLSM mixes prepared using selected soils as fine aggregate. Sample preparation for CLSM mixes and the testing procedures of various tests conducted on them are as explained in the earlier chapter. Various notations followed and the effect of binder proportions, binder types, set accelerator, soil-binder and water binder ratios, and curing time period on target properties (flowability, density, strength and setting time) of CLSM are discussed in the following sections, followed by the results analysis and summary.

4.2 Sample Notation and Mix Proportions

For easy identification of different CLSM mixes, every mix is assigned a certain notation for easy following of the mix type and its constituent's information. For example, two mixes are presented in the form of A_C5L10_S1 or B_C5F10_S2. In these notations, the first symbol refers to the fine aggregate mix used, as A stands for B15 (CH) soil alone as a fine aggregate of CLSM and B stands for a combination of B15 (CH) and B14 (CL) soils, mixed at 1:1 ratio by their dry weights. The second part of the notation, C5L10 or C5F10 represents the proportions of the chemical binders used in the mix, 5% cement and 10% lime or 5% cement and 10% fly ash, respectively, by their dry weight of soil including fine aggregate contents. Water content represented here is to the dry weight of total solids. The third symbol S1 or S2 represents admixture percentage, as S1 stands for 8% of admixture by dry weight of binder and S2 stands for 8% of admixture by dry weight of soil. Admixture contents, S1 and S2 are used to lower the setting time of the CLSM mixes whose compressive strengths met the requirement value of 70 to 150 psi. Tests for flowability, density and compressive strength were repeated to check the variability in properties when set accelerator was used. Materials and symbols used in this research are listed in Table 4.1 where as notations followed and quantities for all the mix proportions that were tried are shown in Table 4.2.

Table 4.1 List of materials and symbols used

Material	**Designation**	**Description**
Soil mix	A	CH only
	B	Combination of CH and CL in 1:1 ratio
Binder	C	% Cement by dry weight of soil
	L	% Lime by dry weight of soil
	F	% Fly Ash by dry weight of soil
Chemical admixture	S1	8% Set accelerator by dry weight of binder
	S2	8% Set accelerator by dry weight of soil mix

Note: CH- High plasticity clay from B15, CL - Low plasticity clay from B14

Table 4.2 Sample notations and quantities of components used

Mix Notation	C (kg/m^3)	FA (kg/m^3)	L (kg/m^3)	Soil (kg/m^3)		Percentage water content (kg/m^3)
				CH	CL	
A_C6	69	0	0	1056	0	72 (810)
A_C10	105	0	0	1056	0	72 (836)
A_C15	155	0	0	1056	0	72 (872)
A_L20	0	0	210	1056	0	74 (937)
A_C5L10	52	0	105	1056	0	74 (898)
A_C5L15	52	0	157	1056	0	74 (936)
A_C5L20	52	0	210	1056	0	76 (1002)
A_C5F20	52	210	0	1056	0	72 (949)
B_C6	69	0	0	528	528	54 (608)
B_C10	105	0	0	528	528	54 (627)
B_C15	155	0	0	528	528	54 (654)
B_L20	0	0	201	528	528	62 (779)
B_C5L10	52	0	135	528	528	58 (721)
B_C5L15	52	0	189	528	528	59 (765)
B_C5L20	52	0	242	528	528	60 (810)
B_C5F20	52	210	0	528	528	59 (778)

Note: C – Cement; FA – Fly Ash; L - Lime

After performing the tests for flowability, density, compressive strength and setting time for the above mixes, set accelerator was added to some of the mixes whose compressive strengths met the required criteria (70 to 150 psi) and all aforementioned tests were repeated on those mixes to check the effect of set accelerator on the desired properties using 8% set accelerator by dry weight of binder and the quantities of set accelerator required are given in Tables 4.3 and 4.4.

Table 4.3 Sample notations and quantities of set accelerator used (8% of binder)

Mix Notation	Set accelerator (kg/m^3)
A_C10_S1	8
A_C15_S1	13
A_C5L10_S1	17
A_C5L15_S1	18
B_C10_S1	8
B_C15_S1	12
B_C5L10_S1	13
B_C5L15_S1	17

Table 4.4 Sample notations and quantities of set accelerator used (8% of dry soil)

Mix Notation	Set accelerator (kg/m^3)
A_C15_S2	84
A_C5L10_S2	84
A_C5L15_S2	84
B_C10_S2	84
B_C15_S2	84
B_C5L10_S2	84
B_C5L15_S2	84

4.3 Basic Soil Properties Test Results

Grain size analysis and Atterberg's limits tests were conducted on soil samples collected from depths of 10 to 15 ft. B15 soil exhibit high Plasticity Index (PI) value of 37 while B14 soil had a PI of 23. B15 and B14 are classified as high plasticity clay (CH) and low plasticity clay (CL) as per Unified Soil

Classification System (USCS) classification system. Table 4.5 shows the Atterberg's limits along with the grain size analysis and USCS classification.

Table 4.5 Physical properties of selected soiils

Property	**ASTM Test Designation**	**Site 1**	**Site 2**
Gravel (%)	ASTM D422	1	12
Sand (%)	ASTM D422	12	25
Silt (%)	ASTM D422	37	61
Clay (%)	ASTM D422	50	2
Liquid Limit	ASTM D4318	62	42
PI	ASTM D4318	37	23
USCS Classification	ASTM D2487-00	CH	CL

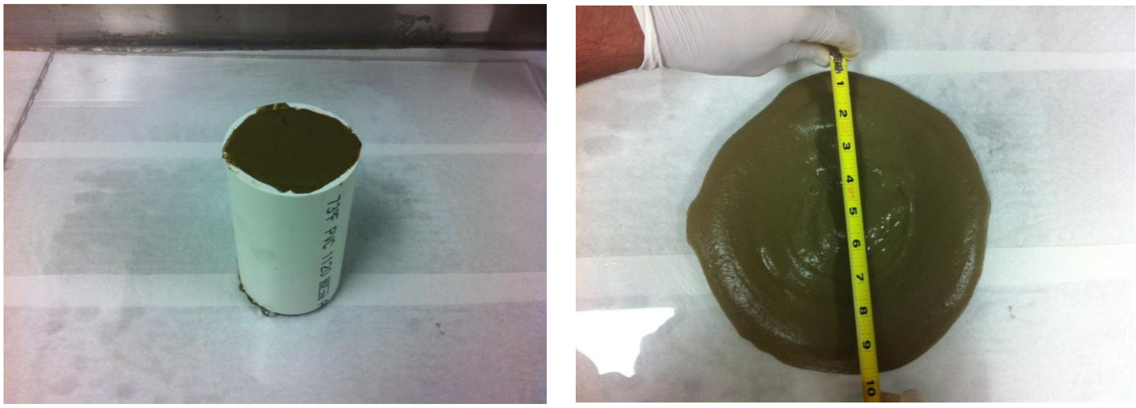
4.4 CLSM Test Results and Analysis

The following sections present results of all the tests conducted on different CLSM mixes. Comparisons were made among different mixes to assess the effects of aggregate type, binder type, binder proportions, curing period, curing conditions and water-binder ratio on CLSM mixes. These comparisons and discussions are presented in the following sections.

4.4.1 *Flow Test Results*

Flow tests were conducted in accordance with ASTM D 6103-97 test method. The mixes were prepared following the step-by-step procedure explained in section 3.3.1 for specimen preparation. Each test was repeated twice and average values are reported in this thesis. For each test, two perpendicular diameters of the slump were measured and the average diameter was calculated. Figure 4.1 presents photographs of the flowability test cylinder with CLSM mix and the measurement of the flowability index after the test.

The optimum moisture content of the CLSM mix depends on the liquid limit of the fine aggregate being used. In this research the fine aggregate is native soil from B15 location which had a very high liquid limit of 62%. Hence, high amounts of water are required to meet the flowability requirement as per ASTM D 6103-97. Initial trial mixes are prepared using B15 soil as fine aggregate and 6% cement as binder. Several trials were made by varying the water content with constant binder percentage till the target flow of 8-12 in. was achieved.


(a)

(b)

Figure 4.1 Flow test performed for 15% cement with 72 % Water content:
a) Flow cylinder with CLSM mix, b) Measuring flowability of the CLSM mix

For the CLSM mix with 6% cement content (A-6C), water content was varied from 62% to 80% to observe the variation of flowability with water content. Figure 4.2 depicts this change in flowability with respect to change in water content at a constant binder content of 6% (cement = 560 kg/m^3). It can be observed from the figure that the mixes with water contents of 72% and more met the flowability requirement of 8 to 12 in. This water requirement is considered high and also not common in CLSM mixes which use conventional fine aggregates such as foundry sand. However, due to the high liquid limit of the high PI soil being used compared to that of foundry sand at least 72% of water by dry weight of the soil is required in order for the material to be able to flow and act as a self-leveling mixture.

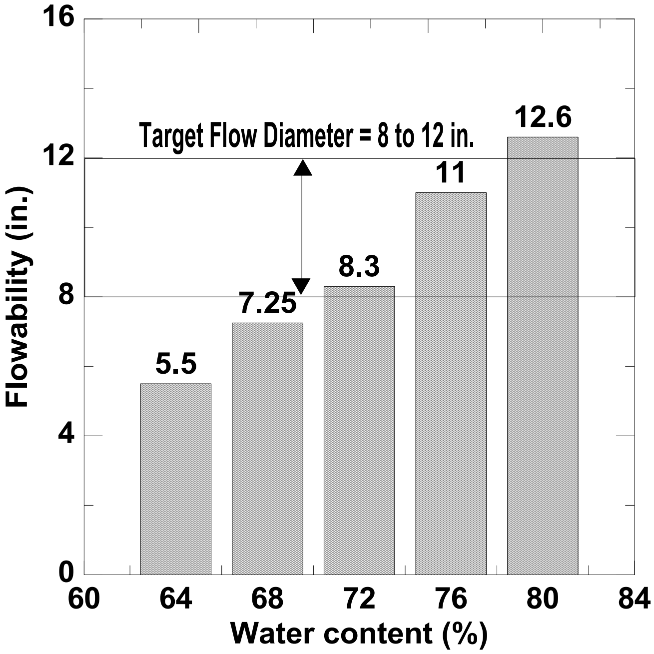


Figure 4.2 Variation of flowability with water content for A_C6

Also, trials were made with a combination of high PI soil from B15 and low PI soil from B14 to address if the water content requirement can be reduced as B14 has a low liquid limit of 42%. Trails were made with 6% cement as binder and soils were mixed in 1:1 ratio. The results of these tests are presented in Figure 4.3. It can be observed from the figure that the mixes with water contents of 50% and higher met the flowability requirement of 8 to 12 in. Hence, there was a reduction in water content of about 22% when using B14 and B15 soils in 1:1 ratio as a fine aggregate in the CLSM mixes.

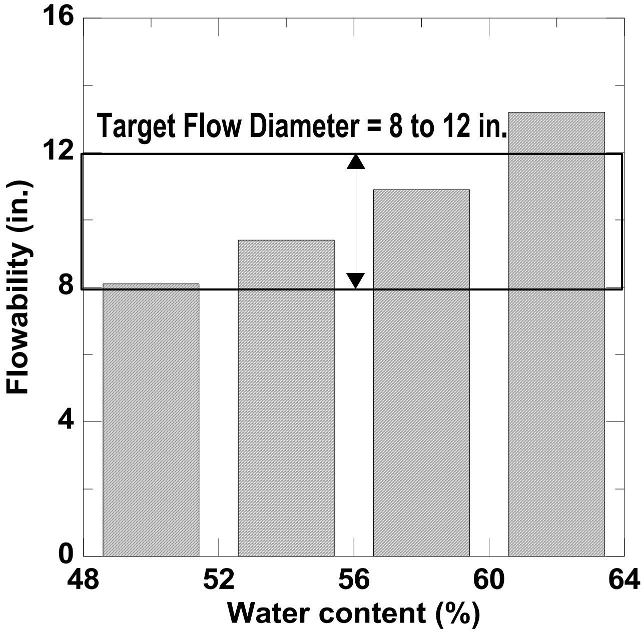


Figure 4.3 Variation of flowability with water content for B_C6

Once the optimum water content was established for the two categories of mixes (one using B15 soil alone and the other using combination of B14 and B15 soils), it gave an initial estimate of the water content for other mixes in each category instead of randomly guessing the initial moisture contents for every CLSM mix attempted in this research.

CLSM mixes with B15 soil alone as fine aggregate will be referred to as A mixes and those with a combination of B15 soil and B14 soil will now onwards be referred to as B mixes. Flow tests were conducted on both A and B mixes to first check on the flowability property of each mix. The actual mix ratios are presented in Table 4.2 and in Table 4.3 above and the flowability test results are presented in Table 4.6 and Table 4.7.

Table 4.6 presents the results for the A mixes while Table 4.7 presents the results for B mixes. It can be observed from these tables that some of the mixes required more than the initial established optimum water contents and this is expected as each mix has different percentages of binders in them and these binders have minor effect on the water content requirement. In order to further understand the effect of the variables such as the binder type, binder dosage and the amount of set accelerator used in these mixes, several comparisons were made and are presented in the following sections.

4.4.1.1 Effect of binder dosage on flowability

To compare the effects of binder dosage on the flowability of CLSM mixes, mixes A_C6, A_C10, A_C15 from A and B_C6, B_C10, B_C15 from B are compared and these results are presented in Figure 4.4. These mixes have cement as binder type. It can be observed from this figure that an increase in binder content results in an increase in flowability, but for some of the mixes with binder other than cement, an increase in binder content resulted in a decrease in flowability. Figure 4.5 shows these results.

Table 4.6 Flow test results for soil A

Material	Water Content	Trail 1 (in.)	Trail 2 (in.)	Average Diameter (in.)
A_C6	72	8.4	8.2	8.3
A_C10	72	9.40	9.60	9.50
A_C15	72	9.90	9.60	9.75
A_F30	72	9.20	8.90	9.05
A_L20	74	8.80	8.70	8.75
A-C5L10	74	9.00	9.20	9.10
A-C5L15	74	9.10	9.00	9.05
A-C5L20	76	8.90	9.00	8.95
A-C5F20	72	9.00	9.00	9.00
A_C10_S1	72	9.50	9.50	9.50
A_C15_S1	72	9.00	9.10	9.05
A_C5L10_S1	74	8.80	8.60	8.70
A_C5L15_S1	74	8.60	8.90	8.75

Table 4.7 Flow test results for soil B

Material	Water Content	Trail 1 (in.)	Trail 2 (in.)	Average Diameter (in.)
B_C6	54	9.2	9.6	9.4
B_C10	54	9.80	10.00	9.90
B_C15	54	10.40	10.30	10.35
B_F30	56	9.60	9.20	9.40
B_L20	62	8.90	9.20	9.05
B_C5L10	58	9.20	9.20	9.20
B_C5L15	59	8.90	9.20	9.05
B_C5L20	60	8.60	8.70	8.65
B_C5F20	59	9.60	9.20	9.40
B_C10_S1	56	9.70	9.70	9.70
B_C15_S1	56	10.10	9.90	10.00
B_C5L10_S1	58	8.90	9.20	9.05
B_C5L15_S1	59	8.90	8.70	8.80

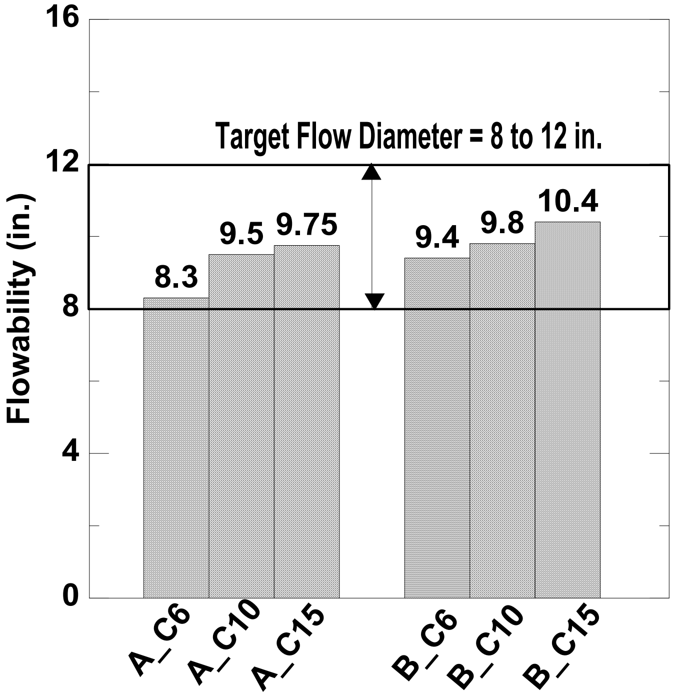


Figure 4.4 Variation of flowability with binder dosage with cement alone

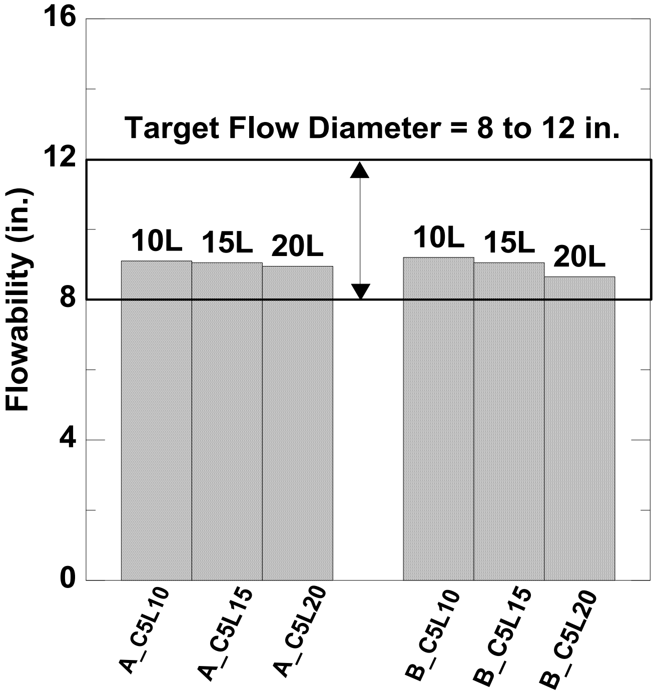


Figure 4.5 Variation of flowability with binder dosage with cement and lime

4.4.1.2 Effect of binder types on flowability

To study the variation in flow diameter with respect to binder type mixes A_C5L20, and A_C5F20 form A soil and B_C5L20, and B_C5F20 from soil B are considered as they have same binder proportion with different binders i.e. lime and fly ash. Figure 4.6 shows the variation of flowability with respect to change in binders. This figure illustrates that lime needs more water content to obtain the same flowability as that of fly ash. Above case also supports the statement that proportion of lime was the major factor that controlled the flow diameter and it needs more water to flow when compared to cement or fly ash with same quantity.

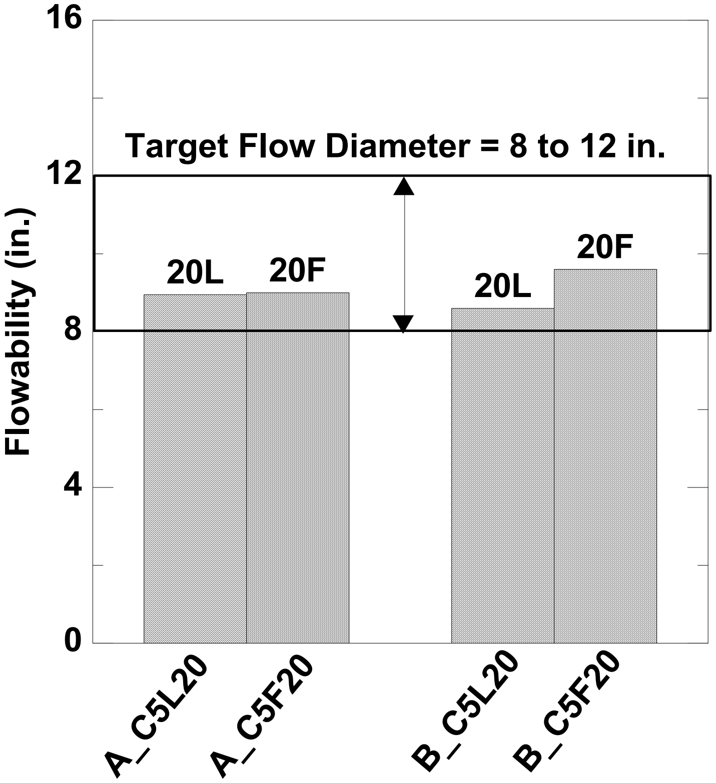


Figure 4.6 Variation of flowability with binder types

4.4.1.3 Effect of set accelerator on flowability

Set accelerator is a chemical admixture often used to enhance the hardening property of any cement soil mixture. It improves the early strength gain of the mix thereby reduces the setting time. Once the setting times were established for all the mixes without set accelerator, set accelerator was tried on some of mixes whose compressive strengths met the requirement (70 to150 psi) and flow tests were repeated on those mixes to study the variability of flow property with respect to set accelerator. Figures 4.7 and 4.8 show the variation of flowability with 8% of set accelerator for both the soil mixes, respectively. Reduction in flowability was observed among these mixes and this reduction can be attributed to the hardening action of set accelerator on the mix. The variations were minimal because the time lapse for flow test was very small.

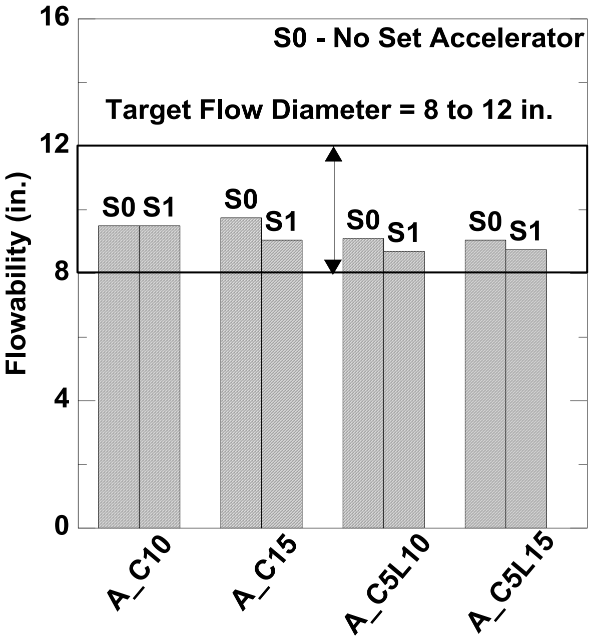


Figure 4.7 Variation of flowability with set accelerator for soil A

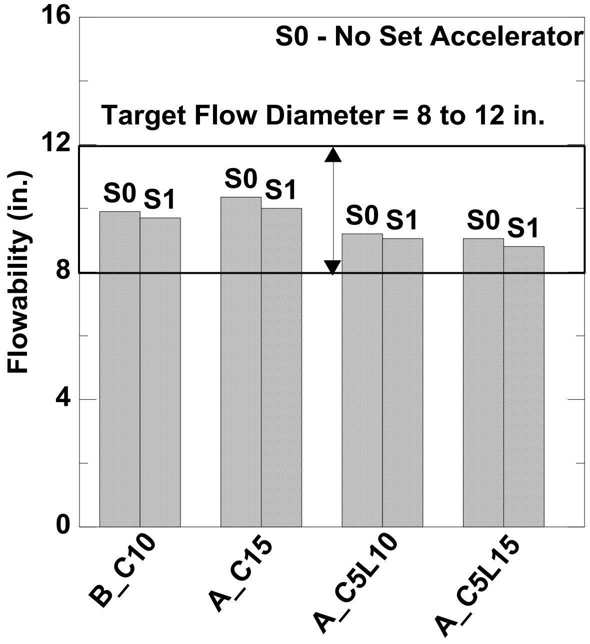


Figure 4.8 Variation of flowability with set accelerator for soil B

4.4.2 *Density Test Results*

Once the water content was established for all the mixes, density tests were conducted under wet state condition. Tests were performed in accordance with the ASTM D 6023-96 standard method. Specimen's density property was also measured at the time of UCS testing to observe its variation with time. Test results obtained for all the mixes for both soil proportions are summarized in Tables 4.8 and 4.9. Both Tables depicts that there was a decrease in density for every mix used from fresh preparation state to the time of testing i.e. at 7 days and 28 days. This change can be attributed to the loss of water for chemical reactions. Mixes with soil A have less density when compared to those of soil B due to an increase of silt content in the place of clay in the B soil mixture used.

Table 4.8 Density values for soil A

Material	**Water Content (%)**	**Density (pcf)**		
		Fresh	**7 days**	**28 days**
A_C10	72	95	91	89
A_C15	72	98	94	93
A_F30	72	98	96	94
A_L20	74	96	92	93
A_C5L10	74	97	93	94
A_C5L15	74	97	93	94
A_C5L20	76	97	93	93
A_C5F20	72	99	95	95
A_C10_S1	72	95	90	89
A_C15C_S1	72	98	92	90
A_C5L10_S1	74	97	92	92
A_C5L15_S1	74	97	92	92

Table 4.9 Density values for soil B

Material	**Water Content (%)**	**Density (pcf)**		
		Fresh	**7 days**	**28 days**
B_C10	54	104	102	100
B_C15	54	104	101	200
B_F30	56	104	101	100
B_L20	62	101	97	97
B_C5L10	58	104	101	101
B_C5L15	59	102	100	100
B_C5L20	60	101	97	99
B_C5F20	59	104	101	101
B_C10_S1	54	104	101	100
B_C15_S1	54	103	100	99
B_C5L10_S1	58	104	101	100
B_C5L15_S1	59	103	102	102

The TRWD specifications require the fresh density of CLSMs range between 95 and 115 pcf which is a typical value for pipeline applications. The present density values measured in this research are compared with the specifications provided by the Tarrant Regional Water District (TRWD). Fresh density values measured for soil A are presented in the Figure 4.9. It shows that the values obtained for all the mixes are within the range specified by TRWD and may not induce any problems in excavatability in future. Once the tests for flowability, density, compressive strength and setting time, set accelerator was added to the mixes whose compressive strength met the requirement. Density tests were repeated on these mixes to observe the variability of density with respect to set accelerator for both the soils.

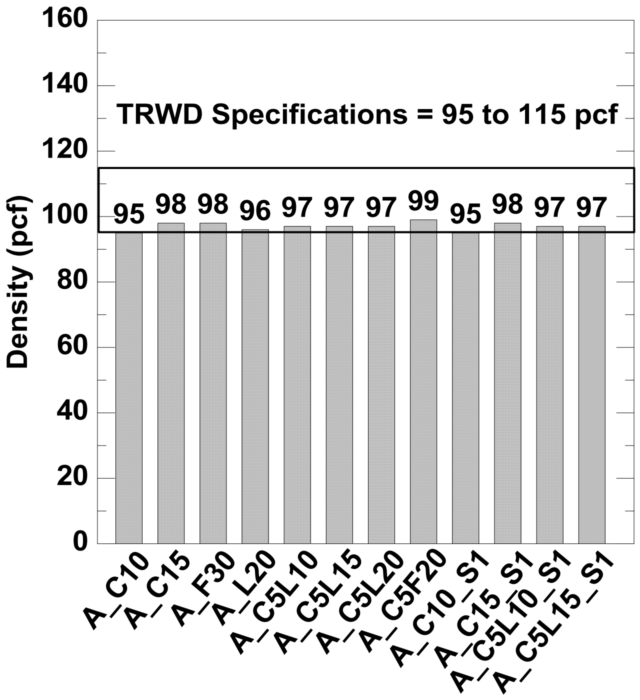


Figure 4.9 Density values for soil A compared to TRWD specifications

Density values obtained for soil B are compared with the TRWD specifications and the comparison is shown in Figure 4.10.

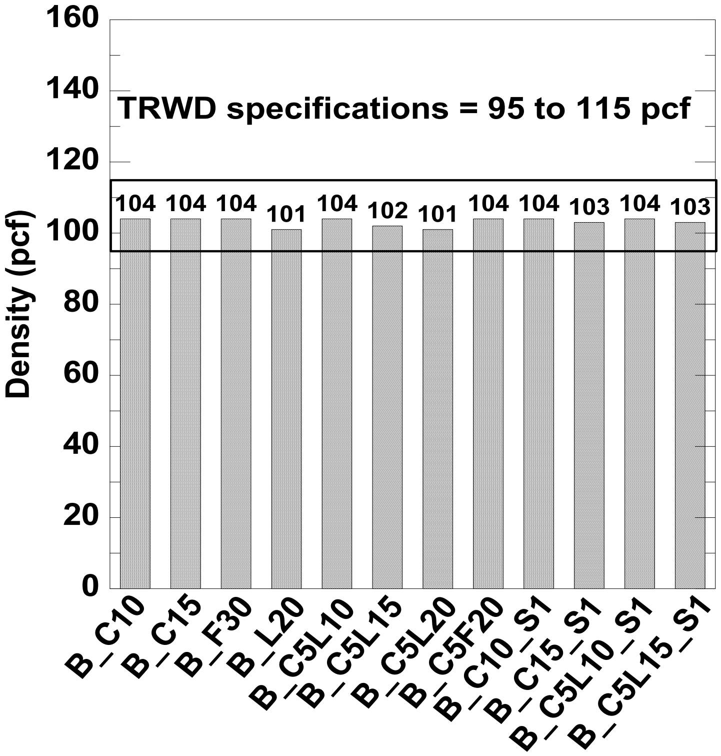


Figure 4.10 Density values for soil B compared to TRWD specifications

Figure 4.10 illustrates that the density values obtained for 'B mixtures' are also within the range as per Tarrant Regional Water District (TRWD) specifications for CLSMs to be used in the pipeline projects. Hence they may not induce any problems in excavatability issues due to potential future repairs of the pipeline projects.

4.4.3 *Compressive strength test results*

Compressive strength tests were performed on all the test specimens in accordance with ASTM D 2166 method. The mixes were prepared following the same procedure as that of flowability test samples. For each mix trial, two samples were prepared and tested. Trails were made to determine the optimum dosage of binder using the water content obtained from flow test results until the required minimum strength of 70 psi (as per TRWD specifications) was achieved Trials were started from 6% cement treated CH soil and specimens were prepared and tested after 28 days of curing to measure their unconfined compressive strength properties.

Compressive strength of 49 psi was achieved with 6% cement and it is less than required (70 psi), so the cement quantity was increased to 10% (167 kg/m^3). These results after enhancing the binder dosage have reached minimum target strength property. Tests were later performed with 15% cement dosage to check the variability of strength with binder content and the results also passed the CLSM criterion. After estimating the optimum binder content, the current research then aimed at different binder combinations in order to replace and/or reduce the cement content by adding other additives including recycled waste additives as this may reduce the project costs due to lower costs of other additives. Same procedure was repeated for B soil to establish the binder contents for their mixtures. Samples were casted and tested in duplicates for all aforementioned binder proportions described in Tables 4.2 and 4.3 and the results are summarized in Tables 4.10 and 4.11. Figures 4.11 to 4.16 shows the typical stress-strain curves for two soils, binder types and set accelerator from UCS tests.

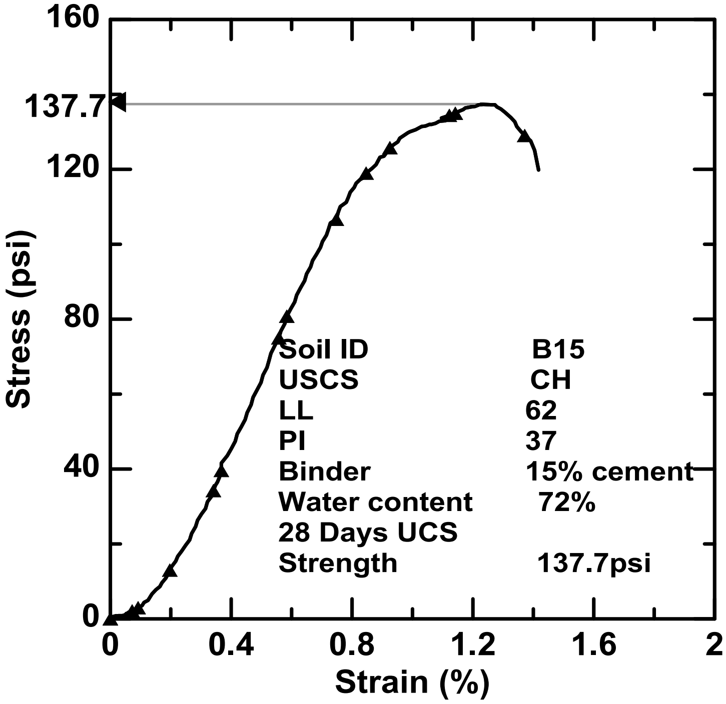


Figure 4.11Stress-Strain plots of soil A with 15% cement

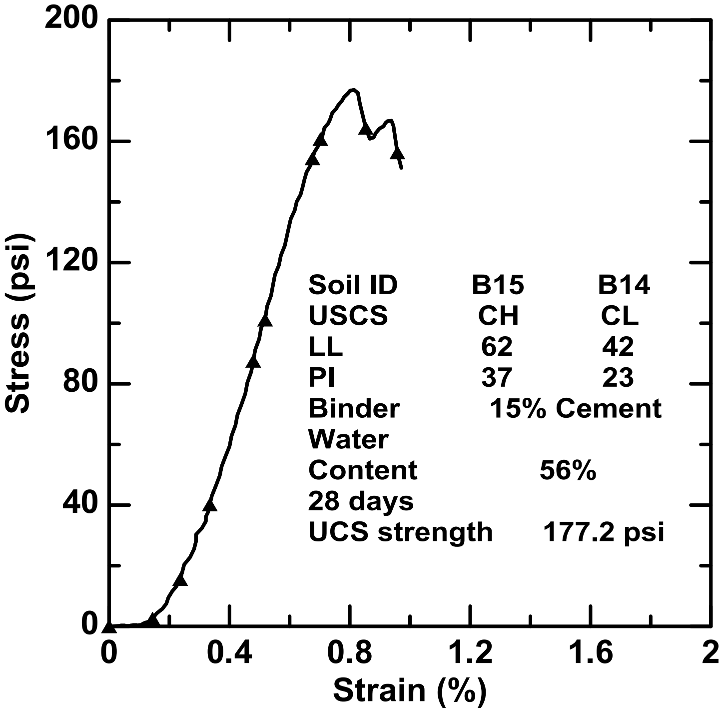


Figure 4.12 Stress-Strain plots of soil B with 15% cement

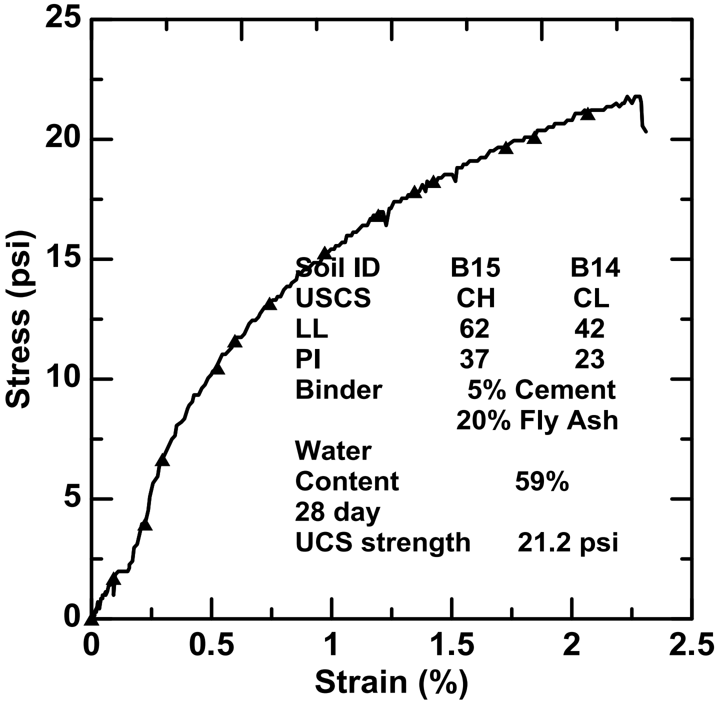


Figure 4.13 Stress-Strain plots of soil B with 5% cement and 20% fly ash

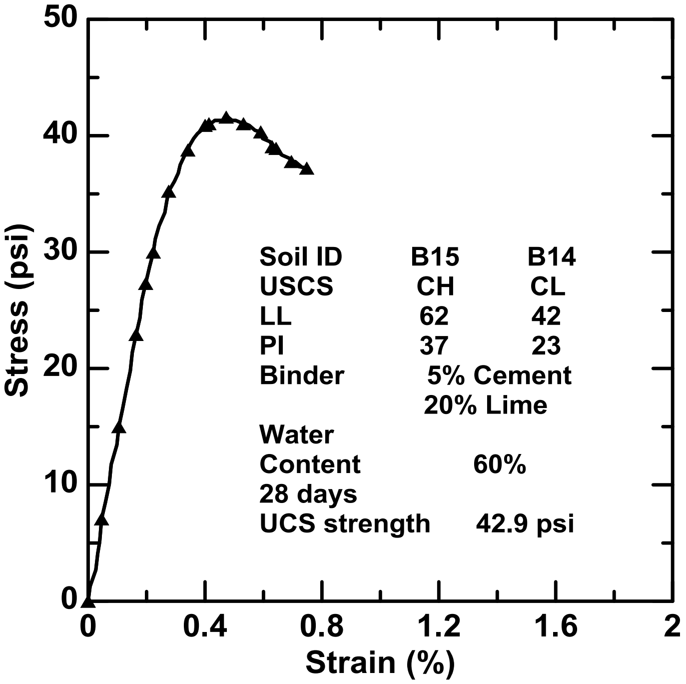


Figure 4.14 Stress-Strain plots of soil B with 5% cement and 20% lime

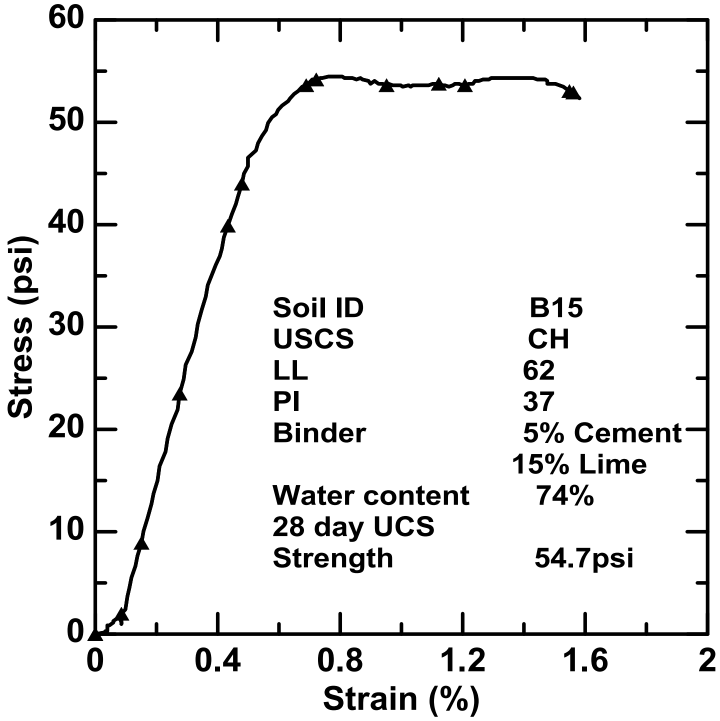


Figure 4.15 Stress-Strain plot of soil A without set accelerator

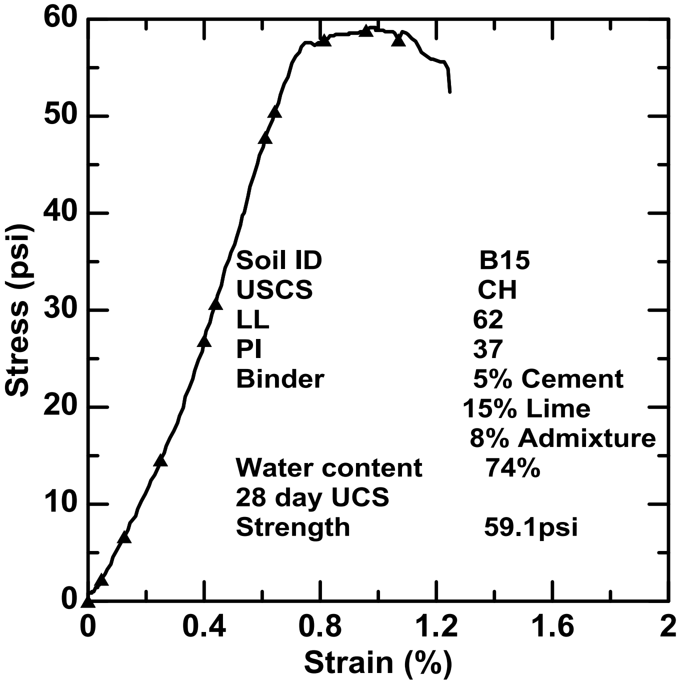


Figure 4.16 Stress-Stain plot of soil A with set accelerator

Figures show the stress strain plots of various mixes and these results indicate that a steep increase in stress with initial strain and also these samples experienced a failure known as brittle failure to semi brittle failure. Due to the presence of large number of variables in these mixes, the compressive test results cannot be compared or analyzed together. Detailed analysis is made in the following sections on the probable factors that might have contributed to the variations in test results such as binder dosage, binder proportion, binder types, and set accelerator. tests for setting time were performed after compressive strength tests, the results obtained for setting time tests did not met the requirement (less than 5 hours) so set accelerator was added to some of the mixes to lower the setting time, tests for compressive strengths with 8% set accelerator by dry weight of binder were conducted to observe the variability of compressive strength with respect to set accelerator and the results obtained are presented here though the tests were performed after the setting time tests. Compressive strength test results obtained for both the soils are shown on Tables 4.10 and 4.11.

Table 4.10 Compressive test results of CLSM mixes for soil A

Material	**Water content at the time of casting (%)**	**Compressive strength (psi)**		**Water content at the time of testing (%)**	
		7 day	**28 day**	**7 day**	**28 day**
A_C6	72	28	49	68	64
A_C10	72	39	96	64	56
A_C15	72	76	134	60	52
A_F30	72	-	-	62	56
A_L20	74	-	10	68	62
A_C5L10	74	18	68	65	54
A_C5L15	74	17	50	68	66
A_C5L20	76	17	46	65	65
A_C5F20	72	11	22	60	56
A_C10_S1	72	*	156	60	54
A_C15_S1	72	*	207	56	52
A_C5L10_S1	74	*	88	61	55
A_C5L15_S1	74	*	59	63	60

Note:"-" not ready for testing, "*" samples were not casted

Table 4.11 Compressive test results of CLSM mixes for soil B

Material	Water content at the time of casting (%)	Compressive Strength (psi)		Water content at the time of testing (%)	
		7 day	28 day	7 day	28 day
B_C6	54	39	56	46	44
B_C10	54	77	101	43	42
B_C15	54	117	178	45	42
B_F30	56	-	-	45	40
B_L20	62	-	20.8	52	51
B_C5L10	58	19	73	48	46
B_C5L15	59	28	63	52	49
B_C5L20	60	17	54	51	50
B_C5F20	59	22	24	46	44
B_C10_S1	54	*	195	41	40
B_C15_S1	54	*	170	44	42
B_C5L10_S1	58	*	85	46	45
B_C5L15_S1	59	*	84	51	50

Note:"-" unfeasible for testing, "*" samples were not casted

4.4.3.1 Effect of binder dosages

Mix proportions from soil A, A_C6, A_C10, A_C15 and from soil B, B_C6, B_C10, B_C15 are analyzed together to study the variations in compressive strengths with the same cement binder. Figures 4.17 and 4.18 illustrate that with an increase in binder content, there was an increase in unconfined compressive strengths for both the soils at both curing periods of 7 and 28 days.

However, this trend changed when test results of combined cement and lime binders are considered for both the soil proportions. When the compressive strengths of cement-lime and cement-fly ash mixes including A_C5L10, A_C5L15, A_C5L20 and B_C5L10, B_C5L15, B_C5L20 are combined and analyzed, the results showed a decrease in unconfined compression strength values with an increase in chemical binder dosages. This trend is quite opposite to the one noted in the case of cement treated CLSM mixes. This variation in trend can be attributed to larger dosages of lime added probably beyond the required dosages. Bell (1996) recommended that because lime has neither appreciable friction nor cohesion, an excess amount serves as lubricant to the soil particles and thereby decreases the unconfined compression strength. Kumar et al. (2007) attributed strength reduction to the platy shape of the unreacted lime particles. Dash et al. (2012) stated that lime produces cementitious gel that has considerable volume of pores after reacting with soil. Therefore, with increased lime content, the soil structure tends to be in porous state that affects the strength gaining nature adversely. At very high lime content, an overall decrease in strength occurs from excessive formation of this gel material.

Figures 4.19 and 4.20 show the variation of compressive strength with binder cement and lime together for both the soil proportions.

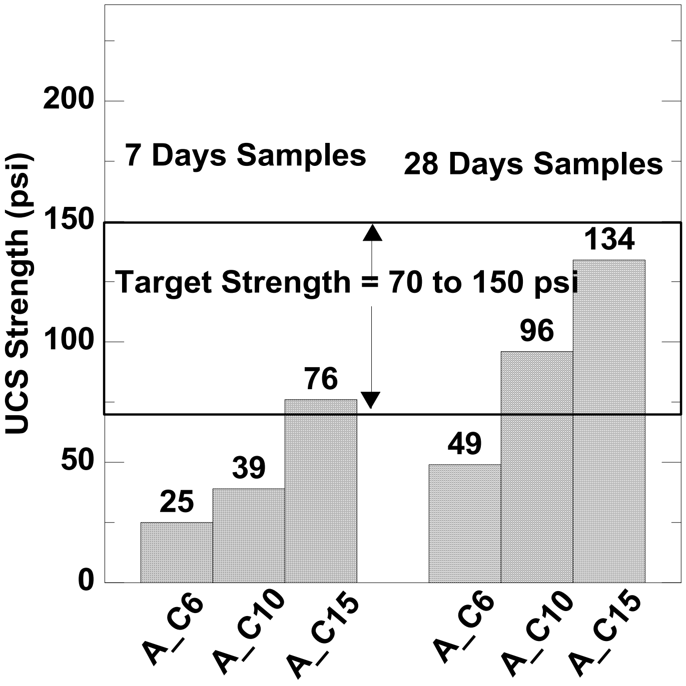


Figure 4.17 Variation of compressive strengths with respect to binder dosage for soil A

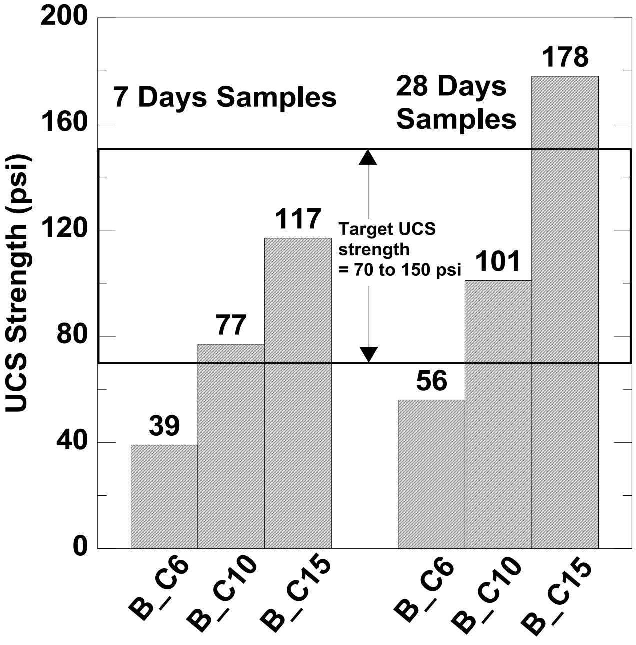


Figure 4.18 Variation of compressive strengths with respect to binder dosage for soil B

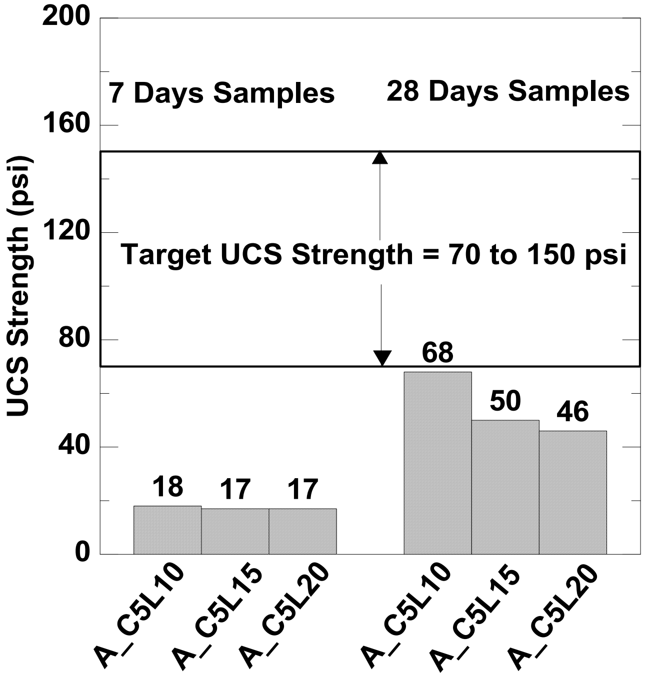


Figure 4.19 Variation of compressive strength with binder dosage for cement-lime mixes for soil A

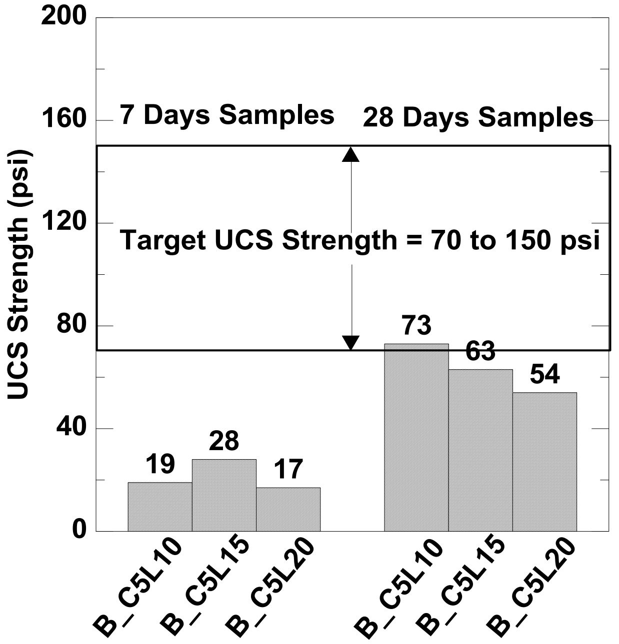


Figure 4.20 Variation of compressive strength with binder dosage for cement-lime mixes for soil B

4.4.3.2 Effect of Binder types used

To study the variations in compressive strengths based on binder types, effects of lime and fly ash admixtures are analyzed using the mixes A_C5L20, A_C5F20 from soil A and B_C5L20, B_C5F20 from soil B as these mixtures have same quantities of cement dosage, but different lime and fly ash additives. Figures 4.21 and 4.22 show that mixes with lime and cement additives have exhibited more strength than the mixes with fly ash and cement binders. This increase in strength of cement-lime mixes can be attributed to active participation of lime in pozzolanic reactions when compared to that of fly ash binder.

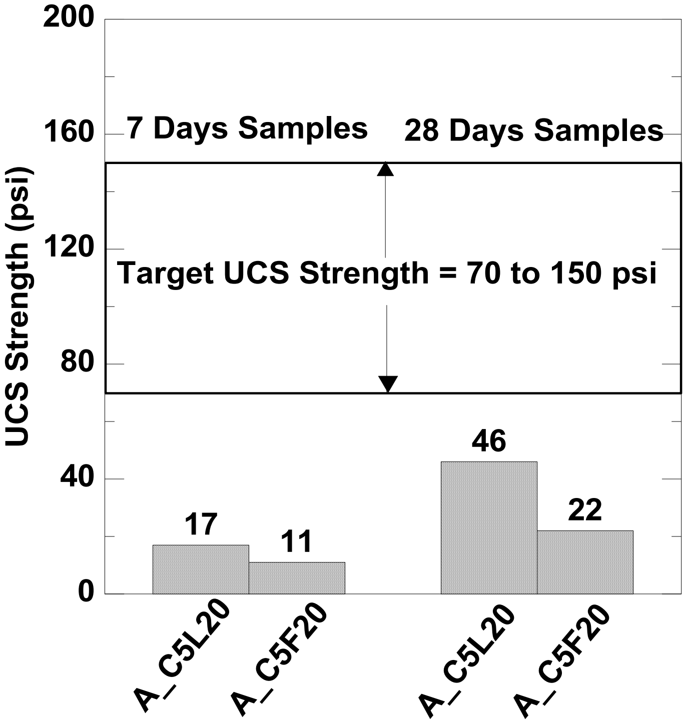


Figure 4.21 Variation of compressive strengths with binder types for soil A

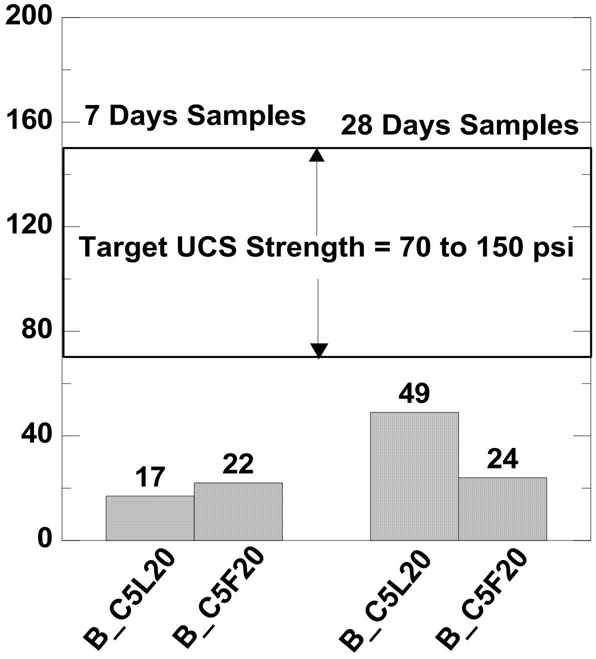


Figure 4.22 Variation of compressive strength with binder types for soil B

4.4.3.3 Effect of set accelerator

Results obtained for setting time tests did not met the requirement (less than 5 hours), so set accelerator was added to some of the mixes to lower the setting time. Tests for compressive strengths with 8% set accelerator by dry weight of binder were conducted to observe the variability of compressive strength with respect to set accelerator. Figures 4.23 and 4.24 depict the variations in compressive strength of mixes with and without set accelerator. It can be clearly noticed that the set accelerator which was used for reducing the hardening time has enhanced the strength property of the mixes. Mix proportions A_C10_S1, A_C15_S1, A_C5L10_S1, A_C5L15_S1 and B_C10_S1, B_C15_S1, B_C5L10_S1, B_C5L15L_S1 can be compared to that of same mix proportions without set accelerator to study the effect of set accelerator on compressive strength. It is believed that accelerating admixture increases the reactivity and hydration of C_3S and C_2S forming CSH (calcium silica hydrate) gel and thereby increases the rate of reaction (http://www.aximconcrete.com). This results with increased reaction of hydrates, especially at early ages.

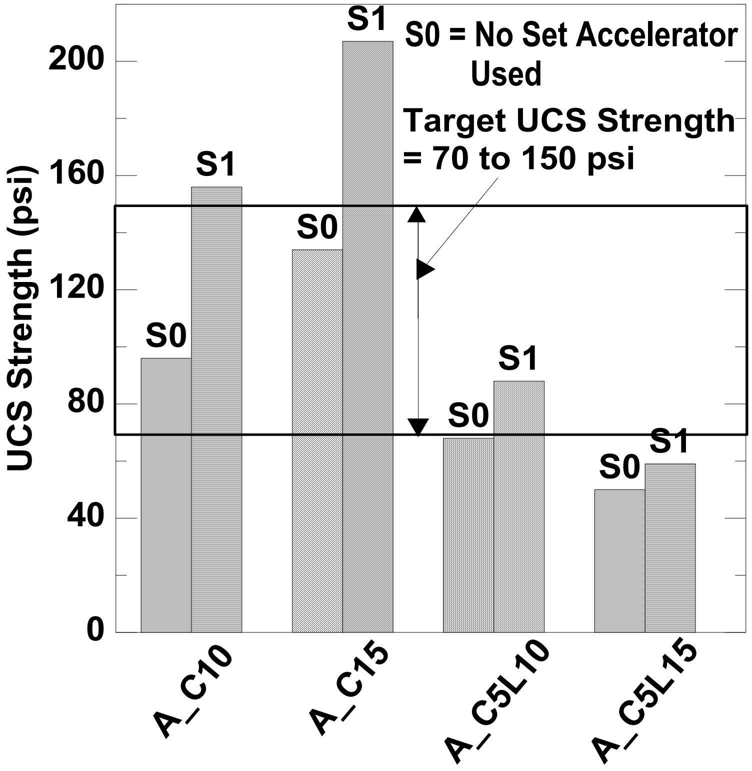


Figure 4.23 Variation of compressive strength with set accelerator for soil A

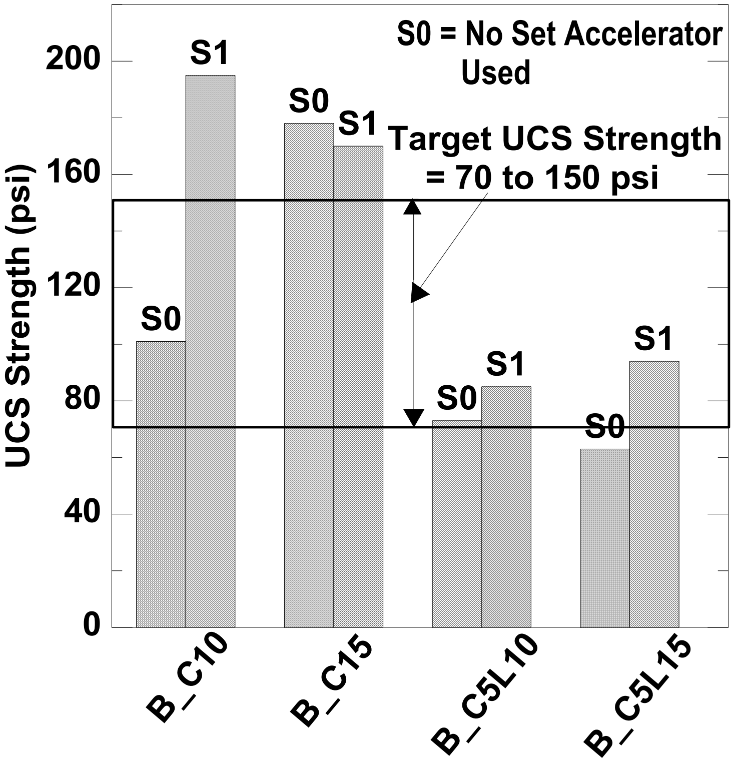


Figure 4.24 Variation of compressive strength with set accelerator for soil B

4.4.4 *Elastic Moduli of CLSM Mixes and Results*

Tables 4.12 and 4.13 shows the initial and secant modulus of all the mixes studied in this research. The initial tangent elastic modulus, E_i denotes the initial slope of the stress-strain curve whereas secant elastic modulus E_{50} denotes the slope of line between the origin and a point where the stress level is half of the peak strength on the stress-strain curve.

Table 4.12 Moduli results for soil A

Material	**UCS (psi)**	**Initial modulus (psi)**	**Secant modulus (psi)**	**E_i/UCS**	**E_{50}/UCS**
A_C6	49	3400.0	6000.0	69.4	122.4
A_C10	96	7000.0	12000.0	72.9	125.0
A_C15	134	14333.3	20000.0	107.0	149.3
A_L20	10	205.9	2000.0	20.6	200.0
A_C5L10	68	3000.0	8871.0	44.1	130.5
A_C5L15	50	2222.2	8538.6	44.4	170.8
A_C5L20	46	1671.6	5789.5	36.3	125.9
A_C5F20	22	555.6	1200.0	25.3	54.5
A_C10_S1	156	1000.0	15000.0	6.4	96.2
A_C15_S1	207	2000.0	24186.0	9.7	116.8
A_C5L10_S1	88	566.7	8800.0	6.4	100.0
A_C5L15_S1	59	5833.3	7142.9	98.9	121.1

The results of this study yielded an E_{50} value in the range of 54 to 240 time's compressive strength. In comparison, Kim et al. (2011) reported that the E_{50} of rubber-added flowable material ranges between 87 to 172 times compressive strength whereas Tang et al. (1996) found that the E_{50} of air-foam added light weight soil was about 40 to 260 times the compressive strength. This shows that the results obtained in this study are within the ranges that are expected of typical CLSMs.

Table 4.13 Moduli results for soil B

Material	UCS (psi)	Initial modulus (psi)	Secant modulus (psi)	E_i/UCS	E_{50}/UCS
B_C6	82	4000.0	7666.7	48.8	93.5
B_C10	101	7500.0	15517.2	74.3	153.6
B_C15	178	16000.0	26000.0	89.9	146.1
B_L20	20.8	3913.0	5000.0	188.1	240.4
B_C5L10	73	5000.0	12037.0	68.5	164.9
B_C5L15	63	4500.0	7000.0	71.4	111.1
B_C5L20	54	1500.0	5000.0	27.8	92.6
B_C5F20	24	2923.1	2100.0	121.8	87.5
B_C10_S1	195	10000.0	12857.1	51.3	65.9
B_C15_S1	170	23529.4	26562.5	138.4	156.3
B_C5L10_S1	85	8000.0	13125.0	94.1	154.4
B_C5L15_S1	84	5000.0	16607.1	59.5	197.7

Figures 4.25 and 4.26 show the moduli behaviors of CLSM with different cement percentage. Elastic modulus over unconfined compressive strength is taken as on ordinate where as abscissa represents the percentage of binder used in the CLSMs. It can be noted that high stiffness values are obtained at higher cement content which is expected with cement alone as the CLSM binder. Both the soils have shown the same trend irrespective of modulus considered.

Figures 4.27 and 4.28 depict the variation of stiffness behavior with lime binder. It is observed that an increase in lime percentage resulted in stiffness softening behavior of specimen. This indicates that lime is not as effective as cement when it comes to enhancing strength and stiffness properties of CLSMs. This also means that, for a given CLSM mixture used, binder types appears to be the most governing factor for the development of stiffness or moduli properties. Also, the results illustrate that mixes with cement as binder are stiffer than those with lime due to high strength capacity of cement binders.

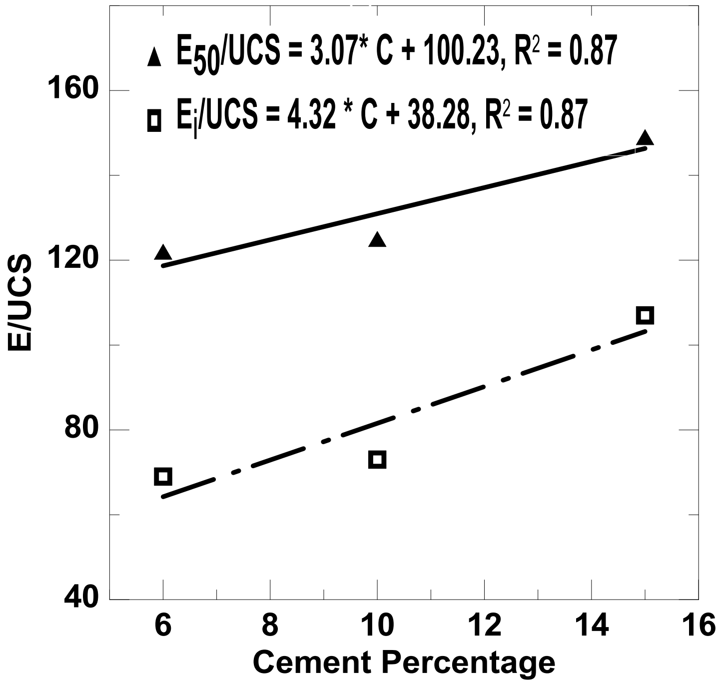


Figure 4.25 Variation of E/UCS with cement percentage for soil A

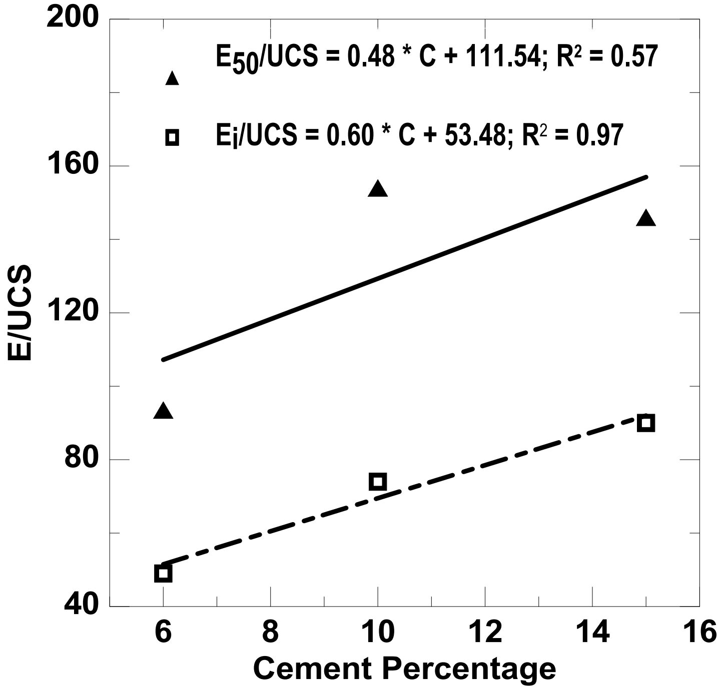


Figure 4.26 Variation of E/UCS with cement percentage for soil B

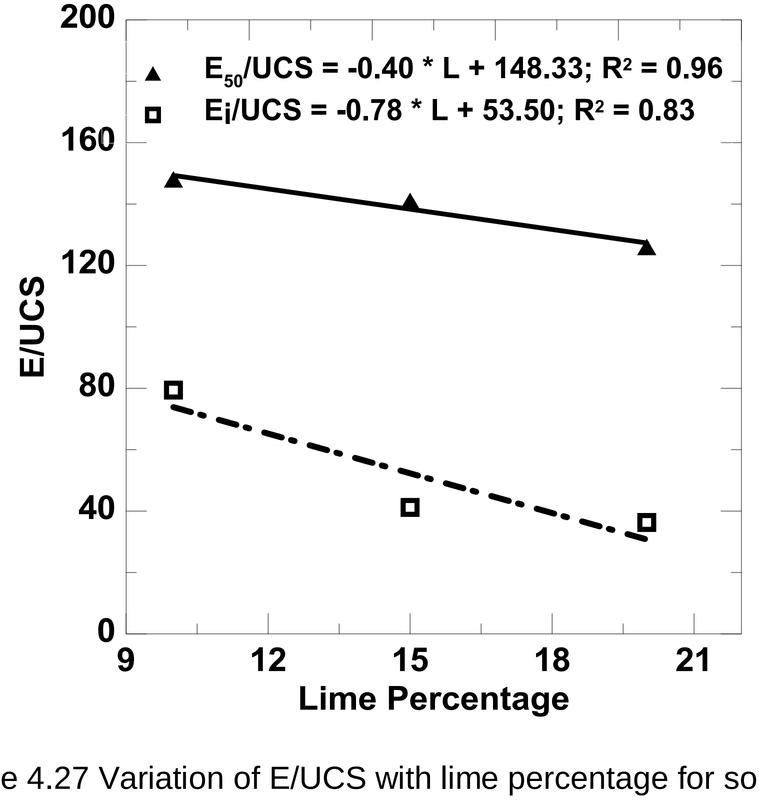


Figure 4.27 Variation of E/UCS with lime percentage for soil A

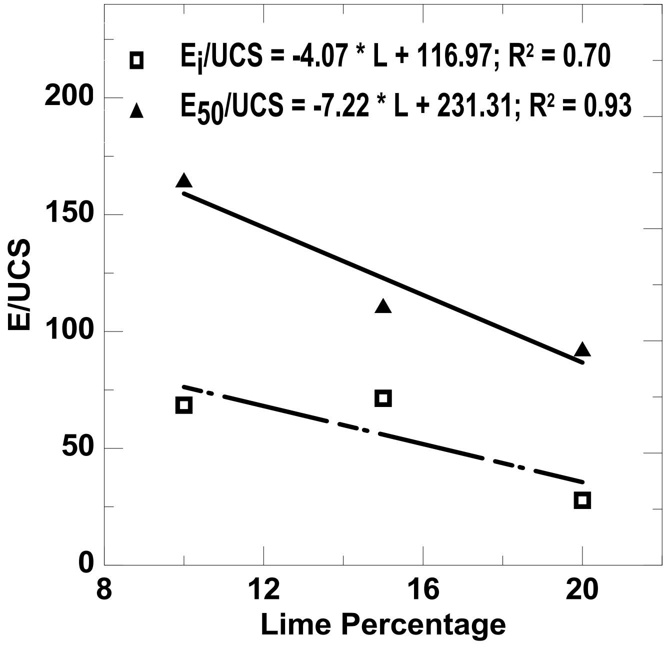


Figure 4.28 Variation of E/UCS with lime percentage for soil B

It can be observed from the figures that the coefficient of determination values obtained for the trends reported in the figures are within the acceptable range, though more mixes with different binders would have enhanced these trends and reliability in these equations. These equations provided can be used to estimate the stiffness value of the CLSM mixes and they need to be validated with select laboratory tests on the CLSM samples.

4.4.5 *Setting time*

Efforts were made in the current research to achieve the setting time of less than 5 hours as per TRWD specifications using Vicat's apparatus. ASTM C 403 procedure was followed for testing the setting time for all the mix proportions. Tests were performed on the initial mix proportions to observe the setting time without adding set accelerator. The results obtained did not meet the specification (less than 5 hours) and these are expected due to use of water content for flowability considerations. Thus setting time of less than 5 hours cannot be achieved without any chemical additives.

Table 4.14 shows the setting times of different mix proportions without any set accelerator. Mixes with the cement as binder have lower setting times as expected because of early strength gaining property of cement binder. Lime and fly ash as well as cement treatments have taken longer time periods to achieve strength hardening of the present soil mixtures.

Table 4.14 Setting time test results for all mix proportions without set accelerator

Material	**Water Content (%)**	**Settingtime(hours)**
A_C6	72	10
A_C10	72	8
A_C15	72	7
A_L20	74	>24
A_C5L10	74	28
A_C5L15	74	29
A_C5L20	76	25
A_C5F20	72	23
B_C6	54	8
B_C10	54	6
B_C15	54	5
B_L20	62	22
B_C5L10	58	18
B_C5L15	59	21
B_C5L20	60	23
B_C5F20	59	14

Set accelerators were added to some of these mix proportions whose 28 days strengths achieved the target strength values (70 to 150 psi). An initial attempt of 8% set accelerator (amount added is equivalent to the percent of dry weight of total binder amount) was added as per the recommendations of manufacturer based on the desired setting time periods. The set period used here is denoted by S1 in the notation. Test results obtained are presented in Table 4.15.

Table 4.15 Setting time results with 8% set accelerator (weight of binder)

Material	Water Content (%)	Setting time (hours)
A_C10_S1	72	8
A_C15_S1	72	7
A_C5L10L_S1	74	28
A_C5L15_S1	74	29
B_C10_S1	54	5
B_C15_S1	54	5
B_C5L10_S1	58	19
B_C5L15_S1	59	21

It can be noticed from the table that the setting times obtained with 8% set accelerator (S1) to dry weight of binder are not in desired range (less than 5 hours). Hence, a second trial of 8% set accelerator, termed as S2 was used. In this case, the amount of set accelerator was established based on dry weight of total soil content used in the mixture. The set accelerator amount was added to the predetermined soil mixes and the test results obtained on these mix samples are shown in Table. 4.16 Some of the results obtained form 2nd trail are still not below the targeted value. However, no other attempts was made because setting time may not be a major concern for CLSMs as potential relaxation of this criteria can be considered. Over utilization of the set accelerator can raise the costs incurred in the preparation of CLSMs.

Table 4.16 Setting time results with 8 % set accelerator (weight of soil)

Material	**Water Content (%)**	**Setting time (hours)**
A_C10_S2	72	5
A_C15_S2	72	4
A_C5L10_S2	74	19
A_C5L15_S2	74	21
B_C10_S2	54	4
B_C15_S2	54	4
B_C5L10_S2	58	16
B_C5L15_S2	59	18

4.4.6 *Excavatability*

The use of CLSM as a backfill material for a pipeline requires the material to be excavatable in future for repair or maintenance of pipeline. Hence, the CLSM should not develop high strength in the future. Several approaches are in practice to predict the long-term strength of CLSMs. In this research, the approach followed studied the excavatability of CLSM using the procedure developed by Hamilton County, Ohio (Hamilton County, 1996). The equation as per this procedure is given in the following:

$$\rule{3cm}{0.4pt} \qquad (2)$$

Where, RE = Removability Modulus

w = In-situ unit weight (pcf)

C = 28-day unconfined compressive strength (psi)

Some of the aforementioned mixes whose 28 day compressive strength nearer or greater than 70 psi are considered for testing the excavatability of material. Materials having the RE factor less than or equal to 1 are said to be excavatable. For ‘A ’ soil, mixes with 10% cement, 5% cement+10% lime, and 5% cement with 10% lime and 8% set accelerator are considered excavatable whereas for soil B, mixes with 5% cement with 10% lime and 5% cement with 15% lime are excavatable with and without set accelerator additive. Excavatability of the considered mixes is shown in Table 4.17.

Finally, Tables 4.18 and 4.19 shows the mixes that are recommended for field implementation and the properties obtained from the tests performed for all the mixes are grouped together. Density values are not included as all the mixes have their densities within the range specified (95 to 115 pcf).

Table 4.17 Excavatability of CLSM mixes

Material	**28 day compressive strength (psi)**	**Fresh Density (pcf)**	**RE**	**Excavatable**
A_C10	96	95	0.9	Yes
A_C15	134	98	1.2	No
A_C5L10	68	97	0.8	Yes
A_C10_S1	156	95	1.2	No
A_C15_S1	207	98	1.5	No
A_C5L10_S1	88	97	0.9	Yes
B_C10	101	104	1.1	No
B_C15	178	104	1.5	No
B_C5L10	73	104	0.9	Yes
B_C5L15	63	102	0.9	Yes
B_C10_S1	195	104	1.5	No
B_C15_S1	170	103	1.4	No
B_C5L10_S1	85	104	1.0	Yes
B_C5L15_S1	84	103	1.0	Yes

Table 4.18 Recommended CLSM mix designs without set accelerator

Sample	Flowability (in.)		Density (pcf)		UCS strength (psi)		Setting time (hrs.)		Ex	RC	RS
	Result	Within range	Result	Within range	Result	Within range	Result	Within range			
A_C6	8.3	✓	95	✓	49	X	10	X	Yes	No	
A_C10	9.50	✓	95	✓	96	✓	8	X	Yes	Yes	Setting time
A_C15	8.75	✓	98	✓	134	✓	7	X	No	No	
A_L20	9.05	✓	96	✓	10	X	>24	X	Yes	No	
A_C5L10	9.10	✓	97	✓	68	X	28	X	Yes	Yes	Setting time
A_C5L15	9.05	✓	97	✓	50	X	29	X	Yes	No	
A_C5L20	8.95	✓	97	✓	46	X	25	X	Yes	No	
A_C5F20	9.00	✓	99	✓	22	X	23	X	Yes	No	
B_C6	9.2	✓	103	✓	56	X	8	X	Yes	No	
B_C10	9.80	✓	104	✓	101	✓	6	X	No	Yes	AEA’s
B_C15	10.40	✓	104	✓	178	X	5	X	No	No	
B_L20	9.60	✓	101	✓	20.8	X	22	X	Yes	No	
B_C5L10	9.20	✓	104	✓	73	✓	18	X	Yes	Yes	Setting time
B_C5L15	8.90	✓	102	✓	63	X	21	X	Yes	No	
B_C5L20	8.60	✓	101	✓	54	X	23	X	Yes	No	
B_C5F20	9.60	✓	104	✓	24	X	14	X	Yes	No	

Table 4.19 Recommended CLSM mix designs with set accelerator

Sample	**Flowability (in.)**		**Density (pcf)**		**UCS strength (psi)**		**Setting time (hrs.)**		**Ex**	**RC**	**RS**
	Result	**Within range**	**Result**	**Within range**	**Result**	**Within range**	**Result**	**Within range**			
A_C10_S1	9.50	✓	95	✓	156	X	8	X	No	No	
A_C15_S1	9.05	✓	98	✓	207	X	7	X	No	No	
A_C5L10_S1	8.70	✓	97	✓	88	✓	28	X	Yes	Yes	Setting time
A_C5L15_S1	8.75	✓	97	✓	59	X	29	X	Yes	No	
B_C10_S1	9.70	✓	104	✓	195	X	5	✓	No	No	
B_C15_S1	10.00	✓	103	✓	170	X	5	✓	No	No	
B_C5L10_S1	9.05	✓	104	✓	85	✓	19	X	Yes	Yes	Setting time
B_C5L15_S1	8.80	✓	103	✓	84	✓	21	X	Yes	No	

Note: AEA's-Decrease the density of mix by using Air Entraining Admixture (AEA's are chemical admixtures used to decrease density); Ex- Excavatable as per Hamilton County, 1996 empirical relation; RC- Recommended; RS- Recommended with corresponding Reservation

4.5 Recommended CLSMs and Summary

This section presents a summary of the experimental results of designed mix proportions that were tested in the laboratory. Water content required for flowability was first established. Setting times required for all the mixes were later established. CLSM mix proportions that satisfy all the requirements are then considered based on the experimental test results. The mix proportions A_C10, A_C5L10 and A_C5L10_S1 achieved the minimum target compressive strength of 70 psi can be implemented in the field provided setting time is not a major concern as these mixes did not meet the set time criteria. Excavatability will be an issue for the mixes, A_C10_S1, A_C15_S1 if set accelerator is used as they cannot be excavated in future as per the empirical relation proposed by Hamilton County, 1996.

When soil B is considered, mix B_C10 is recommended with setting time as limitation by reducing the density using Air Entraining Admixture as the removability modulus is closer to 1. Mixes, B_C5L10, B_C5L10_S1 can be implemented in the field as they achieved the required compressive strength with setting time as limitation and their excavatability modulus is less than 1. Field evaluation should be done on all the mixes whose strengths are greater than the minimum target strength as it is difficult to establish excavatability issues with the laboratory tests.

CHAPTER 5

SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

5.1 Introduction

Two soils which are predominantly clayey were selected to evaluate their use as fine aggregates in CLSM. Efforts were made to reduce the usage of cement to make the mix designs more cost effective by varying binder types and binder proportions. Finally, six mix designs are selected from different trails whose properties met most of the specifications made by TRWD. However, field evaluation has to be done on these mixes to assess the excavatability as it is hard to predict it based on laboratory testing. Overall this research is successful in the developing mix design for CLSM using native soil as a fine aggregate material.

This chapter presents the summary of test results and the conclusions drawn from the analysis of chapter 4. Recommendations for further research are also provided in this chapter.

5.2 Summary and Conclusions

The summary of the results and conclusions derived from this research are summarized as follows.

- Water quantities required for flowability for all the proposed mixes is established by the ASTM standard method, D 6103-97 and the results proven that CLSM starts flowing when the moisture content is around the liquid limit of the fine aggregate component of the CLSM, indicating the flowability of the CLSM is dependent on the moisture properties of the fine material component.
- Water content required for flowability was reduced by 22% when B14 soil was added to the mixture as B14 soil which is CL has a lower liquid limit value than the primary soil which is CH.
- The density results of the proposed mixes are within the range specified by the Tarrant Regional Water District (TRWD) of 95 to 115 pcf.
- Set accelerator used for lowering the setting time had some impact on the flowability of the material. The variations in results were minimal because of the smaller time lapse for flowability test. Flowability of the material was affected by binder types as mixes with cement have higher flow diameters when compared to those of lime based mixtures.
- The specification followed in the present experimental design requires a 28 day minimum strength of 70 psi and a maximum strength of 150 psi for controlled low strength material. The average 28 day compressive strength results obtained for mix proportions including A_C10, A_C15,

A_C5L10_S1, B_C10, B_C5L10, B_C5L10_S1 and B_C5L15_S1 have met this requirement.

- Increase in cement content resulted increase in compressive strength whereas lime content addition has resulted in a decrease of overall strength of the material. This can be attributed to excessive dosage of lime beyond the required for the reactions as excessive lime results in formation of cementitious gel that has considerable volume of pores after reacting with soil and also excess amount serves as lubricant to the soil particles and thereby decreases the strength (Bell, 1996). Best results are observed when 5% cement with 10% lime are used in combination.
- Increase in cement content enhances the stiffness behavior of the material prepared while increase in lime content resulted in a decrease in stiffness of the material. This shows the less hardening behavior of lime when compared to higher hardening of cement binder.
- Set accelerator used to lower the setting time enhanced the strengths of A_C10_S1, A_C15_S1, B_C10_S1 and B_C15_S1 mixes, thus making them unexcavatable in future as per Hamilton County, 1996 empirical relation.
- Higher amounts of set accelerator are needed to lower the hardening time because of the presence of high water content in the mix.

5.3 Recommendations for Future Research

1. Durability tests and analysis needs to be conducted on the proposed mixes to determine the loss of strength with time.
2. Field evaluations have to be made to analyze the excavatability of the material for future repairs as it is hard to estimate the excavatability of the material based on laboratory testing.
3. Cost analysis has to be made to determine the most economical design of all the proposed mixes.
4. Chemical additives other than set accelerator such as air entraining agents which lowers the required water content should to be tried to meet the target setting time.

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