Strength Assessment of Soil Cement

by

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Abstract

Soil cement is a mixture of soil, portland cement and water that, once compacted and cured, forms a strong and durable pavement base. Construction practices and variance among core strength data have led to questions concerning proper quality control practices and testing protocol regarding soil cement. One of the main difficulties in soil-cement base construction is the strength assessment of the fully cured soil-cement base roadbed, which leads to the following questions: is it possible to approach strength testing of soil cement like conventional concrete, and is it plausible to use field-molded samples as control samples to evaluate the strength of soil-cement base?

In order to answer these questions, a field and laboratory testing program was developed to evaluate the effects of curing, capping, and length-to-diameter ratio on compressive strength of soil-cement cylinders. A draft test procedure was developed to prepare and test cylinders molded in the field or laboratory. The results from this research are aimed at providing guidance to transportation agencies when specifying strength assessment parameters for soil-cement base.

Based upon the findings of this research study, it is recommended that soil-cement cylinders made in a manner compliant to the proposed draft specification be considered for quality assurance for the strength assessment of soil cement as delivered to the construction site.

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Chapter 1

Introduction

1.1 Background

Soil cement is a mixture of native soils and/or manufactured aggregates with measured amounts of portland cement and water that hardens after compaction and curing to form a strong, durable, frost-resistant paving material (Halsted, Luhr, and Adaska 2006). Soil cement is often used as base where soil stabilization is required for paving purposes. By mixing portland cement with weak soils, the cement-bound, granular materials become more suitable for sub-bases and provide an increased capacity for loadbearing applications as shown in Figure 1.1.

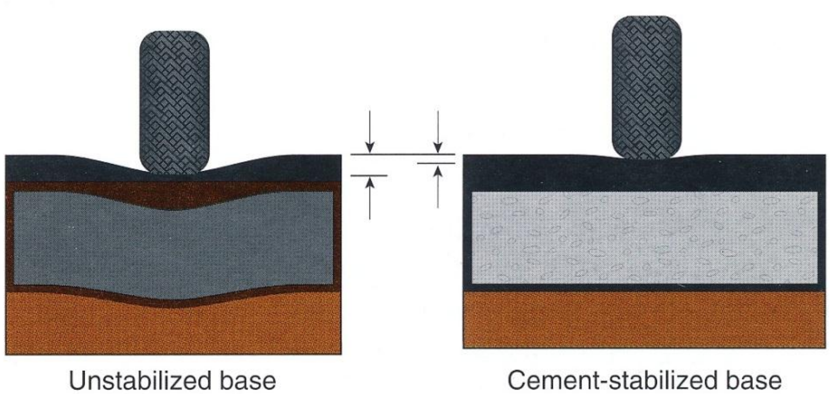

Figure 1.1: Unstabilized Granular Base versus Soil Cement Base (Halsted et al. 2006)

A common use of soil-cement base is as a foundation layer underlying bituminous and concrete pavements. Soil cement is routinely used in circumstances where the native soils are weak and incapable of carrying traffic loads. Most soils can be used for soil-cement production;

however, organic soils, highly plastic clays, soils with medium to high levels of sulfates, and sandy soils that react poorly with cement should not be used. Granular soils are the most common type of soil used for soil cement production. Silty sands, processed or manufactured sands and gravels, along with crushed stone are types of soil typically used in soil cement stabilization (ACI 230 2009).

Soil-cement base can be mixed in place using on-site materials or mixed in a central plant using local or borrow material. Mixed-in-place soil cement base utilizes rubblization techniques that recycle existing roadway materials and blends them with the proper amount of cement that has been applied over the existing, rubblized roadbed. The cement, soil material (rubblized roadbed), and the required amount of water are mixed thoroughly by a pulverizing, mixing machine. The mixture is then compacted to required density specifications to obtain maximum performance.

Central mixing plants are used where borrow material is available. The mixing plant may consist of a continuous flow or batch-type plant. Pug-mill mixers are often used as central mixing plants and an example of this type of plant is shown in Figure 1.2. The soil-cement mixture is delivered to the jobsite and placed on the existing subgrade. The mixture is then compacted to the required density to obtain maximum performance. Compaction and curing procedures are the same for central-plant and mixed-in-place procedures.

Figure 1.2: Typical central mixing plant for soil cement (Halsted et al. 2006)

The final step of soil-cement base construction is curing. The curing of soil-cement base requires the placement of a waterproof coating such as bituminous prime (cutback) or latex-based curing compounds to the surface of the newly compacted roadbed. This provides a membrane that will seal the surface of the roadbed and help to prevent moisture loss through evaporation, allowing better strength development through the hydration of the cement.

A hot-mix, bituminous wearing surface is usually placed over soil-cement base for flexible pavement applications. When used under concrete pavements, soil-cement base will improve support between the concrete pavement and subgrade layers, improve load transfer at joints, and prevent pumping of fine-grained subgrades during wet conditions and heavy truck traffic (ACI 230 2009).

Other advantages of soil-cement base include (Halsted et al. 2006)

- providing a stiffer and stronger base than an unbound granular base, delaying the onset of surface distresses such as fatigue cracking,
- soil-cement base requires less thickness than a granular base due to the strong uniform support provided by the slab-like characteristics and beam strength that are unmatched by granular bases that can fail when aggregate interlock is lost,
- The wide variety of in-situ soils and manufactured aggregates that can be used with soil-cement base, eliminating the need for hauling select materials,
- Reduction of rutting due to the resistance of consolidation and movement of the soil-cement base layer,
- Increased moisture resistance keeps water out and maintains strength when wet, reducing potential for pumping of subgrade soils,
- Resistance to damage from freeze/thaw cycles, and
- Continued strength gain as it ages.

Although the advantages of soil cement are many, construction practices and variance among core strength data have led to questions concerning proper quality control practices and testing protocol. One of the main difficulties in soil cement base construction is the strength assessment of the fully cured soil cement roadbed. Concerns related to the ability to assess the strength of a soil-cement base roadbed have led many to question the quality control methods and coring techniques used in soil-cement base construction.

In most cases, the soil cement roadbed is allowed to cure for at least seven days before placement of the top layer of roadway. Cores are wet cut on day six and delivered to the testing laboratory for final curing and a seven-day compressive strength assessment. The seven-day strength value of the cores determines the pay, if any penalties are applied, or if the section should be removed and replaced. Currently, the Alabama Department of Transportation requires soil cement strengths of 250 psi to 600 psi for seven-day compressive strength values. Compressive strengths that fall outside this strength window will warrant price reductions or removal (ALDOT 2012). Low strengths do not provide adequate support for traffic, and high strengths could lead to reflective cracking in hot-mix applications from shrinkage cracking as a result of higher cement contents. Core strength variability has led to concerns regarding moisture levels of the cores at the time of testing. ALDOT 419 (2008) states that "coring shall be done dry. If the extraction of the core samples cannot be performed dry, a minimum amount of water at a low flow shall be allowed." Cores are then sealed in plastic bags to minimize moisture loss. If water was used during the coring operation, the cores samples shall be allowed to air dry in the shade for 30 minutes before placement in a plastic bag. Upon arrival to the testing laboratory, the core sample is removed from the plastic bag and the bottom surface of the sample is dry sawn, if possible, to remove any irregularities from the surface and to also create a square surface for testing. Both ends of the core sample are capped using sulfur mortar and then the core is allowed to reach a constant mass before strength testing is performed. The correction factor from AASHTO T 22 (2010) is applied to the compressive strength results if the specimen length-to-diameter ratio is less than 1.75.

Results from an ALDOT project on U.S. 84 have shown high variability in core strength values, and an increased concern of the use of this testing protocol as a pay item for this low-strength material. Initially, design strengths for proposed mix designs were based on achieving a seven-day compressive strength of 325 psi. Variability in the field lead to difficulty in meeting all the parameters of the soil cement specification and therefore the specification was modified to increase the target seven-day compressive strength requirement to 450 psi. Seven-day compressive strengths of cores taken from a test strip were considered low and potentially suspect. Additional cores were cut next to the existing core locations on day eight and tested the following day. These compressive strength results are shown in Table 1.1. Typical core holes in soil-cement base can be seen in Figure 1.3. It should be noted that the seven-day cores were tested with no sulfur capping compound used, whereas the nine-day cores were tested with sulfur capping compound.

Table 1.1: Compressive strengths of cores from US-84 project

Compressive Strengths of Cores from US-84 Project	
Testing Age	**Compressive Strength, psi**
7 day	180, 210, 200, 210
9 day	990, 740

Figure 1.3: Core holes in soil-cement base

These variances in core strength assessment have led to the following questions concerning proper quality control practices and testing protocol:

- How should cores be conditioned after removal until testing?
- Should the cores be surface dry at the time of testing?
- Should the cores be capped prior to testing?
- Does the length to diameter ratio (L/D) correction factor need to be applied to soil-cement base cores?
- Is the use of cores to assess the strength of the low strength material appropriate?

In the attempt to answer these questions, the approach taken in this research is to emulate portland cement concrete field practices for strength assessment. ASTM D 1633 (2007), *Standard Test Methods for Compressive Strength of Molded Soil-Cement Cylinders,* recommends the option of using a length to diameter correction factor taken from ASTM C 42, *Standard Test Method for Obtaining and Testing Drilled Cores and Sawed Beams of Concrete*. This method is based upon concrete research, but is considered applicable for use in soil-cement testing. It is therefore reasonable to discuss some of the important aspects of portland cement concrete with regards to the strength assessment of soil-cement.

Conventional concrete practices require making test cylinders at the jobsite with the delivered material and use these cylinder strength values as a check for the strength of the product before placement. It should be noted that payment and acceptance for conventional concrete are based on molded cylinders made from the concrete delivered to the jobsite. If the strength of the cylinders is within specified tolerances, the material is considered to satisfy specification requirements. In-place strength is only assessed when there are low strength values obtained from the cylinders. By applying this approach to soil-cement base, field-molded samples could be used as control samples to evaluate the strength of the material brought to the jobsite location.

ASTM D 1632 (2007), *Standard Practice for Making and Curing Soil-Cement Compression and Flexure Test Specimens in the Laboratory*, was chosen as a basis for making soil-cement cylinders for compressive strength testing in the field. This specification can be used in accordance with Method B of ASTM D 1633 (2007), which requires a test specimen 2.8 in. in diameter and 5.6 in. in height and gives a length-to-diameter ratio of 2.00.

1.2 Research Objectives

This project was undertaken to address concerns about the methodology of strength assessment of soil cement base. Is it possible to approach strength testing of soil cement base like conventional concrete? Payment and acceptance for conventional concrete is based on molded cylinders made from the concrete delivered to the jobsite. In-place strength is only assessed when cylinder strengths are low. This approach checks the strength of the concrete delivered to the jobsite and not the in-place strength of the placed soil cement. Is it plausible to use field-molded samples as control samples to evaluate the strength of soil cement base? The primary objectives of this research were to

- Establish a test procedure to prepare and test soil cement cylinders molded in the field by using techniques similar to ASTM D 1632 (2007),
- Evaluate the pre-conditioning impact of curing on the seven-day compressive strength of molded cylinders,

- Select a suitable curing method for the strength assessment of molded cylinders,
- Evaluate the effects of gypsum capping compound on the compressive strength of molded cylinders,
- Determine the effect of varying L/D ratios on the compressive strength of molded cylinders, and
- Recommend the testing protocol that the Alabama Department of Transportation (ALDOT) should implement to assess the strength of soil cement.

1.3 Research Approach

ASTM D 1632 (2007) was used as a basis for preparing soil-cement cylinders in the field and laboratory. Unresolved issues regarding field-molded cylinders include initial curing of the specimen in the mold along with sealing the molds during initial curing to prevent unwanted and random moisture loss through the ends of the molds. Plugs were milled from 3 in. diameter ultra-high-molecular weight (UHMW) polyethylene rods and used for plugging the top and bottom portions of the cylinder mold. An initial curing time in which the specimens would be allowed to cure undisturbed in the sealed mold was chosen to be not less than 12 hours from completion of specimen preparation. Specimens were placed in the moist-curing room upon removal from the molds until time of testing.

Once the initial curing time in the molds and the method to seal the molds during initial curing was determined, a study of curing pre-conditioning impact on molded cylinders was performed. This study included three laboratory mixtures with 2 batches each using one soil type and three cement contents. The effects of moist curing, bag curing, fan curing and air curing were determined by seven-day compressive strength testing.

Following the pre-conditioning impact study, a suitable curing method for the molded cylinders was evaluated. Six laboratory mixtures with 2 batches each using two different soil sources and three different cement contents were prepared and tested to determine a suitable curing method after initial curing and removal from the molds. Specimens were tested in compression at seven days. On day six of the curing time, half of the specimens were removed from the moist-curing room and individually placed into plastic bags for further curing. A comparison of moist-cured and bag-cured samples was obtained.

Next, a suitable capping method was evaluated. Neoprene and gypsum plaster were evaluated for use as capping methods along with no capping for compression testing of the cylinders. Three field projects were evaluated with three laboratory mixtures with three batches each using three cement contents to determine the best capping method for the molded cylinders.

The effect of using length-to-diameter strength correction factors was determined by the evaluation of twelve laboratory mixtures using two different soil sources and three different cement contents. Length-to-diameter ratios (L/D) of 2.0, 1.75, 1.5, 1.25 and 1.0 were used to evaluate the effect on seven-day compressive strengths of the specimens.

Finally, a test procedure was developed to prepare and test molded, soil cement cylinders. Based on the findings of this research, a strength testing method was prepared for the use of molded cylinders as a pay item for soil cement delivered to the paver at the jobsite.

1.4 Report Outline

An overview of previous research and literature concerning all aspects of this research project is summarized in Chapter 2 of this report. First, materials and mixture proportions of soil cement are discussed. Secondly, the performance and construction of soil cement base is evaluated. Finally, testing concerns related to this research are reviewed.

The experimental plan developed for this research project is documented in Chapter 3. A detailed description of the experimental testing procedures and apparatus is presented. Sample preparation and curing methods are introduced. The soil cement mixtures used are described and their mixture proportions are defined.

The results of the experimental plan are presented in Chapter 4. Results from the pre-conditioning impact study, the suitable curing study, the capping study, and the L/D ratio study are presented and discussed in detail.

The implementation guidelines for a draft ALDOT procedure are discussed in Chapter 5. The objectives of this chapter are to recommend the testing protocol that ALDOT should implement to assess strength variability in soil cement base, and outline a proposed ALDOT procedure for making and curing soil-cement compression test specimens in the field.

All conclusions and recommendations derived from the research performed in this study are summarized in Chapter 6.

Appendices A through F follow Chapter 6. Appendix A contains design curves and gradations for all the mixtures used in the research testing. Appendix B through E contain individual compressive strength test results for the pre-conditioning impact study, the suitable curing study, the capping study and the L/D ratio study, respectively. A draft of a proposed ALDOT procedure is located in Appendix F. Finally, temperature and humidity profiles for the moist-curing room and environmental chamber are presented in Appendix G.

Chapter 2

Literature Review

2.1 Introduction

In this chapter, technical information relating to the properties and performance of soil-cement base are described as well as conventional portland cement concrete practices with the potential for assimilation in soil-cement base strength assessment. In this chapter, the materials and mixture proportions of soil-cement base are discussed. Soil cement properties are presented. Testing concerns related to comparison of soil cement with conventional concrete are discussed. Finally, construction of soil-cement base is discussed.

2.2 Materials and Mixture Proportions of Soil-Cement Base

2.2.1 Soil

Soil is defined as the relatively loose agglomerate of mineral and organic materials and sediments found above the bedrock (Holtz and Kovacs 1981). Previous research by Robbins and Mueller (1960) showed that acidic, organic material usually had an adverse effect on the performance of soil cement. The study showed that sandy soils with more than 2 percent organic content or a pH lower than 5.3 will likely react abnormally with cement. Generally, soil types used for soil-cement base construction include silty sand, processed crushed or uncrushed sand and gravel, and crushed stone (ACI 230 2009).

2.2.1.1 Particle Size

Coarse-grained soils, such as sands and gravels are the recommended choice for soil-cement base construction (PCA 1995). Granular soils are the best candidate for use in soil-cement base due to their ability to pulverize well and mix more easily than fine grained soils. Granular soils are also more economical due to the lesser amounts of cement necessary to provide adequate strength (ACI 230 2009). Fine-grained soils such as fine sands, silts and clays are considered unacceptable for use since higher clay contents require higher cement contents (PCA 1995). Fine-grained soils typically require more cement for particle encompassing and sufficient hardening.   Clays are often more difficult to pulverize for adequate mixing (ACI 230 2009). Typically, finer soils tend to have higher optimum moisture content values. Additionally, finer soils also require higher cement contents. Soils which have high moisture demands also require more cement, making them more prone to drying shrinkage issues (Kuhlman 1994). An increase in the amount of coarse-grained particles will reduce the amount of cement required due to the replacement of the finer particles, which need the additional cement to bind them together. However, too much coarse materials will create voids in the mixture that will not allow the finer particles of soil and cement to bond together and provide structural integrity in the mixture. The fine particles of soil are necessary to provide the structural, cemented bond that holds the larger particles in place (PCA 1995).

Soils that contain between 5 and 35 percent fines passing a No. 200 sieve have been shown to produce successful soil-cement base. Soils which have higher amounts of clay and silt have a tendency to form clay balls, which have difficulty in breaking down during normal mixing procedures. Clay balls are usually formed when the plasticity index is 8 or greater. The presence of clay balls in soil-cement base applications usually does not hinder performance of the base or the pavement (ACI 230 2009). Figure 2.1 shows the specified gradation band recommended by PCA to minimize cement contents. This aggregate gradation band provides the desired range of particle size distribution that will allow for the minimum amount of cement necessary to provide a substantial base material. Gradations that fall outside this range could possibly require more cement due to the material being too fine of particle size or the material may be too coarse to provide the structural interlock necessary to provide strength.

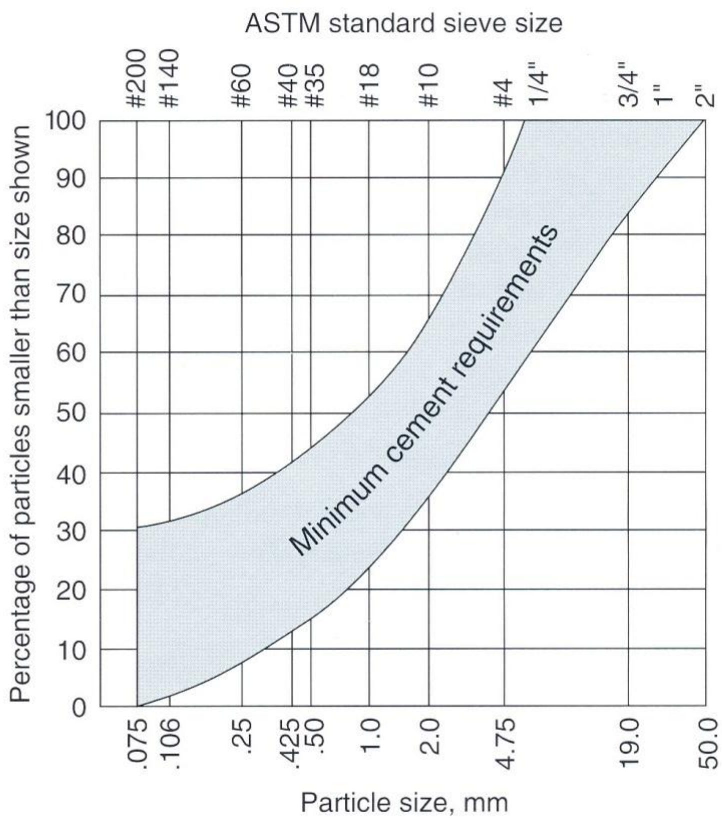

Figure 2.1: Aggregate gradation band for minimum cement content (Halsted et al. 2006)

Gradation requirements are not as confining as for portland cement concrete. ACI 230 (2009) recommends the maximum nominal size aggregate to be limited to 2 in. with at least 55 percent passing the No. 4 sieve. PCA recommends a well-graded material with a nominal maximum aggregate size of less than 3 inches.

2.2.1.2 Density of Soil

Soil-cement base is compacted to a dense state in order to improve its engineering properties. Laboratory compaction tests are used to determine the percent compaction and water content necessary to obtain the desired engineering properties. These tests are also used for quality control measures during construction (ASTM D 698 2007). A series of test specimens are compacted at selected water contents, and the resulting dry unit weights are calculated. Once the relationship between the dry unit weight and the water contents has been established, the resulting data are plotted in a curvilinear relationship known as the compaction curve, as defined by ASTM D 698 (2007). The optimum water content and maximum dry unit weight are determined from the compaction curve.

2.2.2 Portland Cement

Generally, Type I or Type II portland cement conforming to ASTM C 150 is used for soil-cement base production; however, other cementitious materials such as fly ash, slag cement, and hydrated lime have been successful in soil-cement base applications. The amount of cement used is dependent upon the type of soil and the desired properties of the soil-cement base. Cement contents can range from as low as 4 to a high of 16 percent by dry weight of soil. Cement contents above 8 percent may create increased shrinkage, potentially resulting in reflective cracking (Halsted et al., 2006). As stated previously, the cement content will increase with the amount of clay in the soil. Typical cement requirements for various soil types are summarized in Table 2.1. It should be noted that the cement ranges shown in Table 2.1 are not mix-design recommendations, but initial estimates for mix-proportioning procedures (ACI 230 2009).

Table 2.1: Typical cement requirements for various soil types* (ACI 230 2009)

AASHTO soil classification	ASTM soil classification	Typical range of cement requirement,* percent by weight	Typical cement content for moisture-density test (ASTM D558), percent by weight	Typical cement contents for durability tests (ASTM D559 and D560), percent by weight
A-1-a	GW, GP, GM, SW, SP, SM	3 to 5	5	3-5-7
A-1-b	GM, GP, SM, SP	5 to 8	6	4-6-8
A-2	GM, GC, SM, SC	5 to 9	7	5-7-9
A-3	SP	7 to 11	9	7-9-11
A-4	CL, ML	7 to 12	10	8-10-12
A-5	ML, MH, CH	8 to 13	10	8-10-12
A-6	CL, CH	9 to 15	12	10-12-14
A-7	MH, CH	10 to 16	13	11-13-15

*Does not include organic or poorly reacting soils. Also, additional cement may be required for severe exposure conditions such as slope protection.

2.2.3 Water

Water is necessary in soil-cement base in order to achieve maximum compaction through optimum moisture content and for hydration of the portland cement. Moisture contents of soil-cement base usually fall in the range of 5 to 13 percent by weight of oven-dry soil cement (ACI 230 2009). Halsted et al. (2006) recommends that "Water shall be free from substances deleterious to the hardening of the CTB material." ASTM D 1632 (2007) suggests that "The mixing water shall be free of acids, alkalies, and oils, and in general suitable for drinking." ACI 230 (2009) states that potable water free from alkalies, acids, or organic matter, along with seawater may be used. The presence of chlorides in seawater may also increase early strengths (ACI 230 2009). ALDOT (2012) recommends in Section 807 that water should be free of any substance detrimental to the work and total organic solids should be less than 2 percent. Water from city water supplies is generally accepted.

2.2.4 Mixture Proportioning

The primary function of soil-cement base is to provide the necessary strength and durability required to structurally support the HMA or concrete pavement. Proper mixture proportioning allows the adequate strength to be obtained while also maintaining an economical product. Mixture proportions are developed in many different methods by various DOTs and contractors, with compressive strength being a key variable in determining cement content. A suitable design can be obtained with a sieve analysis, a moisture-density test, and a compressive strength test for initial mixture proportioning (PCA 1992). The following ASTM test standards are critical to mixture proportioning

- ASTM D 558 Test for Moisture-Density Relations of Soil-Cement Mixtures,
- ASTM D 1632 Making and Curing Soil-Cement Compression and Flexure Test Specimens in the Laboratory, and
- ASTM D 1633 Test for Compression Strength of Molded Soil-Cement Cylinders.

Typically, mixture proportioning requires test specimens to be molded at three different cement contents while maintaining optimum moisture content from an initial moisture-density test. Compressive strength tests of the three different cement contents are performed at 7 days to provide a range of strength data to determine the required cement content to reach the required 7-day design strength. The end result is to have a “balanced design”, where there is enough cement to provide a strong and durable base, while not reaching strengths high enough to create distresses in the pavements.

2.3 Soil Cement Properties

Soil cement properties can be influenced by several factors, including

- Density,
- Compressive strength,
- Shrinkage and Reflective Cracking, and
- Structural Design.

The following information will show how these and other factors affect soil-cement base properties.

2.3.1 Density

ASTM D 558 (2004) is used to determine maximum dry density and optimum moisture content for soil-cement mixtures. A typical moisture-density curve is shown in Figure 2.2.

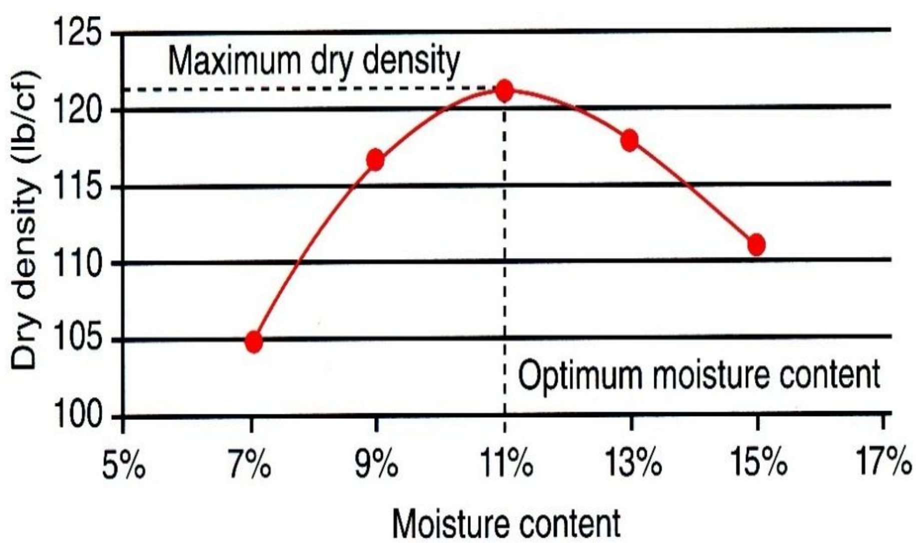

Figure 2.2: Maximum Dry Density and Optimum Moisture Content (Halsted et al. 2006)

It should be noted that the addition of cement to a soil will generally cause some change in both the optimum moisture content and maximum dry density for a given compactive effort. The high specific gravity of the cement relative to the soil tends to produce a higher density, whereas the cement's demand for water for hydration tends to increase the optimum moisture content (ACI 230 2009). Previous research by West (1959) showed the prolonged delays between the mixing of soil cement and compaction have an influence on both density and strength. West (1959) showed that a significant decrease in both density and compressive strength occurs when there is a delay of more than 2 hours between mixing and compaction.

Figure 2.3 indicates the decrease in compressive strength with the regard to elapsed time from mixing.

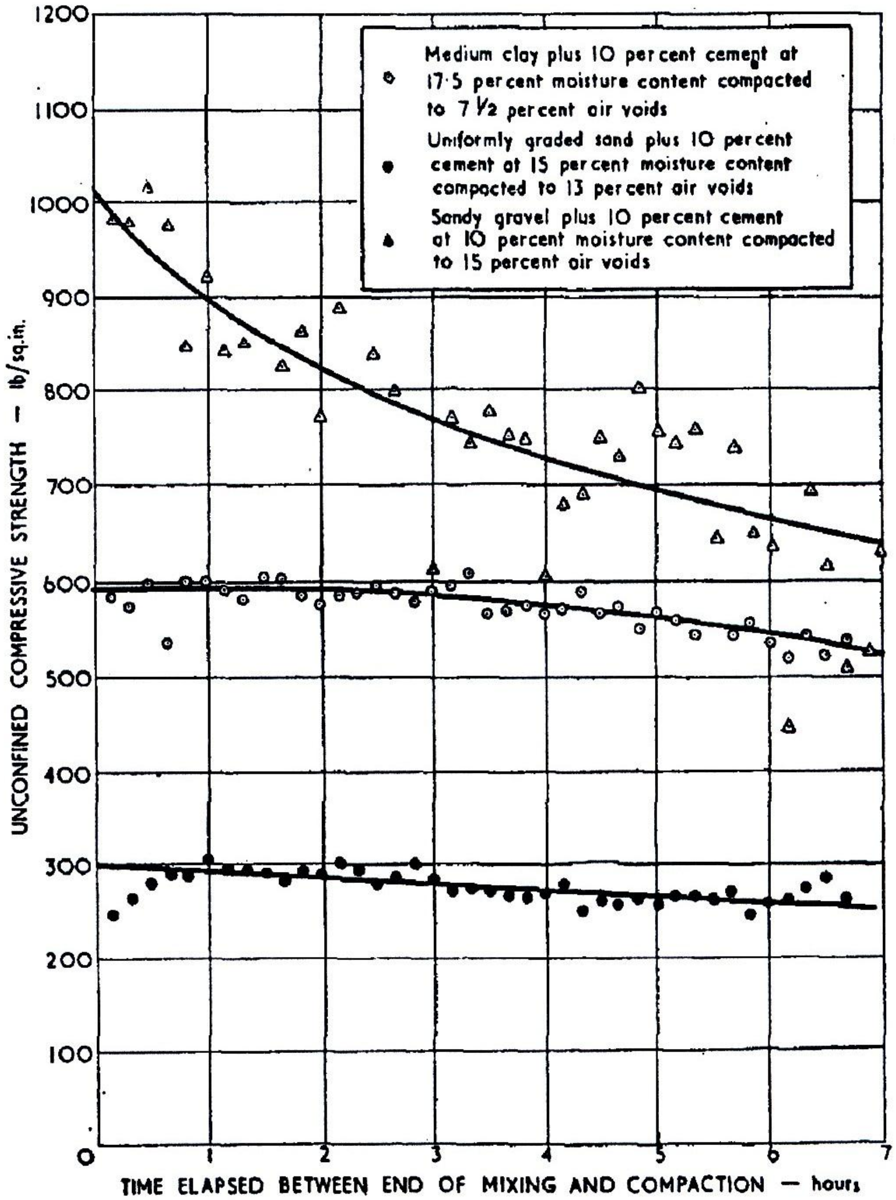

Fig. 2.3: Unconfined Compressive Strength vs. Elapsed Time (West 1959)

Felt (1955) showed that the effect of time delay was minimized when the mixture was allowed to be remixed several times an hour, if the moisture content at the time of compaction was at or slightly above optimum. The most effective moisture content is considered to be the optimum moisture content or slightly above, as lower moisture contents may produce mixtures of inferior quality (Felt 1955).

2.3.2 Compressive Strength

The unconfined compressive strength of soil-cement mixtures has been used effectively to characterize mechanical properties of soil-cement mixtures (Shihata and Baghdadi 2001). ASTM D 1633(2007) is used to measure unconfined compressive strength for soil-cement mixtures. Compressive strength provides a basis for determining minimum cement requirements for mixtures and the proportioning of soil cement. Researched performed by Mohammad, Raghavandra and Huang (2000) provided data that indicate mixtures with higher cement contents exhibit higher strengths than mixtures with lower cement contents.

ACI 230 (2009) recommends soaking specimens prior to testing as required in ASTM D 1633 (2007) since most soil-cement structures may become permanently or intermittently saturated during their service life. Lower strengths are possible under saturated conditions (ACI 230 2009). Examples of compressive strength attainable for soaked, soil-cement specimens are presented given in Table 2.2. The values presented in Table 2.2 correspond to the 7-day compressive strength values required for ALDOT core strengths.

Table 2.2: Typical compressive strength values for soil-cement (ACI 230 2009)

Soil type	Soaked compressive strength,* psi	
	7-day	28-day
Sandy and gravelly soils: AASHTO Groups A-1, A-2, A-3 Unified Groups GW, GC, GP, GM, SW, SC, SP, SM	300 to 600	400 to 1000
Silty soils: AASHTO Groups A-4 and A-5 Unified Groups ML and CL	250 to 500	300 to 900
Clayey soils: AASHTO Groups A-6 and A-7 Unified Groups MH and CH	200 to 400	250 to 600

*Specimens moist-cured 7 or 28 days, then soaked in water before strength testing.
Note: 1 psi = 0.0069 MPa.

Guthrie et al. (2005) evaluated the strength testing of laboratory-mixed and field-mixed soil-cement base. The laboratory-made samples were cured at 100% relative humidity, soaked underwater for 4 hours, capped with gypsum plaster and tested in accordance with ASTM D 1633. The field-mixed material was compacted on site with a modified proctor hammer, and then placed in sealed plastic bags for curing. The field-mixed samples were not subjected to underwater soaking. The results of the compressive strength testing are shown in Figure 2.4.

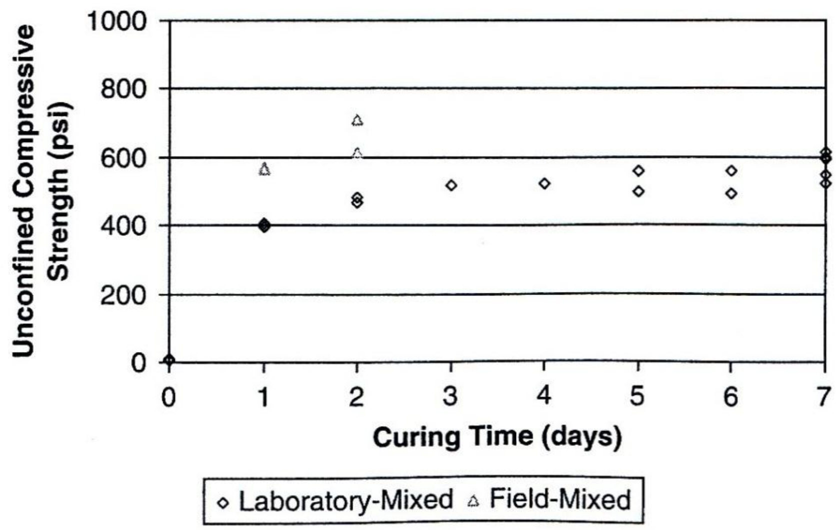

Figure 2.4: Laboratory strength measurements (Guthrie et al. 2005)

The higher strengths of the field-compacted specimens indicate potentially higher cement contents in the field or reduced strength of lab-mixed specimens as a result of underwater soaking (Guthrie et al. 2005).

Since strength and density are directly related, strength is affected similarly to density in regards to compaction effort and moisture content (ACI 230 2009). Mohammad, Raghavandra and Huang (2000) provided data that indicate a significant increase in compressive strength can be obtained by increasing the compaction effort to 100 percent of maximum dry density.

Mohammad et al. (2000) provided molded samples that were wrapped in plastic bags and placed in a 100 percent relative humidity moist-curing room prior to testing. Results from this study show that an increase in curing time will significantly increase compressive strength.

ASTM D 1632 suggests that "compression test specimens shall be cylinders with a length equal to twice the diameter." The required specimen size for ASTM D 1632 is 71 mm (2.8 in.) in diameter by 142 mm (5.6 in.) in length. However, ASTM D 1633(2007) Method A allows compressive strength tests to be performed on soil cement samples with dimensions of 4.0 in. in diameter by 4.6 in. in height that are made with a Proctor mold. The Proctor mold is a common mold used for other soil and soil-cement testing. These samples will have a length-to-diameter ratio (L/D) of 1.15. According to ACI 230 (2009), the L/D of 2.00 reduces complex stress conditions that may occur during crushing of lower L/D specimens. Further exploration into L/D is given in Section 2.4.5.

2.3.3 Shrinkage and Reflective Cracking

Shrinkage cracking can result in reflective cracking in the upper asphalt surface layer. Reflective cracking is identified by relatively uniformly spaced transverse cracks. Water infiltration into these cracks can result in the stripping of asphalt binder from the aggregates, which will allow the weakening of the base layer, and eventual pumping of the subgrade layer (Hadi Shiraz 1997). Figure 2.5 shows an asphalt surface layer with reflective cracking as a result from excessive shrinkage of the base layer.

Figure 2.5: Reflective Cracking from excessive shrinkage of base layer (Scullion 2002)

Most cracking in soil-cement base is the result of restraint of drying shrinkage. Therefore, the less water in the mixture the less prone the mixture will be to cracking (Kuhlman 1994). Shrinkage and subsequent cracking are primarily dependent upon the type of soil, cement content, moisture content, compaction effort, and curing conditions (ACI 230 2009). Granular soils will tend to have lower demand for water and will be less susceptible to drying shrinkage. Shrinkage can be reduced by limiting the clay content or the percentage of fines in the soil (Kuhlman 1994). The moisture necessary to gain the strength benefits of proper cement hydration, along with the desire to be slightly above the optimum moisture content when mixing will tend to increase water content and increase the potential for greater drying shrinkage.

ACI 230 (2009) suggests keeping the soil-cement surface moist beyond the normal curing periods and placing the soil cement at slightly below optimum moisture content. Keeping moisture to a minimum is critical to prevent shrinkage cracking, and it is recommended that soil-cement base be compacted between optimum moisture content and 2% below optimum moisture content to minimize shrinkage cracking (Kuhlman 1994). Proper curing will allow the retention of the necessary moisture for hydration, and should reduce and retard the drying shrinkage stresses until sufficient strength development has occurred to resist these stresses. This would minimize total shrinkage and increase tensile strength so that shrinkage cracking will be minimal (Kuhlman 1994).

2.3.4 Structural Design

For flexible pavement design, the AASHTO Design Method involves a layer coefficient, *a*, where values are given to each layer of material used in the pavement structure. The layer coefficient is a measure of the unit thickness of a given material in a pavement to perform as a structural component of the pavement (Huang 2004). The layer coefficient is used to convert the actual layer thicknesses into a structural number *SN*. This layer coefficient expresses the empirical relationship between *SN* and thickness, *D* (ACI 230 2009). The following equation for structural number reflects the relative impact of the layer coefficient and thickness

$$SN = a_1D_1 + a_2D_2 + a_3D_3 \qquad \textbf{Equation 2.1}$$

where:

a_1, a_2, and a_3 = layer coefficients of surface, base, and subbase, respectively;

D_1, D_2, and D_3 = corresponding layer thicknesses, (in.).

The layer coefficients are based on the resilient modulus, a fundamental material property (Huang 2004). Table 2.3 shows typical soil cement layer coefficient values and corresponding compressive strength requirements for soil cement used by state departments of transportation (ACI 230 2009).

Table 2.3: Examples of AASHTO soil cement layer coefficients used by various state DOTs (ACI 230 2009)

State	Layer coefficient a	Compressive strength requirement
Alabama	0.23	650 psi minimum
	0.20	400 to 650 psi
	0.15	Less than 400 psi
Arizona	0.28	For cement-treated base with minimum 800 psi (plant mixed)
	0.23	For cement-treated subgrade with 800 psi minimum (mixed in place)
Delaware	0.20	—
Florida	0.15	300 psi (mixed in place)
	0.20	500 psi (plant mixed)
Georgia	0.20	350 psi
Louisiana	0.15	200 psi minimum
	0.18	400 psi minimum
	0.23	Shell and sand with 650 psi
Montana	0.20	400 psi minimum
New Mexico	0.23	650 psi minimum
	0.17	400 to 650 psi
	0.12	Less than 400 psi
Pennsylvania	0.20	650 psi minimum (mixed in place)
	0.30	650 psi minimum (plant mixed)
Wisconsin	0.23	650 psi minimum
	0.20	400 to 650 psi
	0.15	Less than 400 psi

Note: 1 psi = 0.0069 MPa.

A cement-stabilized base provides a higher stiffness value than an unstabilized base. Figure 2.6 shows that the low stiffness of an granular base will promote higher deflection values that can eventually result in fatigue cracking. The higher stiffness of the cement-treated base will provide a longer pavement life due to the lower surface strains and deflections (Halstead et al. 2006).

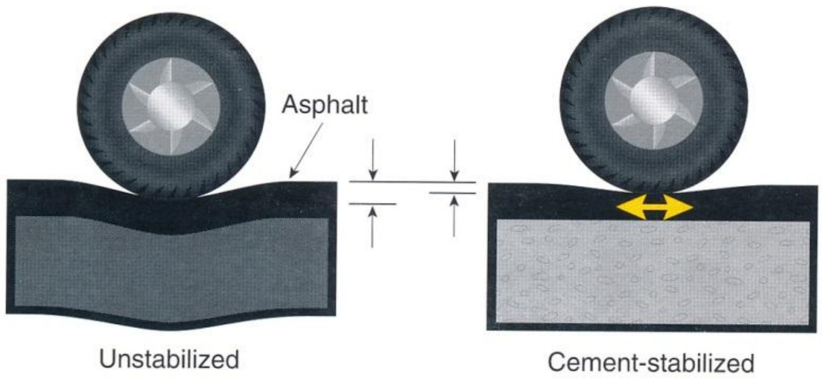

Figure 2.6: Unstabilized Granular Base versus Soil-Cement Base (Halsted et al. 2006)

2.4 Testing Concerns

An ALDOT soil-cement base construction project on US-84 in 2007 led to concerns regarding construction requirements, design specifications and quality control. ALDOT quality control and acceptance requirements mandated that cores be taken from completed soil-cement base roadbeds for in-place compressive strength testing. Figure 2.7 shows a typical soil-cement core hole. In order to achieve full pay, soil-cement base cores were required to have seven-day strengths that fell within a 250 to 450 psi range. The seven-day strength value of the cores determines the pay rate if any penalties are applied, or if the section should be removed and replaced. Cores obtained from a test section had compressive strength values from 180 psi to 210 psi, which fall below the 250 psi minimum strength requirement. Cores taken from the roadway the following day had compressive strength values above the required 450 psi upper limit. Roadway cores taken 4 days later had values similar to but lower than the test section. It should be noted that the test section cores were sawn in order to achieve planeness tolerances, but were not sulfur-capped. The roadway cores were sawn and capped with sulfur mortar prior to testing.

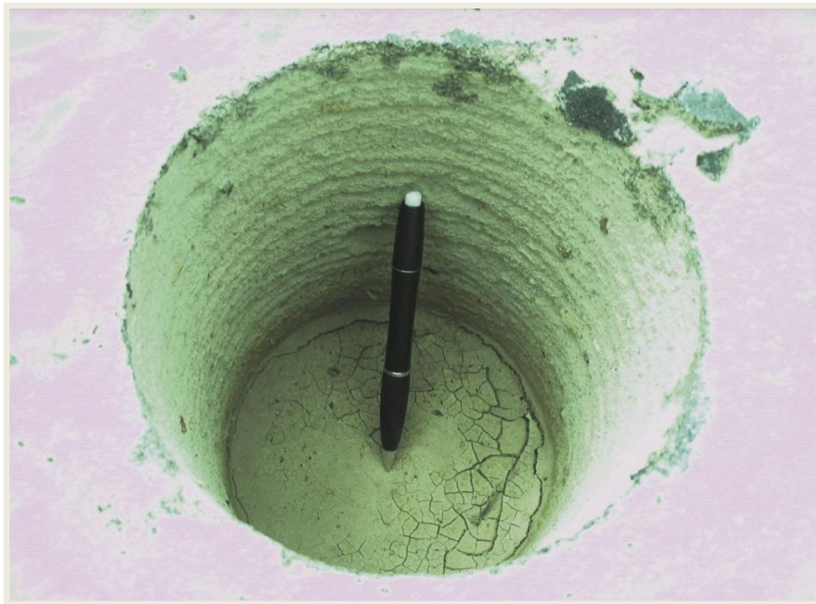

Figure 2.7: Typical soil-cement core hole

2.4.1 Core Strength Variability

There are several different methods used to condition a core from the time it has been removed from the roadbed until the time of testing. ALDOT-419 (2008) recommends sealing cores in plastic bags to minimize internal moisture, but also requires cores that have been wet-sawn to dry in the shade for 30 minutes before sealing in the bag. Once the core has been delivered to the testing laboratory, it is removed from the bag and the bottom surface of the core is dry sawn, if possible, for planeness tolerances. The core is then capped with sulfur mortar and allowed to reach a constant mass before strength testing is performed. After the core has been tested in compression, the correction factor from AASHTO T 22 is applied to the compressive strength results if the specimen length-to diameter ratio is less than 2 to 1.

Once a soil-cement base has been in-place for 7 days, GDT 86 (2003) requires cores taken from the roadbed to air dry at room temperature for a minimum of 15 hours and until constant mass is obtained before capping the cores with sulfur mortar. GDT 86 (2003) requires a minimum compressive strength of 300 psi.

Many of these methods appear to have closely followed procedures for coring, curing, and testing conventional concrete. ASTM C 42 (2004) recommends storing cores in a sealed bag for 5 days before testing concrete cores in order to minimize the effects of moisture gradients introduced by wetting during drilling and specimen preparation.

Standard-cured cylinders are most applicable for acceptance tests of conventional concrete (Bloem 1965). Acceptance tests for concrete strength are usually based on cylinders made at the jobsite and cured in accordance with ASTM standards. The average strength of these cylinders must meet or exceed the specified strength of the design criteria. In general, the core tests are the final verdict in whether the strength on the concrete is sufficient (Campbell and Tobin 1967). ACI 318 (2011) recommends that cores be drilled to verify the in-place strength of a structure if cylinder values fall more than 500 psi below design strength, f'_c. Section 5.6.5.4 of ACI 318 (2011) states the following: "Concrete in an area represented by core tests shall be considered structurally adequate if the average of three cores is equal to at least 85 percent of f'_c and if no single core is less than 75 percent of f'_c. Additional testing of cores extracted from locations represented by erratic core strength results shall be permitted" (ACI 228 2003).

However, Bloem (1965) mentions that when core tests are used to check for the adequacy of strength, the core strength values should be evaluated with judgement, simply because they "cannot be translated to terms of standard cylinder strength with any degree of confidence."

In comparisons of concrete cores to concrete test cylinders, researchers have indicated that coring or cutting through the coarse aggregate may tend to weaken the outer layer of a core (Campbell and Tobin 1967).

2.4.1.1 Core versus Cylinder Strength

Research performed by Campbell and Tobin (1967) comparing the compressive strengths of concrete cores to concrete test cylinders produced data that indicated that the 28-day compressive strengths of cores are lower than the 28-day compressive strengths of laboratory made cylinders. Figure 2.8 shows that 4 in. and 6 in. cores have from 14 to 34 percent lower compressive strengths than ASTM laboratory-cured test cylinders.

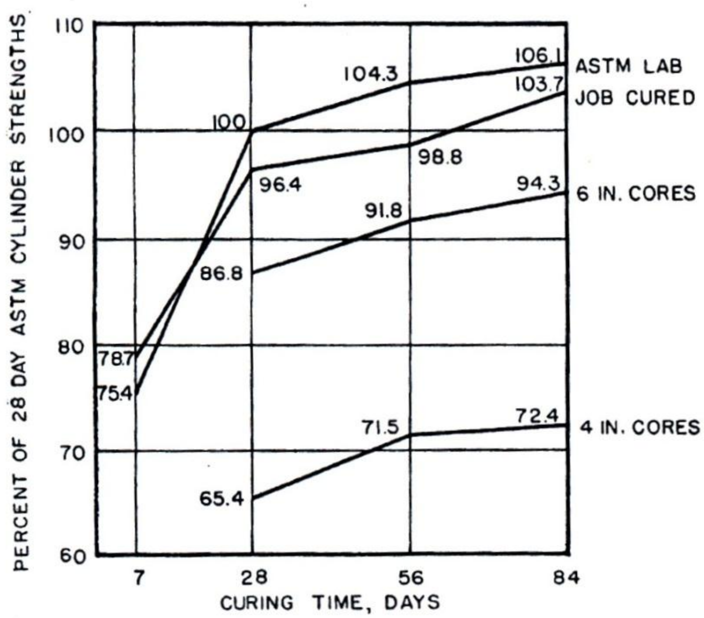

Figure 2.8: Comparison of Core and Cylinder Strengths (Campbell and Tobin 1967)

Research by Bloem (1965) using molded cylinders versus 4-inch diameter cores from slabs and columns indicated that 91-day core strengths were 10 to 40 percent lower than molded cylinder strengths. However, 28-day field cured cylinders compared well with 91-day, air-dried cores which simulated the apparent moisture condition of in-place concrete.

A prediction model based on core strength correction factors presented by Bartlett (1997) recommends that the strength of a concrete core should be converted through a series of correction factors to equivalent in-place strength. The relationship between in-place strength and core strength is shown in Figure 2.9.

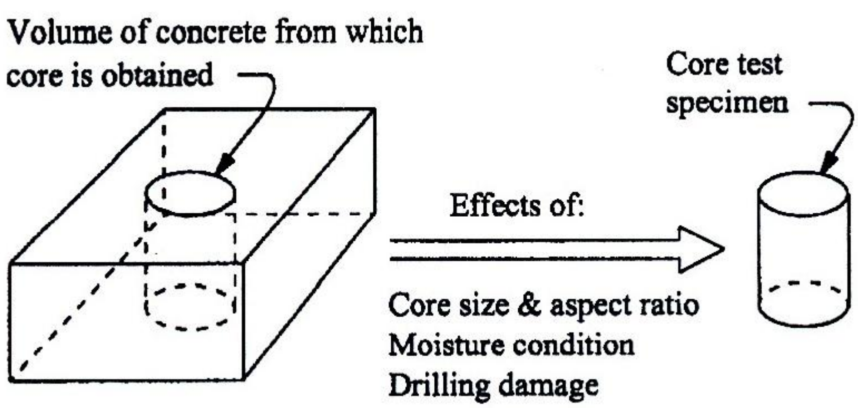

Figure 2.9: Relationship between in-place strength and core strength (Bartlett 1997)

Based on non-uniform variances in the core, such as dimensional differences, core damage from drilling, moisture condition, and possible pieces of reinforcement bar, correction factors have been derived from weighted linear and non-linear regression analyses. It should be noted that for this research, a standard core size was 100 mm in diameter and 200 mm in length. The following model is designed to remove any bias from non-standard core sizes (Bartlett 1997)

$$f_{c,S}=F_{L/D}F_{dia}F_r\,f_{c,NS}$$ **Equation 2.2**

where,

$f_{c,S}$ = compressive strength of standard specimen,

$F_{L/D}$ = effect of length-to-diameter ratio on specimen,

F_{dia} = effect diameter on specimen,

F_r = effect of presence of reinforcing bar(s) on specimen, and

$f'_{c,NS}$ = compressive strength of non-standard specimen.

For non-standard core strength to be converted to standard core strength, the length-to-diameter factor as well as the reinforcement factor will result in an increase in strength for the non-standard core. The diameter factor, depending on whether the diameter is larger or smaller than the 100 mm diameter of a standard core, would either decrease or increase the strength, respectively. The magnitude and precision of the strength correction factors for non-standard cores is presented in Table 2.4.

Table 2.4: Magnitude and precision of strength correction factors for non-standard cores (Bartlett 1997)

Factor	Mean value	V (%)
$F_{l/d}$ ratio †		
soaked ‡	$1-[0.117-4.3(10^{-4})f_{c,NS}](2-l/d)^2$	$2.5(2-l/d)^2$
air dried ‡	$1-[0.114-4.3(10^{-4})f_{c,NS}](2-l/d)^2$	$2.5(2-l/d)^2$
F_{dia}: core diameter		
2-in (50 mm)	1.06	11.8
6-in (150 mm)	0.98	1.8
F_r: reinforcement present		
one bar	1.08	2.8
two bars	1.13	2.8

* To obtain the strength of an equivalent 'standard' core, multiply the test strength of a non-standard core by the appropriate factor(s) in accordance with Eq. (1).

† The constant $-4.3(10^{-4})$ has units 1/MPa. For $f_{c,NS}$ in psi, the constant is $-3(10^{-6})1/\text{psi}$.

‡ Standard treatment specified in ASTM C 42-90 [1].

In order to correlate the compressive strength from a standard core to the in-place strength, the following model is presented (Bartlett 1997)

$$F'_{c,\,ip} = F_{mc} F_d f'_{c,\,s}$$ **Equation 2.3**

where,

$F'_{c,\,ip}$ = in-place concrete strength, psi,

F_{mc} = effect of moisture condition on specimen,

F_d = damage from core drilling, and

$f'_{c,\,s}$ = compressive strength of standard specimen.

For standard core strength to be converted to in-place strength, the moisture content factor would either increase the strength, if soaked, or decrease the strength, if air-dried. The correction factor for any damage from drilling will increase the strength of the core for in-place predictions. The magnitude and precision of factors for predicting in-place strengths from standard core strengths is presented in Table 2.5.

Table 2.5: Magnitude and precision of factors for predicting in-place strengths from standard core strengths (Bartlett 1997)

Factor	Mean value	V (%)
F_{mc}: core moisture content		
soaked ‡	1.09	2.5 §
air dried ‡	0.96	2.5 §
F_d: damage due to drilling	1.06	2.5 §

* To obtain the equivalent in-place concrete strength, multiply the standard core strength by the appropriate factors in accordance with Eq. (2).
‡ Standard treatment specified in ASTM C 42-90 [1].
§ Estimated.

Based on the research by Bartlett (1997), the coefficient of variation for in-place strength prediction can vary from 4 to 12.5 percent with respect to strength correction factors.

2.4.1.2 Wet versus Dry Testing

Previous research by Bloem (1965) states that concrete core strengths are highly dependent upon proper curing and treatment of test specimens. Additional research by Campbell and Tobin (1967) evaluated core samples that were soaked for a minimum of 40 hours before testing. The wet cores had lower strengths than air-cured cores. A few cores were oven-dried to a constant mass and then tested in compression. A large gain in strength was observed for all the oven-dried cores with relation to the cores that were soaked. These data indicate that soaked samples do not test as high in strength as oven-dried samples.

Previous research by Bloem (1965) shows that underwater soaking of cores for 48 hours prior to testing did not improve their relationship with molded cylinders. Bloem (1965) shows that soaking cores in water does not increase the likelihood for compliance with molded cylinders, but cores that have been dried for 7 days prior to testing provided the best similarities with in-place strength.

Bloem (1968) performed research on well-cured cylinders, well-cured slab cores, poorly-cured cylinders, poorly-cured slab cores, and push-out cylinders that were cast-in-place in the slab. From this study, the best correlation of data was relating core strengths to the strengths of field-cured cylinders. Since the core strengths were lower than field cured cylinders, it is recommended that strength data from core tests should be used with discretion while checking for any plausible inadequacies. Bloem (1968) states that cores used to double-check cylinder values should be interpreted with caution as some core strengths never obtain design strength. Moist-cured cylinders appear to have higher strengths than as-measured cores. Figures 2.10 and 2.11 show that the relationship of core strengths from well-cured concrete slabs is 90 percent of well-cured, field-made concrete cylinder strengths and the relationship of core strengths from poorly-cured concrete slabs is 79 percent of poorly-cured, field-made concrete cylinder strengths.

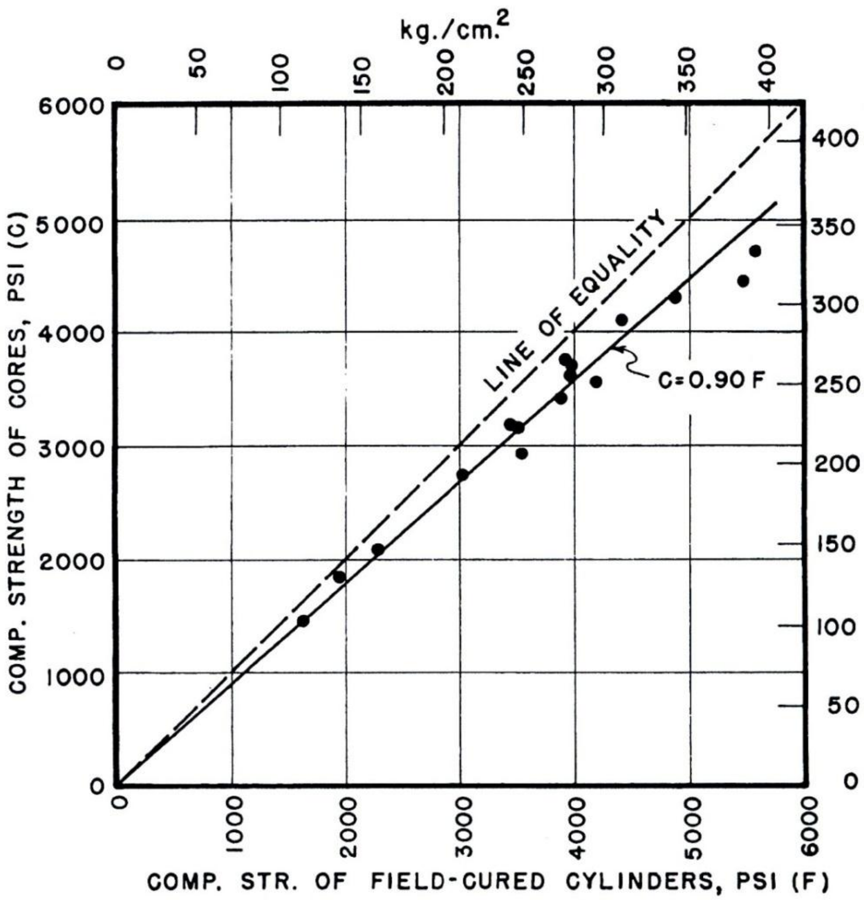

Figure 2.10: Relation between cores from well-cured slabs and well-cured field cylinders (Bloem 1968)

Although there is no significant difference in well-cured and poorly-cured field cylinders, field curing can be somewhat misleading, as field cylinders are impacted less by curing methods than the in-place structure (Bloem 1968). Field curing has shown inconsistencies for determining or estimating core strength values. It should be noted that in Bloem's study field-cured cylinders tested dry produced less reproducible strengths than standard-cured field cylinders (Bloem 1968).

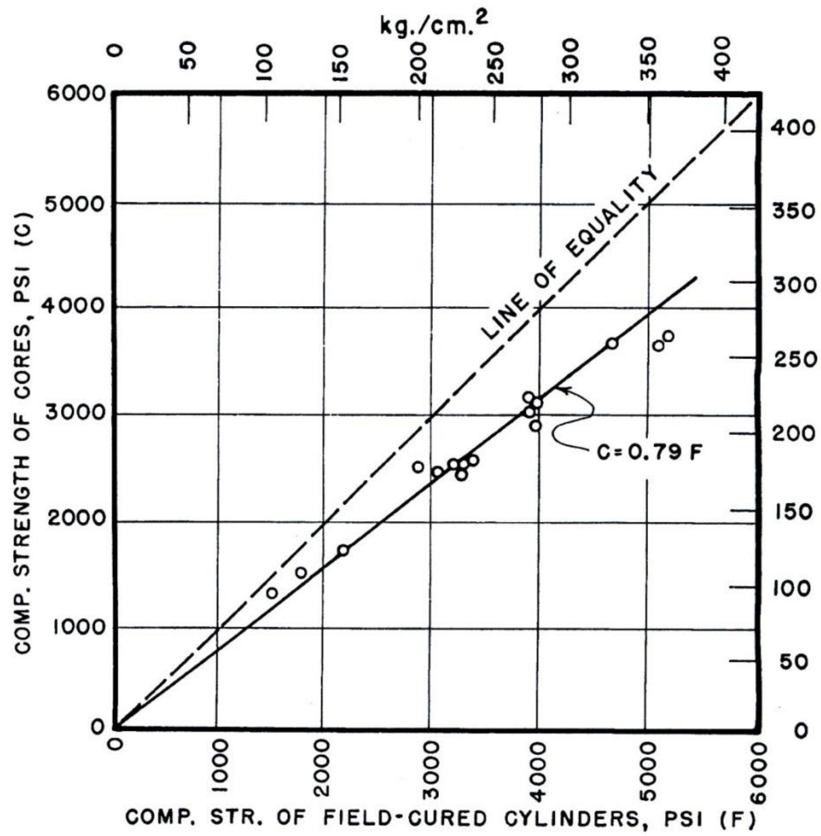

Figure 2.11: Relation between cores from poorly-cured slabs and poorly-cured field cylinders (Bloem 1968)

Bloem's study also indicates that push-out test cylinders provided the most accurate method to obtain in-place strengths. The in-place strength (core strength values) was determined to be 93 percent of the push-out test cylinder strength value. Figure 2.12 shows that core strength is 93 percent of push-out test cylinders. Reproducibility was determined to be the most favorable for field-cured cylinders, followed by the push-out test cylinders, and lastly the core specimens (Bloem 1968). It should be noted that the core specimens along with the push-out test cylinders showed no discernible difference in reproducibility between specimens tested in a dry state or after soaking in water.

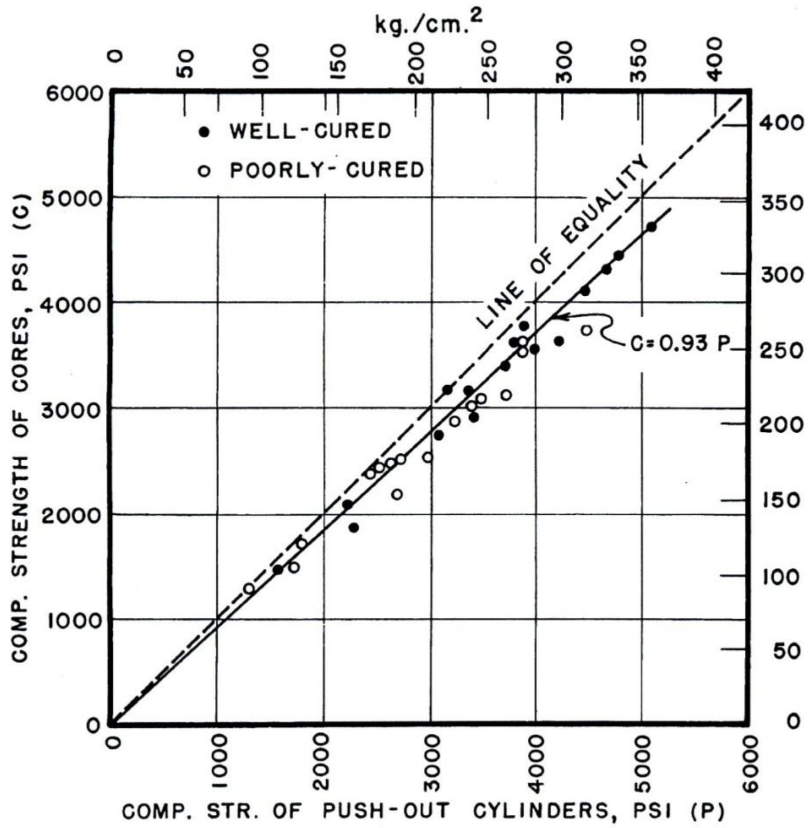

Figure 2.12: Relation between cores and push-out cylinders (Bloem 1968)

2.4.2 Criteria for Concrete Cylinder Strength Testing

The strength testing of molded concrete cylinders is a useful index in determining the quality of the concrete represented (Bloem 1965). However, ASTM C 39 (2009) states that careful interpretation of compressive strength data should be administered as strength is not an inherent property of concrete made from given materials. Molded cylinders made in the laboratory environment and standard cured may be used to develop information for the following purposes (ASTM C 192 2007)

- Mixture proportioning for project concrete,
- Evaluation of different mixtures and materials,
- Correlation with nondestructive tests, and
- Providing specimens for research purposes.

Strength testing is not a direct or quantitative measure for the in-place strength of the concrete, but a representation of the material delivered to the jobsite (Bloem 1965). ASTM C 31 (2009) recommends that the strength data obtained from field-made cylinders that are standard cured are able to be used for the following (ASTM C 31 2009)

- Acceptance testing for specified strength,
- Checking adequacy of mixture proportions for strength, and
- Quality control.

Strength test data from field-made cylinders that are field-cured are able to be used for the following (ASTM C 31 2009)

- Determination of whether a structure is capable of being put in service,
- Comparison with test results of standard cured specimens or with test results from various in-place test methods,
- Adequacy of curing and protection of concrete in the structure, or
- Form or shoring removal time requirements.

ACI 228 (2003) states that in-place testing can be used to predict or estimate concrete strength during construction. This allows operations with certain strength requirements to be performed safely or the satisfactory termination of curing procedures. Typically, three replicate test cylinders are made for each test age and condition, with 1- ,3- ,7- , and 28-day strengths being the most widely used criteria (ASTM C 192 2007).

2.4.2.1 Compression Testing of Concrete Cylinders

ASTM C 39 (2009) is the standard test method for compressive strength of cylindrical concrete specimens. This method is used for molded cylinders as well as drilled cores. Strength test data obtained from this method may be used for the following (ASTM C 39 2009)

- As a basis for quality control of concrete proportioning,
- Mixing and placing operations;
- Determination of compliance with specifications;
- Control for evaluating effectiveness of admixtures.

ASTM C 31 and C 192 both recommend that the diameter of a cylinder to be tested should be at least three times the nominal maximum size of the coarse aggregate in the concrete per ASTM C 125. Nominal maximum size is defined as the smallest sieve opening through which the entire amount of the aggregate is permitted to pass (ASTM C 125 2009). However, specifications on aggregates usually stipulate a sieve opening through which all of the aggregate may, but need not, pass so that a stated maximum proportion of the aggregate may be retained on that sieve. A sieve opening so designated is the *nominal maximum size* of the aggregate (ASTM C 125 2009).

Test specimens should be cylindrical, with tolerances of 0.5 percent from perpendicularity to the longitudinal axis. If necessary, sawing or grinding the ends of the test cylinders is necessary in order to meet the planeness tolerance requirements of 0.002 in. of the whole surface.

Cylinders may also be capped in accordance with either ASTM C 617 or ASTM C 1231 (ASTM C 39 2009). Cylinders are to be tested at a stress rate of 35 +/- 7 psi/s. Once the cylinder has shown a reduction in load capacity, and a fracture pattern has developed, the maximum load carried by the cylinder is recorded, and compare the fracture pattern with typical patterns as found in Figure 2.13 is documented.

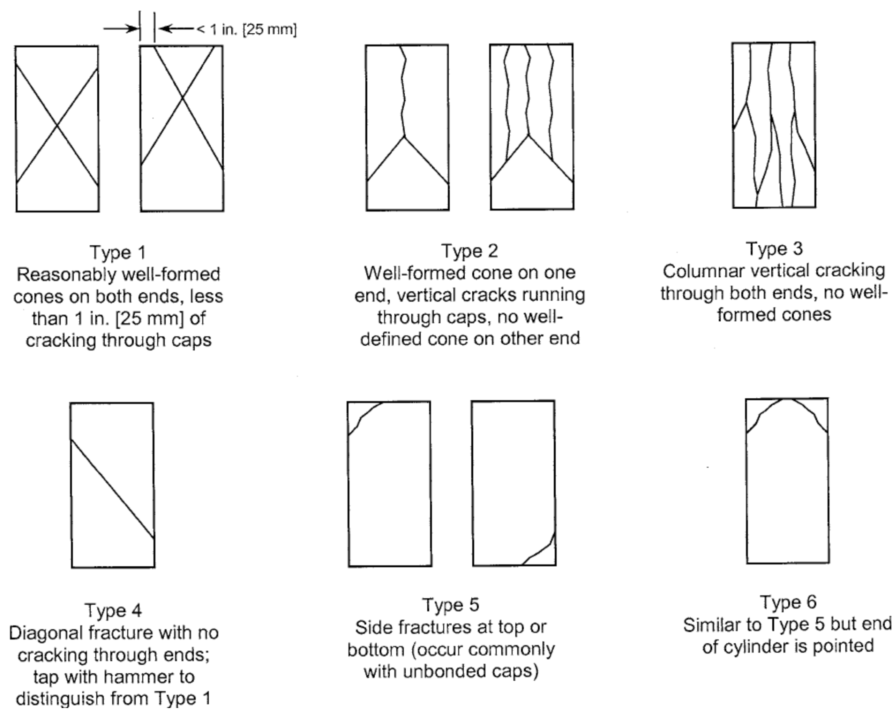

Figure 2.13: Schematic from Typical Fracture Patterns (ASTM C 39 2009)

ASTM C 39 states that if the specimen length to diameter ratio is 1.75 or less, use the appropriate correction factor shown in the Table 2.6 to adjust the strength value obtained.

Table 2.6: Correction factors for length-to-diameter ratio (ASTM C 39 2009)

L/D	Correction factors for L/D (ASTM C 39 2009)			
	1.75	**1.50**	**1.25**	**1.00**
Factor	0.98	0.96	0.93	0.87

Interpolation should be used to determine correction factors for L/D values between those given in the table. It should be noted that these correction factors should only be applied to low-density concrete weighing between 100 and 120 lb/ft^3 or to normal-density concrete. These factors are applicable to concrete with nominal concrete strengths from 2,000 to 6,000 psi. Concrete with higher strengths may need larger correction factors than the ones in Table 2.6 (ASTM C 39 2009). ASTM D 1633 (2007) recommends these factors as applicable with regard to soil-cement base compression testing.

2.4.2.2 Acceptance Testing Used for Traditional Concrete

Traditionally, slump, air content, and compressive strength are the primary indicators for acceptability of concrete delivered to the jobsite. Once the concrete has been designated as acceptable, proper quality control in the areas of placement, consolidation and curing will ensure the concrete's ability to perform according to design specifications and requirements (ACI 228 2003). ASTM C 31 (2009) recommends cylinders shall be 6 by 12 in. or 4 by 8 in. for compressive strength acceptance testing.

ACI 318 (2002) states as follows: "Strength level of an individual class of concrete shall be considered satisfactory if both of the following requirements are met:

- Every arithmetic average of any three consecutive strength tests equal or exceed f'_c;

- No individual strength test (average of two cylinders) falls below f'_c by more than 500 psi when f'_c is 5000 psi or less; or by $0.10f'_c$ when f'_c is more than 5000 psi."

These measures can be adapted to soil-cement base without many concerns. ASTM D 1632 and 1633 allow for a two to one length-to-diameter ratio. Strength measures that follow ACI 318 (2002) could easily be scaled for soil-cement base strength values.

2.4.3 Curing Issues

The primary reason for curing concrete in a moist state at early ages is the prevention of cracking. The moisture content and moisture distribution in the specimen are also important factors in the promotion of concrete's engineering properties (Popovics 1986).

Bloem's (1965) data indicates that a change in moisture content between drilling and testing will affect the strength of cores more so than the total moisture content at the time of testing. The reduction in compressive strength is more a result from the moisture gradient effect which occurs between the surface of the core and the inner portion of the specimen (Bartlett and MacGregor 1994). Concrete strength is reduced if the moisture content is increased uniformly throughout the specimen volume (Bloem 1965). Soaking a concrete specimen will also create a moisture gradient that will reduce the strength of the specimen (Bartlett and MacGregor 1994).

Popovics (1986) states that a dry or surface-dry concrete specimen will have a higher compressive strength than the same specimen in a saturated-surface-dry or fully-saturated state.

As stated in Section 2.5.1, Bloem indicates that the best indication for in-place strength are cores that are dried for 7 days to eliminate any water absorbed from the drilling operations. However, Bartlett and MacGregor (1994) have concluded that a 7-day drying period could be “excessively long for this purpose.” Previous research by de Larrard and Bostvironnois (1991) shows that variations in strength are due to the effects of drying. The strength of the specimen is dependent upon the extent of the moisture gradient, which is in turn, affected by the length of the drying periods.

After drilling, surface-dry cores are placed in sealed plastic bags to prevent moisture loss until end preparations such as capping are completed (ASTM C 42 2004). ASTM C 42 (2004) recommends a 5-day waiting period in sealed plastic bags before testing cores in order to promote a moisture condition that minimizes the effects of moisture gradients introduced by wetting during drilling and specimen preparation.

2.4.3.1 Strength Change due to Moisture

Bartlett and MacGregor (1994) indicate that the loss in strength from soaking concrete test specimens has been attributed to the absorption of water by the gel pores of the concrete. This phenomenon is also considered responsible for the gain in strength when concrete specimens are allowed to dry in air. The moisture gradient from soaking that is created between the surface and interior of the specimen results in swelling at the surface of the concrete. The interior portion of the specimen maintains constant moisture levels and does not absorb any of the moisture from the soaking of the concrete. This produces residual stresses, which can result in a reduction of compressive strength. Drying the specimen, however, will promote an increase in compressive strength due to the drying shrinkage on the surface of the specimen (Bartlett and MacGregor 1994).

Popovics (1986) continues to further investigate by stating that drying the surface of concrete decreases the volume of the hardened cement paste. Surface tension increases in the water-filled pores during the drying process, and reduces the distance between surfaces in the cement gel. As long as the drying process does not result in shrinkage cracking, additional strength is provided based upon secondary bonds between the surfaces of the specimen. Adding moisture would result in an increase in volume, and an increase in distance between the surfaces of the cement gel, and a reduction in strength would transpire.

Additionally, an increase in internal pore pressure from compression testing may also lead to low strengths when fully saturated. The moisture is being driven out of the pores during compression testing, but the small capillary pore sizes prevent free migration of the water, resulting in an increase in un-measured external load. The pore pressure escalates the crack propagation, which in turn reduces the external load capacity of the specimen (Popovics 1986). This is only valid for fully saturated specimens, as a slight amount of air in the pores will lessen the changes in pore pressure while loading. If the specimen is partially saturated, it may become fully saturated during loading, and lower strengths may result (Popovics 1986).

Studies by Bloem (1965) and Meininger et al.(1977) show a 10 to 20 percent increase in core strengths for cores that have been air-dried as opposed to cores that have been soaked in water.

Bartlett and MacGregor (1994) show that compressive strengths for dry specimens are up to 14 percent greater than soaked specimens using the model

$$f'_{c,\,dry} = 1.144\, f'_{c,\,wet} \qquad \textbf{Equation 2.4}$$

where,

$f'_{c,\,dry}$ = dry specimen concrete strength, and

$f'_{c,\,wet}$ = wet specimen concrete strength.

Bartlett and MacGregor (1994) show that compressive strengths for as-drilled specimens are up to 9 percent greater than soaked specimens using the model

$$f'_{c,\,ad} = 1.090\, f'_{c,\,wet} \qquad \textbf{Equation 2.5}$$

where,

$f'_{c,\,dry}$ = dry specimen concrete strength, and

$f'_{c,\,wet}$ = wet specimen concrete strength.

These data can be further expressed in Figure 2.14, which shows considerable scatter of the observed average values about the predicted values of 1.144 and 1.090, respectively. Bartlett and MacGregor (1994) show that on average, air-dried cores are probably 5 to 9 percent stronger than as-drilled cores.

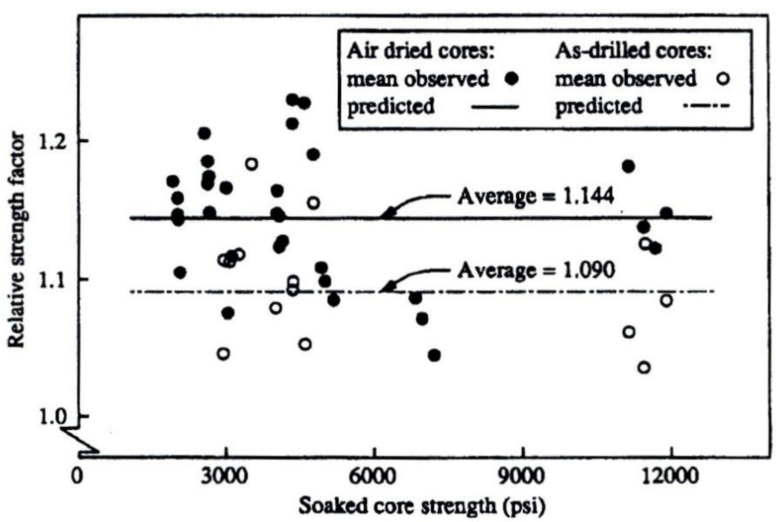

Figure 2.14: Strength of air-dried and as-drilled cores relative to soaked cores (Bartlett and MacGregor 1994)

Bartlett and MacGregor (1994) show in Figure 2.15 that the effect of 7 days of air-drying can generate a moisture gradient that will "artificially increase the strength of the specimen by about 5 percent above the true in situ strength."

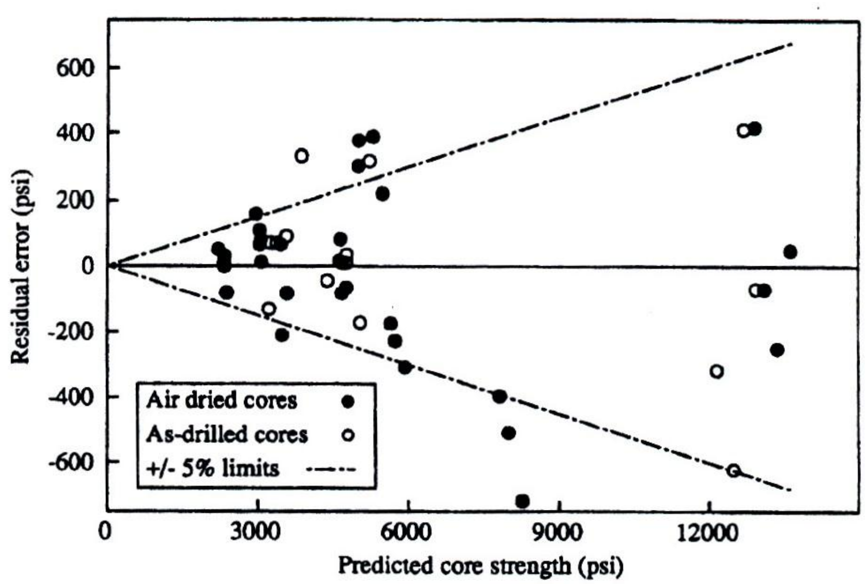

Figure 2.15: Residual versus predicted core strengths (Bartlett & MacGregor 1994)

Popovics (1986) shows in Figure 2.16 the impact of moisture on curing. Humidity is necessary in order to further cement hydration. Strength development is more substantial when concrete is allowed to cure in a moist environment rather than a dry environment.

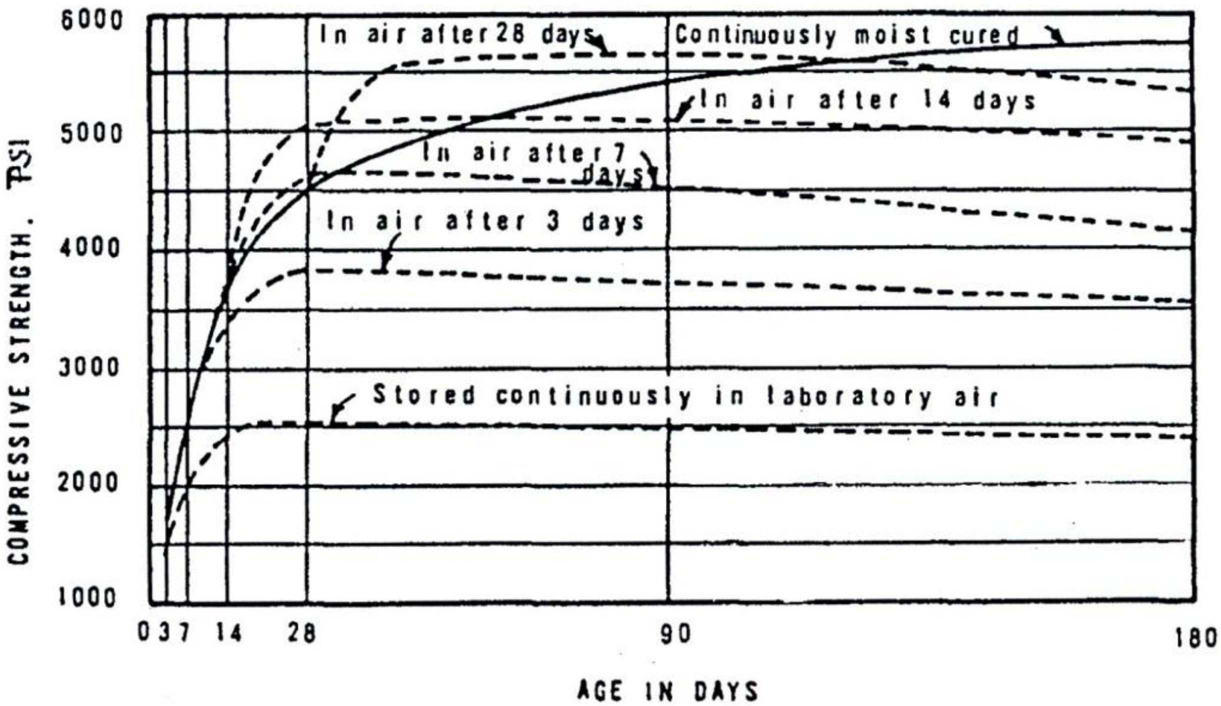

Figure 2.16: Compressive strength of air dried concrete after previous moist-curing (Popovics 1986).

From the data provided by Popovics (1986), Figure 2.17 shows that moist-cured strengths are very similar to air-dried strengths at 3 days. However, the increase in strength from moist curing at 7 days is substantial for both sets of data.

Figure 2.17 shows that changes in the total moisture content of concrete specimens produced appreciable changes in the compressive strengths. Popovics (1986) indicates that a moisture gradient will impact the compressive strength positively when the surface of the specimen has less moisture than the interior. Strengths will be reduced when the inner portion of the specimen is drier than the surface (Popovics 1986).

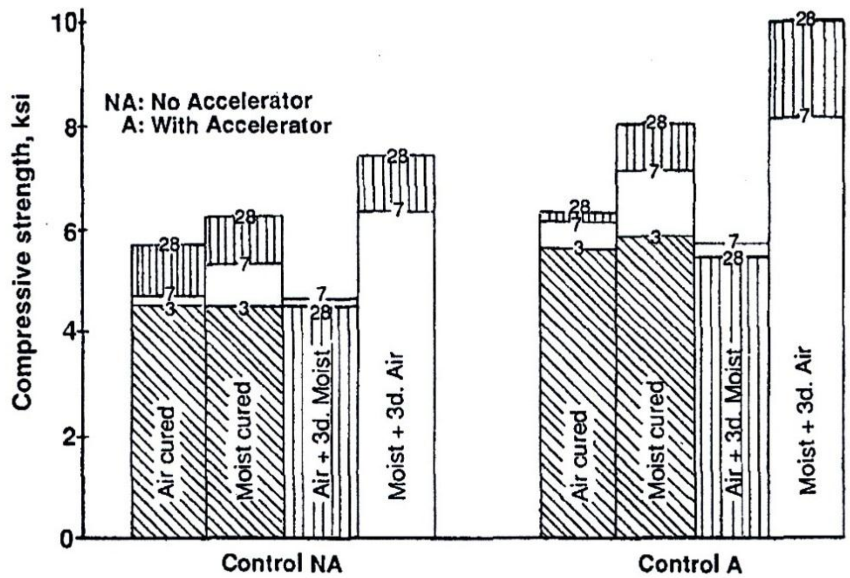

Figure 2.17: Effect of curing method on the compressive strengths of concretes (Popovics 1986).

ASTM D 1633 (2007) recommends to cure soil-cement samples in the molds in the moist room for 12 hours or longer until sample extrusion from the molds. The samples are to be returned to the moist room and protected from dripping water for the duration of the moist-curing period. Typically, the specimens are tested in the moist condition shortly after removal from the moist room.

2.4.4 Capping Concerns

The purpose of capping concrete cylinders, drilled concrete cores or other specimens is to provide plane surfaces on the ends of the specimens in order to meet planeness and perpendicularity requirements of applicable specifications and standards. ASTM C 617 (2009) requires gypsum plaster or sulfur mortar to be used for capping conventional concrete cylinders. The strengths of the capping materials are shown in Table 2.7.

Table 2.7: Compressive strength and maximum thickness of capping materials (ASTM C 617 2009)

Cylinder Compressive Strength, psi	**Compressive strength and maximum thickness of capping materials (ASTM C 617 2009)**		
	Minimum Strength of Capping Material	**Maximum Average Thickness of Cap**	**Maximum Thickness Any Part of Cap**
500 to 7000 psi	5000 psi or cylinder strength whichever is greater	1⁄4 in.	5⁄16 in.
greater than 7000 psi	Compressive strength not less than cylinder strength	1⁄8 in.	3⁄16 in.

ASTM C 1231 (2010) allows for unbonded neoprene caps for use in compression testing. The neoprene pads deform under initial loading and contour to the ends of the test cylinder. The metal pad retainers prevent excessive lateral spreading by restraining the pads. A near-uniform load distribution is obtained with the proper use of the neoprene pads. This system is not to be used for acceptance testing of cylinders with compressive strengths below 1,500 psi or above 12,000 psi (ASTM C 1231 2010).

Sauter and Crouch (2000) evaluated the use of different capping methods on Controlled-Low Strength Material (CLSM), which is defined as a mixture of soil, cementitious materials, water, and sometimes admixtures, that hardens into a material with a higher strength than the soil but less than 1,200 psi (ASTM D 4832 2002). The American Concrete Institute Committee 229 (1994) limits CLSM to 1,200 psi compressive strength at 28 days. The results on CLSM may be applicable to soil cement as their strength levels are more similar than conventional-strength concrete. The capping methods available for testing CLSM were gypsum cement, sulfur, neoprene pads, and no capping method. These capping methods were developed for conventional concrete testing, and most were inappropriate and difficult to use for the low strength material. Therefore, neoprene made from wetsuit material was used as an additional capping medium (Sauter and Crouch 2000).

Data from Sauter and Crouch (2000) show that both the non-air-entrained and air-entrained mixtures indicate comparible strengths and standard deviations for the neoprene caps and no-capping medium. Gypsum plaster strengths were roughly 25 percent higher than the neoprene and the no-capping method. However, the strength increases from the air-entrained mixtures show greater variability with the gypsum plaster and neoprene pad mixtures than the no-cap mixtures.

2.4.4.1 Sulfur Mortar and Gypsum Plaster Capping

Sauter and Crouch (2000) state that sulfur mortar along with gypsum capping methods resulted in many cylinders being damaged during capping due to the low strength and fragile nature of CLSM cylinders. The National Ready Mixed Concrete Association (NRMCA) has stated that the use of sulfur mortar was promoting early breaks and lower indications of strength values on CLSM cylinders. NRMCA (1989) also indicates that neoprene caps did not seat well on the cylinders and recommended high-strength gypsum plaster for CLSM.

2.4.4.2 Neoprene Pads

Sauter and Crouch (2000) indicate that unbonded capping methods, such as neoprene pads and no capping method, are up to 75 times faster than using gypsum plaster for a capping medium. Obviously, using no capping medium is the most time efficient.

Sauter and Crouch (2000) state that the standard 50 to 70 durometer neoprene pads are not flexible enough at the low stress levels produced by CLSM testing. The neoprene pads act more like a rigid plate mechanism than a material suitable for capping CLSM cylinders (Sauter and Crouch 2000).

Technicians working on the construction of the Denver International Airport observed that the use of unbonded neoprene caps did not provide reliable results for the low-strength CLSM test cylinders (Clem et al. 1994).

2.4.4.3 Fragility

Sauter and Crouch (2000) indicated that cylinders of low compressive strengths are fragile and can be difficult to work with while demolding, curing, and testing. ASTM D 4832 (2002) recommends careful handling of CLSM cylinders during mold removal and capping. Also, sulfur mortars should not be used for capping CLSM cylinders as the cap strength of sulfur caps is significantly greater than the CLSM cylinder which can lead to erroneous strength values (ASTM D 4832 2002).

2.4.5 Length-to-Diameter Ratio

As mentioned previously, ACI 230 (2009) states that the use of L/D of 2.00 provides a more accurate measure of compressive strength, because it reduces complex stress conditions that may occur during crushing of lower L/D specimens. Chung (1979) and Bartlett and MacGregor (1994a) and Meininger, Wagner, and Hall (1977) indicate that a core with an L/D less than two will fail in compression at a higher load than a similar core with an L/D of two.

This is a result from the axial compressive load from the steel platens of the testing machine promoting lateral expansion of the test specimen. Friction is created between the platens and the ends of the specimen and creates confining stresses that in turn constrain the lateral expansion of the cylinder or core. This creates a state of triaxial stresses in the concrete which increase the compressive strength of the specimen as the L/D decreases (Chung 1979). The maximum lateral strain will be found at midpoint of the specimen and decrease to zero at each end of the specimen (Chung 1979).

This effect can be seen in Figure 2.18 as the core specimen deforms to a barrel shape under loading due to the constrained ends and maximum lateral strain at midpoint. The dashed lines represent unrestrained lateral expansion of the core specimen at endpoints.

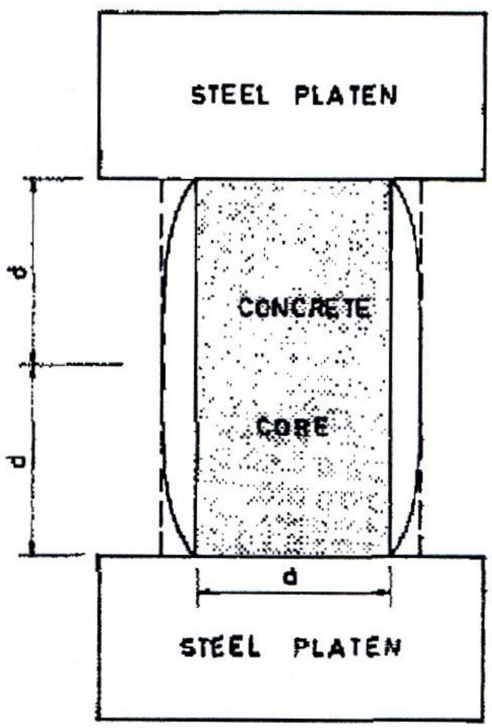

Figure 2.18: Deformation of concrete core relative to steel platens (Chung 1979)

Since this effect is seen mostly at the specimen ends and becomes negligible as the distance from the ends reach approximately $(\sqrt{3}/2)d$**,** the confining stresses at mid-length are zero for an L/D = 2. The compressive strength of the specimen is controlled by the unconfined stresses at mid-length, which in turn indicates that end restraint should not affect compressive strength values for specimens with an L/D of two (Chung 1979). The effect of end restraint is assumed to be negligible for L/D = 2 (Bartlett and Macgregor 1994a).

2.4.5.1 Diameter of Specimens

The L/D is much more significant as the diameter of the specimen decreases, as smaller diameters require greater correction factors (Arioz et al. 2007; Kesler 1959; Bartlett and MacGregor 1994). This could be a result from the reduction in volume of the smaller sample. Another consideration is the desire for core diameters to be at least 3 times the maximum aggregate size (Arioz et al. 2007). However, studies by Kesler (1959) indicate that specimens of different diameters showed no consistent difference regarding correction factors. Correction factors appeared similar for 3 in. or 6 in. diameter specimens (Kesler 1959). Arioz et al. (2007) states that correction factors are generally less than 1 for larger than standard diameters and greater than 1 for smaller than standard diameters.

2.4.5.2 Strength of Specimens

Kesler (1959) indicates that correction factors are strength dependent. Both Kesler (1959) and Bartlett and MacGregor (1994a) agree that lower strength concretes need greater L/D strength correction factors than high-strength concretes. This effect can be seen in Figure 2.19.

The lower the L/D the higher the apparent strengths become, resulting in a correction factor that furthers itself from 1.

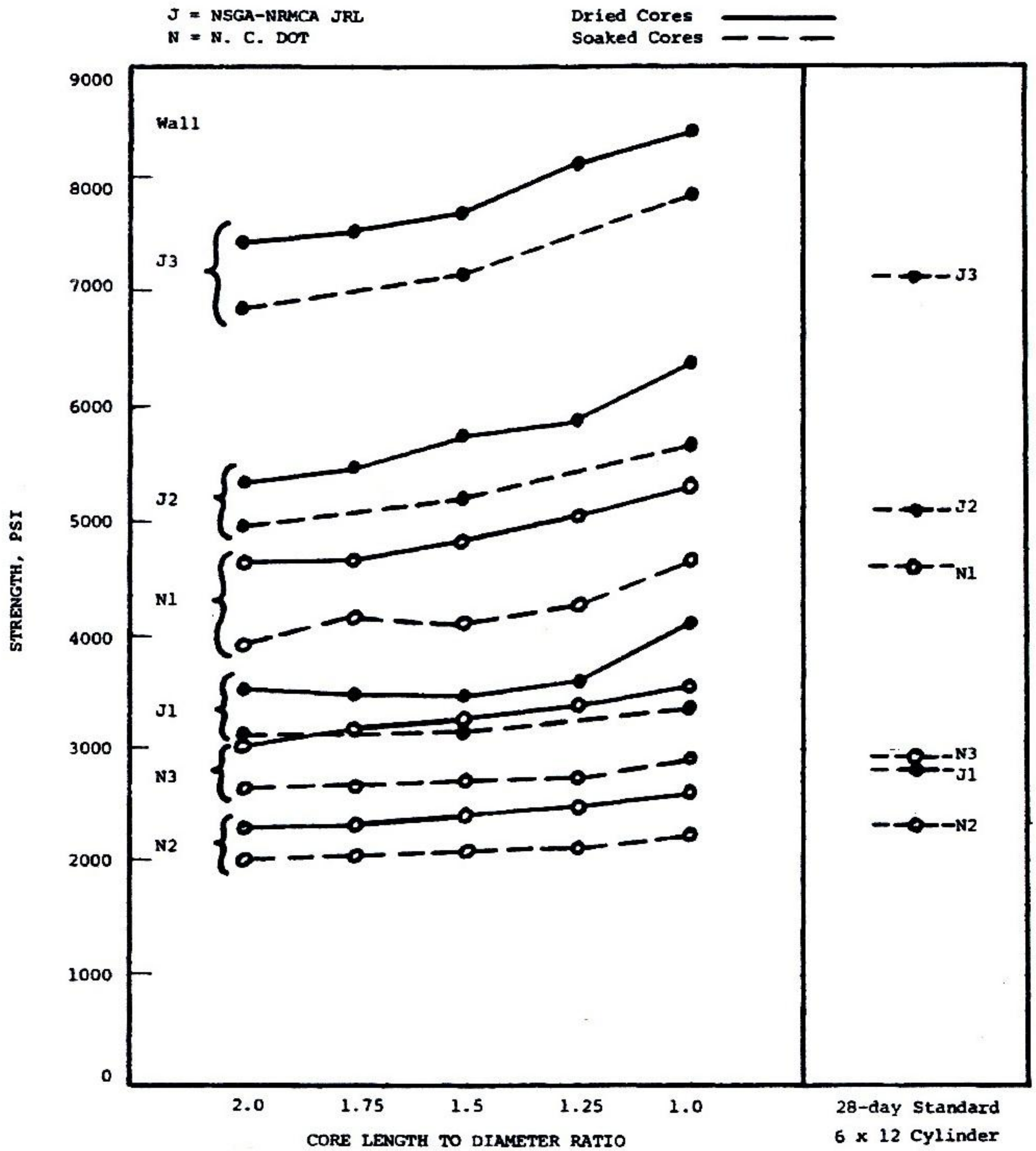

Figure 2.19: Effect of L/D on core strength (Meininger, Wagner, and Hall 1977)

2.5 Construction of Soil-Cement Base

2.5.1 Construction

ACI 230 (2009) states that in the construction of soil cement, the objective is to obtain a thoroughly mixed, adequately compacted, and cured material. Air temperatures above 45 ºF and subgrades that are not frozen are primarily the two major factors regarding climate for soil-cement construction. ALDOT (2012) requires that soil-cement base shall not be placed when the ambient ground temperature in the shade is below 40 °F. A light rainfall should not delay construction, and after the mixture has been compacted, rain is usually not detrimental (ACI 230 2009).

2.5.1.1 General Requirements

Soil cement is either mixed-in-place or mixed in a central-mixing plant. A transverse single-shaft mixer is commonly used for mixed-in-place construction, whereas a central-mixing plant will normally use a rotary-drum mixer or a continuous or batch-type pug mill. Researched performed by Mohammad et al. (2000) using 2.8 in. by 5.6 in. molded samples shows no significant difference in strengths obtained from plant-mixed and mixed-in-place soil cement.

2.5.1.2 Mixed-In-Place Method

Transverse single-shaft mixers are well-equipped to thoroughly pulverize and mix most types of soil, from granular to fine-grained. Figure 2.20 shows a typical single-shaft traveling mixer used in mixed-in-place construction. These mixers are designed for roadway applications, whereas agricultural-type equipment is generally not recommended. Agricultural equipment has been shown to provide poor mixing quality in soil-cement applications (ACI 230 2009). Soils with higher fine contents are generally more difficult to pulverize and mix. In some cases, the mixed-in-place method has been shown to have lower strength values than those obtained in the laboratory, therefore in these circumstances, an increase in 1 or 2 percent cement content may compensate for the in efficiency of the mixing method (ACI 230 2009).

Figure 2.20: Single-shaft traveling mixer used in mixed-in-place construction (Halsted et al. 2006)

In order to support the compaction equipment, all soft or wet subgrade areas should be located and stabilized (Halsted et al. 2006). It is also critical that stumps, roots, organic soils, and aggregates larger than 3 in. be removed from the roadbed before mixing is started.

Bulk distribution of cement is obtained by using a mechanical spreader. The main intent of the cement-spreading operation is to provide a uniform distribution of the cement to the roadbed. The mechanical spreader must be operated at a uniform speed with a consistent amount of cement dispensed to the roadbed. Generally, the amount of cement required is specified as a percentage by weight of oven-dry soil, or in pounds of cement per cubic foot of compacted soil cement (ACI 230 2009). Cement is being applied to the roadbed by a spreader truck in Figure 2.21.

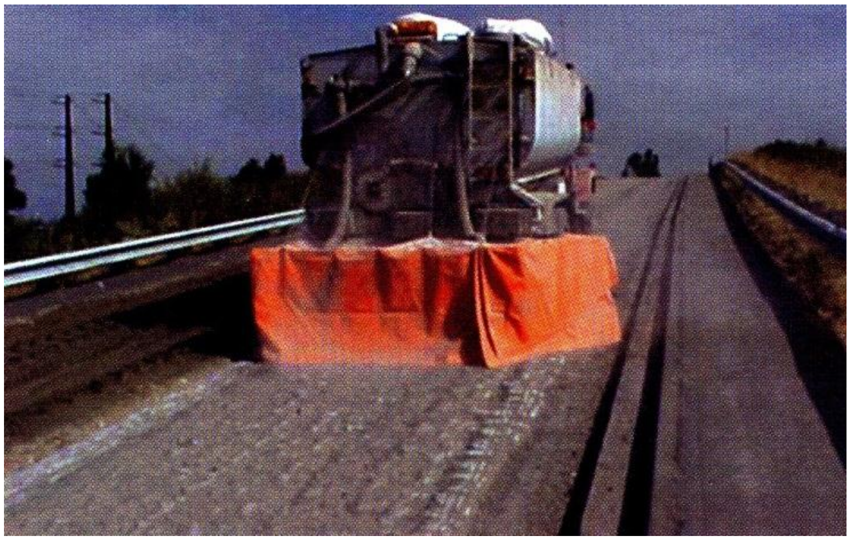

Figure 2.21: Application of cement to roadbed by mechanical spreader (Halsted et al. 2006)

2.5.1.3 Central-Mixing Plant Method

The two basic types of central plant mixers are pug-mill and rotary-drum mixers. Figure 2.22 details the pug-mill mixing operation, a more common type of central plant setup. Generally, a central-mixing plant will include a soil stockpile, conveyor belts that deliver the soil and cement to the pug-mill mixer, a cement storage silo with surge hopper, a pug-mill mixer, a metered water source and a storage hopper to temporarily store the mixed soil cement.

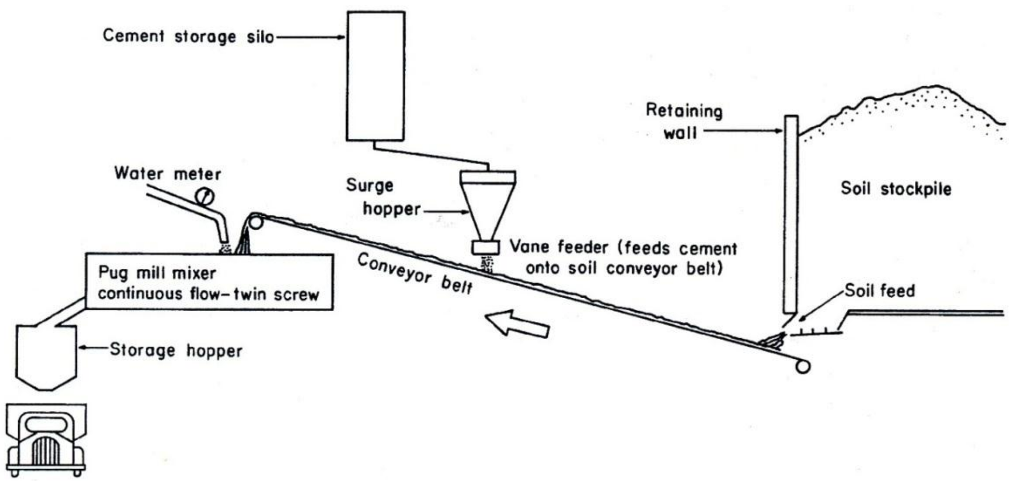

Figure 2.22: Diagram of pug-mill mixing operations (ACI 230 2009)

The mixing chamber of the pug-mill includes twin parallel shafts with paddles selectively placed along each shaft. Each shaft rotates in opposite directions of one another, and the materials are moved through the mixer and mixed thoroughly by the paddles. Figure 2.23 shows a typical twin-shaft parallel mixer. ACI 230 (2009) states that standard production rates vary between 200 and 800 tons per hour with this type of mixer.

Figure 2.23: Twin-shaft pug-mill mixing chamber (Halsted et al. 2006)

Central-mixing plants are generally used for projects which involve the use of borrow materials. Granular borrow materials are preferred due to their low cement requirements and ease in mixing. Most soil borrow sites are located near the construction site or roadway. In general, natural soil deposits usually do not consist of homogenous and uniform materials. Therefore, mixing for gradation uniformity is usually in demand for most borrow materials. This can be done at the plant location with the help of bulldozers and front-end loaders. Successful blending of borrow materials at the stockpile can be easily obtained. An adequate check for unsuitable materials should be performed routinely to ensure that large particles and clay balls are removed. Most plants will have a 1” to 1-1/2” mesh to screen the material before mixing.

Adjustments such as material feed, belt speed, and paddle pitch are monitored to optimize the mixing in the pug mill. The controlling factor in central plant mixing is the length of time the material is blended in the pug mill. Minimum blending times of 30 seconds are often specified; however, satisfactory blending has been achieved in shorter periods, depending on the efficiency of the mixer (ACI 230 2009). ALDOT requires mixing plants use a minimum 30 second net mixing time (ALDOT 2012). Blending time is an important factor, since it is standard practice that no more than 60 minutes should elapse between the addition of water to the cement and the start of compaction. ALDOT recommends that soil-cement base shall be delivered and spread within 45 minutes after mixing, and if a mixture has not been compacted within three hours of placement it is to be rejected and removed at the contractor’s expense (ALDOT 2012). Most haul times are usually limited to 30 minutes (ACI 230 2009).

Once the material has reached the jobsite, the soil cement should be placed on a pre-moistened, firm subgrade in sufficient quantity that will meet requirements for design uniform thickness and density. Once the material has been placed on the roadbed, a motor grader or dozer with a spreader box attached will spread the material. Figure 2.24 shows a motor grader spreading the plant-mixed soil-cement base before compaction efforts take place. In some states spreading may be done with asphalt-type pavers as well (ACI 230 2009). Placement is usually 25 to 50 percent thicker than design thickness, depending upon soil type, degree of compaction, and contractor experience.

Figure 2.24: Spreading operations (Halsted et al. 2006)

2.5.1.4 Compaction

Compaction starts as soon as possible and is desired to be completed within 2 hours of the addition of water to cement at initial mixing. The detrimental effects of delayed compaction on density and strength have already been described in Section 2.3.1. In order to obtain maximum density, it is standard practice to compact the soil-cement mixture at or near optimum moisture content as determined by ASTM D 558. Standard practice requires soil-cement base to be compacted to a minimum of between 95 and 98 percent of maximum density. Transportation agencies in Alabama and Georgia require soil-cement base to be compacted to within two percentage points of optimum as determined by the required laboratory test (ALDOT 2012; GDT 301 2003).

The primary types of rollers used for soil cement are sheepsfoot rollers, multiple-wheel, rubber-tire rollers, and steel-wheeled vibratory rollers. Standard practice for fine-grained mixtures requires the sheepsfoot roller for initial compaction, followed by the rubber tire roller for finishing. Examples of these rollers are found in Figures 2.25 and 2.26, respectively.

Figure 2.25: Sheepsfoot roller used to compact soil-cement base (FHWA 2011)

Figure 2.26: Multiple-wheel, rubber-tire roller used to compact soil-cement base (Dynapac 2012)

Coarse-grained or granular soils require the vibratory roller for compaction. Finishing usually requires a steel-wheeled roller without vibration. Most designs require a layer thickness ranging from 6 to 9 inches. Compactive effort continues until the required density is achieved (ACI 230 2009). A vibratory steel-wheel roller is shown in Figure 2.27.

Figure 2.27: Steel-wheel vibratory roller used to compact soil-cement base (Halsted et al. 2006)

2.5.1.5 Finishing and Curing

Once the density requirement is obtained and compaction is nearing completion, grade requirements and cross sections are finalized and curing is started. The curing of soil cement is of great importance since the strength gain of the mixture is dependent upon time, temperature, and the presence of water. As previously stated, drying shrinkage can occur if curing conditions are inadequate. Strength gain due to the hydration of the cement requires a moist environment. ALDOT requires soil-cement base to be kept moist enough for proper curing. Curing has to start once compaction and finishing have been completed. Typically, the soil-cement base is allowed to cure for 3 to 7 days before construction is allowed to continue. During this time, light traffic is generally allowed on the soil-cement base as long as the curing seal is not compromised.

Standard practices for most soil cement curing applications are water-sprinkling or bituminous coatings. By keeping the surface sprinkled with water, along with light rolling to seal the surface, the soil-cement base can maintain moisture levels adequate to promote appreciable strength gain. A bituminous prime coat usually consists of asphalt emulsion or cutback asphalt. Typically, the application rates vary from 0.15 to 0.30 gallon per square yard (ACI 230 2009). If the soil-cement base is opened to traffic after a bituminous coating has been applied, a light sanding of the surface will prevent tracking of the prime coat. Other curing methods that are successful are covering the soil-cement base with wet burlap and plastic tarps, a method used in concrete curing practices. Climate requirements demand that soil-cement base be protected from freezing during the curing period (ACI 230 2009).

2.5.2 Quality Control Testing and Inspection

Quality control is necessary to ensure that the soil-cement base will meet the requirements of the design of the roadbed. It is also an in-place check system to ensure that the contractor has performed work within the requirements of the design plans and specifications. Field inspection of soil-cement base construction involves controlling the following properties (ACI 230 2009):

- Cement content,
- Moisture content,
- Mixing uniformity,
- Compaction,
- Lift thickness and surface tolerance, and
- Curing.

2.5.2.1 Cement Content

Typically, in mixed-in-place construction, cement is placed using bulk cement spreaders. A check on the accuracy of the cement spread is made in by spot-checking or by area calculations after a truckload of cement has been distributed. Spot-checking involves placing a sheet of canvas with known dimensions ahead off the spreader. The spreader applies cement to the surface of the canvas, which is then weighed and cement rates are calculated and adjusted if necessary.

In a central-mixing plant operation, cement is weighed before being transferred to the mixer. Usually, weighing scales are located on the conveyor belt. By checking the accuracy of the scale on the belts, feed rates can be adjusted to maintain proper cement flow rates (ACI 230 2009).

2.5.2.2 Moisture Content

Optimum moisture content obtained from ASTM D 558 is typically used for field control of moisture content during construction. Standard practice allows for roughly 2 percent additional moisture to be added to the material to account for cement hydration and evaporation.

Moisture content estimation is fairly empirical. Estimations of moisture content by look and feel are quite common in quality control practices for soil-cement base construction. Standard practice states that a soil-cement mixture that is near or at optimum moisture content will leave your hands slightly damp when the material is squeezed in a tight ball. Material that is above optimum moisture content will appear wet and leave excess water on the hands. Soil-cement mixtures that are below optimum will appear dry and easily crumble. It is possible to determine actual moisture content by oven-drying material using conventional or microwave ovens. Visually, the compacted soil cement will appear to have a smooth, moist, tightly knit surface free of cracks and surface dusting if the moisture content is within optimum moisture content tolerances (ACI 230 2009). ALDOT (2012) requires moisture content at the time of in-place density tests to be within ± 2% of the laboratory moisture content obtained from ASTM D 558 (2004).

2.5.2.3 Mixing Uniformity

In mixed-in-place construction, mixing uniformity is typically checked by digging a series of holes and inspecting the color of the exposed material. A streaked appearance of the exposed material indicates insufficient mixing. Depth checks are made routinely to ensure proper thickness is achieved.

For central-plant-mixed soil cement, mixing uniformity is often visually inspected on the conveyor belts at the mixing plant. Obviously, mixing uniformity can also be checked at the roadbed (ACI 230 2009).

2.5.2.4 Compaction

Standard practice requires the soil-cement mixture to be compacted at or near optimum moisture content to a specified minimum percent of maximum density. Field density requirements range from 95 to 100 percent of the maximum density obtained in the laboratory by ASTM D 558. The most common methods for determining in-place density are the nuclear density gauge (ASTM D 6938), the sand-cone method (ASTM D 1556), and the balloon method (ASTM D 2167). In-place densities are measured at various locations depending upon agency requirements. The measurements are taken immediately following initial rolling, and continue until specification tolerances are met. Adjustments in compactive efforts are made based upon field density results and their comparison to laboratory values (ACI 230 2009).

ALDOT requires in-place density measurements to be taken with a nuclear gauge, with the sand-cone method as an alternate in-place density measurement (ALDOT 2012). Figure 2.28 shows a typical nuclear-gauge density measurement.

Figure 2.28: Nuclear Density Measurement (FHWA 2011)

2.5.2.5 Lift Thickness and Surface Tolerance

Compacted lift thickness is measured similar to checking for mixing uniformity. Another method for determining lift thickness is to core the fully-cured soil-cement base.

Surface tolerances or smoothness is typically measured with a 10 or 12 ft straightedge or surveying equipment. Many state transportation departments have limited the maximum departure from a 12 ft or 10 ft straightedge to about 3/8 in. Also, departures from design grade of up to 5/8 in. are usually allowed (ACI 230 2009). ALDOT requires that the finished surface of soil-cement base should not vary more than 1/2 in. in any 25-foot distance (ALDOT 2012).

Chapter 3

Experimental Plan

3.1 Introduction

It is the objective of this research project to determine if conventional concrete testing practices can be used to effectively provide consistent data when testing field-molded soil cement samples in compression. In order to accomplish this objective, a field and laboratory testing program was developed to evaluate the compressive strength of soil-cement mixtures. At the time this research was initiated, several soil-cement projects were available for research advancement. However, shortly after field work began, many projects were reconsidered and other methods than soil-cement bases were used. The lack of field projects using central plant soil-cement construction led to moving the research into the laboratory.

This chapter provides an overview of the experimental testing program. The soil-cement mixtures used are described and their mixture proportions are defined. The development of the procedure for making soil-cement compression test specimens in the field is discussed. A detailed description of testing procedures and apparatus are presented. Finally, details of sample preparation and curing methods are covered.

3.2 Experimental Testing Program

In the attempt to determine if it is possible to approach strength testing of soil-cement base like conventional concrete, the experimental testing program is defined. Soil-cement mixtures that were evaluated are defined, along with the field and laboratory testing. The pre-conditioning impact study, suitable curing study, capping study, and L/D study are all defined in this section.

3.2.1 Soil-Cement Mixtures Evaluated

3.2.1.1 Field Mixtures

The field mixtures evaluated for this research are shown in Table 3.1. These data were obtained from design studies provided by the Georgia Department of Transportation. This information was presented at the time of field molding specimens at the jobsite and was used in the development of mixtures made for each specific field project. Additional information including design curves and gradation analyses can be found in Appendix A.

Table 3.1: Mixture properties of field mixtures

Pit Location	Mixture properties of field mixtures		
	Cement Content, %	Optimum Moisture Content, %	Maximum Dry Density, lb/ft^3
Blakely	7	9.2	117.8
Jesup	5	14.1	115.3

3.2.1.2 Laboratory Mixtures

The laboratory mixtures include Blakely and Dothan materials at 5, 6, and 7 percent cement contents. The cement contents, optimum moisture contents, and maximum densities are shown in Table 3.2. These data were obtained from design studies provided by the Georgia Department of Transportation and the Alabama Department of Transportation. This information was used in the development of mixtures made in the laboratory. The field mixture for the

Blakely design was also used for laboratory efforts. Additional information including design curves and gradation analyses can be found in Appendix A.

Table 3.2: Mixture properties of laboratory mixtures

Pit Location	**Mixture properties of laboratory mixtures**		
	Cement Content, %	**Optimum Moisture Content, %**	**Maximum Dry Density, lb/ft^3**
Blakely	5	9.5	115.8
Blakely	6	9.7	116.7
Blakely	7	9.2	117.8
Dothan	5	11.0	123.8
Dothan	6	11.0	123.1
Dothan	7	11.8	122.0

3.2.2 Field Testing

The objective of the field testing program was initiated to determine the effects of no capping method (NC), gypsum plaster (GP), and neoprene pads (NP) on the compressive strength of soil cement cylinders. Two field projects in Georgia were evaluated for strength assessment of soil-cement base. Project locations were US-27 in Blakely, GA, and US-84 in Jesup, GA. This research involved travelling to the jobsite and making field-molded cylinders from plant-mixed material. Field samples were made in a mobile laboratory shown in Figure 3.1.

Figure 3.1: Sample compaction at field location

The cylinders were initially cured at the jobsite and transported the following day to the laboratory. Samples were de-molded with the smaller vertical hand jack and placed in the moist room for final curing. Samples were tested in compression at 3, 7, and 28 days. One third of the specimens were capped with gypsum, one third of the specimens were tested using neoprene pads, and the final third of the specimens were tested with no capping medium.

3.2.3 Laboratory Testing

After obtaining several 55–gallon drums of stockpile and borrow pit material, soil-cement production initiated in the laboratory with the following criteria

- Blakely and Dothan were the two soil materials used for the testing,
- Cement contents of 5, 6, and 7 percent were used to include typical design cement contents,
- Each mixture had two replicates, and
- After removal from the molds, all specimens were moist cured until the appropriate time of testing or specific pre-test conditioning.

3.2.3.1 Pre-Conditioning Impact

The pre-conditioning impact of curing on molded cylinders was evaluated to determine the effects of moist curing, bag curing, fan curing, and air curing on the 7-day compressive strength of soil-cement cylinders. This study was performed to determine if there were any characteristic differences in curing specimens in a moist environment, a sealed, plastic bag, in front of a fan, or sitting on the counter in the laboratory. Three laboratory mixtures with two batches each using material from Dothan at cement contents of 5, 6, and 7 percent were evaluated. A large vertical hand jack was used to de-mold the specimens, and the samples were moist-cured until day six of the curing time and then subjected to the required curing variable. A set of 6 cylinders were used for each curing variable for a total of 24 cylinders per mixture. The methods used to obtain different curing conditions are as follows:

- Moist-Cured: Specimens were continually moist-cured until time of testing.

- Bag-Cured: Specimens were continually moist-cured until day 6 and then removed from the moist room and placed into sealed plastic bags in a controlled temperature and humidity room until time of testing.
- Air-Cured: Specimens were continually moist-cured until day 6 and then removed from the moist room and placed in a controlled temperature and humidity room until time of testing.
- Fan-Cured: Specimens were continually moist-cured until day 6 and then removed from the moist room and placed in front of a fan set at low speed until time of testing.

3.2.3.2 Suitable Curing

Following the pre-conditioning impact study, a suitable curing method for the molded cylinders was evaluated. A further continuation of the pre-conditioning impact study using moist-curing and bag-curing was performed to determine if there was any major differences in curing specimens in a moist environment compared to curing specimens in a sealed, plastic bag. This study consisted of six laboratory mixtures with 2 batches each. This study involved using material from Blakely and Dothan with cement contents of 5, 6, and 7 percent for each source. A large vertical hand jack was used to de-mold the specimens, and the samples were moist-cured until the appropriate time of testing or conditioning. Samples were tested in compression at 3, 7, and 28 days. The day before testing, half of the samples to be tested were removed from the moist-curing room and individually placed into plastic bags for further curing. A set of 5 cylinders were used for each curing variable for a total of 30 cylinders per mixture. The methods used for each curing condition is as follows:

- Moist-Cured: Specimens were continually moist-cured until time of testing.
- Bag-Cured: Specimens were continually moist-cured until the day before testing and then removed from the moist room and placed into sealed plastic bags in a controlled temperature and humidity room until time of testing.

3.2.3.3 Capping

Next, a suitable capping method was evaluated. Neoprene and gypsum plaster were evaluated for use as capping methods along with no capping substrate used for the compression testing of the cylinders. This study was performed to determine if there were any characteristic differences in testing specimens with various capping methods. This study consisted of nine laboratory mixtures using material from the Blakely Pit with cement contents of 5, 6, and 7 percent. The hydraulic jack was used to de-mold the specimens, and the samples were moist-cured until the appropriate time of testing or capping. Samples were tested in compression at 3, 7, and 28 days. A set of 5 cylinders were used for each capping method for a total of 30 cylinders per mixture. The following different capping methods were evaluated:

- Neoprene pads,
- Gypsum plaster, and
- No capping medium.

3.2.3.4 Length-to-Diameter Ratio

The effect of length-to-diameter reduction factors was evaluated by the making of six laboratory mixtures with two batches each. This study involved using material from Blakely and Dothan with cement contents of 5, 6, and 7 percent for each source. This phase of testing incorporated the use of a large vertical hand jack. Samples were moist-cured until the time of testing. Length-to-diameter ratios (L/D) of 2.0, 1.75, 1.5, 1.25 and 1.0 were used to evaluate the 7-day compressive strengths of the cylinders. Aluminum spacer disks were manufactured and placed into each mold for use in obtaining the desired specimen L/D. These can be seen in Figure 3.2.

Figure 3.2: Aluminum spacer disks for the L/D study

Since the diameter of the specimen remained constant at 2.8 inches, volumetric mixture calculations were adjusted for each L/D and specimens were made based upon desired heights. A set of 6 cylinders were used for each L/D for a total of 30 cylinders per mixture.

3.3 Development of Procedure for Making Soil-Cement Compression Test Specimens in the Field

Based on the findings of this research, a strength testing guideline was prepared for the use of field-molded cylinders as a pay item by verifying the quality of the soil-cement base delivered to the paver at the jobsite. There were several changes and alterations made to ASTM D 1632 in order to apply the specimen molding and curing procedure to field applications.

Sampling material from the paver, determining if the material is within the moisture window to achieve 98 percent density or higher and the use of ultra-high molecular weight polyethylene (UHMW) plugs to prevent moisture from escaping the molds during initial curing at the project jobsite are the primary issues regarding the making of molded soil-cement cylinders in the field.

Other modifications and issues regarding special provisions to the procedure are discussed in detail in Section 3.4.3. Further discussion regarding the procedure and its implementation are provided in Chapter 5. The common goal of preparing soil-cement specimens for compressive strength testing in accordance with ASTM D 1633 is accomplished by producing molded cylinders which are 2.8 in. in diameter and 5.6 in. in length.

3.3.1 Sampling Material from the Paver

The material sampled from the paver was taken in shovel-size quantities from random locations in the hopper and placed into a five-gallon bucket. Figure 3.3 shows a paver hopper where samples were obtained to form a composite sample.

Figure 3.3: Paving hopper from soil-cement construction

To prevent moisture loss, the bucket was completely filled and the lid was placed on the bucket directly after the last portion of the sample was obtained. The bucket was then transported to the testing location where the test specimens were to be molded. The sample was protected from the sun, wind, and other sources of evaporation and contamination during the preparation of the specimens. A typical composite sample from field testing is shown in Figure 3.4.

Figure 3.4: Composite sample of soil-cement mixture in 5-gallon bucket

3.3.2 Determining the Mass of Soil-Cement Specimens

Initially, the mass of soil cement required for specimens was determined from the plant's daily moisture content sample. From that moisture content, the mass of material for a specimen was computed volumetrically. However, fluctuations of moisture contents throughout the day made it necessary to amend this method and perform a moisture content test (ASTM D 4959) on the obtained composite field sample. This gave a better indication of moisture present in the field sample. The determination of whether the composite sample's moisture content fell within the 98 percent range of optimum moisture content (OMC) was performed by using OMC curves previously plotted from the design mixture. Figure 3.5 shows the allowable moisture content range, which is a range of upper and lower moisture limits that border the 98 percent density values on the compaction curve.

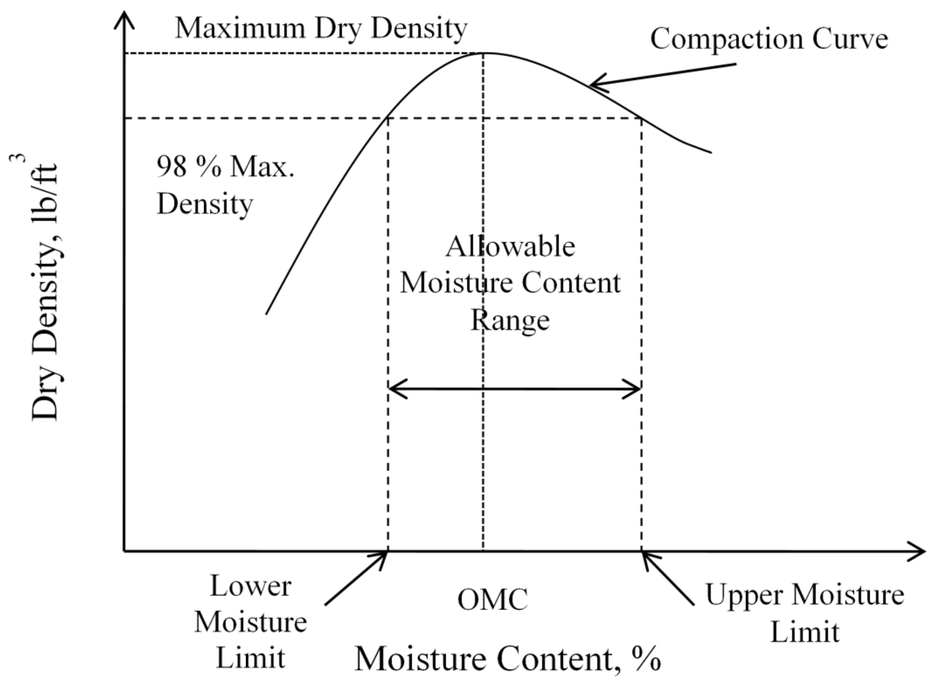

Figure 3.5: Allowable Moisture Content Range

If the moisture content of the composite sample was within the allowable moisture content range, the mass of soil-cement was determined by using the dry unit weight corresponding to composite sample moisture content in lb/ft^3 and converting it to g/in^3. The volume of the specimen molds for molding test specimens is 2.8 in. in diameter by 5.6 in. high. This provides a sample volume of 34.5 $in.^3$. This gives the following equations for determining the mass of soil-cement material needed for making the test specimens:

$$M_{sc} = \left(\gamma_{dry}\frac{lb}{ft^3}\right) X \left(\frac{1 ft^3}{1728 in.^3}\right) X \left(\frac{1kg.}{2.2046 lb}\right) X \left(34.5 in.^3 \, X \, \frac{1000g}{1kg}\right) \quad \textbf{Equation 3.1}$$

which reduces to $$M_{sc} = 9.056\gamma_{dry}\frac{lb}{ft^3} \quad \textbf{Equation 3.2}$$

where,

M_{sc} = mass of soil-cement (gram), and

γ_{dry} = dry unit weight corresponding to composite sample moisture content, lb/ft^3.

If the moisture content of the composite sample falls outside the allowable moisture content range, the following steps are taken:

- Below the Lower Moisture Limit — material is too dry and composite sample is discarded. The Project Engineer is notified that the material delivered to the paver is at a moisture content lower than required to obtain 98% of the maximum dry unit weight.
- Above the Upper Moisture Limit — material is too wet and sample needs to be spread out on clean, non-absorbent plastic sheeting to dry to a moisture content which falls within the moisture window to achieve 98 percent density or higher.

Once the material has been determined to be within the 98 percent range of OMC, the material was used to prepare cylindrical compression testing samples.

3.3.3 UHMW Plugs

The addition of mold plugs, similar in shape to the top and bottom pistons, having a diameter 0.005 in. less than the mold, machined from waterproof, UHMW polyethylene were used to prevent moisture from escaping the molds during initial curing periods, as well as fill the air voids left in the mold by the removal of the top and bottom pistons. UHMW is a very tough and non-corrosive material that has extremely low moisture absorption along with a low coefficient of friction. Waterproof, metal foil tape was placed around the joints between the plug and mold to seal mold plugs to the specimen mold and prevent moisture from escaping during the initial curing period. Mold plugs are shown in Figures 3.6 and 3.7.

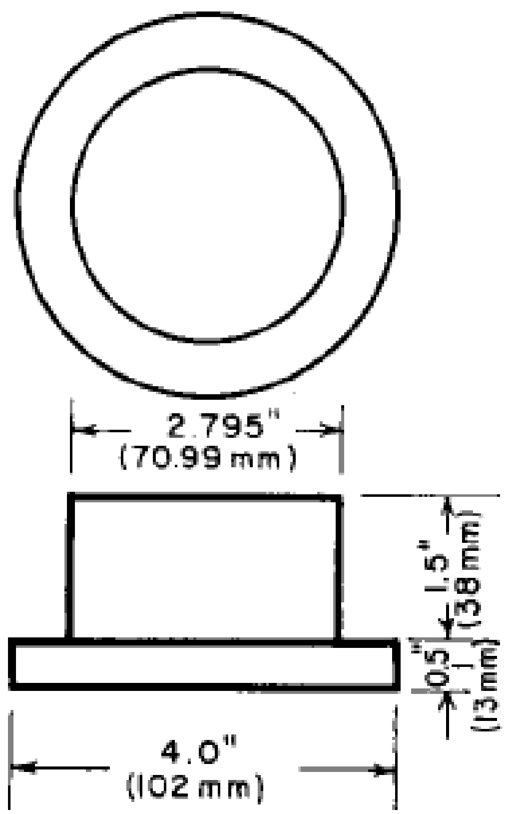

Figure 3.6: UMHW Mold Plugs (Adapted from ASTM D 1632)

Figure 3.7: UMHW Mold Plugs

3.4 Experimental Procedures

3.4.1 Production of Soil Cement in the Field

Initially, two field projects were evaluated for assessment of strength of soil-cement base. Project locations were US-27 in Blakely, GA, and US-84 in Jesup, GA. The primary additions and modifications to ASTM D 1632 for field use include the procedure for sampling material from the paver, determining the moisture window to achieve 98 percent density or higher, and the use of ultra-high molecular weight polyethylene (UHMW) plugs to prevent moisture from escaping the molds during initial curing at the project jobsite.

3.4.2 Production of Soil-Cement Mixtures in the Laboratory

Several 55-gallon drums of soil were taken from stockpiles and borrow pits related to the field projects. The stockpile of material at the Blakely Pit is shown in Figure 3.8.

Figure 3.8: Sampling stockpile at Blakely Pit

The borrow pit material from the US 27 – Blakely, GA and AL 52 – Dothan, AL projects were used for several aspects of this research. The portland cement used for this research was a Type I/II manufactured by LaFarge North America. Water obtained from the laboratory was used in making the soil-cement specimens.

3.4.2.1 Batching

Prior to mixing soil cement in the laboratory, a sufficient amount of soil material was removed from the drum and placed into a large, square metal pan. The material was mixed thoroughly and a representative moisture content sample was obtained and tested. Once the moisture content was determined to be within the moisture window to achieve 98 percent density or higher, the batch weights were determined. The proper amount of soil, cement, and water were batched by weight and prepared for mixing.

3.4.2.2 Mixing

Mixing was achieved in the laboratory by using a 60-quart, Hobart mixer. This mixer is shown in Figure 3.9. The soil material was weighed to the nearest gram and placed into the mixing bowl.

Figure 3.9: Hobart 60-quart mixer

The mixer was powered and set on its lowest setting. Water was weighed and added to the soil in the mixer if necessary. While the soil and water were mixing, cement was weighed and carefully placed into the mixer in small amounts. Once all the cement had been placed into the mixer, the materials were mixed on low speed for an additional two minutes. This was followed by a one-minute mixing of materials at the medium speed setting on the mixer. A three-minute rest period followed, and the final mixing of two minutes at low speed adequately mixed soil cement for sample preparation. This mixing method is a similar method to method outlined in ASTM C 192. The mixing bowl and paddle used in this project can be seen in Figure 3.10.

Figure 3.10: Soil and water being mixed in mixer bowl

After mixing was completed, the material was deposited into a clean, damp, metal pan, and remixed with a hand scoop, as shown in Figure 3.11.

Figure 3.11: Soil-cement in pan

3.4.3 Common Practices

The remaining practices are considered common to both field and laboratory mixing.

3.4.3.1 Sample Preparation

Sample preparation followed ASTM D 1632 rather closely. Molds having an inside diameter of 2.8 ± 0.01 in. and a height of 9 in. for molding test specimens 2.8 in. in diameter and 5.6 in. high were used for making specimens. ASTM D 1632 suggests that "compression test specimens shall be cylinders with a length equal to twice the diameter." According to ACI 230 (2009), the L/D of 2.00 reduces complex stress conditions that may occur during crushing of lower L/D specimens. The molds also included machined steel top and bottom pistons having a diameter 0.005 in. less than the mold, a 6-in. long mold extension, and a spacer clip. Two aluminum separating disks 1⁄16-in. thick by 2.78 in. in diameter were also used in specimen preparation. Specimen molds are shown in Figures 3.12 and 3.13.

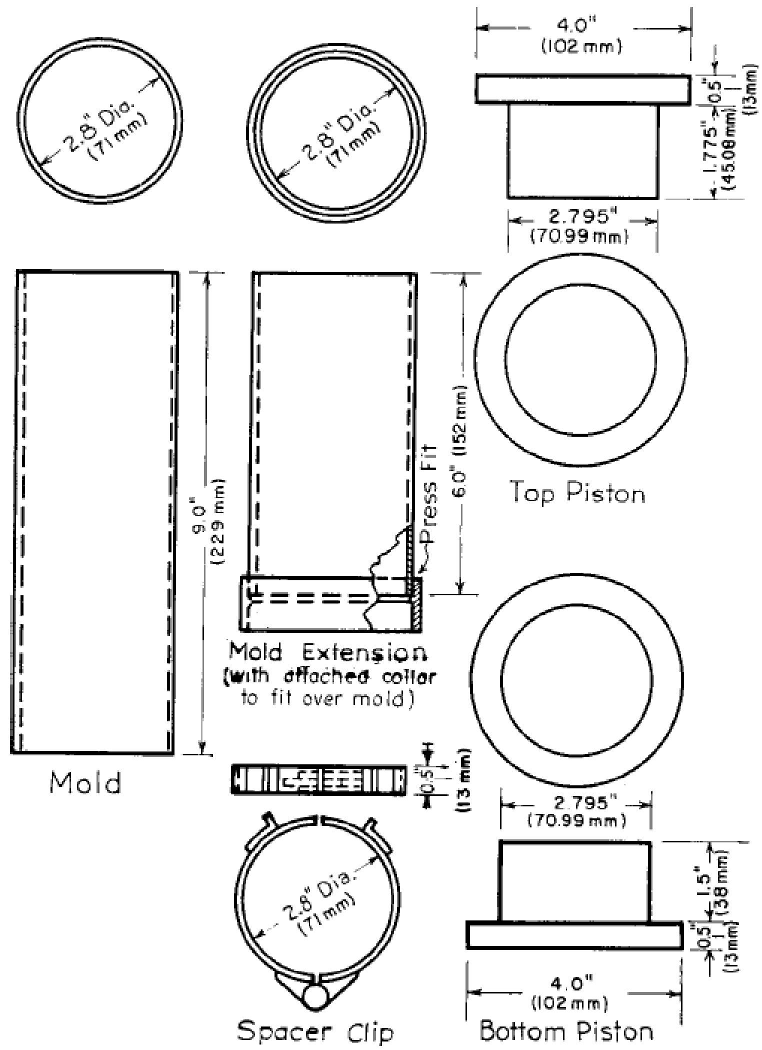

Figure 3.12: Soil-cement cylinder mold (ASTM D 1632 2007)

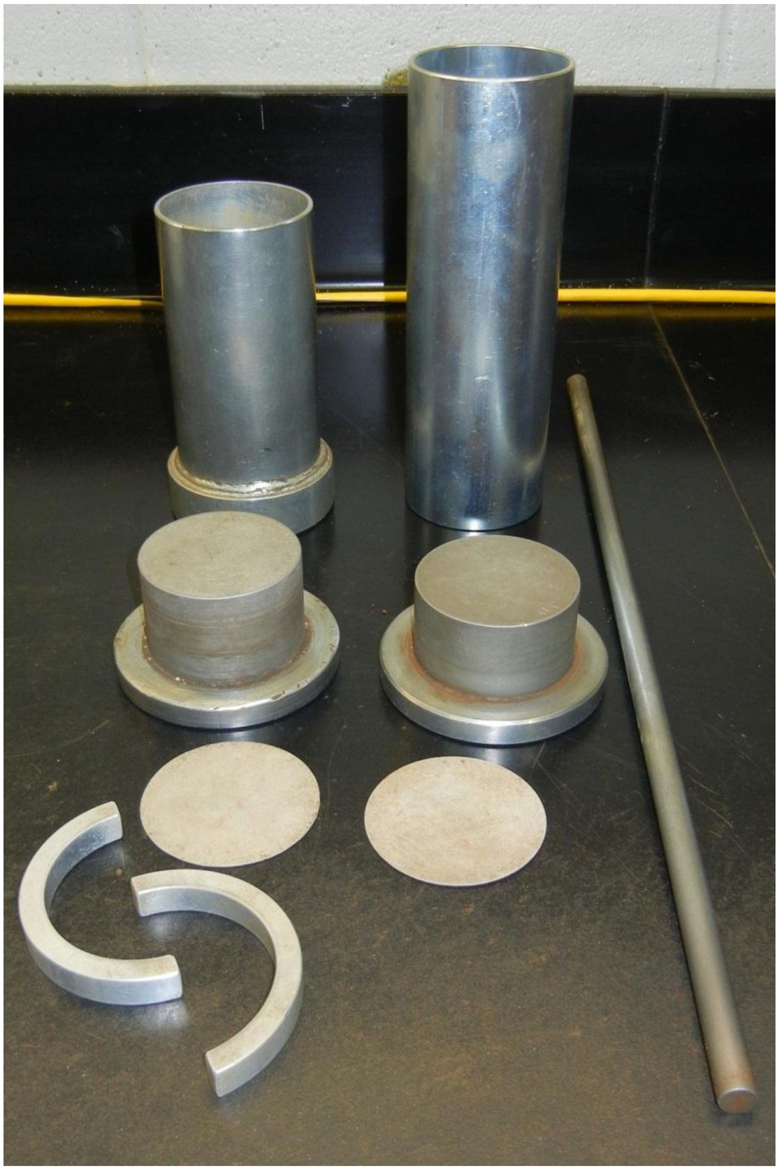

Figure 3.13: Soil-cement cylinder mold

A typical dropping-weight compacting machine consisting of a 15 lb. hammer which meets the requirements of ASTM D 1632 was used for the field and laboratory testing. This testing machine can be seen in Figure 3.14.

Figure 3.14: Dropping-weight compacting machine with mold

Specimen molds and separating disks were lightly coated with a low-viscosity oil. The molds were put together in standard fashion with the spacer clips installed between the bottom piston and the mold. A separating disk was placed into the mold and the extension sleeve was placed on top of the mold. The mold was placed on the scale and the predetermined amount of soil-cement mixture was placed into the mold, as shown in Figure 3.15.

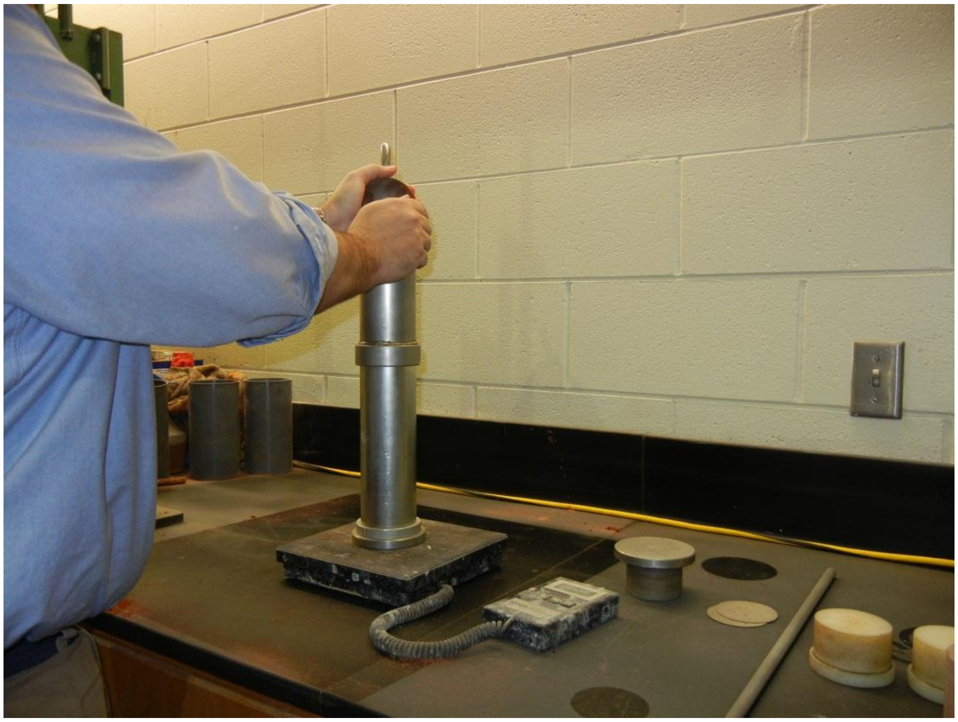

Figure 3.15: Soil-cement mixture being placed into the mold

The soil-cement mixture was then compacted initially from the bottom up by steadily and firmly forcing (with little impact) a square-end cut 1⁄2 in. diameter, smooth steel rod repeatedly through the mixture from the top down to the point of refusal, the roddings being distributed uniformly over the cross-section of the mold. This can be seen in Figure 3.16.

Figure 3.16: Soil-cement mixture being rodded uniformly over the cross section of the mold

Once the mass is packed out to a height of approximately 6 in., the extension sleeve was removed and a separating disk was placed on the surface of the soil cement. The spacer clip supporting the mold on the bottom piston was removed, and the top piston was placed on top of the mold.

Figure 3.17 shows a dynamic load being repeatedly applied by the compacting device until refusal by evidence of the top and bottom pistons being in contact with the edges of the specimen mold.

Figure 3.17: Soil-cement mixture being compacted until refusal

The pistons and separating disks were removed from the mold assembly, and UHMW mold plugs were inserted into each end of the mold, as seen in Figure 3.18.

Figure 3.18: Molded specimens before foil tape addition

Field samples were taped with metal foil tape to ensure no moisture was lost during initial curing. The metal foil tape was not used for laboratory-made specimens, as it was deemed unnecessary since the specimens were in a controlled environment.

3.4.3.2 Initial Curing

Field specimens were cured in the molds under conditions that limit exposure to sun, wind, and other sources of rapid evaporation, and from contamination for 12 hours or longer if required. Samples were stored in the shade when possible, and in a location where they would be safe and secure until transportation back to the laboratory for removal of molds and sample extrusion. Typical field curing can be seen in Figure 3.19. After the initial 12-hour or longer curing period, cylinders were transported to the laboratory at Auburn University where final curing occurred. During transportation, the cylinders were protected with suitable cushioning material to prevent damage.

Figure 3.19: Molded specimens stored during initial curing

Laboratory specimens were cured in the laboratory for 12 h, or longer if required, to permit subsequent removal from the molds using the sample extruder. Typically, samples were prepared and allowed to remain in the molds for initial curing overnight, and were extruded the following day.

3.4.3.3 Sample Extrusion

After initial curing, the mold plugs were removed and the samples were extruded from the specimen molds. A standard vertical specimen extruder was used for de-molding the specimens. However, this process was overly time consuming as the stroke of the piston on the jack was small and the frame had to be re-configured during the extruding process in order to fully extrude the specimen.

In an attempt to reduce variables in the initial testing, it was decided to use a hydraulic sample extruder to speed up the process and get the specimens from the molds to the moist room in a more expedient manner. The hydraulic extruder was a horizontally mounted extruder. The hydraulic extruder was very efficient in removing samples from the molds and reduced the time it took to de-mold the specimens and get them into the moist room for final curing. The hydraulic extruder can be seen in Figure 3.20.

Figure 3.20: Horizontally mounted hydraulic extruder

The hydraulic extruder created edge cracking in the samples as they were close to being completely removed from the mold. Evidence of edge cracking is shown in Figure 3.21. The self-weight of the specimen was creating flexure or bending on the specimen as it was slightly restrained in the mold during the final stages of being released from the mold. This became very apparent as early testing data were highly variable during this research effort. The hydraulic extruder was no longer used after the edge cracking continued to occur.

Figure 3.21: Edge cracking from horizontally mounted, hydraulic extruder

Finally, a larger and taller vertical sample extruder was obtained for use in specimen de-molding. This extruder had a piston with sufficient stroke to fully extrude a specimen without having to re-configure the jack frame. It also showed no signs of causing edge cracking. This extruder, shown in Figures 3.22 and 3.23, was used for the majority of the research.

Figure 3.22: Vertical hand-jack used for sample de-molding

Figure 3.23: Close up of vertical hand-jack used for sample de-molding

3.4.3.4 Final Curing

Final curing was initiated as soon as the specimens were removed from the mold and placed into the moist room. The specimens were kept in the moist room, protected from dripping water, and they remained in this room until time of testing.

For the majority of the test specimens, the specimens were tested in the moist condition directly after removal from the moist room. However, some specimens were tested after different curing situations were implemented. Further detail on this topic is discussed in Sections 3.2.3.1 and 3.2.3.2.

3.4.3.5 Testing

Compression testing followed ASTM D 1633 (2007) with a few exceptions:

- Specimens were not immersed in water for 4 hours prior to final curing,
- Specimens were not capped, except for capping research specimens, and
- The loading rate of 20 ± 10 psi/s was changed to 10 ± 5 psi/s.

Due to the various procedures required for the research performed, the specimens were not in all cases immersed in water for four hours prior to final curing. Different physical requirements for necessary modifications involving the pre-curing impact and suitable curing studies made it unfeasible to immerse the specimens.

The research specimens for this study were made in a manner in which the configuration of the specimen molds with caps and the method of making the soil-cement cylinders provided the planeness and perpendicularity tolerances necessary to meet the criteria of ASTM C 1633 (2007). Therefore, the capping of cylinders was only evaluated during the capping study.

The loading rate was decreased from 20 ± 10 psi/s to 10 ± 5 psi/s in order to better emulate the time to failure as determined by ASTM C 39. This was based upon a standard 4 in. by 8 in. concrete cylinder with a specified compressive strength, f'_c, of 4,000 psi, and a corresponding required mean strength, f'_{cr}, of 5,200 psi. The loading rate of 35 ± 7 psi/s as required in ASTM C 39 allows this 4 in. by 8 in. concrete cylinder to be tested with a time to failure from 1 to 2 minutes. By reducing the rate for soil-cement cylinders to 10 ± 5 psi/s, the specimen will have a time to failure from 0.3 to 2.0 minutes, which is closer to the time frame of the concrete cylinder. Table 3.3 shows the comparison of the ASTM C 39 loading rate for concrete cylinder along with the recommended loading rate for soil-cement cylinders. The current ASTM D 1633 (2007) loading rate of 20 ± 10 psi/s for soil-cement cylinders would produce a time to failure of 0.1 to 1.0 minutes. The decreased loading rate was determined to be more suitable for the strength requirements of soil cement.

Table 3.3: Comparison of ASTM C 39 and recommended loading rates

Specimen and Material Type	Required load at failure, lb.	Time Required to Reach Failure Load	
		ASTM C 39 (2007) Loading Rate 35±7 psi/s	Recommended Loading Rate 10±5 psi/s
4 in. by 8 in. concrete cylinder at 4000 psi	50,265	1.6 to 2.4 minutes	N/A
2.8 in. by 5.6 in. soil-cement cylinder at 600 psi	3,695	0.2 to 0.4 minutes	0.7 to 2.0 minutes
2.8 in. by 5.6 in. soil-cement cylinder at 250 psi	1,540	0.1 minute	0.3 to 0.8 minute

The use of the 100-kip compression testing machine allowed for more precise control of the loading rate. The 100-kip compression testing machine used for this research is shown in Figure 3.24.

Figure 3.24: Compression testing machine

Figure 3.25 shows the specimen placed on the lower bearing block, making certain that the vertical axis of the specimen is aligned with the center of thrust of the spherically shaped, upper platen.

Figure 3.25: Sample loaded into compression testing machine

The load was applied continuously and without shock. The loading rate was adjusted to be within the limits of 10 ± 5 psi/sec. The total load at failure of the test specimen was recorded to the nearest 10 lb. The unit compressive strength of the specimen was calculated by dividing the maximum load by the cross-sectional area. Figure 3.26 shows a typical failure pattern of a molded soil-cement cylinder. The strength value from one cylinder was discarded if its individual result exceeded ±15 percent of the average of the other four or five cylinders in the set.

Figure 3.26: Sample after failure

Chapter 4

Presentation and Analysis of Results

4.1 Introduction

In this chapter, results from the field and laboratory testing programs described in Chapter 3 are presented and reviewed. The compressive strength results of the soil cement mixtures with respect to each phase of testing are presented and evaluated. A summary of all data collected for each soil cement mixture may be found in Appendices B through E.

4.2 Results of Pre-Conditioning Impact Study

As previously stated in Section 3.2.3.1, the curing pre-conditioning impact on molded cylinders was targeted to determine the effects of moist curing (MC), bag curing (BC), fan curing (FC), and air curing (AC) on the seven-day compressive strength of soil cement cylinders. Specimens were removed from moist curing on day six and conditioned according to their curing variable.

The average seven-day compressive strength test results can be found in Table 4.1. The values presented in Table 4.1 are averages of six cylinders per strength value. A summary of all data collected for this study may be found in Appendix B.

Table 4.1: Seven-day compression test results for pre-conditioning impact study

Material and Cement Content		7-Day Compression Test Results (psi)			
		Moist Cured (MC)	Bag Cured (BC)	Fan Cured (FC)	Air Cured (AC)
D5	Batch 1	330	390	570	570
	Batch 2	400	400	550	540
D6	Batch 1	350	360	520	520
	Batch 2	370	330	510	550
D7	Batch 1	370	380	500	480
	Batch 2	340	320	440	450

Popovics (1986) reported that a dry or surface-dry concrete specimen will have a higher compressive strength than the same specimen in a saturated-surface-dry or fully-saturated state. Figure 4.1 shows that both curing variables involving the reduction in available moisture (fan cured and air cured) have from 28 to 73 percent higher strengths than that of the moist cured specimens. The trend in these results are similar to those from Bartlett and MacGregor (1994) that show compressive strengths for dry specimens are approximately 14 percent greater than soaked specimens and with data provided by Popovics (1986), in which air curing can result in an increase in strength of 25 percent or more. Figure 4.1 also illustrates that the compressive strength results of the bag-cured specimens were the most similar to those of the moist-cured specimens, with the fan-cured and air-cured specimens having much higher strengths with respect to those of the moist-cured specimens. The fan-cured and the air-cured specimens have strengths higher than the moist-cured or bag-cured, which matches the finding of Popovics (1986).

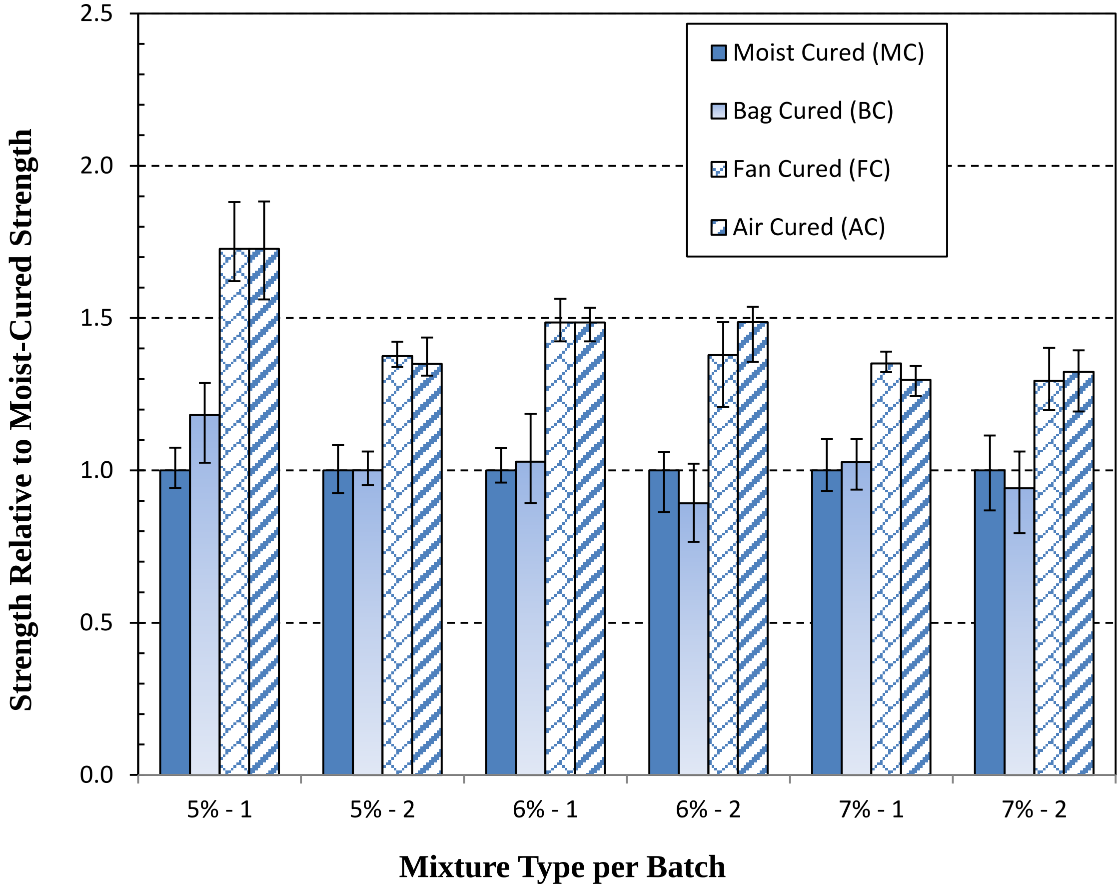

Figure 4.1: Cement content versus strength relative to moist-cured strength

It should be noted that for this study, moist-cured samples were treated as control samples and each of the three remaining curing variables were compared to the moist cured. Figures 4.2 through 4.4 show the individual comparisons of curing variable with respect to the strength of moist-cured specimens.

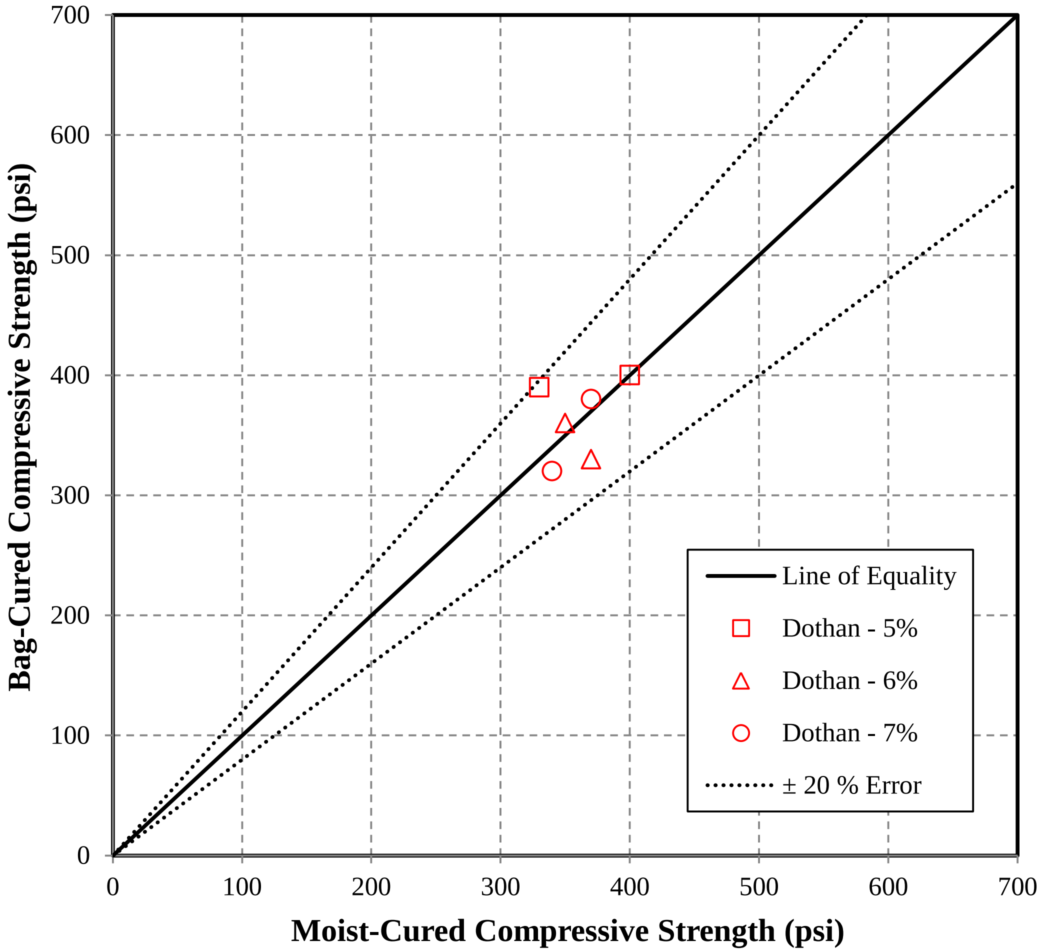

Figure 4.2: Moist-cured versus bag-cured compressive strengths

Based on these data, the strength of the bag-cured specimens tend to be reasonably similar to those of the moist-cured specimens. Figure 4.2 shows that the strength of the bag-cured specimens are within the ± 20 percent error margins when compared to those of the moist-cured specimens, and these are thus very similar.

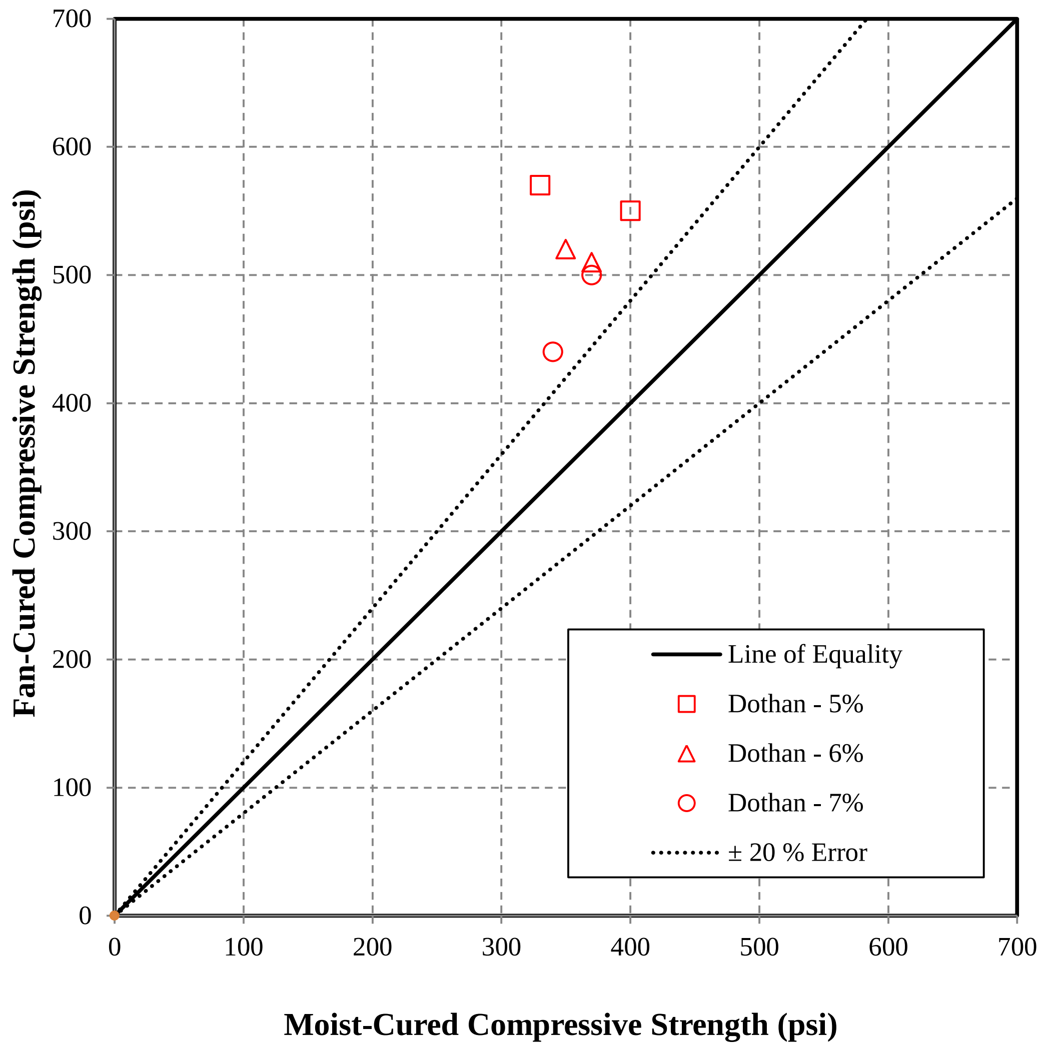

Figure 4.3: Moist-cured versus fan-cured compressive strengths

As mentioned previously, the fan-cured strengths are considerably higher than the moist-cured strengths. Figure 4.3 shows that these data fall outside of the preferable ± 20 percent error range. This increase in strength may be a result of moisture gradients presented throughout the specimen, where the amount of moisture on the surface of the specimen is less than the moisture amount on the inside of the specimen. Bartlett and MacGregor (1994) report that the moisture gradient created from this type of curing results in an artificial increase in strength that is largely due to the effects of shrinkage from drying on the surface of the specimen.

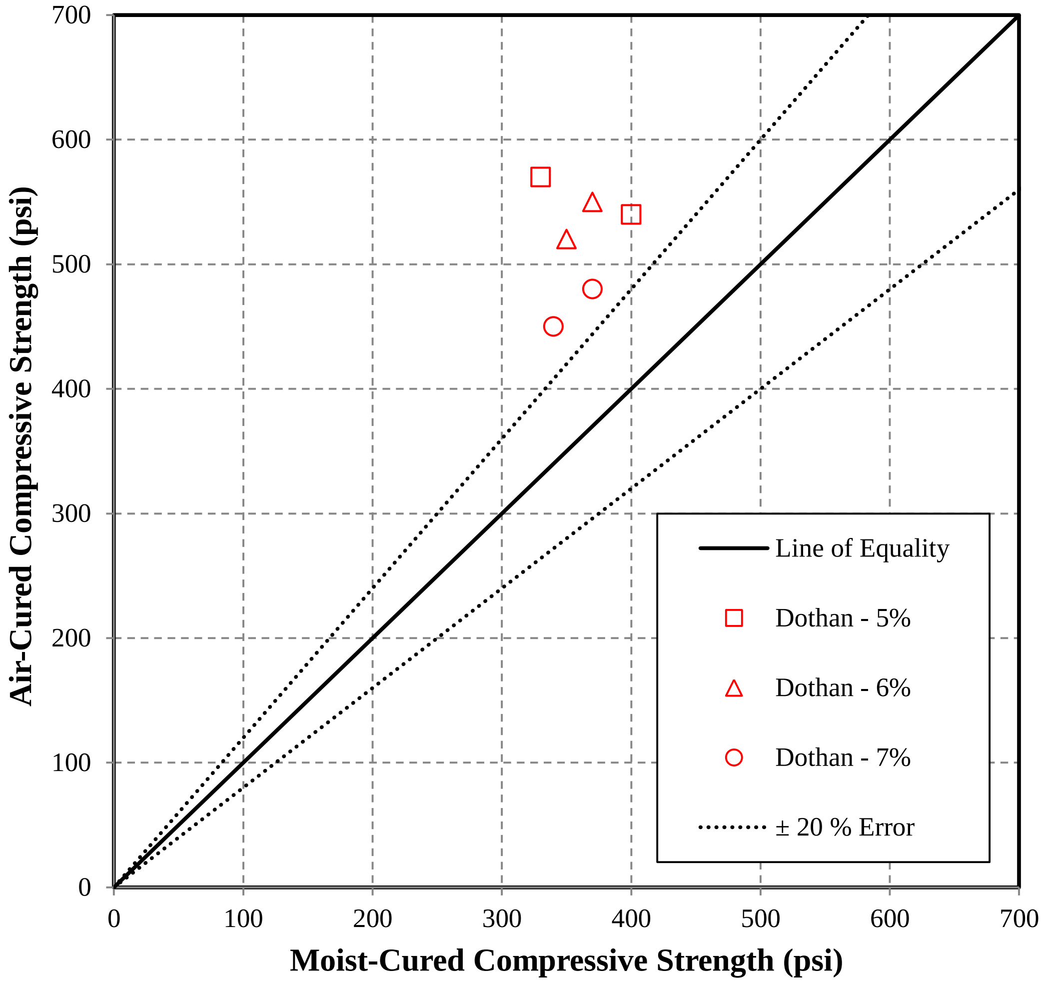

Figure 4.4: Moist-cured versus air-cured compressive strengths

Similar to the fan-cured strengths, the air-cured strengths are considerably higher than the moist-cured strengths as the data points are all above the + 20 percent error margins, as shown in Figure 4.4. Figure 4.5 shows the results of fan-cured specimens with respect to air-cured specimens. Although these strengths are much higher than the moist cured strengths, the air cured and fan cured strengths are very similar and both follow research by de Larrard and Bostvironnois (1991) which states that variations in strength are due to the effects of drying.

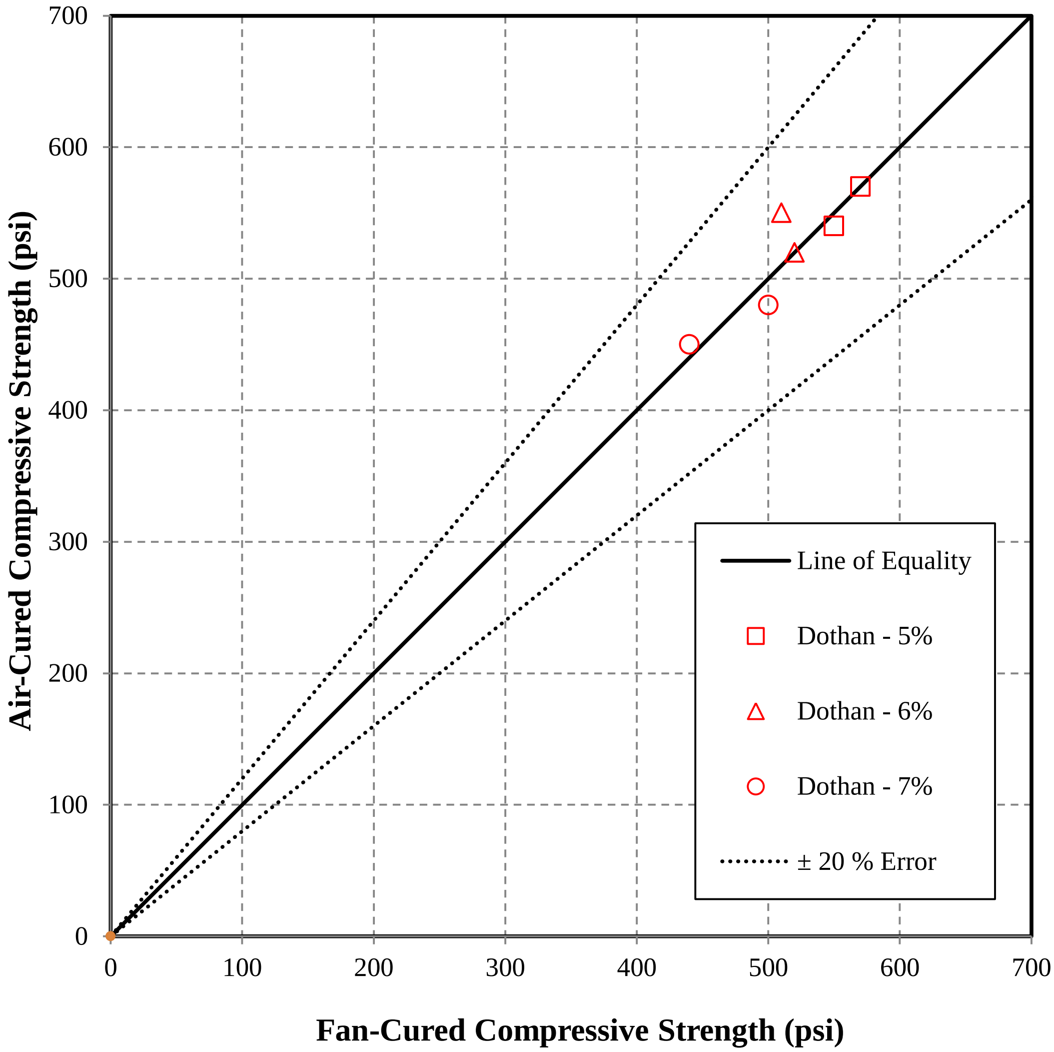

Figure 4.5: Fan-cured versus air-cured compressive strengths

In order to analyze the data for this study, it was necessary to adjust the data to remove such variables as age and cement content. Since compressive strength is a time-dependent variable, it was necessary to remove the differentiation of strength values from different ages. Additionally, difference in strength due to varying cement contents was also normalized to provide a better comparison of the data. The individual test result for each batch was taken and divided by the mean average of the data set. This will allow the evaluation of the ratio of each test result with respect to the average of the six values. By evaluating the strength ratios, the age and cement content of each curing condition are no longer variables.

The coefficient of variation results of the ratios of normalized data from the statistical analysis for the values obtained in the pre-conditioning impact study are presented in Table 4.2. From this table it can be seen that the variability is the highest for fan curing conditioning.

Table 4.2: Statistical analysis for pre-conditioning impact

Statistical Analysis for Pre-Conditioning Impact	
Curing Variable	**Coefficient of Variation, %**
Moist Cured	6.5
Bag Cured	7.0
Fan Cured	8.3
Air Cured	5.9

Popovics (1986) concludes that the inconsistency of strength results can be reduced by tightening curing specifications and eliminating moisture gradients. Previous research by Bloem (1965) indicates that compressive strength deviates significantly with the competency of specimen curing and treatment. The method of curing greatly influences the variation of strength of the concrete within a specimen. As a result from this study, it was determined to further investigate the variation between moist-cured and bag-cured specimens. Due to the unwanted increase in strength test results and the potential to introduce variability in the results, it was also determined to discontinue the fan-cured and air-cured specimen testing.

4.3 Results of Suitable Curing Method Study

The further continuation of the pre-conditioning impact study resulted in the suitable curing method portion of the research. The purpose of this study was to evaluate the effects of changes in moisture content that occur after a core has been taken from the roadbed. The moist-curing environment was used to represent the moist environment of the material being cured in the roadbed. Typically, once a core has been cut and removed from the roadbed, it is placed into a plastic bag until the core has reached the laboratory for testing. In order to simulate the curing conditions of the field, specimens were moist-cured until the appropriate time of testing or conditioning. The day before testing, half of the samples to be tested were removed from the moist-curing environment and individually placed into plastic bags for further curing. The bags with the specimens were placed in an environmental chamber and maintained at 73º F and 50 percent relative humidity. The specimens were removed from the bags at the time of testing, and tested in compression. The compressive strength test results are shown in Table 4.3.

The values presented in Table 4.3 are averages of five cylinders per strength value. A summary of all data collected for this study may be found in Appendix C. Figure 4.6 shows the results of bag-cured specimens with respect to moist-cured specimens. The results of this study provide a group of data that is well within the ± 20 percent error margins.

Table 4.3: Suitable curing compression test results

Material and Cement Content		Suitable Curing Compression Test Results (psi)					
		Moist-Cured (MC)	Bag-Cured (BC)	Moist-Cured (MC)	Bag-Cured (BC)	Moist-Cured (MC)	Bag-Cured (BC)
		3 Day	3 Day	7 Day	7 Day	28 Day	28 Day
B5	**Batch 1**	230	230	300	310	320	360
	Batch 2	260	270	290	290	320	320
B6	**Batch 1**	280	300	320	330	370	440
	Batch 2	370	310	370	370	420	430
B7	**Batch 1**	410	440	510	480	530	510
	Batch 2	390	390	510	520	620	630
D5	**Batch 1**	280	280	360	340	420	430
	Batch 2	190	180	310	310	590	570
D6	**Batch 1**	330	330	500	490	520	530
	Batch 2	290	290	440	430	500	510
D7	**Batch 1**	350	340	490	470	590	570
	Batch 2	360	380	450	470	580	570

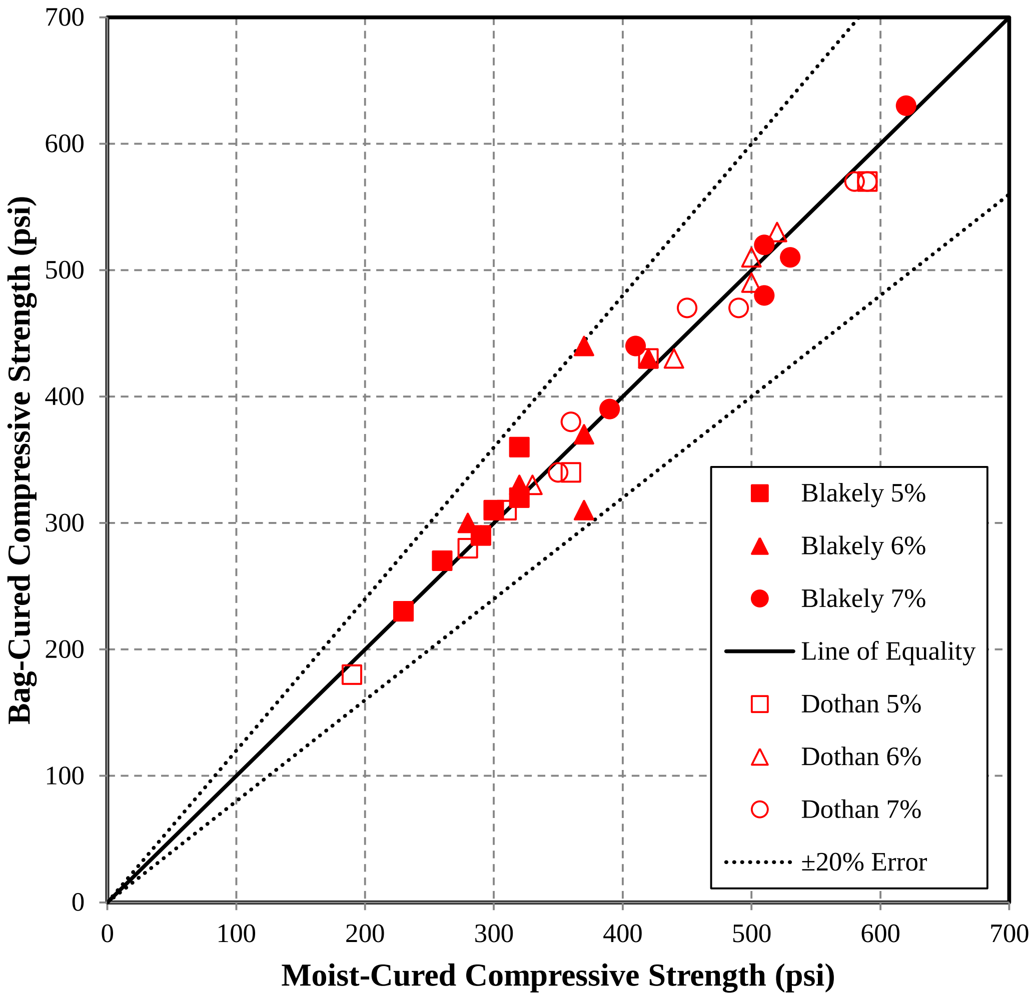

Figure 4.6: Moist cured versus bag cured compressive strengths

It should be noted that the largest separation of values from these data is 40 psi, or 12.5 percent of the average, with many data sets having bag-cured specimens identical to moist-cured specimens. The data in Figure 4.6 provide considerable agreement between bag-cured and moist-cured specimens. Based on these data, it was determined that there is no considerable difference in compressive strength between moist-cured and bag-cured specimens when conditioned according to these two methods.

The coefficient of variation results of the ratios of normalized data from the statistical analysis for the values obtained in the suitable curing study are presented in Table 4.4. From this table it can be seen that the variability is the highest for moist curing conditioning.

Table 4.4: Statistical analysis for suitable curing

Curing Variable	Coefficient of Variation, %
Moist-Cured	11.9
Bag-Cured	10.8

4.4 Results of Capping Study

Neoprene pads and gypsum plaster were evaluated for use as capping methods along with no capping for the compression testing of field and laboratory made specimens. Initially, the three capping mediums were evaluated by the making of field specimens. Neoprene pads were eliminated after the field study, and further study involved evaluating gypsum compound as capping media and no-capping medium for testing.

4.4.1 Results of Field Projects

Initial testing of field specimens was conducted to determine the effects of no capping method (NC), gypsum plaster (GP), and neoprene pads (NP) on the compressive strength of soil cement cylinders. Results from this study are shown in Table 4.5. The values presented in Table 4.5 are averages of three cylinders per strength value. However, many cylinders were damaged during the capping process and subsequently discarded. A summary of all data collected for this study may be found in Appendix D.

Table 4.5: Field capping study compression test results

Material and Cement Content	Field Capping Study Compression Test Results (psi)								
	No Cap			Gypsum			Neoprene		
	Age			Age			Age		
	3-Day	7-Day	28-Day	3-Day	7-Day	28-Day	3-Day	7-Day	28-Day
B7	250	280	290	290	350	410	220	270	310
J6	210	210	220	190	240	250	170	190	190

Figures 4.7 and 4.8 show the results of the neoprene pads and gypsum capping compound with respect to specimens where no capping method was used. Figure 4.7 shows that the neoprene pads produced marginally lower strengths than the specimens with no capping method. It should be noted that these data all fell within the preferable ± 20 percent error range.

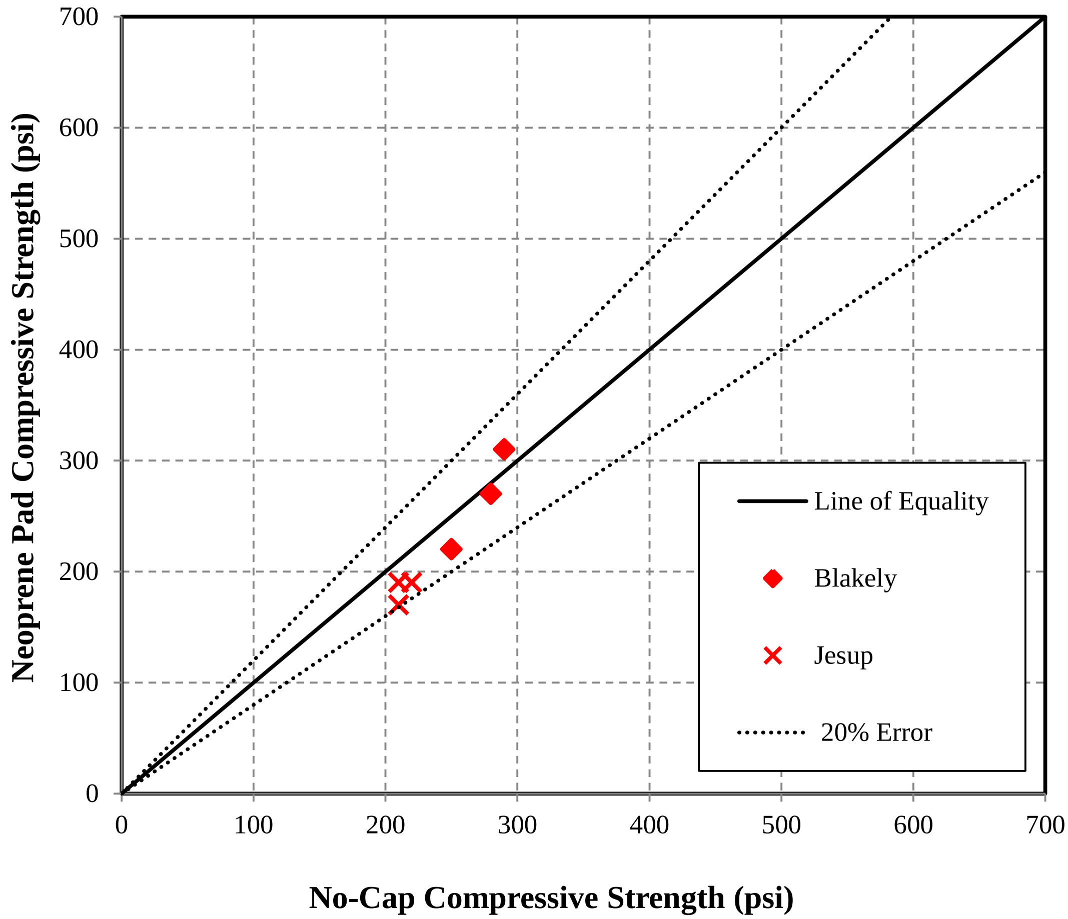

Figure 4.7: No-cap versus neoprene pad compressive strengths

According to ASTM C 1231 (2010), the neoprene pad system is not to be used for acceptance testing of concrete cylinders with compressive strengths below 1,500 psi or above 12,000 psi. NRMCA also indicates that neoprene caps did not seat well on the cylinders used in a field project and recommended high-strength gypsum plaster for CLSM capping (NRMCA 1989). Sauter and Crouch (2000) state that the standard 50 to 70 durometer neoprene pads are not flexible enough at the low stress levels produced by CLSM testing. Based on the data presented, along with the recommendations from Sauter and Crouch (2000), which indicate that the neoprene pads act more like a rigid plate mechanism than a material suitable for capping low-strength cylinders, it was determined that the neoprene pads were not suitable for use in capping soil cement cylinders. It was determined to eliminate neoprene pads from the testing program and focus efforts on comparing the gypsum capping compound to the no-capping method.

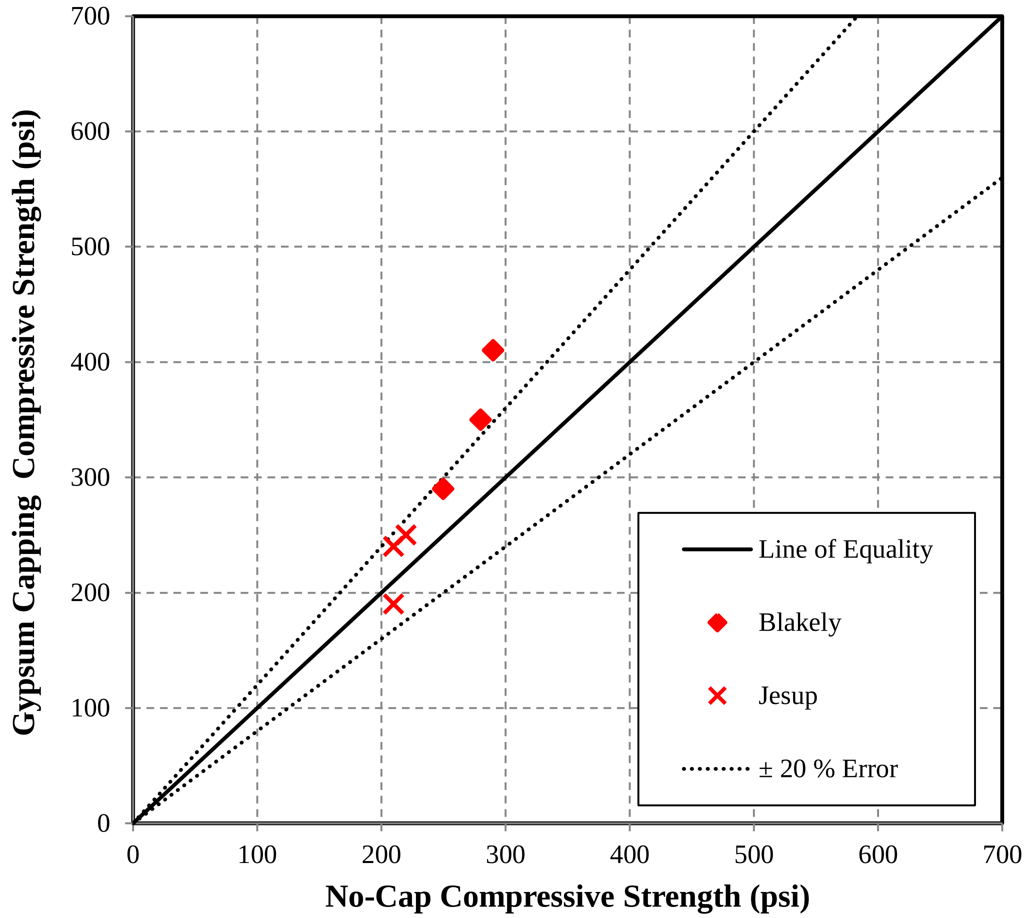

Figure 4.8: No-cap versus gypsum capping compressive strengths (Field)

Figure 4.8 shows that the gypsum capping compound produced compressive strengths moderately higher than the no-cap specimens. Most of the data fell along or above the + 20 percent error margin and are in agreement with data from Sauter and Crouch (2000) suggesting that gypsum plaster strengths were roughly 25 percent higher than the neoprene and the no-capping method. These results lead to further investigation in the laboratory.

4.4.2 Laboratory Assessment of Capping Method

Gypsum plaster and no-capping method were evaluated in the laboratory to determine the most suitable cylinder end treatment method for the compression testing of the specimens. The laboratory compressive strength test results are shown in Table 4.6.

Table 4.6: Capping study compression test results

Material and Cement Content		Capping Study Compression Test Results (psi)					
		No Cap (NC)	Gypsum (GP)	No Cap (NC)	Gypsum (GP)	No Cap (NC)	Gypsum (GP)
		3 Day	3 Day	7 Day	7 Day	28 Day	28 Day
B5	Batch 1	270	300	300	310	310	330
	Batch 2	305	310	310	330	360	380
	Batch 3	220	280	265	340	290	390
B6	Batch 1	390	420	450	470	400	500
	Batch 2	360	350	350	360	390	390
	Batch 3	310	340	390	390	460	530
B7	Batch 1	520	530	560	670	670	740
	Batch 2	390	460	520	600	690	710
	Batch 3	410	420	560	650	690	720

The values presented in Table 4.6 are averages of five cylinders per strength value. A summary of all data collected for this study may be found in Appendix D.

Figure 4.9 shows the results of gypsum-capped specimens with respect to no-capped specimens. Similar to the field capping study, Figure 4.9 shows that the gypsum capping produced compressive strengths slightly more than ten percent higher on average than the no-cap specimens. Most of the data fell between the upper boundary of the line of equality and the + 20 percent error margin.

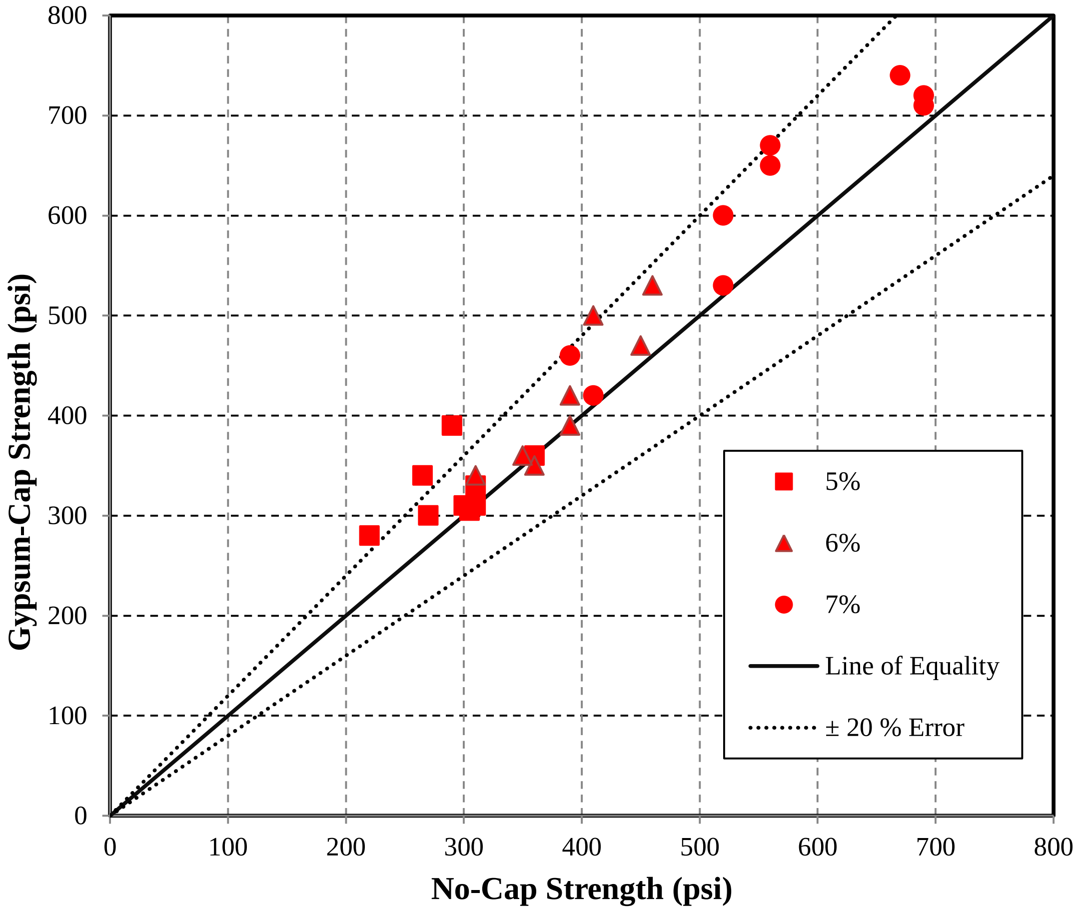

Figure 4.9: No-cap versus gypsum-capping compressive strengths (Laboratory)

The coefficient of variation results of the ratios of normalized data from the statistical analysis for the values obtained in the capping study are presented in Table 4.7. From this table it can be seen that the variability is the highest for no cap conditioning.

Table 4.7: Statistical analysis for capping study

Statistical Analysis for Capping Study	
Capping Variable	**Coefficient of Variation, %**
No-Cap	7.1
Gypsum Cap	5.9

4.4.2.1 Testing Observations

Research from Sauter and Crouch (2000) indicates that sulfur mortar along with gypsum capping methods resulted in many cylinders being damaged during capping due to the low strength and fragile nature of CLSM cylinders. This was experienced in this study with many cylinders being damaged during the gypsum capping procedure. The release agent used to remove the cap from the capping frame was not effective, and many cylinders were damaged and broken during the attempt to remove the capped cylinder from the capping frame. Additional release agents proved unsuccessful. Sauter and Crouch (2000) indictate that the amount of within-test control achieved is directly related to the precision in handling, capping, and testing of compressive strength specimens.

The purpose of capping concrete cylinders, drilled concrete cores or other specimens is to provide plane surfaces on the ends of the specimens in order to meet planeness and perpendicularity requirements of applicable specifications and standards. The mechanical advantage of the specimen molds and the method of making the soil-cement cylinders provide the planeness and perpendicularity tolerances necessary to meet the criteria of ASTM C 1633 (2007). Based on the results of this study and the information provided in Section 2.5.4, it is recommended to test soil cement specimens made according to requirements of ASTM C 1632 (2007) without any capping medium, unless for some reason the cylinder does not meet the planeness and perpendicularity tolerances of ASTM D 1633 (2007). It was determined to eliminate the gypsum capping compound and to continue further testing of specimens without any capping medium.

4.5 Results of the Length-to-Diameter Ratio Study

The effect of L/D strength correction factors was determined by evaluating the seven day compressive strengths of cylinders which had L/D of 2.0, 1.75, 1.5, 1.25 and 1.0.

The 7-day compressive strength test results from the L/D study are found in Table 4.8. The values presented in Table 4.8 are averages of six cylinders per strength value. A summary of all data collected for this study may be found in Appendix E.

Table 4.8: 7-day compression test results for L/D study

Material and Cement Content		7-Day Compression Test Results (psi)				
		L/D = 2.0	**L/D = 1.75**	**L/D = 1.50**	**L/D = 1.25**	**L/D = 1.0**
B5	**Batch 1**	350	290	320	320	360
	Batch 2	290	300	310	310	330
B6	**Batch 1**	410	420	410	420	410
	Batch 2	440	440	470	420	380
B7	**Batch 1**	510	480	520	530	510
	Batch 2	520	510	500	520	530
D5	**Batch 1**	440	420	440	420	430
	Batch 2	440	430	420	440	450
D6	**Batch 1**	470	480	480	470	470
	Batch 2	480	470	470	460	480
D7	**Batch 1**	540	570	530	510	540
	Batch 2	500	490	490	500	530

ASTM C 39 (2009) states that if the specimen length-to-diameter ratio is 1.75 or less, appropriate correction factors should be used to adjust the strength value obtained. These strength correction factors are also recommended for soil cement by ASTM D 1633 (2007). These factors are shown in Table 4.9 and are designed to reduce the strength of a specimen with an L/D < 2 and correlate that specimen back to one with an L/D of 2.0.

Table 4.9: Correction factors for length-to-diameter ratio (ASTM C 39 2009)

L/D	**L/D Strength Correction Factors for (ASTM C 39 2009)**			
	1.75	**1.50**	**1.25**	**1.00**
Factor	0.98	0.96	0.93	0.87

The ASTM C 39 (2009) correction factors were used on the measured values of L/D = 2.00 in order to provide an estimated compressive strength of cylinders with an L/D of less than 2.00. The comparison of measured compressive strength specimens with respect to the ASTM estimated compressive strength specimens are shown in Figure 4.10. According to Figure 4.10, the ASTM C 39 (2009) correction factors primarily underestimate the strength values for most of the test data.

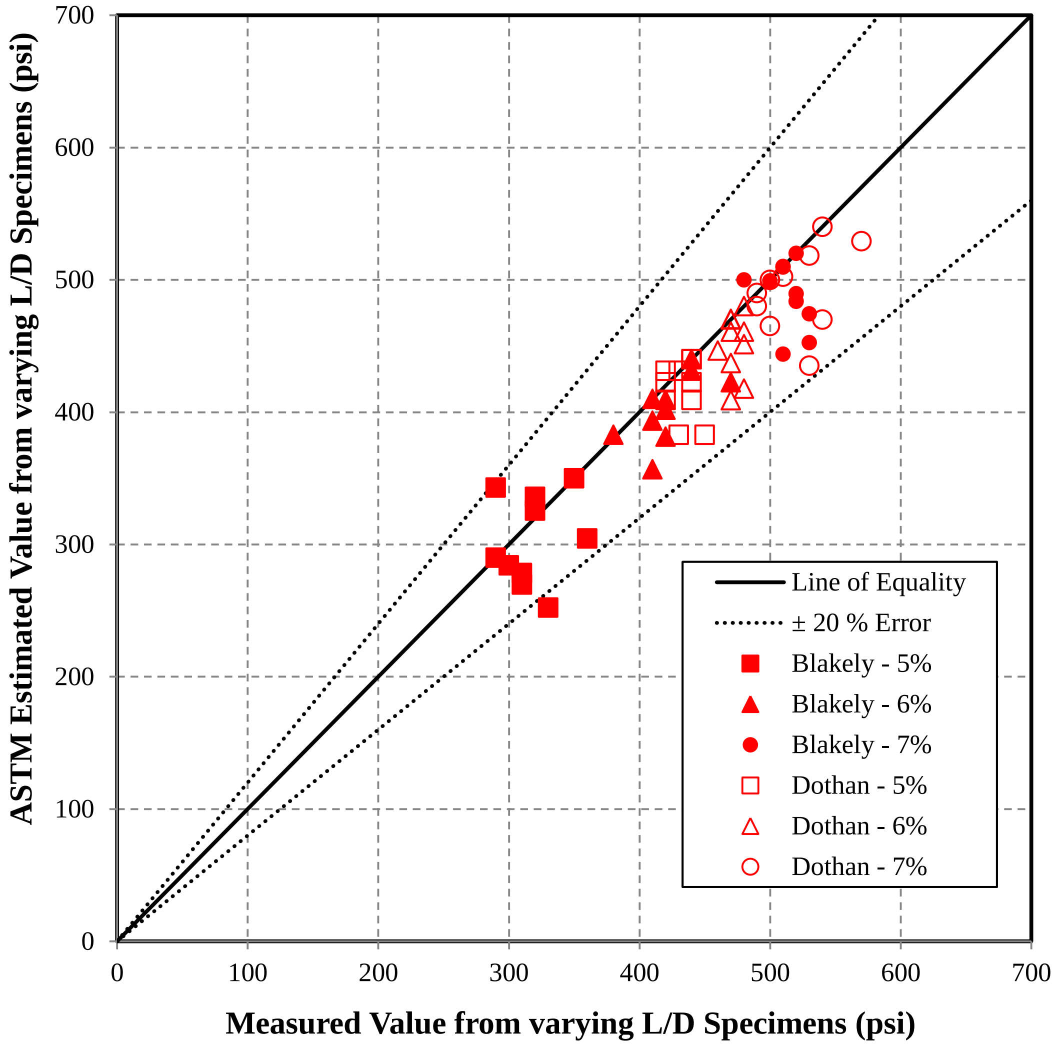

Figure 4.10: Measured value versus ASTM predicted value

Figure 4.11 shows that the comparison of measured compressive strength specimens with respect to no correction factor being used in the estimation of compressive strengths for specimens that do not meet the L/D = 2.00. This comparison shows results that are predominately in agreement with the line of equality.

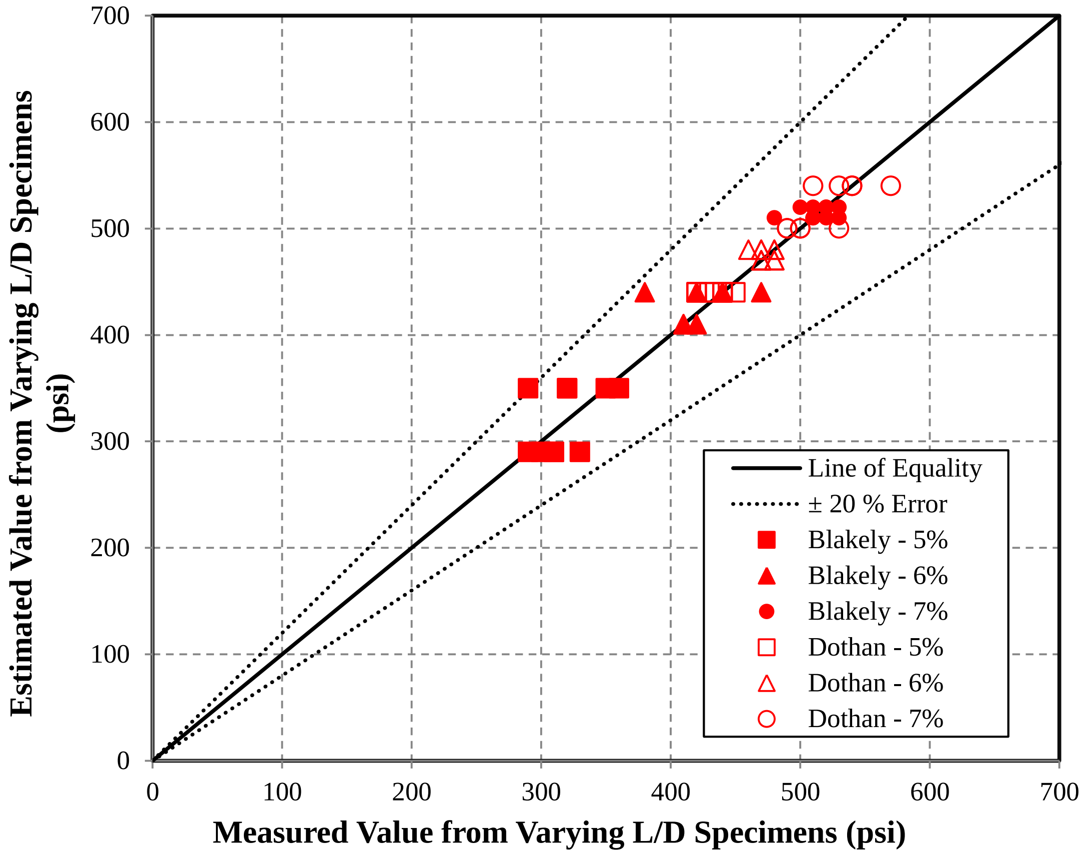

Figure 4.11: Measured value versus estimated value with no correction factor

From the data presented in Figures 4.10 and 4.11, it can be observed that the ASTM C 39 (2009) correction factors do not adequately correct the strength of specimens of various L/D to that of a specimen with L/D = 2.00.

A statistical evaluation of the absolute error was performed on the error from the ASTM C 39 (2009) estimated compressive strength data and the error from the no correction factor being used in the estimation of compressive strengths for specimens that do not meet the L/D = 2.00 data. The unbiased estimate of the standard deviation of the absolute error for each approach was calculated by Equation 4.1 (McCuen 1985).

$$S_j = \sqrt{\frac{1}{n-1}\sum_i^n \Delta_i{}^2} \qquad \textbf{Equation 4.1}$$

where,

S_j = unbiased estimate of the standard deviation (percent),

n = number of data points (unitless), and

Δ_i = absolute error (percent).

The absolute error was calculated using the following equation.

$$\Delta_i = [((S_i)_{est}-(S_i)_{meas})/ (S_i)_{meas}] \times 100 \qquad \textbf{Equation 4.2}$$

where,

Δ_i = absolute error (percent),

$(S_i)_{est}$ = value of the estimated compressive strength (psi), and

$(S_i)_{meas}$ = value of the measured compressive strength (psi).

Based on this statistical evaluation, the unbiased estimate of the standard deviation for the error from the use of the L/D strength correction factors of ASTM C 39 (2009) was determined to be 35 percent. The unbiased estimate of the standard deviation for the error from the no correction factor being used in the estimation of compressive strengths for specimens that do not meet the L/D = 2.00 was determined to be 5.8 percent. From this data, it can be stated that the unbiased estimate of the standard deviation for the error from the ASTM C 39 (2009) estimated compressive strength data is 6 times as large as the unbiased estimate of the standard deviation for the error from the no correction factor being used in the estimation of compressive strengths for specimens that do not meet the L/D = 2.00. This illustrates that the L/D does not significantly affect the strength of soil cement cylinders when tested in the methods used for this study.

Additionally, the data were presented with respect to the ASTM C 39 curve for further evaluation. Figure 4.12 shows the collected data with regard to the estimated correction factors obtained by dividing the compressive strength of the specimens not having an L/D of 2.00 by the compressive strength of L/D = 2.00. The L/D strength correction factor used in ASTM C 39 is also shown on this figure for reference purposes.

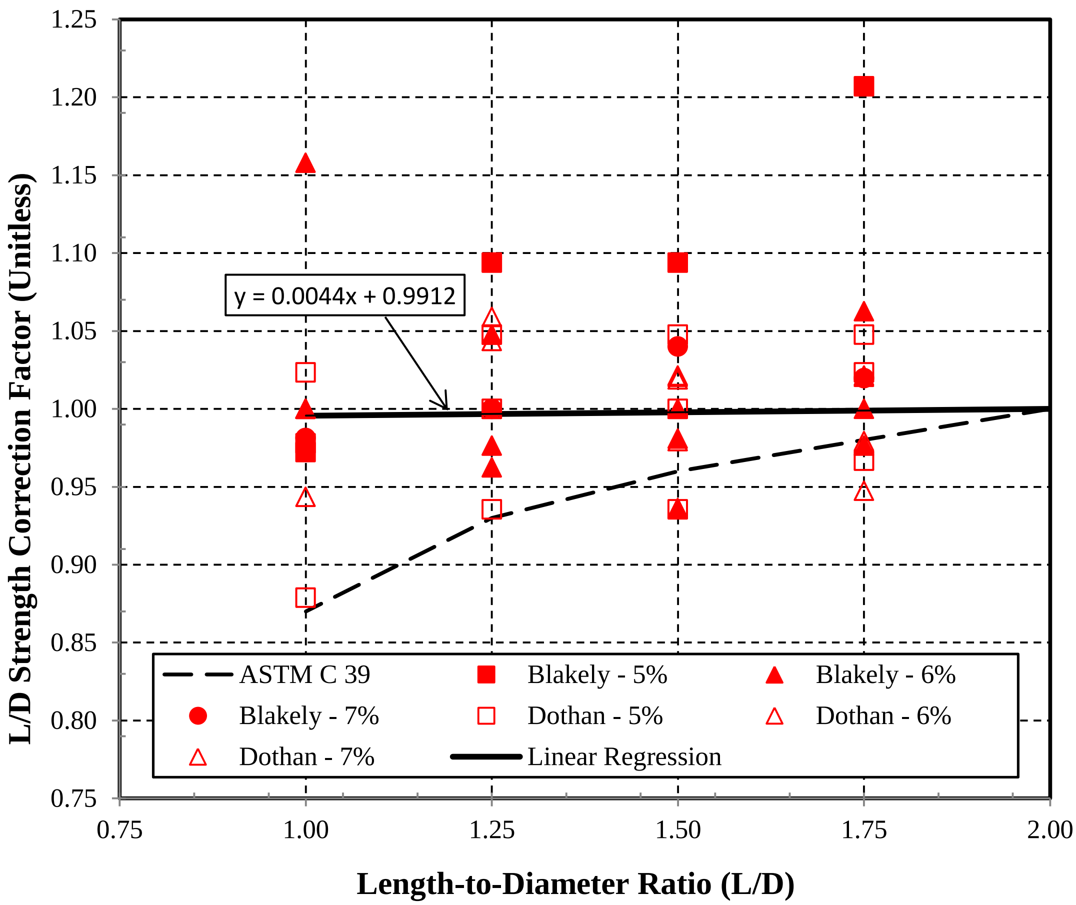

Figure 4.12: L/D versus L/D strength correction factor

Figure 4.12 shows the linear regression trendline of all data is very close to an L/D strength correction factor of 1.00. From this result, it can be seen that soil cement cylinders do not follow the same trends for correction factors as concrete cylinders have demonstrated with ASTM C 39. It should be noted that there is a wide scatter in strength results at the L/D of 1.00 (correction factors ranging from 0.88 to 1.16) and that scatter generally becomes less as the L/D becomes closer to 2.00.

Kesler (1959) indicates that correction factors are strength dependent. Both Kesler (1959) and Bartlett and MacGregor (1994a) agree that lower-strength concretes need greater correction factors than high-strength concretes. The lower the L/D the higher the strengths become, resulting in a correction factor that furthers itself from 1. This does not correlate well with the average compressive strength results of soil-cement cylinders evaluated in this study. From these data it can be determined that the ASTM C 39 L/D strength correction factors are not applicable to soil-cement cylinders when made and tested in accordance with ASTM D 1632 and ASTM D1633, respectively. It is recommended that no strength correction factor be applied for length-to-diameter ratios between 1.0 and 2.0.

4.6 Summary

In this chapter, sample results from each of the test methods outlined in Chapter 3 are presented and discussed. Results from the pre-conditioning impact study, the suitable curing study, the capping study and the L/D study are presented and discussed. The key findings of the work covered in this chapter are as follows

- The bag-cured specimens showed the least amount of difference with respect to moist-cured specimens, with fan-cured and air-cured having much higher strengths with respect to moist-cured specimens.
- There is no considerable difference in compressive strength between moist-cured and bag-cured specimens when conditioned according to the methods used.
- Neoprene pads are not suitable for use in capping soil-cement cylinders.
- The configuration of the specimen molds with caps and the method of making the soil-cement cylinders provide the planeness and perpendicularity tolerances necessary to meet the criteria of ASTM C 1633 (2007). It is recommended to test soil-cement cylinders made according to requirements of ASTM C 1632 (2007) without any capping medium, unless planeness and perpendicularity tolerances are suspect. Gypsum capping compound should be used if required for planeness and perpendicularity tolerances.
- The ASTM C 39 L/D correction factors are not applicable to soil-cement cylinders when made and tested in accordance with ASTM D 1632 and ASTM D1633, respectively. It is recommended that no strength correction factor be applied for length-to-diameter ratios between 1.0 and 2.0.

Chapter 5

Implementation Guidelines for Draft Procedure

5.1 Introduction

Based on the findings of this research, a proposed procedure was drafted to provide a strength testing guideline for the use of field-molded cylinders as a pay item to verify the quality of the soil cement delivered to the jobsite. The objectives of this chapter are to recommend the testing protocol that the Alabama Department of Transportation (ALDOT) should implement to assess strength variability in soil-cement base, and outline a proposed ALDOT procedure for making and curing soil-cement compression test specimens in the field and laboratory. A draft of a proposed ALDOT procedure is presented in Appendix F.

5.2 Current Practice

ALDOT Section 304 of Alabama Standard Specifications, 2008 Edition, states that a job mixture design shall be used to provide a material that will produce compressive strengths from cores taken from in-place soil cement that are at least 250 psi and not more than 600 psi.

Section 304 states that a uniform moisture content from 100 to 120 percent of the optimum moisture content shall be maintained during compaction, and the density after compaction shall be at least 98 percent of the theoretical maximum dry density.

Acceptance of the soil-cement structure is based upon the 98 percent density requirement along with the in-place compressive strength of cores taken. The coring requirements and testing method were discussed in detail in Section 2.4.1. The seven-day compressive strength of the soil-cement is the average of two consecutive test results, and strengths must fall within a 250 psi to 600 psi range. Since the compressive strength of the soil-cement cores is a pay item, a price reduction is applied if the strengths do not meet the required criteria of 250 psi to 600 psi. Compressive strengths that fall more than 50 psi outside the range will require the structure to be removed and replaced at the contractor's expense.

5.3 Necessary Requirements for Implementation

An acceptable procedure should contain well-defined and efficient instructions on how to make and cure soil-cement compression test specimens in the field. The procedure should define the steps necessary to produce soil-cement specimens in the field that are suitable for compression testing. Several important steps requiring detailed descriptions include

- Sampling the material from the paver,
- Determining the 98 percent density range,
- Making test specimens,
- Curing test specimens, and
- Compression strength testing of molded soil-cement cylinders.

The results of following this procedure should provide a suitable method for the assessment of the strength of the soil cement used. An example to assist ALDOT and contractor personnel that details proper procedures on determining if the material is within the moisture window to achieve 98 percent density or higher should be included with the procedure.

5.3.1 Sampling from the Paver

The material sampled from the paver should be taken in shovel-size quantities from random locations in the hopper and placed into a five-gallon bucket. Each five-gallon bucket should be completely filled. A lid should be placed on the bucket after each portion has been obtained in order to prevent moisture loss. The composite sample size to be used for strength tests should be a minimum of 2/3 ft^3. The elapsed time should not exceed 15 minutes between obtaining the first and final portions of the composite sample. The composite sample should be transported to the location where test specimens are to be molded. The composite sample should be remixed with a shovel the minimum amount necessary to ensure uniformity and compliance.

5.3.2 Determining the Moisture Window to Achieve 98 Percent Density or Higher

The targeted moisture content range should be that which corresponds to 98 percent or greater of the maximum dry unit weight. In order to determine the moisture window to achieve 98 percent density or higher, reference to the compaction curve determined in the mixture design is necessary. The moisture content of the composite sample is used to determine the corresponding dry unit weight. Figure 5.1 shows the allowable moisture content range, which is a range of upper and lower moisture limits that border the 98 percent density values on the compaction curve. The allowable moisture content range is plotted on the compaction curve. Using the optimum moisture content (OMC) curves previously plotted from the design mixture, the determination of whether the composite sample's moisture content is within the 98 percent range of OMC is observed.

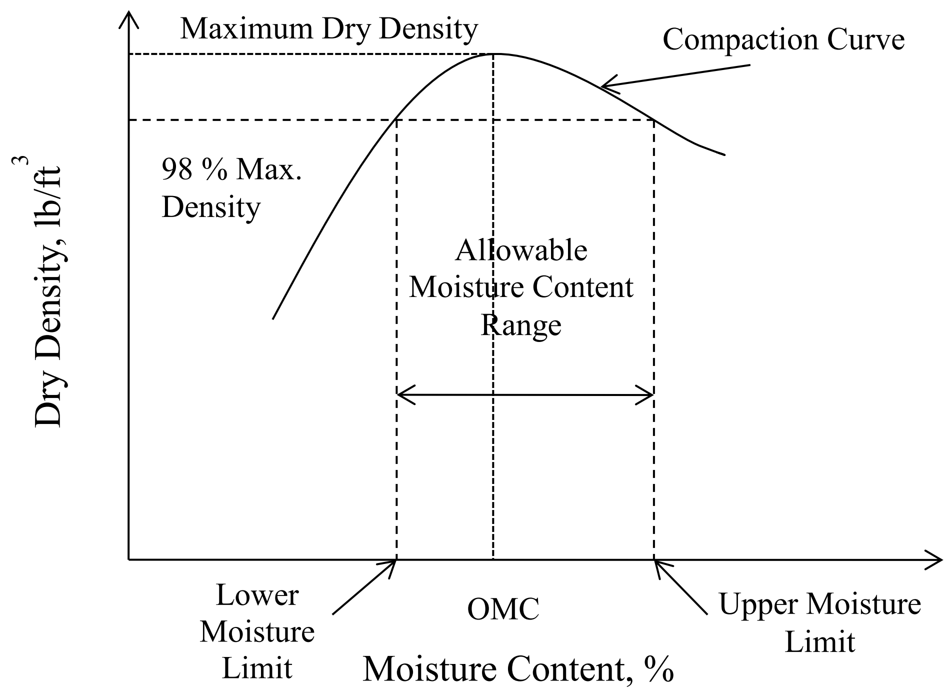

Figure 5.1: Allowable Moisture Content Range

If the moisture content of the composite sample is within the allowable moisture content range, the mass of soil-cement is determined by using the dry unit weight corresponding to composite sample moisture content in lb/ft^3 and converting it to g/in^3. The volume of the specimen molds for molding test specimens is 2.8 in. in diameter by 5.6 in. high. This provides a sample volume of 34.5 in^3. This gives the following equations for determining the mass of soil-cement material needed for making the test specimens:

$$M_{sc} = \left(\gamma_{dry} \frac{lb}{ft^3} \right) X \left(\frac{1 ft^3}{1728 in.^3} \right) X \left(\frac{1 kg.}{2.2046 lb} \right) X \left(34.5 in.^3 \ X \ \frac{1000 g}{1 kg} \right) \quad \textbf{Equation 5.1}$$

which reduces to: $$M_{sc} = 9.06 \gamma_{dry} \frac{lb}{ft^3} \quad \textbf{Equation 5.2}$$

where:

M_{sc} = mass of soil cement, g

γ_{dry} = dry unit weight corresponding to composite sample moisture content, lb/ft^3

If the moisture content of the composite sample falls outside the allowable moisture content range, the following steps should be taken:

- Below the Lower Moisture Limit — material is too dry and composite sample shall be discarded. The Project Engineer shall be notified that the material delivered to the paver is at a moisture content lower than required to obtain 98% of the maximum dry unit weight.
- Above the Upper Moisture Limit — material is too wet and sample needs to be spread out on clean, non-absorbent plastic sheeting to dry to a moisture content that falls within the moisture window to achieve 98 percent density or higher.

Once the material has been determined to be within the 98 percent range of OMC, the material may be used to prepare cylindrical compression testing samples.

5.3.3 Making Test Specimens

Specimens should be made in accordance with ASTM D 1632, Section 10. Upon removal of the top and bottom pistons and separating disks from the mold assembly, mold plugs should be inserted into each end of the mold.

Mold plugs are discussed in detail in Section 3.2.3.1. The mold plugs are used and sealed with metal foil tape to prevent moisture from escaping the molds during initial curing periods. Mold plugs are shown in Figures 5.2 and 5.3.

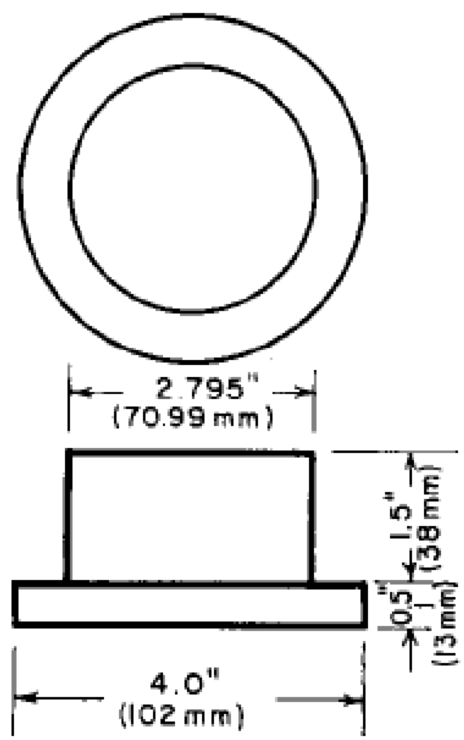

Figure 5.2: UMHW Mold Plugs (Adapted from ASTM D 1632)

Figure 5.3: UMHW Mold Plugs

5.3.4 Curing Test Specimens

5.3.4.1 Initial Curing

Field specimens should be cured in the molds under conditions that limit exposure to sun, wind, and other sources of rapid evaporation, and from contamination for 12 hours or longer if required. Samples should be stored in the shade when possible, and in a location where they are secure until delivery to the laboratory for removal of molds and sample extrusion. Field samples should be taped with metal foil tape to minimize moisture loss during initial curing. Typical field curing can be seen in Figure 5.4. After the initial 12 hour or longer curing period, cylinders are transported to the laboratory where final curing can occur. During transporting, the cylinders should be protected with suitable cushioning material to prevent damage.

Figure 5.4: Molded specimens during initial curing period

5.3.4.2 Sample Extrusion

After initial curing, mold plugs should be removed and samples should be extruded from the specimen molds. A tall, standard *vertical* specimen extruder that can fully extrude a sample without the need to be re-configured during the extruding process should be used for de-molding the specimens. *Horizontal* specimen extruders should not be used as they can cause damage at the ends of the specimens.

5.3.4.3 Final Curing

Final curing should be initiated as soon as the specimens are removed from the mold and placed into the moist room. The specimens should be kept in the moist room, protected from dripping water, and remain there until time of testing.

5.3.4.4 Compression Strength of Molded Soil-Cement Cylinders

Compression testing of the soil-cement field specimens should follow ASTM D 1633 with a few exceptions:

- Specimens should not be immersed in water for 4 hours prior to final curing,
- Specimens should not be capped, unless they do not meet the planeness and perpendicularity requirements of ASTM D 1633, and
- A loading rate of 10 ± 5 psi/s should be used.

5.4 Summary

A draft outline of a proposed ALDOT procedure is located in Appendix F. Final details and procedures shall be approved by ALDOT. The proposed procedure was written to employ the testing procedures currently implemented by ALDOT. Minor changes can be incorporated in the testing procedure to comply with existing ALDOT practices and procedures.

Chapter 6

Summary, Conclusions and Recommendations

6.1 Summary

Soil-cement base is a mixture of soil, portland cement and water that forms a strong and durable paving material once compacted and cured. Some of the advantages of soil-cement base include

- Providing a stiffer and stronger base (slab-like characteristics and beam strength) than an unbound granular base,
- Allowing the use of in-situ soils and manufactured aggregates, which eliminates the need for hauling select materials, and
- The reduction of rutting due to the resistance of consolidation and movement of the soil-cement layer.

Although the advantages of soil-cement base are many, construction practices and variance among core strength data have led to questions concerning proper quality control practices and testing protocol. One of the main difficulties in soil-cement base construction is its strength assessment.

Is it possible to approach strength testing of soil-cement base like conventional concrete? Is it plausible to use field-molded samples as control samples to evaluate the strength of soil-cement base? The primary objectives of this research were to

- Evaluate the pre-conditioning impact of curing on seven-day molded cylinders,
- Select a suitable curing method for molded cylinders,
- Evaluate the effects of gypsum capping compound on molded cylinders,
- Determine the effect of L/D on molded cylinders,
- Establish test procedure to prepare and test soil-cement base cylinders molded in the field by using techniques similar to ASTM D1632 (2007), and
- Recommend the testing protocol that the Alabama Department of Transportation (ALDOT) should implement to assess the strength of soil-cement base.

Soil-cement base is often used where soil stabilization is required for paving purposes. To effectively assess the strength behavior of soil-cement base, the task of field-molding soil-cement cylinders was conducted. ASTM D 1632 (2007) was used as a basis for preparing soil-cement cylinders in the field.

A study of pre-conditioning impact of curing on molded cylinders was performed. This study included three laboratory mixtures with two batches each using one soil type and three cement contents. The effects of moist curing, bag curing, fan curing and air curing were determined by seven-day compressive strength testing. Following the pre-conditioning impact study, a suitable curing method for the molded cylinders was evaluated. Six laboratory mixtures with two batches each using two different soil sources and three different cement contents were prepared and tested to determine a suitable curing method after initial curing and removal from the molds. Samples were tested in compression at seven days. On day six of the curing time, half of the samples were removed from the moist-curing room and individually placed into plastic bags for further curing. A comparison of moist-cured and bag-cured samples was obtained.

Next, a suitable capping method was evaluated. Neoprene pads and gypsum plaster were evaluated for use as capping methods along with no capping substrate used for the compression testing of the cylinders. Two field projects were evaluated and three laboratory mixtures with three batches each using three cement contents were developed to determine the best capping method for the field-molded cylinders.

The effect of length-to-diameter ratio reduction factors was determined by the evaluation of six laboratory mixtures with two batches each using two different soil sources and three different cement contents. Length-to-diameter (L/D) ratios of 2.0, 1.75, 1.5, 1.25 and 1.0 were used to evaluate the seven-day compressive strengths of the cylinders.

Finally, a test procedure was developed to prepare and test cylinders molded in the field. Based on the findings of this research, a strength testing guideline was prepared for the use of field-molded cylinders as a pay item by verifying the quality of the soil-cement base delivered to the jobsite.

The results from this research are aimed at providing guidance to transportation agencies when specifying strength assessment parameters for soil-cement base.

6.2 Conclusions

The conclusions corresponding to the pre-conditioning impact study, the suitable curing study, the capping study and the L/D study are presented. The key findings of the research can be summarized as follows:

- There is no considerable difference in compressive strength between moist-cured and bag-cured specimens when conditioned according to the methods used.
- The bag-cured specimens showed the least amount of difference with respect to moist-cured specimens, with fan-cured and air-cured having much higher strengths with respect to moist-cured specimens.
- Neoprene pads are not suitable for use in capping soil-cement cylinders.
- The configuration of the specimen molds with caps and the method of making the soil-cement cylinders provide the planeness and perpendicularity tolerances necessary to meet the criteria of ASTM C 1633 (2007). It is recommended to test soil-cement cylinders made according to requirements of ASTM C 1632 (2007) without any capping medium unless planeness and perpendicularity tolerances are suspect.
- Gypsum capping compound should be used only if needed to satisfy planeness and perpendicularity tolerances.
- The ASTM C 39 L/D correction factors are not applicable to soil-cement cylinders when made and tested in accordance with ASTM D 1632 and ASTM D1633, respectively. It is recommended that no strength correction factor be applied for length-to-diameter ratios between 1.0 and 2.0.

6.3 Recommendations

After completing the laboratory testing and data analysis required for this research, there are recommendations that can be made for future work. To gain further knowledge on the strength assessment of soil-cement base, it is recommended that additional testing be performed to evaluate the procedure to make field-molded cylinders recommended in this report. It is recommended that the strength from field-molded cylinders should be used to evaluate the results from cores to determine the source of variability in the core results. Additional testing should be performed on field projects to further identify potential variability in strength data.

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Appendix A

Design Curves and Gradations

The design curves and gradations used in this research are presented in Appendix A. The data presented was obtained from design studies provided by the Georgia Department of Transportation and the Alabama Department of Transportation.

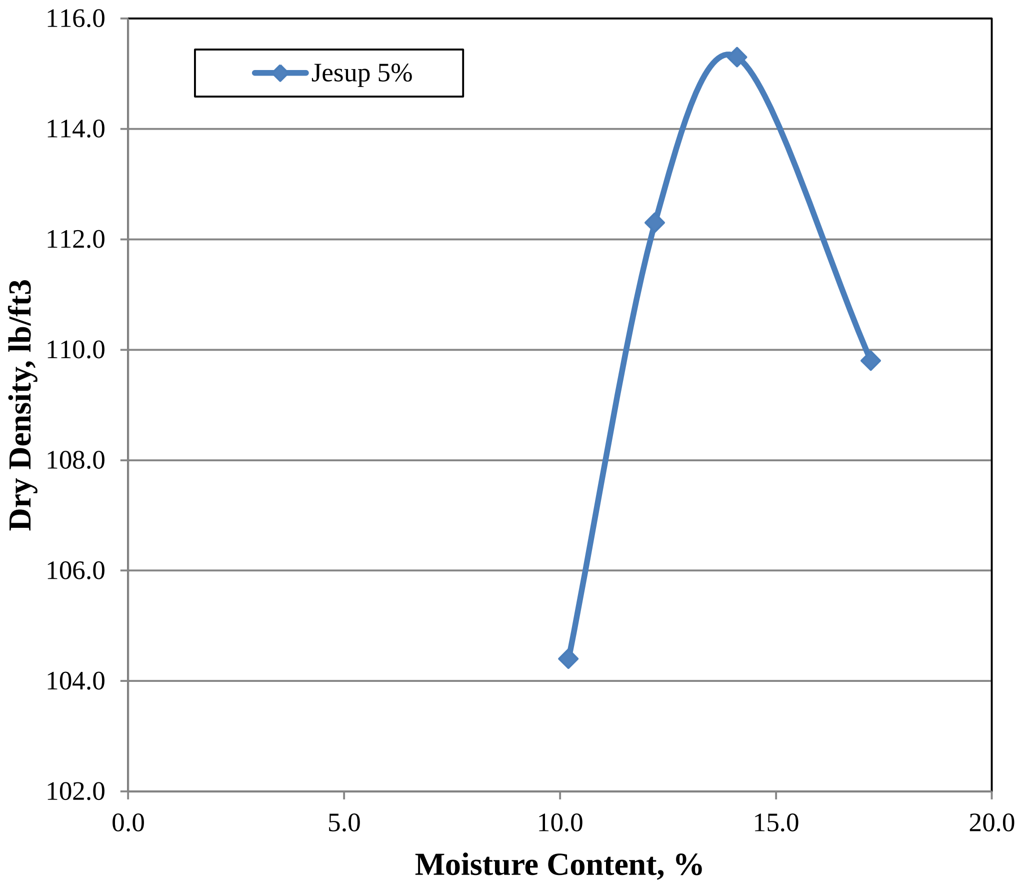

Figure A.1: Design curve for Jesup material with five percent cement content

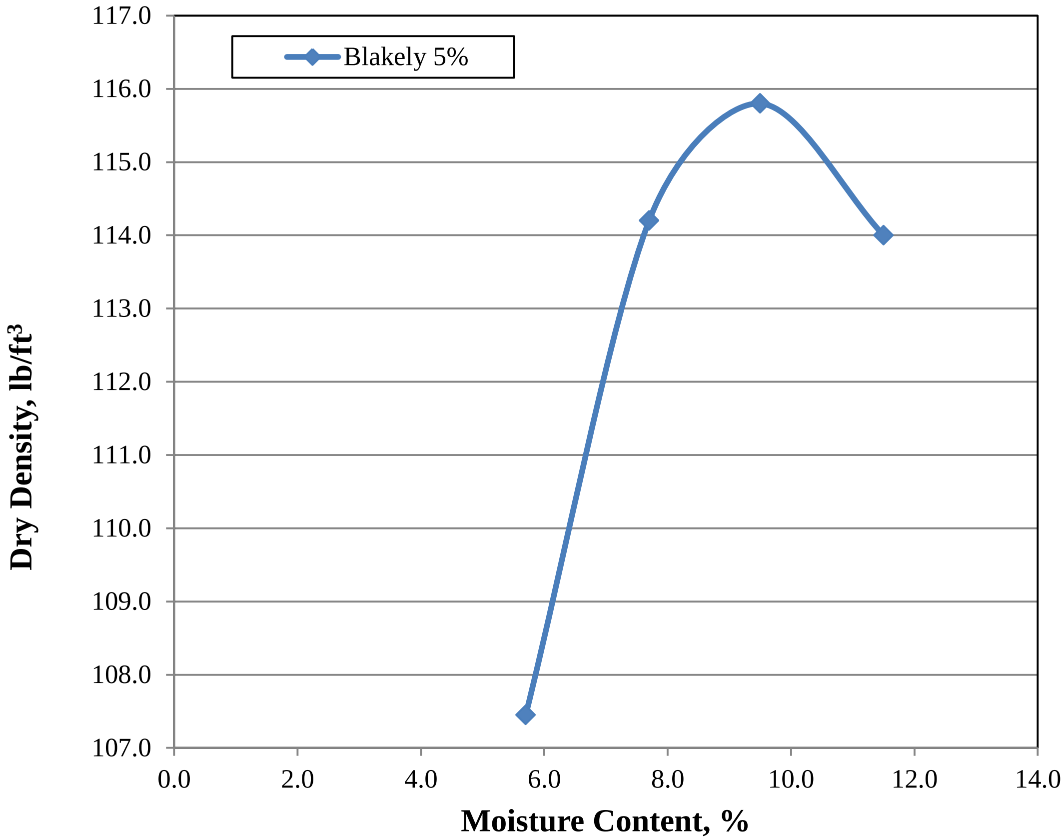

Figure A.2: Design curve for Blakely material with five percent cement content

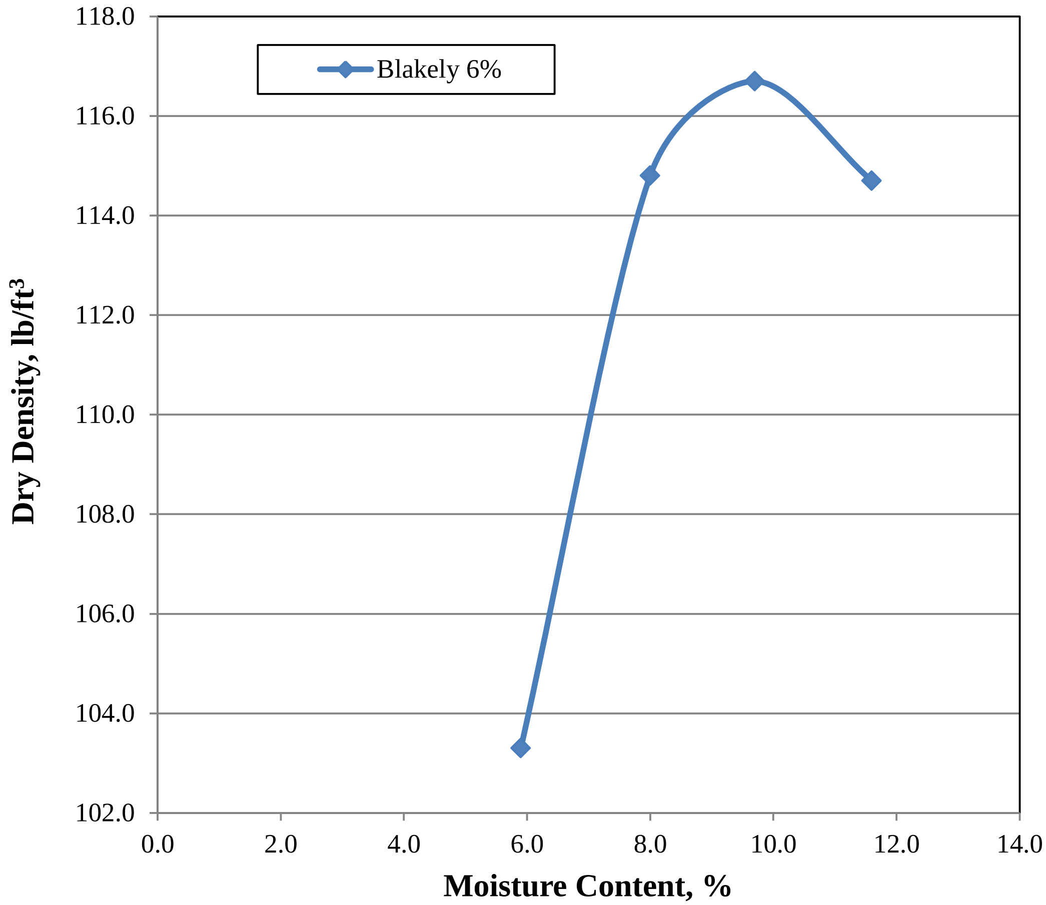

Figure A.3: Design curve for Blakely material with six percent cement content

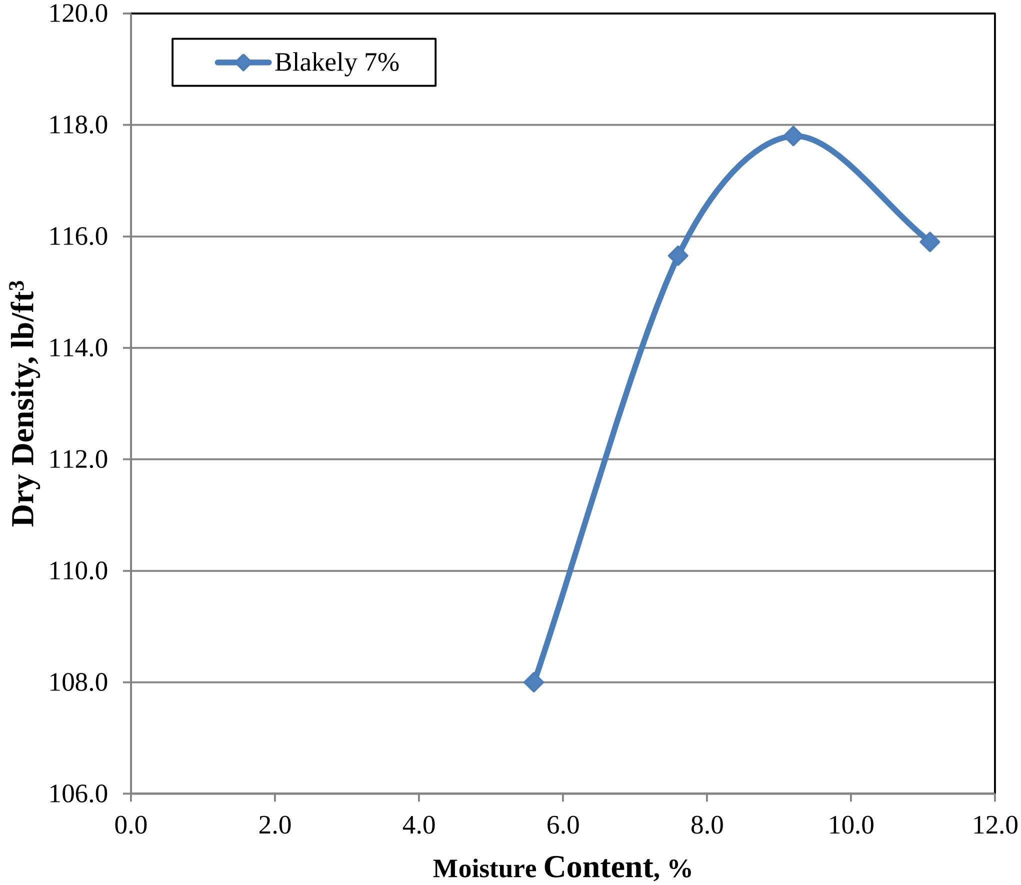

Figure A.4: Design curve for Blakely material with seven percent cement content

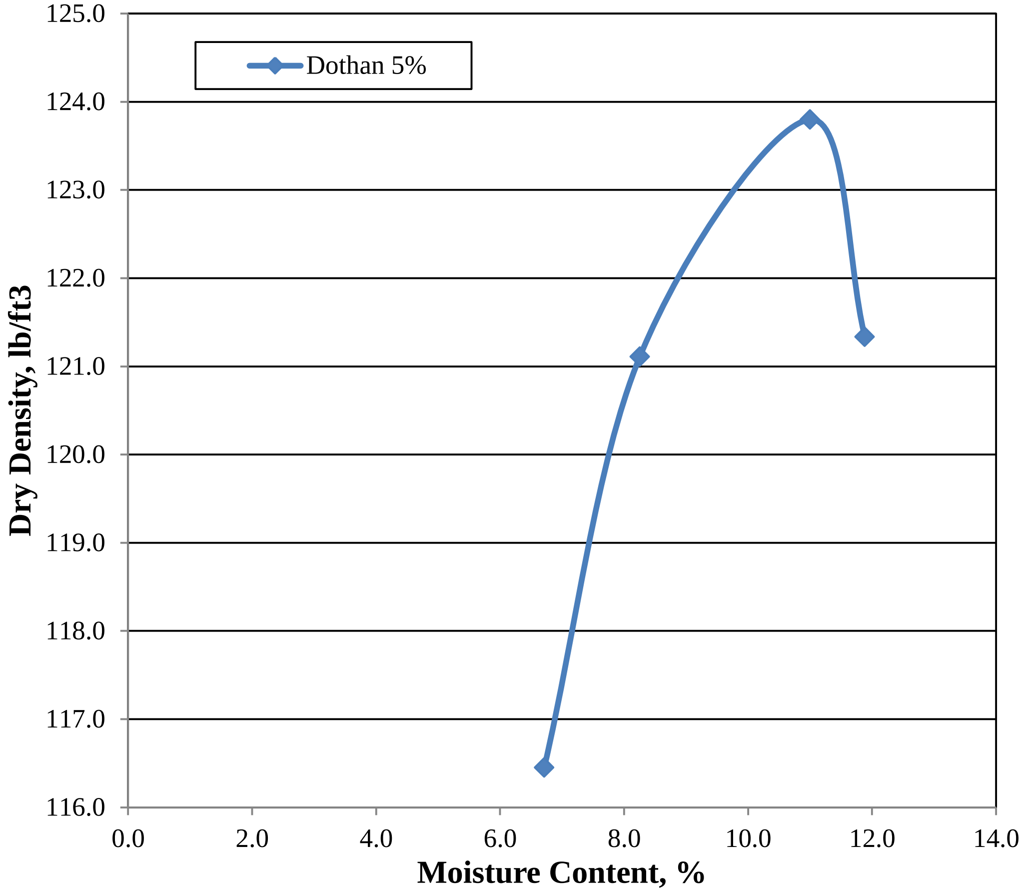

Figure A.5: Design curve for Dothan material with five percent cement content

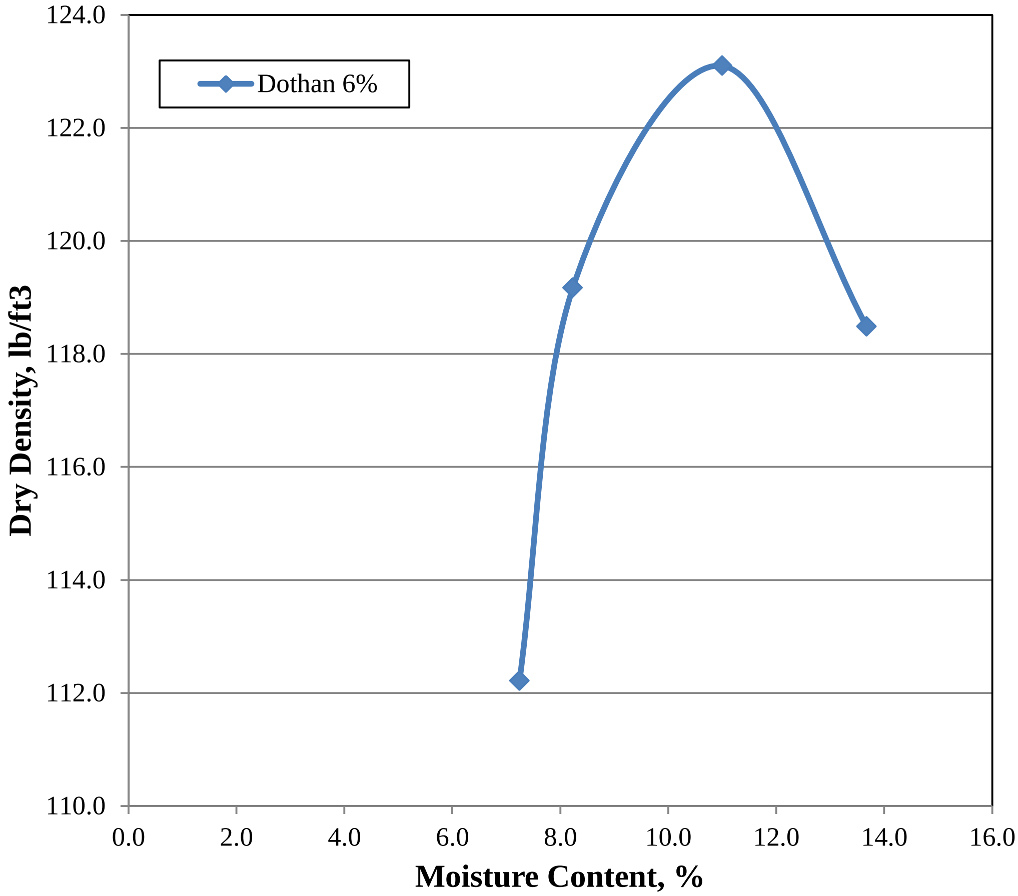

Figure A.6: Design curve for Dothan material with six percent cement content

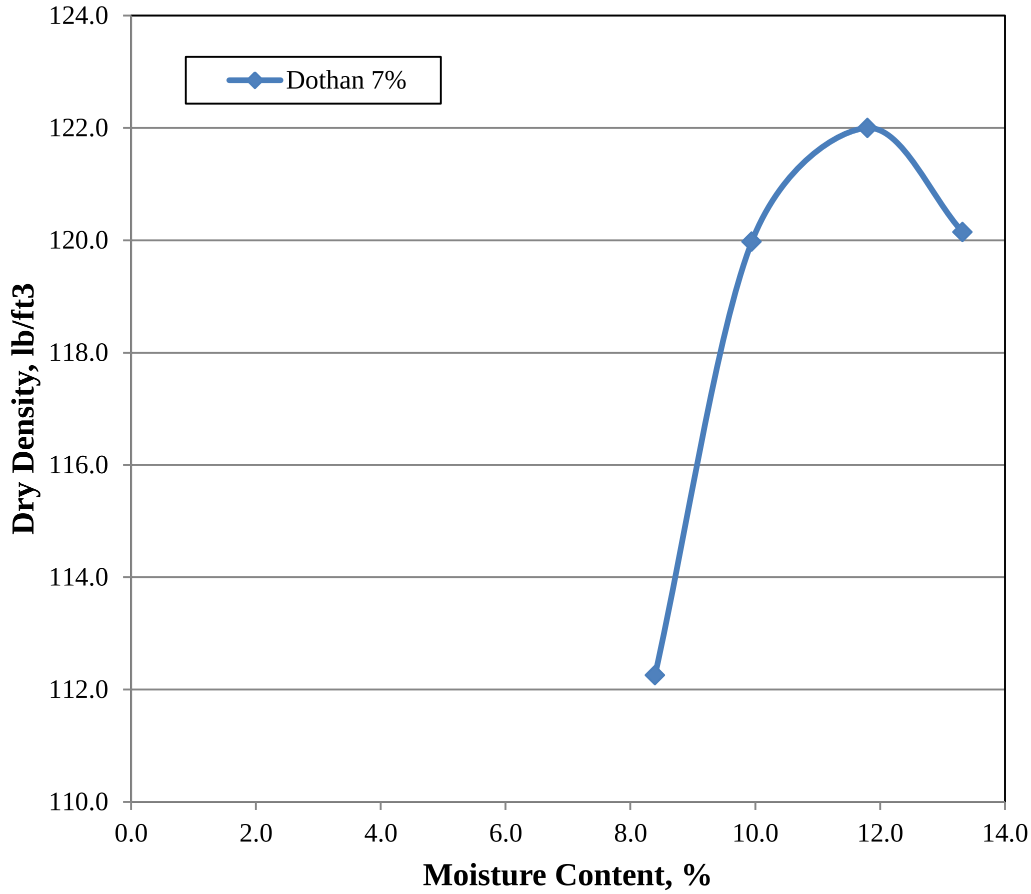

Figure A.7: Design curve for Dothan material with seven percent cement content

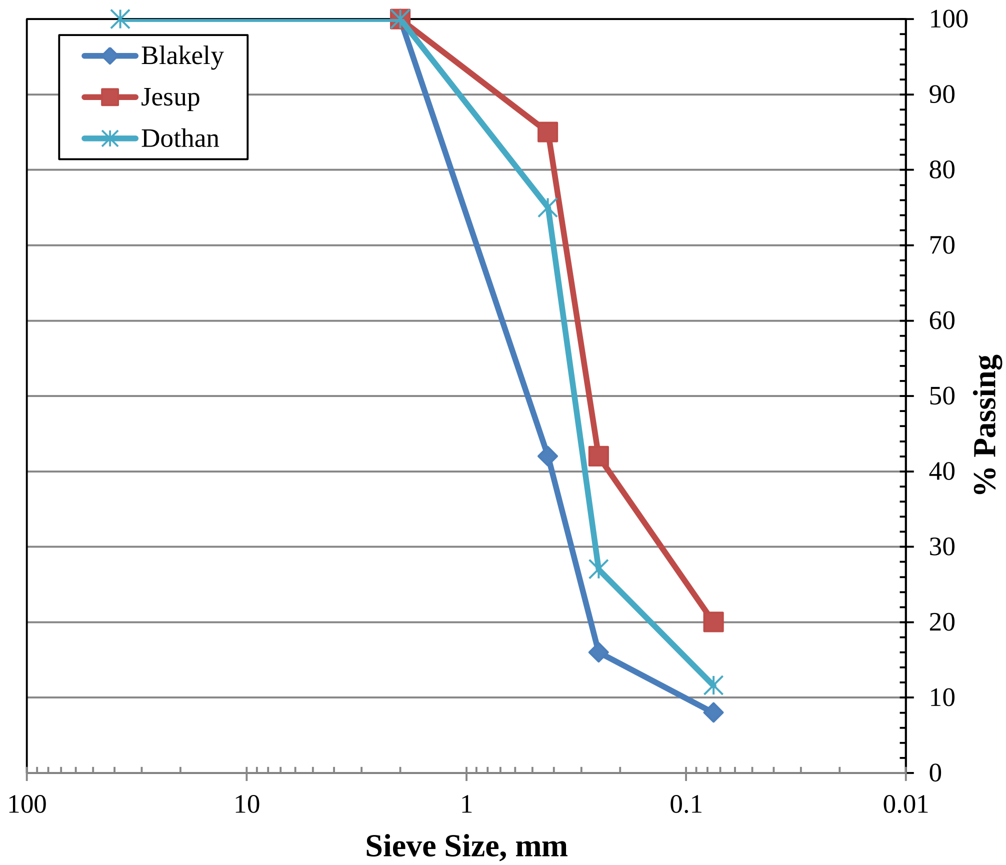

Figure A.8: Particle size for Jesup, Blakely, and Dothan materials

Appendix B

Pre-Conditioning Impact Data

A summary of the data for the curing pre-conditioning impact study is presented in Appendix B. All results in Appendix B are presented in psi. The nomenclature “EIT” is used for results where there was an error in testing.

Table B.1: Test results for Dothan 5% Batch 1

Moist Cured	**Test Results for Dothan 5% Batch 1**					
	1	2	3	4	5	6
Compressive Strength, psi	320	EIT	330	310	320	350
Fan Cured	1	2	3	4	5	6
Compressive Strength, psi	510	530	650	520	650	540
Bag Cured	1	2	3	4	5	6
Compressive Strength, psi	400	420	390	320	410	340
Air Cured	1	2	3	4	5	6
Compressive Strength, psi	490	470	660	550	580	650

Table B.2: Test results for Dothan 5% Batch 2

Moist Cured	**Test Results for Dothan 5% Batch 2**					
	1	2	3	4	5	6
Compressive Strength, psi	370	430	380	400	410	EIT
Fan Cured	1	2	3	4	5	6
Compressive Strength, psi	550	530	570	540	560	540
Bag Cured	1	2	3	4	5	6
Compressive Strength, psi	410	430	400	380	390	410
Air Cured	1	2	3	4	5	6
Compressive Strength, psi	530	590	530	520	550	520

Table B3: Test results for Dothan 6% Batch 1

Moist Cured	**Test Results for Dothan 6% Batch 1**					
	1	2	3	4	5	6
Compressive Strength, psi	EIT	370	390	350	360	350
Fan Cured	1	2	3	4	5	6
Compressive Strength, psi	540	490	500	560	500	550
Bag Cured	1	2	3	4	5	6
Compressive Strength, psi	320	420	340	360	380	370
Air Cured	1	2	3	4	5	6
Compressive Strength, psi	500	520	550	540	490	540

Table B.4: Test results for Dothan 6% Batch 2

Moist Cured	**Test Results for Dothan 6% Batch 2**					
	1	2	3	4	5	6
Compressive Strength, psi	340	380	320	390	390	390
Fan Cured	1	2	3	4	5	6
Compressive Strength, psi	570	560	470	500	540	420
Bag Cured	1	2	3	4	5	6
Compressive Strength, psi	300	290	330	350	370	320
Air Cured	1	2	3	4	5	6
Compressive Strength, psi	480	550	580	560	570	560

Table B.5: Test results for Dothan 7% Batch 1

Moist Cured	**Test Results for Dothan 7% Batch 1**					
	1	2	3	4	5	6
Compressive Strength, psi	390	360	410	350	370	350
Fan Cured	1	2	3	4	5	6
Compressive Strength, psi	480	480	510	500	520	480
Bag Cured	1	2	3	4	5	6
Compressive Strength, psi	390	380	410	350	390	380
Air Cured	1	2	3	4	5	6
Compressive Strength, psi	470	510	500	460	490	480

Table B

B.6: Test results for Dothan 7% Batch 2

Moist Cured	**Test Results for Dothan 7% Batch 2**					
	1	2	3	4	5	6
Compressive Strength, psi	360	310	350	360	380	300
Fan Cured	1	2	3	4	5	6
Compressive Strength, psi	430	450	450	450	490	400
Bag Cured	1	2	3	4	5	6
Compressive Strength, psi	290	290	270	EIT	360	320
Air Cured	1	2	3	4	5	6
Compressive Strength, psi	390	450	450	460	450	480

Appendix C

Suitable Curing Data

A summary of the data for the suitable curing study is presented in Appendix C. All results in Appendix C are presented in psi. The nomenclature "EIT" is used for results where there was an error in testing.

Table C.1: Test results for Blakely 5% Batch 1

3-Day Test Results for Blakely 5% Batch 1					
Moist Cured	1	2	3	4	5
Compressive Strength, psi	240	190	200	220	270
Bag Cured	1	2	3	4	5
Compressive Strength, psi	230	200	230	260	260
7-Day Test Results for Blakely 5% Batch 1					
Moist Cured	1	2	3	4	5
Compressive Strength, psi	320	270	300	310	270
Bag Cured	1	2	3	4	5
Compressive Strength, psi	290	300	320	310	310
28-Day Test Results for Blakely 5% Batch 1					
Moist Cured	1	2	3	4	5
Compressive Strength, psi	320	340	320	290	320
Bag Cured	1	2	3	4	5
Compressive Strength, psi	400	350	350	350	340

Table C.2: Test results for Blakely 5% Batch 2

3-Day Test Results for Blakely 5% Batch 2					
Moist Cured	1	2	3	4	5
Compressive Strength, psi	240	230	290	260	280
Bag Cured	1	2	3	4	5
Compressive Strength, psi	270	220	270	270	260
7-Day Test Results for Blakely 5% Batch 2					
Moist Cured	1	2	3	4	5
Compressive Strength, psi	260	290	280	300	310
Bag Cured	1	2	3	4	5
Compressive Strength, psi	270	320	300	280	280
28-Day Test Results for Blakely 5% Batch 2					
Moist Cured	1	2	3	4	5
Compressive Strength, psi	330	320	330	310	310
Bag Cured	1	2	3	4	5
Compressive Strength, psi	330	300	320	330	340

Table C.3: Test results for Blakely 6% Batch 1

3-Day Test Results for Blakely 5% Batch 1					
Moist Cured	1	2	3	4	5
Compressive Strength, psi	260	280	300	300	EIT
Bag Cured	1	2	3	4	5
Compressive Strength, psi	310	270	330	310	EIT
7-Day Test Results for Blakely 6% Batch 1					
Moist Cured	1	2	3	4	5
Compressive Strength, psi	300	270	360	350	300
Bag Cured	1	2	3	4	5
Compressive Strength, psi	380	330	320	360	290
28-Day Test Results for Blakely 6% Batch 1					
Moist Cured	1	2	3	4	5
Compressive Strength, psi	340	360	370	420	EIT
Bag Cured	1	2	3	4	5
Compressive Strength, psi	EIT	460	410	440	450

Table C.4: Test results for Blakely 6% Batch 2

3-Day Test Results for Blakely 6% Batch 2					
Moist Cured	1	2	3	4	5
Compressive Strength, psi	350	330	410	370	350
Bag Cured	1	2	3	4	5
Compressive Strength, psi	300	310	320	290	EIT
7-Day Test Results for Blakely 6% Batch 2					
Moist Cured	1	2	3	4	5
Compressive Strength, psi	310	390	390	360	410
Bag Cured	1	2	3	4	5
Compressive Strength, psi	420	360	330	410	350
28-Day Test Results for Blakely 6% Batch 2					
Moist Cured	1	2	3	4	5
Compressive Strength, psi	410	480	400	400	390
Bag Cured	1	2	3	4	5
Compressive Strength, psi	410	460	380	460	430

Table C.5: Test results for Blakely 7% Batch 1

3-Day Test Results for Blakely 5% Batch 1					
Moist Cured	1	2	3	4	5
Compressive Strength, psi	340	460	450	410	390
Bag Cured	1	2	3	4	5
Compressive Strength, psi	420	400	470	450	460
7-Day Test Results for Blakely 7% Batch 1					
Moist Cured	1	2	3	4	5
Compressive Strength, psi	530	480	490	540	520
Bag Cured	1	2	3	4	5
Compressive Strength, psi	540	480	430	470	510
28-Day Test Results for Blakely 7% Batch 1					
Moist Cured	1	2	3	4	5
Compressive Strength, psi	440	540	530	570	580
Bag Cured	1	2	3	4	5
Compressive Strength, psi	520	470	580	480	480

Table C.6: Test results for Blakely 7% Batch 2

3-Day Test Results for Blakely 7% Batch 2					
Moist Cured	1	2	3	4	5
Compressive Strength, psi	370	330	380	440	420
Bag Cured	1	2	3	4	5
Compressive Strength, psi	420	350	360	400	410
7-Day Test Results for Blakely 7% Batch 2					
Moist Cured	1	2	3	4	5
Compressive Strength, psi	500	470	570	500	490
Bag Cured	1	2	3	4	5
Compressive Strength, psi	470	540	550	540	510
28-Day Test Results for Blakely 7% Batch 2					
Moist Cured	1	2	3	4	5
Compressive Strength, psi	580	650	550	610	700
Bag Cured	1	2	3	4	5
Compressive Strength, psi	650	640	680	610	580

Table C.7: Test results for Dothan 5% Batch 1

3-Day Test Results for Dothan 5% Batch 1					
Moist Cured	1	2	3	4	5
Compressive Strength, psi	270	280	280	320	230
Bag Cured	1	2	3	4	5
Compressive Strength, psi	280	280	250	250	280
7-Day Test Results for Dothan 5% Batch 1					
Moist Cured	1	2	3	4	5
Compressive Strength, psi	380	300	380	350	370
Bag Cured	1	2	3	4	5
Compressive Strength, psi	330	330	370	380	290
28-Day Test Results for Dothan 5% Batch 1					
Moist Cured	1	2	3	4	5
Compressive Strength, psi	400	440	370	430	460
Bag Cured	1	2	3	4	5
Compressive Strength, psi	390	420	460	460	410

Table C.8: Test results for Dothan 5% Batch 2

3-Day Test Results for Dothan 5% Batch 2					
Moist Cured	1	2	3	4	5
Compressive Strength, psi	180	210	200	170	190
Bag Cured	1	2	3	4	5
Compressive Strength, psi	180	160	190	190	220
7-Day Test Results for Dothan 5% Batch 2					
Moist Cured	1	2	3	4	5
Compressive Strength, psi	290	320	350	290	310
Bag Cured	1	2	3	4	5
Compressive Strength, psi	300	320	320	330	280
28-Day Test Results for Dothan 5% Batch 2					
Moist Cured	1	2	3	4	5
Compressive Strength, psi	430	410	390	430	410
Bag Cured	1	2	3	4	5
Compressive Strength, psi	420	370	420	430	430

Table C.9: Test results for Dothan 6% Batch 1

3-Day Test Results for Dothan 6% Batch 1					
Moist Cured	1	2	3	4	5
Compressive Strength, psi	320	300	300	380	360
Bag Cured	1	2	3	4	5
Compressive Strength, psi	330	360	330	290	340
7-Day Test Results for Dothan 6% Batch 1					
Moist Cured	1	2	3	4	5
Compressive Strength, psi	540	460	470	540	480
Bag Cured	1	2	3	4	5
Compressive Strength, psi	550	530	430	500	450
28-Day Test Results for Dothan 6% Batch 1					
Moist Cured	1	2	3	4	5
Compressive Strength, psi	540	490	500	540	520
Bag Cured	1	2	3	4	5
Compressive Strength, psi	520	520	500	560	550

Table C.10: Test results for Dothan 6% Batch 2

3-Day Test Results for Dothan 6% Batch 2					
Moist Cured	1	2	3	4	5
Compressive Strength, psi	300	310	300	250	310
Bag Cured	1	2	3	4	5
Compressive Strength, psi	250	320	350	300	240
7-Day Test Results for Dothan 6% Batch 2					
Moist Cured	1	2	3	4	5
Compressive Strength, psi	480	440	390	420	470
Bag Cured	1	2	3	4	5
Compressive Strength, psi	450	440	380	480	390
28-Day Test Results for Dothan 6% Batch 2					
Moist Cured	1	2	3	4	5
Compressive Strength, psi	480	450	560	460	540
Bag Cured	1	2	3	4	5
Compressive Strength, psi	440	520	540	500	540

Table C.11: Test results for Dothan 7% Batch 1

3-Day Test Results for Dothan 7% Batch 1					
Moist Cured	1	2	3	4	5
Compressive Strength, psi	350	370	320	360	340
Bag Cured	1	2	3	4	5
Compressive Strength, psi	340	390	410	360	320
7-Day Test Results for Dothan 7% Batch 1					
Moist Cured	1	2	3	4	5
Compressive Strength, psi	480	510	550	470	430
Bag Cured	1	2	3	4	5
Compressive Strength, psi	440	470	490	470	490
28-Day Test Results for Dothan 7% Batch 1					
Moist Cured	1	2	3	4	5
Compressive Strength, psi	600	570	630	570	600
Bag Cured	1	2	3	4	5
Compressive Strength, psi	580	520	600	580	550

Table C.12: Test results for Dothan 7% Batch 2

3-Day Test Results for Dothan 7% Batch 2					
Moist Cured	1	2	3	4	5
Compressive Strength, psi	320	370	300	400	390
Bag Cured	1	2	3	4	5
Compressive Strength, psi	380	370	390	310	300
7-Day Test Results for Dothan 7% Batch 2					
Moist Cured	1	2	3	4	5
Compressive Strength, psi	420	420	460	460	480
Bag Cured	1	2	3	4	5
Compressive Strength, psi	410	480	480	480	520
28-Day Test Results for Dothan 7% Batch 2					
Moist Cured	1	2	3	4	5
Compressive Strength, psi	560	580	550	590	620
Bag Cured	1	2	3	4	5
Compressive Strength, psi	520	570	640	590	560

Appendix D

Capping Data

A summary of the data for the capping study is presented in Appendix D. All results in Appendix D are presented in psi. The nomenclature “EIT” is used for results where there was an error in testing.

Table D.1: Test results for Blakely field project

3-Day Test Results for Blakely Field Project			
No Capping	1	2	3
Compressive Strength, psi	250	250	280
Neoprene Pads	1	2	3
Compressive Strength, psi	220	210	240
Gypsum Capping	1	2	3
Compressive Strength, psi	280	310	EIT
7-Day Test Results for Blakely Field Project			
No Capping	1	2	3
Compressive Strength, psi	320	240	270
Neoprene Pads	1	2	3
Compressive Strength, psi	250	260	290
Gypsum Capping	1	2	3
Compressive Strength, psi	310	370	370
28-Day Test Results for Blakely Field Project			
No Capping	1	2	3
Compressive Strength, psi	240	320	310
Neoprene Pads	1	2	3
Compressive Strength, psi	300	280	340
Gypsum Capping	1	2	3
Compressive Strength, psi	420	410	380

Table D.2: Test results for Jesup field project

3-Day Test Results for Jesup Field Project			
No Capping	1	2	3
Compressive Strength, psi	230	200	190
Neoprene Pads	1	2	3
Compressive Strength, psi	180	140	210
Gypsum Capping	1	2	3
Compressive Strength, psi	200	210	170
7-Day Test Results for Jesup Field Project			
No Capping	1	2	3
Compressive Strength, psi	190	210	250
Neoprene Pads	1	2	3
Compressive Strength, psi	190	170	190
Gypsum Capping	1	2	3
Compressive Strength, psi	180	290	270
28-Day Test Results for Jesup Field Project			
No Capping	1	2	3
Compressive Strength, psi	190	210	240
Neoprene Pads	1	2	3
Compressive Strength, psi	170	150	250
Gypsum Capping	1	2	3
Compressive Strength, psi	300	190	300

Table D.3: Test results for Blakely 5% Batch 1

3-Day Test Results for Blakely 5% Batch 1					
No Capping	1	2	3	4	5
Compressive Strength, psi	260	230	270	290	280
Gypsum Capping	1	2	3	4	5
Compressive Strength, psi	300	EIT	EIT	EIT	EIT
7-Day Test Results for Blakely 5% Batch 1					
No Capping	1	2	3	4	5
Compressive Strength, psi	330	320	290	280	250
Gypsum Capping	1	2	3	4	5
Compressive Strength, psi	320	300	320	290	310
28-Day Test Results for Blakely 5% Batch 1					
No Capping	1	2	3	4	5
Compressive Strength, psi	350	280	340	310	290
Gypsum Capping	1	2	3	4	5
Compressive Strength, psi	300	360	330	340	EIT

Table D.4: Test results for Blakely 5% Batch 2

3-Day Test Results for Blakely 5% Batch 2					
No Capping	1	2	3	4	5
Compressive Strength, psi	310	300	320	250	280
Gypsum Capping	1	2	3	4	5
Compressive Strength, psi	310	310	270	270	300
7-Day Test Results for Blakely 5% Batch 2					
No Capping	1	2	3	4	5
Compressive Strength, psi	280	330	310	250	300
Gypsum Capping	1	2	3	4	5
Compressive Strength, psi	330	350	330	310	350
28-Day Test Results for Blakely 5% Batch 2					
No Capping	1	2	3	4	5
Compressive Strength, psi	350	350	300	EIT	370
Gypsum Capping	1	2	3	4	5
Compressive Strength, psi	380	350	410	380	EIT

Table D.5: Test results for Blakely 5% Batch 3

3-Day Test Results for Blakely 5% Batch 3					
No Capping	1	2	3	4	5
Compressive Strength, psi	220	230	190	200	250
Gypsum Capping	1	2	3	4	5
Compressive Strength, psi	280	280	290	280	290
7-Day Test Results for Blakely 5% Batch 3					
No Capping	1	2	3	4	5
Compressive Strength, psi	250	210	260	280	210
Gypsum Capping	1	2	3	4	5
Compressive Strength, psi	340	330	330	370	EIT
28-Day Test Results for Blakely 5% Batch 3					
No Capping	1	2	3	4	5
Compressive Strength, psi	310	270	260	300	EIT
Gypsum Capping	1	2	3	4	5
Compressive Strength, psi	370	390	410	400	370

Table D.6: Test results for Blakely 6% Batch 1

3-Day Test Results for Blakely 6% Batch 1					
No Capping	1	2	3	4	5
Compressive Strength, psi	390	400	360	410	410
Gypsum Capping	1	2	3	4	5
Compressive Strength, psi	410	400	400	440	450
7-Day Test Results for Blakely 6% Batch 1					
No Capping	1	2	3	4	5
Compressive Strength, psi	440	460	450	440	460
Gypsum Capping	1	2	3	4	5
Compressive Strength, psi	460	500	480	490	450
28-Day Test Results for Blakely 6% Batch 1					
No Capping	1	2	3	4	5
Compressive Strength, psi	390	400	EIT	410	390
Gypsum Capping	1	2	3	4	5
Compressive Strength, psi	500	520	520	450	EIT

Table D.7: Test results for Blakely 6% Batch 2

3-Day Test Results for Blakely 6% Batch 2					
No Capping	1	2	3	4	5
Compressive Strength, psi	300	380	390	360	320
Gypsum Capping	1	2	3	4	5
Compressive Strength, psi	360	370	340	350	350
7-Day Test Results for Blakely 6% Batch 2					
No Capping	1	2	3	4	5
Compressive Strength, psi	330	350	310	370	380
Gypsum Capping	1	2	3	4	5
Compressive Strength, psi	420	340	360	360	350
28-Day Test Results for Blakely 6% Batch 2					
No Capping	1	2	3	4	5
Compressive Strength, psi	380	470	380	400	420
Gypsum Capping	1	2	3	4	5
Compressive Strength, psi	380	390	400	390	EIT

Table D.8: Test results for Blakely 6% Batch 3

3-Day Test Results for Blakely 6% Batch 3					
No Capping	1	2	3	4	5
Compressive Strength, psi	310	300	310	300	250
Gypsum Capping	1	2	3	4	5
Compressive Strength, psi	330	350	360	310	EIT
7-Day Test Results for Blakely 6% Batch 3					
No Capping	1	2	3	4	5
Compressive Strength, psi	420	350	380	380	450
Gypsum Capping	1	2	3	4	5
Compressive Strength, psi	380	390	420	390	EIT
28-Day Test Results for Blakely 6% Batch 3					
No Capping	1	2	3	4	5
Compressive Strength, psi	450	480	470	430	440
Gypsum Capping	1	2	3	4	5
Compressive Strength, psi	530	540	500	550	EIT

Table D.9: Test results for Blakely 7% Batch 1

3-Day Test Results for Blakely 7% Batch 1					
No Capping	1	2	3	4	5
Compressive Strength, psi	430	510	500	530	520
Gypsum Capping	1	2	3	4	5
Compressive Strength, psi	600	540	540	470	510
7-Day Test Results for Blakely 7% Batch 1					
No Capping	1	2	3	4	5
Compressive Strength, psi	560	570	580	570	530
Gypsum Capping	1	2	3	4	5
Compressive Strength, psi	690	640	640	710	670
28-Day Test Results for Blakely 7% Batch 1					
No Capping	1	2	3	4	5
Compressive Strength, psi	660	720	660	610	690
Gypsum Capping	1	2	3	4	5
Compressive Strength, psi	750	770	650	780	730

Table D.10: Test results for Blakely 7% Batch 2

3-Day Test Results for Blakely 7% Batch 2					
No Capping	1	2	3	4	5
Compressive Strength, psi	EIT	450	370	350	EIT
Gypsum Capping	1	2	3	4	5
Compressive Strength, psi	700	440	480	430	490
7-Day Test Results for Blakely 7% Batch 2					
No Capping	1	2	3	4	5
Compressive Strength, psi	580	470	440	530	520
Gypsum Capping	1	2	3	4	5
Compressive Strength, psi	590	620	630	590	570
28-Day Test Results for Blakely 7% Batch 2					
No Capping	1	2	3	4	5
Compressive Strength, psi	560	680	680	720	560
Gypsum Capping	1	2	3	4	5
Compressive Strength, psi	760	720	680	670	EIT

Table D.11: Test results for Blakely 7% Batch 3

3-Day Test Results for Blakely 7% Batch 3					
No Capping	1	2	3	4	5
Compressive Strength, psi	400	420	410	390	EIT
Gypsum Capping	1	2	3	4	5
Compressive Strength, psi	400	450	400	410	EIT
7-Day Test Results for Blakely 7% Batch 3					
No Capping	1	2	3	4	5
Compressive Strength, psi	460	580	550	530	580
Gypsum Capping	1	2	3	4	5
Compressive Strength, psi	630	650	610	670	680
28-Day Test Results for Blakely 7% Batch 3					
No Capping	1	2	3	4	5
Compressive Strength, psi	690	580	670	700	690
Gypsum Capping	1	2	3	4	5
Compressive Strength, psi	700	720	710	700	770

Appendix E

Length-to-Diameter Ratio Data

A summary of the data for the capping study is presented in Appendix E. All results in Appendix E are presented in psi. The nomenclature "EIT" is used for results where there was an error in testing.

Table E.1: Test results for Blakely 5% Batch 1

Test Results for Blakely 5% Batch 1						
L/D = 2.0	1	2	3	4	5	6
Compressive Strength, psi	EIT	350	340	350	360	360
L/D = 1.75	1	2	3	4	5	6
Compressive Strength, psi	300	330	290	280	270	300
L/D = 1.50	1	2	3	4	5	6
Compressive Strength, psi	300	330	330	270	350	320
L/D = 1.25	1	2	3	4	5	6
Compressive Strength, psi	270	310	350	300	330	360
L/D = 1.00	1	2	3	4	5	6
Compressive Strength, psi	340	420	360	EIT	370	320

Table E.2: Test results for Blakely 5% Batch 2

Test Results for Blakely 5% Batch 2						
L/D = 2.0	1	2	3	4	5	6
Compressive Strength, psi	270	290	EIT	260	320	310
L/D = 1.75	1	2	3	4	5	6
Compressive Strength, psi	290	320	290	320	290	290
L/D = 1.50	1	2	3	4	5	6
Compressive Strength, psi	350	330	320	280	280	320
L/D = 1.25	1	2	3	4	5	6
Compressive Strength, psi	310	330	300	320	280	310
L/D = 1.00	1	2	3	4	5	6
Compressive Strength, psi	330	360	340	350	330	280

Table E.3: Test results for Blakely 6% Batch 1

Test Results for Blakely 6% Batch 1						
L/D = 2.0	1	2	3	4	5	6
Compressive Strength, psi	400	430	400	410	400	450
L/D = 1.75	1	2	3	4	5	6
Compressive Strength, psi	410	440	400	410	430	440
L/D = 1.50	1	2	3	4	5	6
Compressive Strength, psi	420	390	380	450	410	430
L/D = 1.25	1	2	3	4	5	6
Compressive Strength, psi	430	420	440	420	390	430
L/D = 1.00	1	2	3	4	5	6
Compressive Strength, psi	400	410	370	390	430	480

Table E.4: Test results for Blakely 6% Batch 2

Test Results for Blakely 6% Batch 2						
L/D = 2.0	1	2	3	4	5	6
Compressive Strength, psi	430	460	440	420	460	450
L/D = 1.75	1	2	3	4	5	6
Compressive Strength, psi	430	440	410	450	480	450
L/D = 1.50	1	2	3	4	5	6
Compressive Strength, psi	450	460	470	410	480	460
L/D = 1.25	1	2	3	4	5	6
Compressive Strength, psi	370	450	420	420	480	380
L/D = 1.00	1	2	3	4	5	6
Compressive Strength, psi	430	380	320	350	390	380

Table E.5: Test results for Blakely 7% Batch 1

Test Results for Blakely 7% Batch 1						
L/D = 2.0	1	2	3	4	5	6
Compressive Strength, psi	520	520	500	520	500	510
L/D = 1.75	1	2	3	4	5	6
Compressive Strength, psi	530	530	470	420	470	440
L/D = 1.50	1	2	3	4	5	6
Compressive Strength, psi	510	490	540	550	480	560
L/D = 1.25	1	2	3	4	5	6
Compressive Strength, psi	570	530	520	520	550	470
L/D = 1.00	1	2	3	4	5	6
Compressive Strength, psi	510	520	510	490	500	550

Table E.6: Test results for Blakely 7% Batch 2

Test Results for Blakely 7% Batch 2						
L/D = 2.0	1	2	3	4	5	6
Compressive Strength, psi	440	520	580	470	550	560
L/D = 1.75	1	2	3	4	5	6
Compressive Strength, psi	560	490	520	490	480	510
L/D = 1.50	1	2	3	4	5	6
Compressive Strength, psi	460	570	510	500	470	470
L/D = 1.25	1	2	3	4	5	6
Compressive Strength, psi	470	500	570	580	520	500
L/D = 1.00	1	2	3	4	5	6
Compressive Strength, psi	510	490	560	500	520	600

Table E.7: Test results for Dothan 5% Batch 1

Test Results for Dothan 5% Batch 1						
L/D = 2.0	1	2	3	4	5	6
Compressive Strength, psi	410	430	460	410	470	450
L/D = 1.75	1	2	3	4	5	6
Compressive Strength, psi	380	460	410	410	430	430
L/D = 1.50	1	2	3	4	5	6
Compressive Strength, psi	400	450	460	490	410	450
L/D = 1.25	1	2	3	4	5	6
Compressive Strength, psi	420	400	440	400	410	450
L/D = 1.00	1	2	3	4	5	6
Compressive Strength, psi	410	430	440	400	480	410

Table E.8: Test results for Dothan 5% Batch 2

Test Results for Dothan 5% Batch 2						
L/D = 2.0	1	2	3	4	5	6
Compressive Strength, psi	410	410	470	430	440	490
L/D = 1.75	1	2	3	4	5	6
Compressive Strength, psi	420	430	410	420	460	440
L/D = 1.50	1	2	3	4	5	6
Compressive Strength, psi	410	410	400	440	420	460
L/D = 1.25	1	2	3	4	5	6
Compressive Strength, psi	440	440	430	430	430	450
L/D = 1.00	1	2	3	4	5	6
Compressive Strength, psi	440	450	490	430	450	470

Table E.9: Test results for Dothan 6% Batch 1

Test Results for Dothan 6% Batch 1						
L/D = 2.0	1	2	3	4	5	6
Compressive Strength, psi	490	450	500	490	420	440
L/D = 1.75	1	2	3	4	5	6
Compressive Strength, psi	500	480	440	520	480	480
L/D = 1.50	1	2	3	4	5	6
Compressive Strength, psi	490	440	520	510	460	470
L/D = 1.25	1	2	3	4	5	6
Compressive Strength, psi	480	460	460	470	450	540
L/D = 1.00	1	2	3	4	5	6
Compressive Strength, psi	480	EIT	490	510	470	420

Table E.10: Test results for Dothan 6% Batch 2

Test Results for Dothan 6% Batch 2						
L/D = 2.0	1	2	3	4	5	6
Compressive Strength, psi	440	500	510	490	440	500
L/D = 1.75	1	2	3	4	5	6
Compressive Strength, psi	440	420	520	500	450	480
L/D = 1.50	1	2	3	4	5	6
Compressive Strength, psi	430	460	510	440	450	510
L/D = 1.25	1	2	3	4	5	6
Compressive Strength, psi	410	530	410	480	430	530
L/D = 1.00	1	2	3	4	5	6
Compressive Strength, psi	510	480	520	450	420	530

Table E.11: Test results for Dothan 7% Batch 1

Test Results for Dothan 7% Batch 1						
L/D = 2.0	1	2	3	4	5	6
Compressive Strength, psi	490	530	560	560	570	530
L/D = 1.75	1	2	3	4	5	6
Compressive Strength, psi	590	600	520	560	590	560
L/D = 1.50	1	2	3	4	5	6
Compressive Strength, psi	510	550	560	520	520	510
L/D = 1.25	1	2	3	4	5	6
Compressive Strength, psi	520	530	510	430	530	530
L/D = 1.00	1	2	3	4	5	6
Compressive Strength, psi	550	570	540	570	520	500

Table E.12: Test results for Dothan 7% Batch 2

Test Results for Dothan 7% Batch 2						
L/D = 2.0	1	2	3	4	5	6
Compressive Strength, psi	500	510	490	470	510	520
L/D = 1.75	1	2	3	4	5	6
Compressive Strength, psi	490	450	490	430	520	550
L/D = 1.50	1	2	3	4	5	6
Compressive Strength, psi	450	450	530	490	560	460
L/D = 1.25	1	2	3	4	5	6
Compressive Strength, psi	460	570	430	450	570	490
L/D = 1.00	1	2	3	4	5	6
Compressive Strength, psi	530	440	570	570	530	500

Appendix F

Proposed ALDOT Procedure

This appendix is the proposed Alabama Department of Transportation procedure for making and curing soil-cement compression test specimens in the field. The contents of this appendix are only the recommended procedure from results concluded for this project conducted by Auburn University researchers. The final procedure will be approved and implemented by the Alabama Department of Transportation.

ALDOT – XXX

Making and Curing Soil-Cement Compression Test Specimens in the Field

1. General

1.1. This procedure provides a method for making and curing molded compression test specimens of soil cement under field conditions.

1.2. Compression test specimens shall be cylinders with a length equal to twice the diameter. This method provides for specimens 2.8 in. in diameter by 5.6 in. in length.

1.3. This practice for making soil-cement specimens for compression and flexure tests is used primarily with soil materials having not more than 35 % aggregate retained on the No. 4 sieve and not more than 85 % retained on the No. 40 sieve.

1.4. The soil-cement mixture design shall be submitted to the Materials and Tests Engineer for approval no later than 14 days prior to start of soil-cement placement.

1.5. This method consists of the following five steps:

1.5.1. Sampling the Material from the Paver (Section 3)

1.5.2. Determining the 98% Density Range (Sect. 4)

1.5.3. Making Test Specimens (Sect. 5)

1.5.4. Curing Test Specimens (Sect. 6)

1.5.5. Compression Strength of Molded Soil-Cement Cylinders (Sect. 7)

2. Apparatus

2.1. The Contractor shall supply all necessary equipment to use this procedure. The equipment will be approved by the Materials and Tests Engineer prior to use.

2.2. *Compression Test Specimen Molds*—Molds (Fig. 1) having an inside diameter of 2.8 ± 0.01 in. and a height of 9 in. for molding test specimens 2.8 in. in diameter and 5.6 in. high; machined steel top and bottom pistons having a diameter 0.005 in. less than the mold; a 6-in. long mold extension; and a spacer clip. At least two aluminum separating disks 1⁄16-in. thick by 2.78 in. in diameter shall be provided.

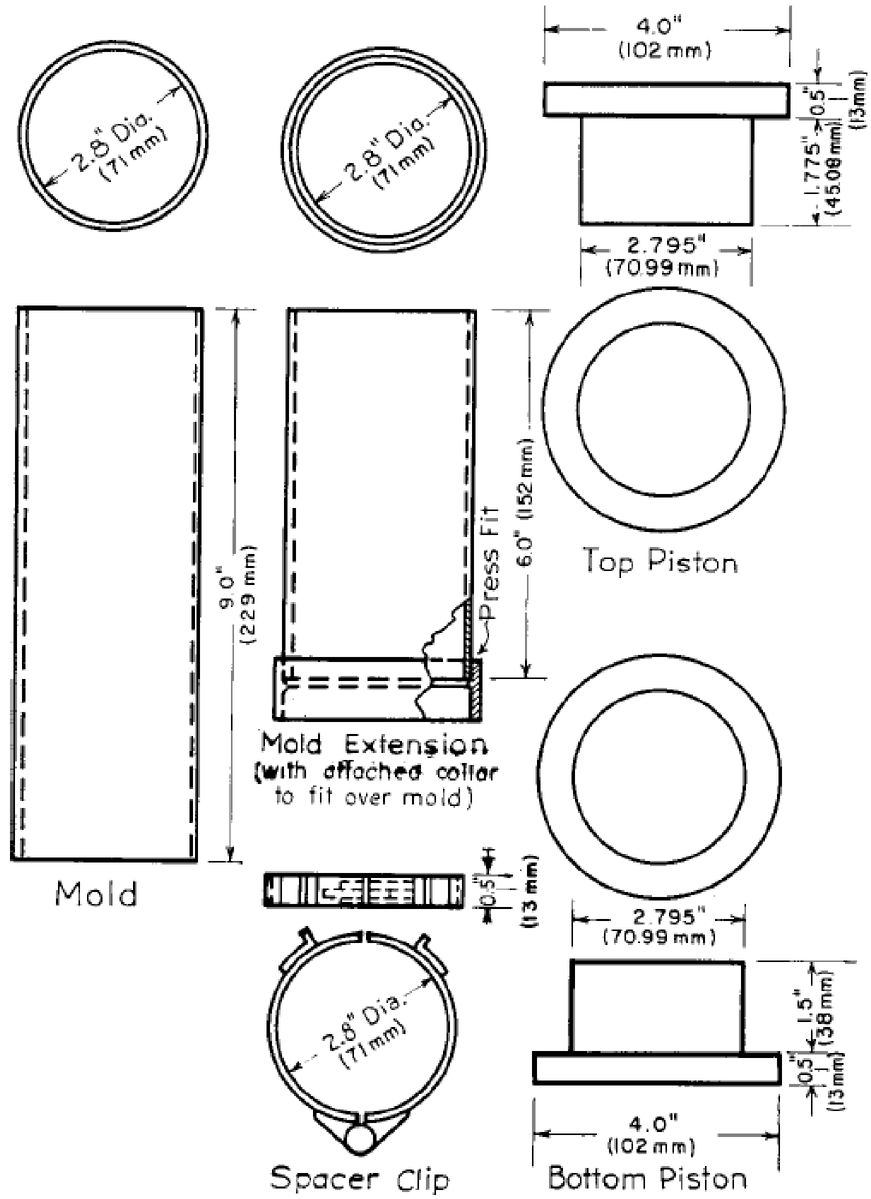

FIG. 1 Soil-Cement Cylinder Mold (ASTM D 1632)

2.3. *Mold Plugs*—(Fig. 2) similar in shape to the top and bottom pistons, having a diameter 0.005 in. less than the mold, machined from ultra-high molecular weight (UHMW) polyethylene. Two mold plugs are required for each molded specimen to be tested. Mold plugs are to be replaced when noticeable free movement is observed when installed in mold.

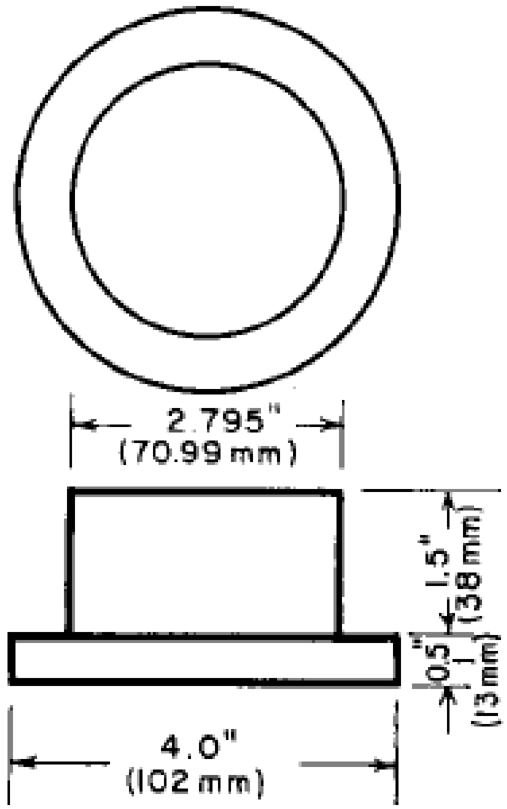

FIG. 2 UMHW Mold Plugs (Adapted from ASTM D 1632)

2.4. *Sieves*—2-in., 3⁄4-in., No. 4 and No. 16 sieves conforming to the requirements of ASTM Specification E 11.

2.5. *Balances*—A balance of 1000-g capacity, sensitive to 0.1 g, both meeting the requirements of ASTM Specification D 4753.

2.6. *Dropping-Weight Compacting Device*—A controlled dropping-weight device of 15 lb for striking the top piston, for optional use in compacting compression test specimens (see Fig. 3 and Fig. 4). When this equipment is used, the top piston listed in 2.2 is made the foot of the compacting device.

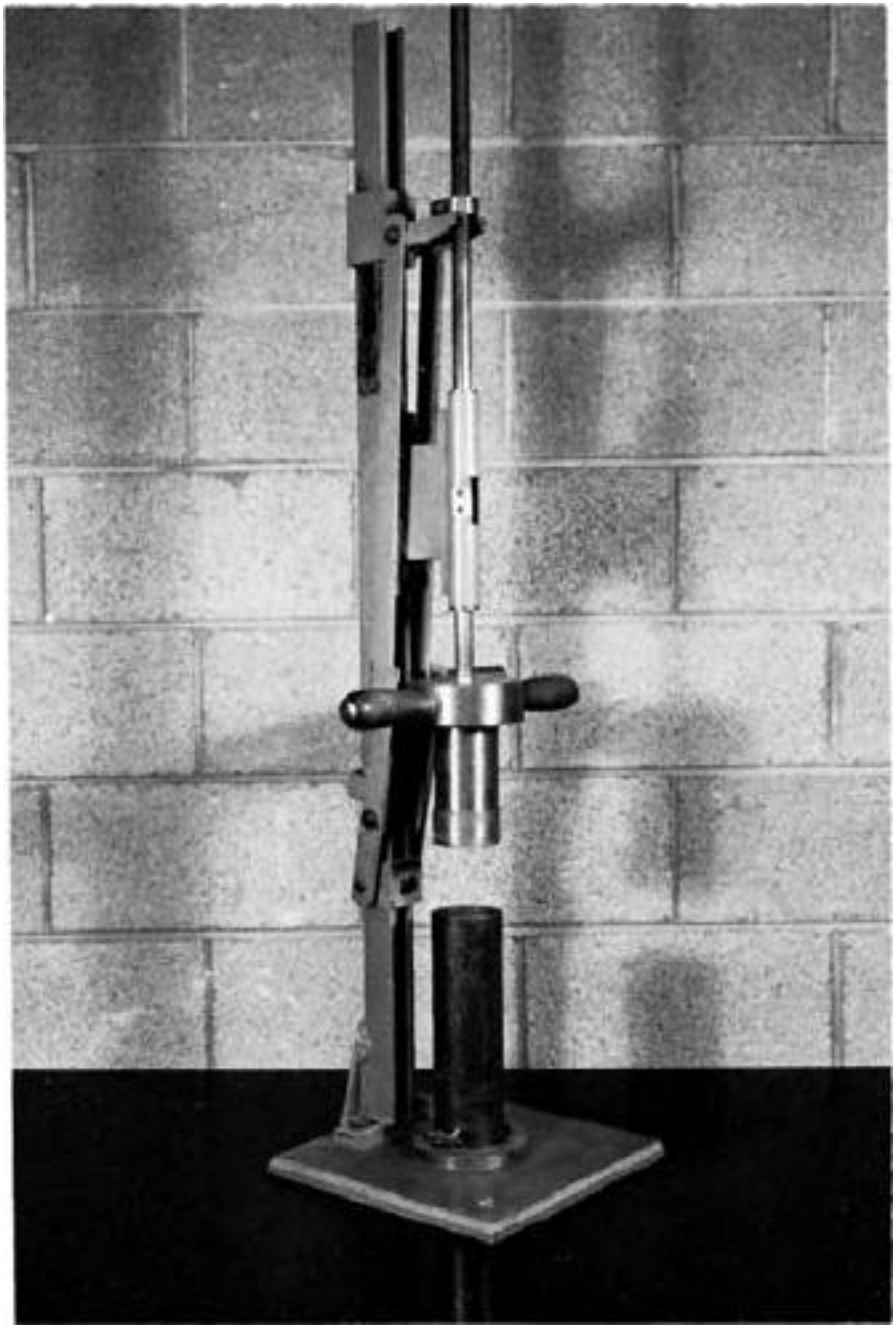

FIG. 3 Device for Compacting Compression Test Cylinder (ASTM D 1632)

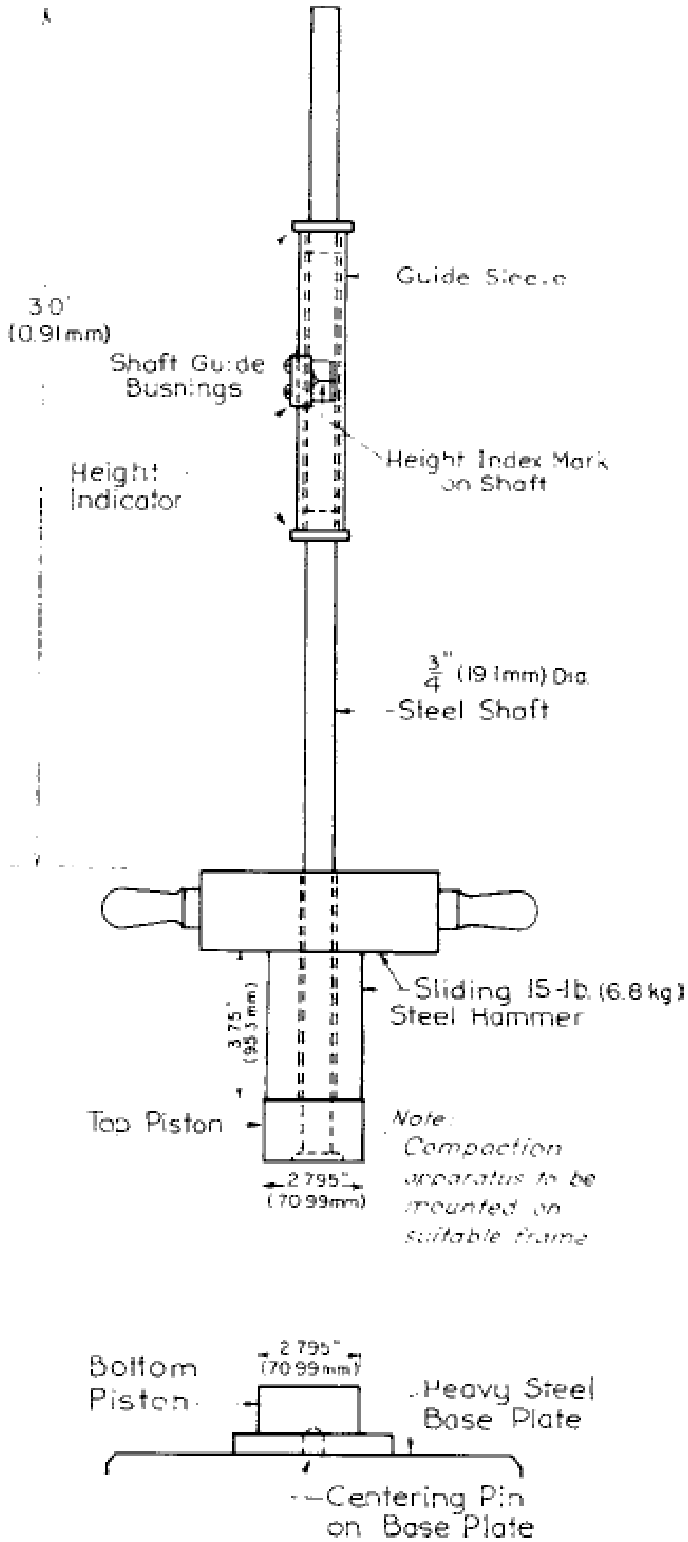

FIG. 4 Schematic Drawing of a Suitable Compacting Device (ASTM D 1632)

2.7. *Compression Specimen Extruder*—consisting of a piston or jack, and frame for extruding specimens from the mold.

2.8. *Metal Foil Tape*—1 ¾ in. in height, to seal mold plugs to the specimen mold and prevent moisture from escaping during initial curing period.

2.9. *Plastic Sheeting*—Clean, non-absorbent plastic sheeting at least 3 mil in thickness, large enough to cover an area that will contain the composite sample for air drying.

2.10. *Miscellaneous Equipment*—Tools such as trowel, spatula, pan, moisture sample cans, and the like.

2.11. *Tamping Rod*—A square-end cut, 1⁄2-in. diameter, smooth steel or aluminum rod approximately 20 in. in length.

2.12. *Moist Room or Cabinet*—A moist room or cabinet capable of maintaining a temperature of 73.4 ± 3°F and a relative humidity of not less than 96 % for moist curing specimens.

2.13. *Compression Testing Machine*—This machine may be of any type having sufficient capacity and control to provide the rate of loading prescribed in 7.3. It shall conform to the requirements of Section 15 of Practices E 4. The testing machine shall be equipped with two steel bearing blocks with hardened faces, one of which is a spherically seated head block that normally will bear on the upper surface of the specimen, and the other a plain rigid block on which the specimen will rest. The bearing faces shall be at least as large, and preferably slightly larger, than the surface of the specimen to which the load is applied. The bearing faces, when new, shall not depart from a plane by more than 0.0005 in. at any point, and they shall be maintained within a permissible variation limit of 0.001 in. In the spherically seated block, the diameter of the sphere shall not greatly exceed the diameter of the specimen and the center of the sphere shall coincide with the center of the bearing face. The movable portion of this block shall be held closely in the spherical seat, but the design shall be such that the bearing face can be rotated freely and tilted through small angles in any direction.

3. Procedure for Sampling Material from the Paver

3.1. The material shall be sampled by the Contractor between batching and final placement.

3.2. A composite sample shall be created from the material once it has been placed into the paver. The material shall be sampled by taking a shovel-size quantity from random locations in the hopper and placing each portion into a five-gallon bucket. Place the lid on the bucket after each portion has been obtained in order to prevent moisture loss.

3.3. The composite sample size to be used for strength tests is a minimum of 2/3 ft^3.

3.4. The elapsed time shall not exceed 15 min. between obtaining the first and final portions of the composite sample.

3.5. Transport the composite sample to the location where test specimens are to be molded. The composite sample shall be combined and remixed with a shovel the minimum amount necessary to ensure uniformity and compliance with the maximum time limits specified in 3.4.

3.6. Start molding specimens for strength tests within 15 min. after fabricating the composite sample. Expeditiously obtain and use the sample and protect the sample from the sun, wind, and other sources of rapid evaporation, and from contamination.

3.7. A set of cylinders is three (3) cylinders that are tested at the same age. A minimum of 3 cylinders per testing age shall be prepared for roadway pavement applications.

4. Determining the Mass of Soil-Cement Specimens

4.1. The mass of soil cement required for specimens shall be determined by the moisture content of the composite sample.

4.2. The dry unit weight in lb/ft^3 shall be plotted to the nearest 0.1 lb/ft^3 on the ordinate scale and the corresponding water content to the nearest 0.1 % on the abscissa scale. Draw the compaction curve as a smooth curve through the plotted points.

4.3. The compaction curve from the mixture design shall be used in determining the Allowable Moisture Content Range (Fig. 5). The targeted moisture content range shall be that which corresponds to 98% or greater of the maximum dry unit weight.

4.4. Refer to the compaction curve determined in the mixture design and plot the allowable moisture content range on the curve. Use the moisture content of the composite sample to determine the corresponding dry unit weight.

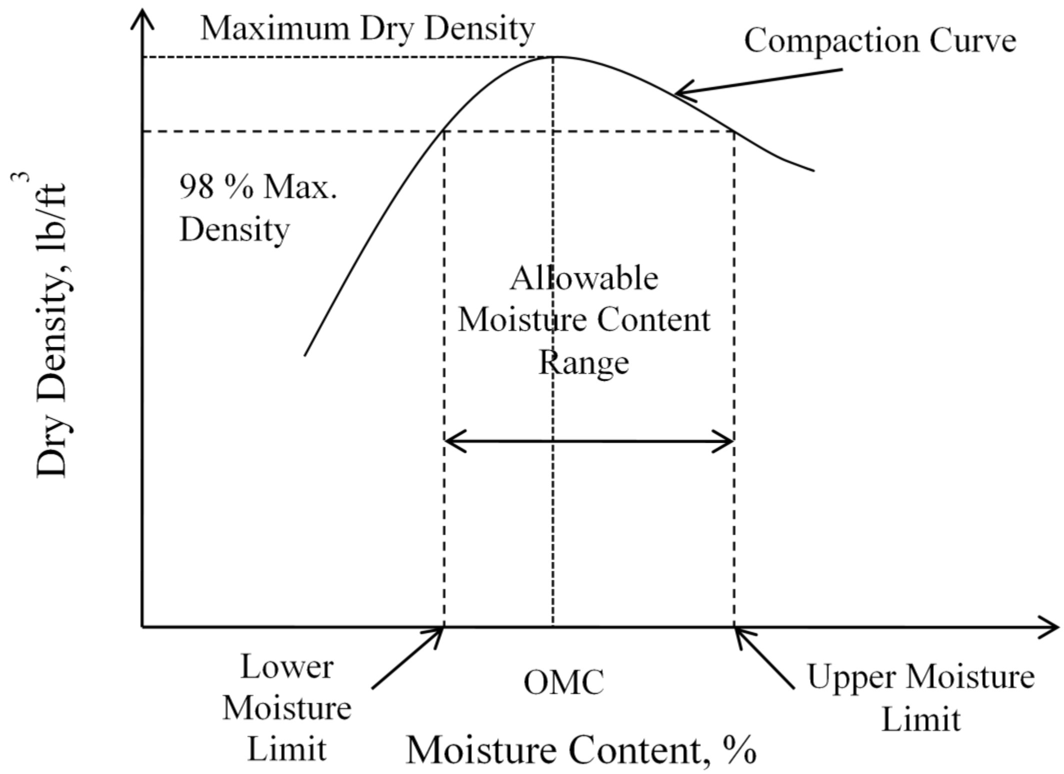

FIG 5. Allowable Moisture Content Range

4.5. If the moisture content of the composite sample is within the Allowable Moisture Content Range, the mass of soil-cement is determined by the following equation:

$$M_{sc} = \gamma_{dry}, \frac{lb}{ft^3} x \frac{1\,ft^3}{1728 in.^3} x \frac{1 kg.}{2.2046 lb} x 34.5 in.^3 x \frac{1000 g}{1 kg}$$

which reduces to:

$$M_{sc} = 9.06 \gamma_{dry,} \frac{lb}{ft^3}$$

where:

M_{sc} = mass of soil-cement, g
γ_{dry} = dry unit weight corresponding to composite sample moisture content, lb/ft^3

4.6. Round the mass of soil-cement to the nearest 0.1 g.

4.7. If the moisture content of the composite sample is outside the allowable moisture content range, the following steps shall be taken:

4.7.1. Below the Lower Moisture Limit — material is too dry and composite sample shall be discarded. Notify the Project Engineer that the material delivered to the paver is at a moisture content lower than required to obtain 98% of the maximum dry unit weight.

4.7.2. Above the Upper Moisture Limit — material is too wet and sample shall be spread out on clean, non-absorbent plastic sheeting to allow to dry to a moisture content which falls within the Allowable Moisture Content Range.

5. Making Test Specimens

5.1. Determine the moisture content of the composite sample in accordance with ASTM D 4959.

5.2. Verify that the moisture content of the composite sample is within the allowable moisture content range.

5.3. Lightly coat the mold and the two separating disks with commercial form release agent. Hold the cylinder mold in place with the spacer clip over the bottom piston so that the piston extends about 1 in. into the cylinder.

5.4. Place a separating disk on top of the bottom piston and place the extension sleeve on top of the mold. Place in the mold the predetermined mass of the composite soil-cement as determined in 4.4 to provide a specimen of the designed unit weight when 5.6 in. high. When the soil-cement contains aggregate retained on the No. 4 sieve, carefully spade the mix around the mold sides with a thin spatula. Then compact the soil-cement initially from the bottom up by steadily and firmly forcing (with little impact) a square-end cut 1⁄2-in. diameter smooth steel rod repeatedly through the mixture from the top down to the point of refusal, distributing the roddings uniformly over the cross-section of the mold. Perform the operation carefully so as not to leave holes in clayey soil-cement mixtures. Repeat the process until the mass is packed out to a height of approximately 6 in.

5.5. Remove the extension sleeve and place a separating disk on the surface of the soil-cement. Remove the spacer clip supporting the mold on the bottom piston. Put the top piston in place and apply a dynamic load by the compacting device until the specimen is 5.6 in. high.

5.6. Remove the pistons and separating disks from the mold assembly, but leave the specimen in the mold.

5.7. Insert the mold plugs into each end of the mold and use the metal foil tape to tape mold plugs to specimen mold to ensure no moisture is lost during initial curing.

6. Curing Test Specimens

6.1. Initial Curing—All cylinders shall be initially cured in the field under conditions that limit exposure to sun, wind, and other sources of rapid evaporation, and from contamination for 12 hours or longer if required, to permit subsequent removal from the molds using the sample extruder.

6.2. During the initial curing period, cylinders shall be plugged with mold plugs and sealed with foil tape while exposed to ambient temperature conditions, and in a vibration-free environment.

6.2.1. After the initial 12 hour or longer curing period, cylinders shall be transported to the facility at which final curing will occur.

6.2.2. During transporting, cylinders and molds shall be protected with suitable cushioning material to prevent damage.

6.2.3. During cold weather, cylinders and molds shall be protected from freezing with suitable insulation material.

6.3. Removal of Mold Plugs and Molds—After transportation to the final curing location, mold plugs shall be removed and samples shall be extruded.

6.4. Final Curing—Final curing shall start immediately after mold removal and specimens shall be placed in an appropriate moist room or curing cabinet as specified in 2.11.

6.3.1 Unless otherwise specified all specimens shall be moist cured at 73.5 ± 3.5°F from the time of de-molding until the moment of testing.

6.3.2 Molded specimens shall be protected from dripping water for the specified moist curing period.

6.3.3 As applied to the treatment of de-molded specimens, moist curing means that the test specimens shall have free water maintained on the entire surface area at all times. This condition is met by using a moist room or cabinet as specified in 2.11.

6.3.4 The specimens shall be tested in the moist condition directly after removal from the moist room or curing cabinet.

7. Compression Strength of Molded Soil-Cement Cylinders

7.1. Compression specimens shall not be capped before testing. Check the planeness of the faces with a straightedge. A plane, clean surface shall be observed. Compression test specimens that contain faces that are not plane within 0.002 in. shall be discarded. Note any voids or imperfections on the faces.

7.2. The diameter used for calculating the cross-sectional area of the test specimen shall be determined to the nearest 0.01 in. by averaging two diameters measured at right angles to each other near mid-height of the specimen.

7.3. Place the lower bearing block on the table or platen of the testing machine directly under the spherically seated (upper) bearing block. Place the specimen on the lower bearing block, making certain that the vertical axis of the specimen is aligned with the center of thrust of the spherically seated block. As this block is brought to bear on the specimen, rotate its movable portion gently by hand so that uniform seating is obtained.

7.4. Apply the load continuously and without shock. A screw power testing machine, with the moving head operating at approximately 0.05 in./min when the machine is running idle, may be used. With hydraulic machines, adjust the loading to a constant rate within the limits of 10 ± 5 psi/sec, depending upon the strength of the specimen. Record the total load at failure of the test specimen to the nearest 10 lbf. Note the fracture pattern according to Fig. 5.

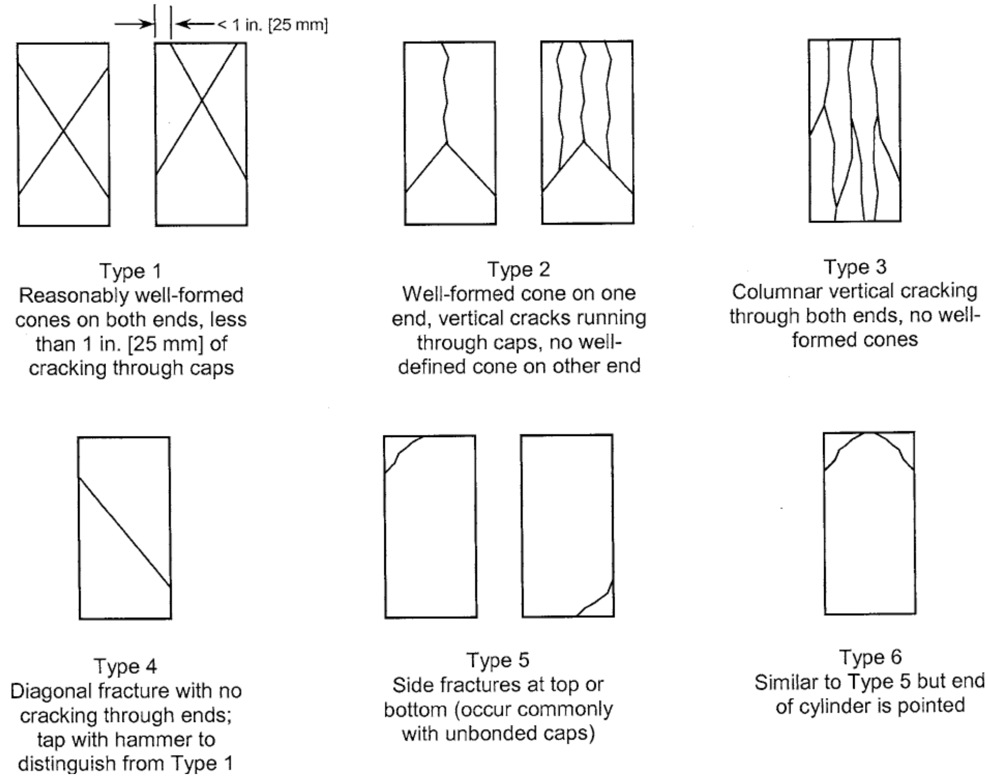

FIG. 6 Schematic from Typical Fracture Patterns (ASTM C 39)

7.5. Calculate the unit compressive strength of the specimen by dividing the maximum load by the cross-sectional area.

7.6. When three cylinder strengths are available in a set, the data from one cylinder shall be discarded if its individual result exceeds ±15 percent of the average of the other two cylinders.

7.7. When only two cylinder strengths remain in a set, the difference in their results, expressed as a percent of their average, shall not exceed ±15 percent.

7.8. When the two remaining cylinders in a set do not meet the criteria in 7.7, then a new batch must be evaluated unless additional cylinders cast from the same batch are available for testing at this age.

8. Report

8.1. The following minimum data shall be reported:

- Technician name,
- Soil-cement testing laboratory name,
- Raw material types and sources,

- Mix design data including compaction curve plot showing control points, point of maximum dry unit weight and optimum water content, allowable moisture content range,
- Moisture content of composite sample, if additional drying was required and mass of soil-cement used to mold specimens,
- Fracture pattern, and
- Compressive strength of each specimen to the nearest 10 psi.

8.2. The data shall be signed by the Contractor or his representative and submitted to the Materials and Tests Engineer for review and approval.

Appendix

Example:

The mixture design provides the following information:

Optimum Moisture Content = 9.2 %

Maximum Dry Density = 117.8 lb/ft^3

Cement Content = 7%

Control Points for Compaction Curve:

%Moisture	γ_{dry}, lb./ft^3
5.6	108.0
7.6	115.7
9.2	117.8
11.1	115.9

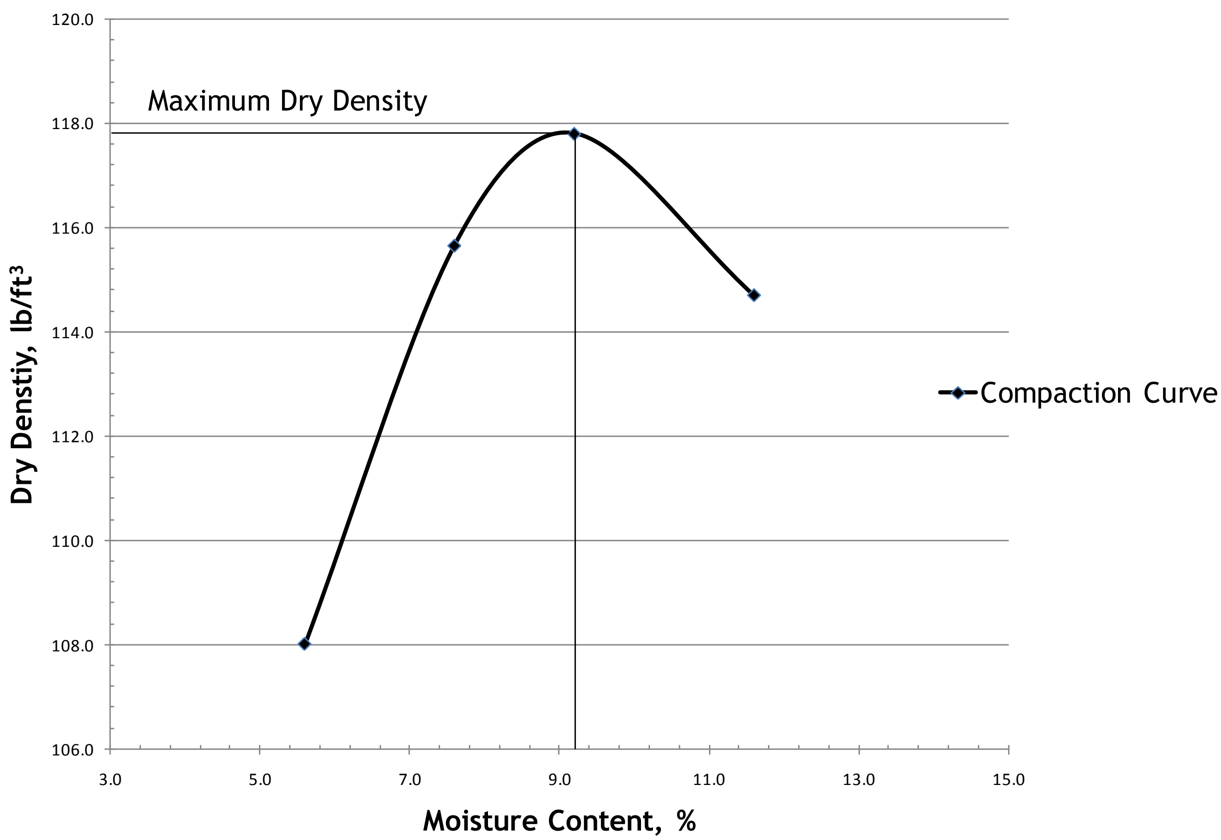

FIG 7. Compaction Curve showing Optimum Moisture Content and Maximum Dry Density.

1. Plot the Allowable Moisture Content Range on the compaction curve:

$$0.98 \times \gamma_{dmax} = 0.98 \times 117.8 = 115.4 \text{ lb/ft}^3$$

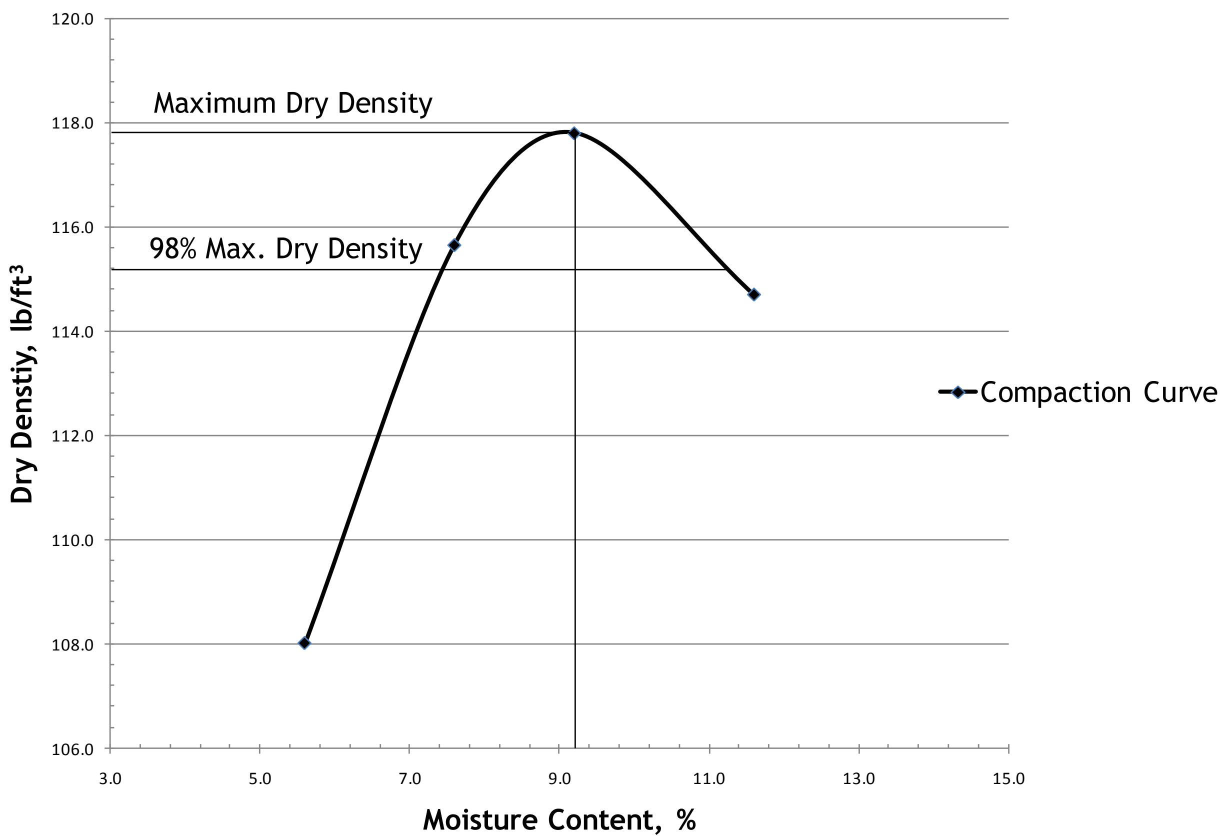

FIG 8. Compaction Curve showing 98 % Maximum Dry Density.

2. Plot Upper and Lower Moisture Limits on compaction curve:

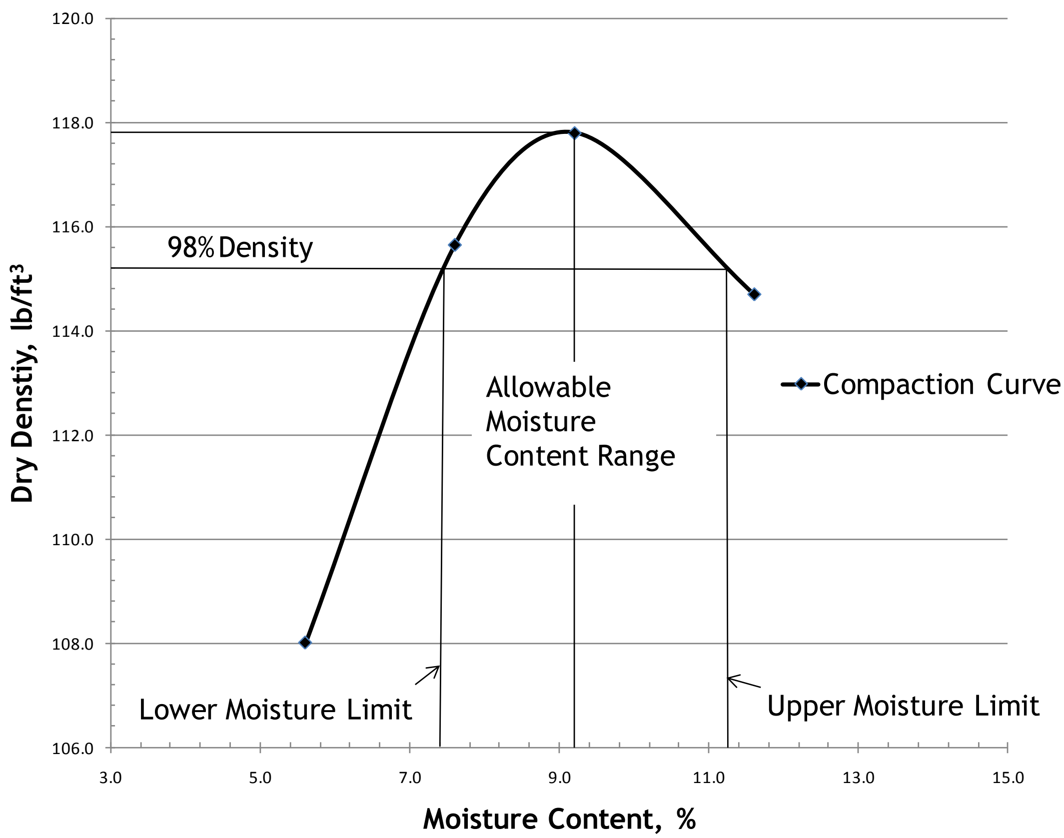

FIG 9. Compaction Curve showing Upper and Lower Moisture Limits.

3. The moisture content of the composite sample is 7.8%. Plot the moisture content and corresponding dry unit weight of the composite sample and verify that it is within the allowable moisture content range.

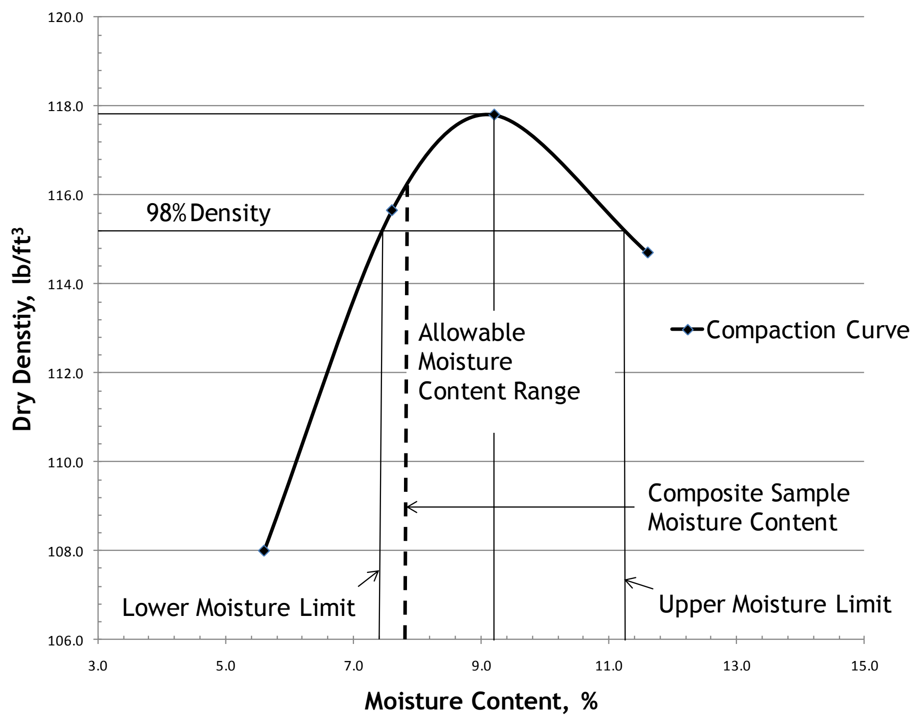

FIG 10. Compaction Curve showing Composite Sample Moisture Content.

4. If the moisture content of the composite sample is within the allowable moisture content range, the mass of soil-cement is determined by the following equation:

$$M_{sc} = \gamma_{dry}, \frac{lb}{ft^3} x \frac{1 ft^3}{1728 in.^3} x \frac{1kg.}{2.2046 lb} x 34.5 in.^3 x \frac{1000 g}{1 kg}$$

or

$$M_{sc} = 9.056 \gamma_{dry,} \frac{lb}{ft^3}$$

where:

M_{sc} = mass of soil-cement
γ_{dry} = dry unit weight corresponding to composite sample moisture content

The moisture content of the composite sample is 7.8% and the corresponding dry unit weight is 116.2 lb/ft^3, which is within the allowable moisture content range. Therefore, the mass of soil-cement is:

$$M_{sc} = 116.2\ \frac{lb}{ft^3}\, x\, \frac{1\,ft^3}{1728 in.^3}\, x\, \frac{1kg.}{2.2046lb}\, x 34.5 in.^3\, x\, \frac{1000g}{1kg} = 1052.3\text{g}$$

If the moisture content of the composite sample is outside the allowable moisture content range, the following steps shall be taken:

Below the Lower Moisture Limit — material is too dry and sample shall be discarded. Notify the Project Engineer that the material delivered to the paver is at a moisture content lower than required to obtain 98% of the maximum dry unit weight.

Above the Upper Moisture Limit — material is too wet and sample shall be spread out on clean, non-absorbent plastic sheeting to allow to dry to a moisture content which falls within the Allowable Moisture Content Range.

Reference:

ASTM C 31, “Standard Practice for Making and Curing Concrete Test Specimens in the Field”

ASTM C 39, “Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens”

ASTM C 172, “Standard Practice for Sampling Freshly Mixed Concrete”

ASTM D 558, “Standard Test Methods for Moisture-Density (Unit Weight) Relations of Soil-Cement Mixtures”

ASTM C 617, “Standard Practice for Capping Cylindrical Concrete Specimens”

ASTM D 1632, “Standard Practice for Making and Curing Soil-Cement Compression and Flexure Test Specimens in the Laboratory”

ASTM D 1633, “Standard Test Methods for Compressive Strength of Molded Soil-Cement Cylinders”

ASTM D 4959, “Standard Test Method for Determination of Water (Moisture) Content of Soil By Direct Heating”

Appendix G

Temperature and Humidity Profiles

The temperature and humidity profiles are presented in Appendix G. The temperature profile for the moist-curing room and the temperature and humidity profile for the environmentally controlled room are presented.

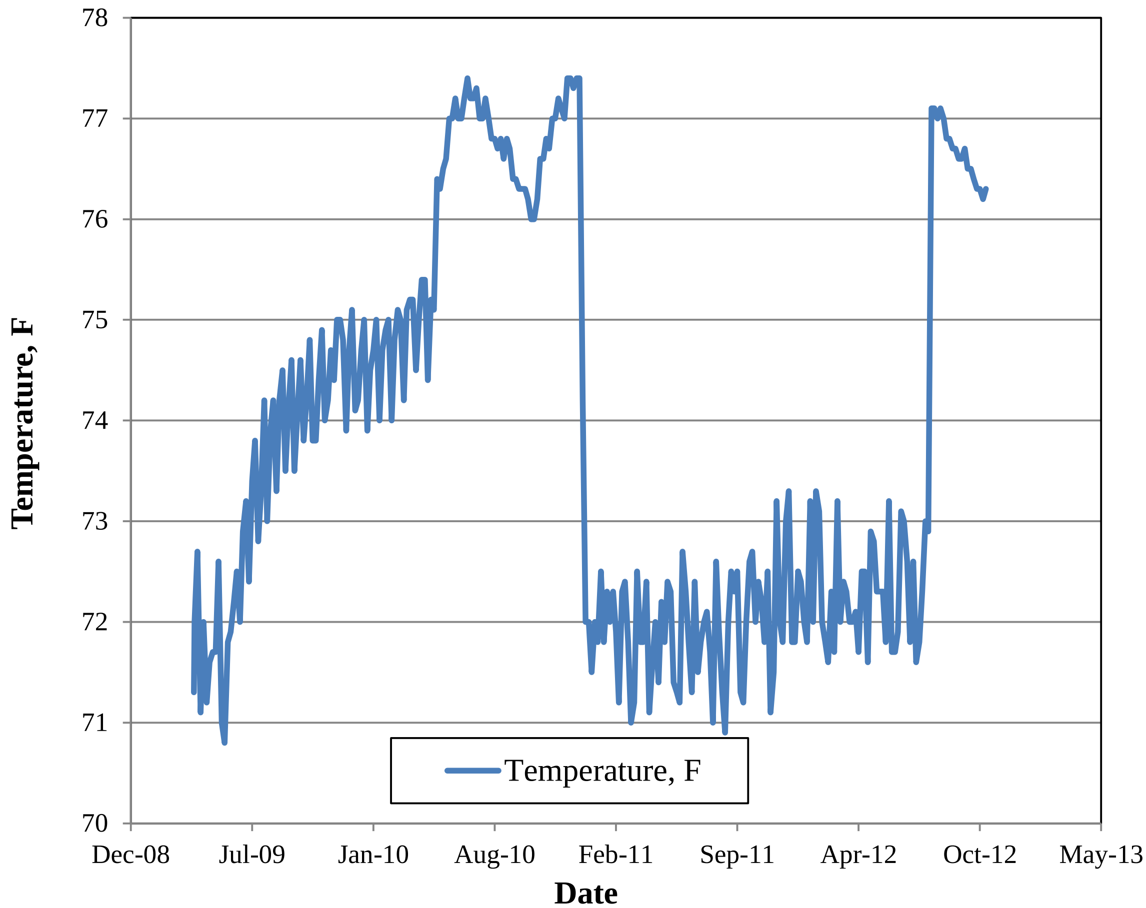

Figure G.1: Temperature profile for moist-curing room

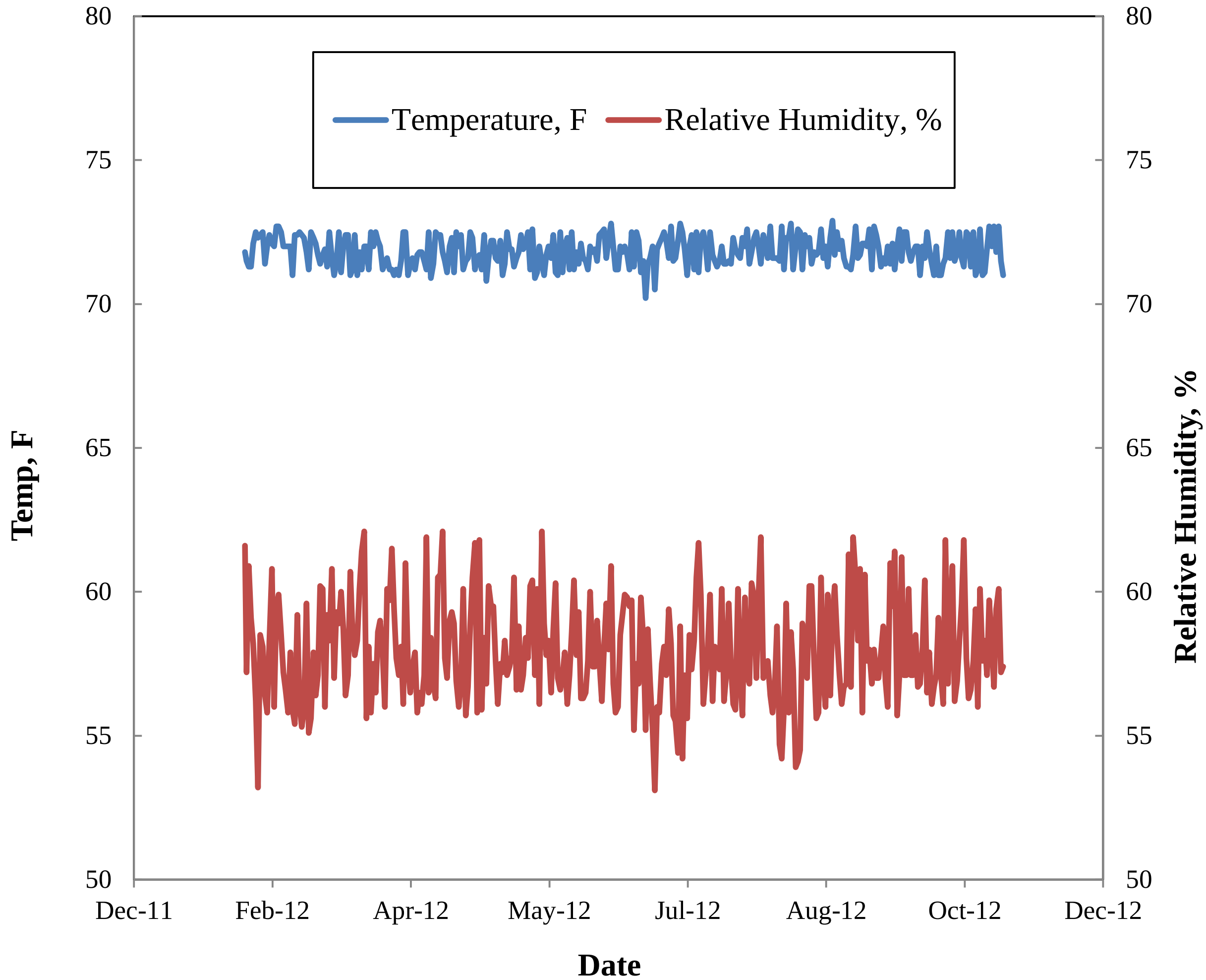

Figure G.2: Temperature and humidity profile for environmentally controlled room