Strength Assessment of Soil Cement

by

Jordan Michelle Nemiroff

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Approved by

Anton K. Schindler, Chair, Professor of Civil Engineering
J. Brian Anderson, Co-Chair, Associate Professor of Civil Engineering
Robert W. Barnes, Associate Professor of Civil Engineering

Abstract

Soil cement is a mixture of soil, portland cement, and water that is compacted and cured to form a pavement base. Due to construction practices and variances in core strengths, questions have arisen concerning quality control and testing protocol. A major concern in this area is strength assessment, which became the main objective of this research.

In order to develop a method that reliably assesses the strength of soil cement base, a laboratory testing program was developed to evaluate the suitability of using the dynamic cone penetrometer based on ASTM D 6951 and molded cylindrical samples based on ASTM D 1632. Testing was done to establish the relationship between the dynamic cone penetrometer and molded compressive strength between 100 and 800 psi.

Based on the results from this research it can be concluded that the molded cylinder specimens should be cured using the sealed plastic bag method, the dynamic cone penetrometer is able to penetrate specimens with strengths less than approximately 800 psi, and a logarithmic function is the best fit for the correlation between the dynamic cone penetrometer and the molded cylinder strength. It is recommended that soil cement cylinders and the dynamic cone penetrometer be considered for quality assurance for the strength assessment of soil cement base.

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Chapter 1

Introduction

1.1 Background

Soil cement base is a mixture of native soils with measured amounts of portland cement and water that forms a strong, durable, frost-resistant paving material (Halsted, Luhr, and Adaska 2006). Soil cement can be mixed in place using on site materials or mixed in a central plant and hauled to the construction location (Halsted, Luhr, and Adaska 2006). It is used throughout the industry as a pavement base for highways, roads, streets, parking areas, airports, industrial facilities, and materials handling and storage areas (Halsted, Luhr, and Adaska 2006). The Alabama Department of Transportation (ALDOT) uses soil cement as a base where crushed stone is unavailable or costs too much to transport to the site.

Research has shown that a soil cement base requires an upper and lower bound on strength requirements so that it can produce a quality product. Strengths that are too low are undesirable because the base will not provide adequate support for traffic, resulting in rutting and large deflections (George 2002). Strengths that are too high are undesirable since excessive cement content may lead to wide shrinkage cracks (George 2002). These wide cracks can cause reflective cracking in the hot mix asphalt surface (George 2002).

Due to these restrictions, ALDOT 304 (2014) requires seven-day compressive strengths of cores to be between 250 to 600 psi to receive full payment. If the compressive strength is less than 250 psi, a price reduction will be imposed following Equation 1.1 (ALDOT 304 2014). If the compressive strength is greater than 600 psi, a price reduction will be imposed following Equation 1.2 (ALDOT 304 2014). For compressive strengths less than 200 psi or greater than

650 psi, the soil cement structure shall be removed and replaced without additional compensation (ALDOT 304 2014). A summary of this is presented in Table 1.1.

$$Price\ Reduction = (0.4\ \%\ per\ psi) \times (250psi - f_c) \qquad \text{(Equation 1.1)}$$

$$Price\ Reduction = 20\% - (0.4\ \%\ per\ psi) \times (650psi - f_c) \qquad \text{(Equation 1.2)}$$

Where:

Price Reduction = reduction in pay (%)

f_c = compressive strength (psi)

Table: 1.1: ALDOT (2014) compressive strength specifications

Average 7-day Stength (f_c)	**Action**
f_c < 200 psi	Remove and Replace
200 ≤ f_c < 250 psi	Price Reduction
250 ≤ f_c ≤ 600 psi	No Price Reduction
600 ≤ f_c ≤ 650 psi	Price Reduction
f_c > 650 psi	Remove and Replace

Due to construction practices and variances among core strength, questions have arose concerning quality control and testing protocol. Like many other states, ALDOT cores on the sixth day of curing and tests the compressive strength of the cores on the seventh day. Results from various ALDOT projects have shown high variability among core strength values, which has led to an increase in concern of the in place strength and the use of coring as a pay item. Cores taken a few feet apart on U.S. 84 had in-place strengths that differed by more than 200 percent. Figure 1.1 is a graph representing 7-day core strengths from ALDOT project STPAA-0052 (504) in Houston and Geneva Counties, AL. Depicted on the graph are the strength limits used for the pay scales that ALDOT uses. As shown, there were multiple sections that required the contractor to remove and replace the section and some that resulted in a reduction of pay.

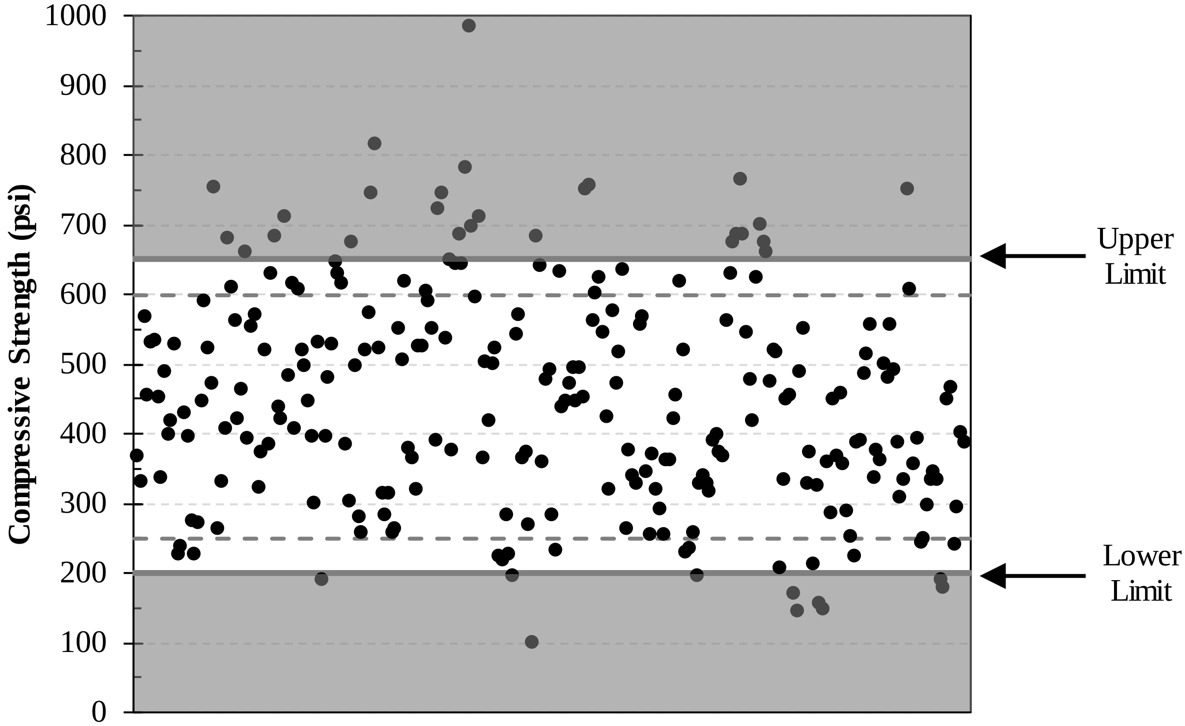

Figure: 1.1: Compressive strengths from ALDOT project STPAA-0052 (504)

Due to the high variability in core strength, other techniques have been researched and developed to create a reliable method to assess the strength of soil cement. One method created by Wilson (2013) utilizes a modified method of ASTM D 1632 (2007), *Standard Practice for Making and Curing Soil Cement Compressive and Flexure Test Specimens in the Laboratory*. Wilson (2013) modified this method to treat soil cement as conventional concrete cylinders that are made at the job-site with the delivered material and used as a check for the strength of the produce before placement.

The other method of testing used during this research was the dynamic cone penetrometer (DCP). This device has been correlated to a variety of engineering properties such as the

California Bearing Ratio (Mohammadi et al. 2008), soil classification (Huntley 1990), and compressive strength (McElvaney and Djatnika 1991; Patel and Patel 2012). The procedure used for testing is based on ASTM D 6951 (2009), *Standard Test Method for Use of the Dynamic Cone Penetrometer in Shallow Pavement Applications*.

1.2 Research Objectives

This project was undertaken to develop a method to reliably assess the strength of soil cement base. The objectives of this research were to

- Evaluate the suitability of using the dynamic cone penetrometer to assess the strength of soil cement,
- Evaluate the suitability of using molded cylindrical samples based on ASTM D1632 to assess the strength of soil cement,
- Establish the correlation between the dynamic cone penetrometer results and 7-day molded compressive strength of 100 to 800 psi.

1.3 Research Approach

At the time of research, there were no ALDOT soil cement base projects, so the field research was moved to the laboratory. To develop a method that reliably assesses the strength of soil cement base, this research tested many aspects of soil cement. ASTM D 1632, *Standard Practice for Making and Curing Soil Cement Compression and Flexure Test Specimens in the Laboratory*, was used as a basis for preparing soil cement cylinders in the laboratory.

First, a method to efficiently mix soil cement in the laboratory, including trying different types and capacities, was established. Next, a method to test the DCP specimens resembling in-place base conditions was developed. Then, to understand the soils and to create the mix designs, all soils used were classified using the AASHTO method and the UCS method. Once the materials were classified, a soil classification impact study was performed to determine the effects of fine particle percentages on the strength of soil cement. This was accomplished by comparing two mix designs: one with very little fines and one with a higher fines content.

Next, to evaluate the impact of curing time on the strength of soil cement base, a curing time impact study was performed that compared the three- and seven-day strengths of the molded cylinders and the dynamic cone penetrometer specimens. The suggested curing method from research performed by Wilson (2013) was modified based on results from the curing method impact study performed during this research. The curing method impact study included a comparison of the molded cylinder strengths of specimens cured in the moist room and specimens cured in plastic bags inside the moist room.

After these studies were complete, the suitability of the dynamic cone penetrometer for determining the strength of soil cement base was evaluated. The DCP was tested on specimens that ranged from 100 psi to 1000 psi. Once, the strength range that was suitable was observed, the most efficient penetration depth was tested. Lastly, a correlation was developed between the molded cylinder strength and the dynamic cone penetrometer index.

1.4 Thesis Outline

Chapter 2 presents a summary of previous research and literature concerning all aspects of this research project. First, an overview of soil cement base construction is discussed pertaining to the mixing methods, compaction, curing, and quality control. Secondly, the materials that are used to make soil cement are presented. Next, the influence of important properties such as density and compressive strength are discussed. The last section discusses the use of the dynamic cone penetrometer and molded cylinders to determine the strength of soil cement.

The experimental plan developed for this research is presented in Chapter 3. First, the laboratory mixtures evaluated are presented. Next, each study is introduced and the purpose explained. Lastly, a detailed description of the apparatuses and the testing procedures are outlined and discussed.

The results from this study are presented in Chapter 4. Results from the soil classification, curing time and curing method impact studies are discussed. Lastly, a correlation between the dynamic cone penetrometer result and the molded cylinder strength is presented.

A summary of the research performed is presented in Chapter 5. Also, all conclusions and recommendations made from this research are summarized in that chapter.

Appendices A through K follow Chapter 5. Appendix A contains design curves and gradations for all the mixtures used in the research testing. Appendix B contains the results from the soil classification study that compares the molded cylinder strength of two soils. Appendix C contains the data from the curing method study that compares the molded cylinder strength of two curing methods. The curing time impact study results are found in Appendix D and contain all molded cylinder strengths and DCP strengths for 3 and 7 days. Appendices E through I contain the DCP penetration results where the penetration is plotted against the blow count. Finally, Appendix K contains the results of the DCP to MCS study.

Chapter 2

Literature Review

2.1 Introduction

In this chapter, a literature review of the process and quality control of soil cement base construction is discussed. Also, an overview of the materials used in production of soil cement base is presented. Next, the properties such as density and compressive strength are presented. Lastly, an evaluation of strength using the dynamic cone penetrometer and molded cylinders is discussed.

2.2 Overview of Soil Cement Base Construction

2.2.1 Soil Cement Base Construction

ACI 230 (2009) states that the objective of soil cement construction is to obtain a thoroughly mixed, adequately compacted, and cured material. First, the two main mixing methods, mixed in-place and mixing at a central-mixing plant are discussed. Next, the processes of compacting, finishing, and curing are presented.

2.2.1.1 Mixed In-Place Method

Mixed in-place construction can be used with almost all types of soils, from granular to fine grained, due to its ability to adequately pulverize and mix the soils. In addition, mixing can be performed with borrow material or material already in place.

Before construction can begin, soil preparations must be made. All deleterious material such as stumps, roots, organic soils, and aggregates larger than 3 in. should be removed (ACI 230 2009). Once this is accomplished, the soil is shaped to the approximate final lines and grades. Next, a mechanical spreader is used to distribute the cement evenly to obtain the proper proportions as shown in Figure 2.1. For a uniform cement spread, the mechanical spreader must be operated at a uniform speed with a constant level of cement in the hopper (ACI 230 2009). The mechanical spreader can be attached to either a dump truck or a bulk-cement truck. When a bulk-cement truck is utilized, cement is moved pneumatically from the truck through an air-separator cyclone that dissipates the air pressure; the cement then falls into the hopper of the spreader (ACI 230 2009).

Figure 2.1: Cement truck with mechanical spreader used to place cement

Once the cement has been evenly applied, typically a single-shaft mixer is used to pulverize and mix the cement with the soil. A single-shaft mixer used to pulverize and mix is shown in Figure 2.2. Next, a water truck is used to apply the appropriate amount of water to the surface of the mixture to obtain the desired water content of the mixture. Then, the single-shaft mixer mixes the material one more time to ensure a properly mixed material. Once mixed, the compaction process begins.

Figure 2.2: Single-shaft mixer used in in the mixed in-place method

Soils with higher fines contents and plasticity have shown to be more difficult to pulverize and mix. Also, the strength of mixed in place soil cement sometimes can be lower than that obtained in the laboratory. To compensate, sometimes the cement content is increased by 1 or 2 percent (ACI 230 2009).

ACI 230 (2009 recommends that fine-grained soils be mixed at a moisture content near optimum for the most effective pulverization. In addition, ACI 230 (2009) recommends that to reduce the formation of cement balls, granular soils should be mixed at less than optimum moisture content (ACI 230 2009).

2.2.1.2 Plant-Mixed Method

The plant-mixed method can be divided into two types: the pugmill mixer and the rotary mixer. Pugmill mixers can be further divided into two types: the continuous flow or batch. The most commonly used is the continuous pugmill mixer, which has production rates from 200 to 800 t/hr (ACI 230 2009).

A typical continuous-flow pugmill plant, shown in Figure 2.3, consists of a soil bin or stockpile, a cement silo with surge hopper, a conveyor belt to deliver the soil and cement to the mixing chambers, a mixing chamber, a water storage tank for adding water during mixing, and a holding hopper to temporarily store the mixed soil cement prior to loading (ACI 230 2009).

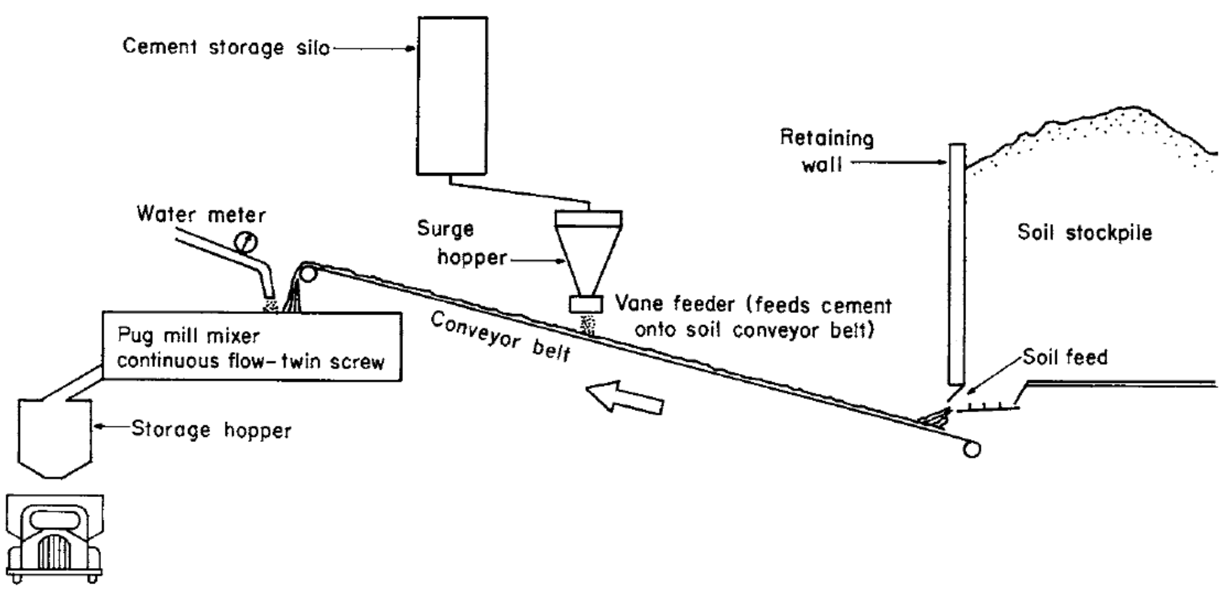

Figure 2.3: Diagram of continuous-flow pugmill plant (ACI 230 2009)

When mixing is being performed in a continuous-flow pugmill plant, soil is fed from the soil bins or the silo onto a conveyor belt. Cement is added to the conveyor belt through a hopper from a cement storage silo. The soil and cement are transported along the conveyor belt to the mixing chamber that consists of two parallel shafts with paddle along each shaft that rotate in opposite directions. A typical twin-shaft parallel mixer is shown in Figure 2.4. At this point water is fed into the mixer also. Once mixing is complete the freshly mixed soil cement is fed into a storage hopper until the time of transportation to the site. To optimize the amount of mixing, the material feed, belt speed, pugmill tilt, and paddle pitch can be adjusted (ACI 230 2009).

Figure 2.4: Twin shaft pugmill mixing chamber (Halsted et al. 2006)

The freshly mixed soil cement is typically transported using dump trucks. During transportation, evaporation loss must be accounted for. Typically, to reduce evaporation during hot, windy conditions, or possible showers, rear and bottom dump trucks are equipped with protective covers (ACI 230 2009). ACI 230 (2009) recommends that no more than 60 minutes should elapse between the start of moist mixing and the start of compaction. They also recommend that haul time be limited to 30 minutes.

ACI 230 (2009) recommends that the mixed soil cement be placed on a firm subgrade in a quantity that will produce a compacted layer of uniform thickness and density. Even though there are a variety of spreading devices and methods, the use of a motor grader, a spreader box, or asphalt-type pavers are the most common (ACI 230 2009). Some devices are equipped with one or more tamping bars that provide initial compaction. The soil cement is usually placed in a layer 25 to 50 percent thicker than the final compacted thickness (ACI 230 2009).

When readily available, central mixing plants use a granular borrow material because of their low cement requirements and ease in handling and mixing (ACI 230 2009). Clayey soils are avoided because they are difficult to pulverize (ACI 230 2009).

2.2.1.3 Compaction

Compaction should begin as soon as possible and should be completed within 2 hours of initial mixing (West 1959). The detrimental effects of delayed compaction on density and strength are discussed in section 2.4.1. No section should be left unworked for longer than 30 minutes (Catton and Felt 1943).

The same principles that apply to virgin soil apply to soil cement for compaction. The maximum density should be compacted at or near optimum moisture content is determined in accordance with ASTM D 558 or D 1557 (ACI 230 2009). Standard practice requires soil cement to be uniformly compacted to a minimum of between 95 and 98 percent of maximum density (ACI 230 2009). ALDOT 304 (2014) requires the density be no less than 98 percent of the theoretical maximum dry density.

The main types of rollers used for compaction of soil cement are sheepsfoot rollers, multiple-wheel rubber-tired roller, vibratory steel-wheeled roller, and heavy rubber-tired roller. Sheepsfoot rollers are used for the initial compaction of fine-grained soils and are typically followed by a multiple-wheel rubber-tired roller for finishing (ACI 230 2009). A vibratory steel-wheeled roller or a heavy rubber-tired roller is typically used for granular soils (ACI 230 2009). In soil cement construction, the general rule is to use the greatest amount of pressure without exceeding the bearing capacity of the soil (ACI 230 2009).

2.2.1.4 Curing

Curing is important because the strength gain of hydrating cement is dependent upon time, temperature and the presence of water. The most common method of curing is done with the use of a bituminous coating. Bituminous-coat curing is performed by a light application of water followed by an emulsified asphalt (ACI 230 2009). Curing can also be done by covering the compacted soil cement with wet burlap or plastic tarps; however, this is impractical for large placements. In addition, where applicable, freshly placed soil cement must be protected from freezing by the use of insulation blankets or straw (ACI 230 2009).

2.2.2 Quality Control

Quality control is important to ensure that the final product will be adequate for the intended use and to ensure that the contractor has performed the work in accordance with the plans and specifications (ACI 230 2009). Field inspection may include the following factors:

- Cement content,
- Moisture content,
- Mixing uniformity, and

- Compaction.

2.2.2.1 Cement Content

For mixed in-place construction, the inspector must check the accuracy of the cement spread by the bulk spreaders to ensure the proper quantity is being applied. One way to check this is by spot checking. This is done by placing a 1 yd^2 of canvas in front of the spreader. Once the spreader has passed, the canvas is picked up and weighed. The spreader is then adjusted and the process repeated until the correct amount is applied (ACI 230 2009). The other method is by performing an overall check. This is done by measuring the distance or area which a truckload of cement with a known weight is spread. The actual area covered is then compared to the theoretical area (ACI 230 2009).

When batch-type pugmills or rotary drum mixing plants are used, the proper quantities of soil, cement and water for each batch are weighed before being transferred to the mixer. These types of plants are checked to ensure the accuracy of the weight scales. For continuous-flow mixing plants, two methods can be used to check for accuracy. The first method consists of running soil through the plant for a given amount of time and collecting the material, while cement is diverted directly from the feeder into a truck. Both the cement and soil are then weighed and adjusted until the correct amount of cement is released (ACI 230 2009). The second method consists of running only soil on the main conveyor belt. Soil is then collected from a selected length of the belt and the dry weight determined. Next, the plant is operated with only cement feeding onto the conveyor belt. The cement feeder is adjusted until the correct amount is released (ACI 230 2009). Typically, central mixing plants are calibrated at least daily at the beginning of the project.

For a more accurate determination, ASTM D 5982 (2015) outlines a test method that determines the cement content of fresh mixed soil cement. This method can reliably determine the cement content in approximately 15 to 20 minutes to ±1 percent by mass (ASTM D 5982 2015). One limitation of this test is that the cement content must be between 3 and 16% (ASTM D 5982 2015). Another limitation is that the soil cement mixture must have a maximum particle size of 3 in. (75mm) (ASTM D 5982 2015).

The cement content can also be determined using a sample from a hardened mixture. ASTM D 806 (2011) outlines a test method for determining the cement content of hardened soil cement mixtures through chemical analysis. This test determines the calcium oxide (CaO) content of the sample (ASTM D 806 2011). The test may not be applicable for soils or aggregates that produce significant amounts of dissolved calcium oxide under the test conditions (ASTM D 806 2011).

2.2.2.2 Moisture Content

As previously discussed, proper moisture content is necessary for adequate compaction and hydration of the cement. One way of checking the moisture content is to take a sample and use conventional or microwave-oven drying techniques. A quick way to check the moisture content is by collecting a sample in one’s hand. The mixture will be at or near optimum moisture content if the hand is dampened when it is tightly squeezed. Also the sample can be broken into two pieces with little or no crumbling. If the mixture is above optimum, excess moisture will be left on the hand, but if the mixture is below optimum the sample will crumble easily (ACI 230 2009).

If the graying of the surface of the soil cement begins to occur during compaction and finishing, it is a sign that the surface is becoming too dry (ACI 230 2009). To remedy this, a very light application of water can be made to restore the moisture to the desired level.

2.2.2.3 Mixing Uniformity

For mixed in-place construction, the uniformity is checked by digging trenches or a series of holes at regular intervals for the full depth of the treatment. The material is checked to ensure uniform color and texture from the top to the bottom and that the proper depth was treated. If the soil cement has a streaked appearance, then the mixture has not been mixed sufficiently. After compaction, a two percent phenolphthalein solution can be squirted down the side of a freshly cut face of evenly compacted soil cement. If the soil is not treated, it will retain its natural color while the treated soil will turn a pinkish-red color (ACI 230 2009).

The uniformity is checked visually at central mixing plants, but can also be checked during placement using similar methods used for mixed in-place construction. For most central mixing plants, the mixing time depends on the soil gradation and the type of plant used, but typically soil cement requires 20 to 30 sec. of mixing time (ACI 230 2009).

2.2.2.4 Compaction

Compaction is important to achieve the maximum density of the soil cement. Generally, the density requirements range from 95 to 100 percent of the maximum density determined using ASTM D 558 (2004) or D 1557 (2012). ALDOT requires the density to be no less than 98% (ALDOT 304 2014). The most common methods for determining the in-place density are the nuclear-gauge method using ASTM D 2922 (2005) and D 3017 (2005), the sand-cone method using ASTM D 1556 (2015), and the balloon method using ASTM D 2167 (2015) (ACI 230 2009). The in-place density should be determined daily, tested immediately after rolling to ensure compliance with job specifications (ACI 230 2009).

2.3 Materials

2.3.1 Soil

According to ACI 230 (2009), almost all soils can be used in the construction of soil cement except organic soils, highly plastic clays, and poorly reacting sandy soils. Though almost all soils can be used, granular soils are preferred because they pulverize and mix easier than fine-grained soils. The most commonly used soils are silty sand, processed crushed or uncrushed sand and gravel, and crushed stone (ACI 230 2009).

Some types of sandy soils cannot be used in the production of soil cement because they can have an adverse effect on soil cement. In a study by Robbins and Mueller (1960), they observed that a sandy soil with an organic content greater than 2 percent or having a pH lower than 5.3 will probably not react normally with cement. They also showed that acidic organic material often had adverse effects of strength development in soil cement mixtures (Robbins and Mueller 1960).

2.3.1.1 Particle Size

For this research, the AASHTO terminology was used to clarify the boundary between coarse- and fine-grained soils. Coarse-grained soils are soils with more than 35% retained on or above the No. 200 sieve and fine-grained soils are soils with 35% or more passing the No. 200 sieve (McCarthy 2007).

Practically all types and sizes of soil can be hardened with portland cement because its stability is obtained from the hydration of the cement and not by the cohesion and internal structure of the material (PCA 1995). Though any type may be used, the most preferred choice are coarse-grained soils because of their ability to pulverize and mix more easily (PCA 1995, ACI 230 2009). In addition, coarse-grained soils most often require less cement than fine-grained soils (ACI 230 2009). ACI 230 (2009) mentions that coarse-grained soils containing between 5% and 35% fines passing the No. 200 sieve produce the most economical soil cement.

ACI 230 (2009) recommends the maximum nominal size aggregate be limited to 2 in. with at least 55 percent passing the No. 4 sieve. While PCA (1995) recommends a well-graded material with a nominal maximum aggregate size of less than 3 in. Halsted (2006) states that for typical applications, the aggregate should have 100% passing the 3 in. (75 mm) sieve, at least 95% passing the 2 in. (50 mm) sieve, and at least 55% passing the No. 4 (4.75 mm) sieve. ALDOT requires 100% passing the 1.5 in. sieve, 80%-100% passing the No. 4 sieve, 15%-65% passing the No. 50 sieve, and less than 25% No. 200 sieve (ALDOT 304 2014). ALDOT also requires that the clay content be between 4% and 25% (ALDOT 304 2014).

Figure 2.5 shows an aggregate gradation band for minimum cement requirements. This band provides a desired range that will require the least amount of cement necessary to produce a quality base. A gradation outside of this range will require more cement due to the material being too fine or coarse to provide the structural interlock necessary for strength. An increase in the quantity of coarse material with reduce the cement required, up to a certain limit, but too much coarse material can interfere with compaction of the matrix of finer particles (Halsted 2006). Since gap graded soils consist of two or three sizes, they are not desirable for most applications (Halsted 2006).

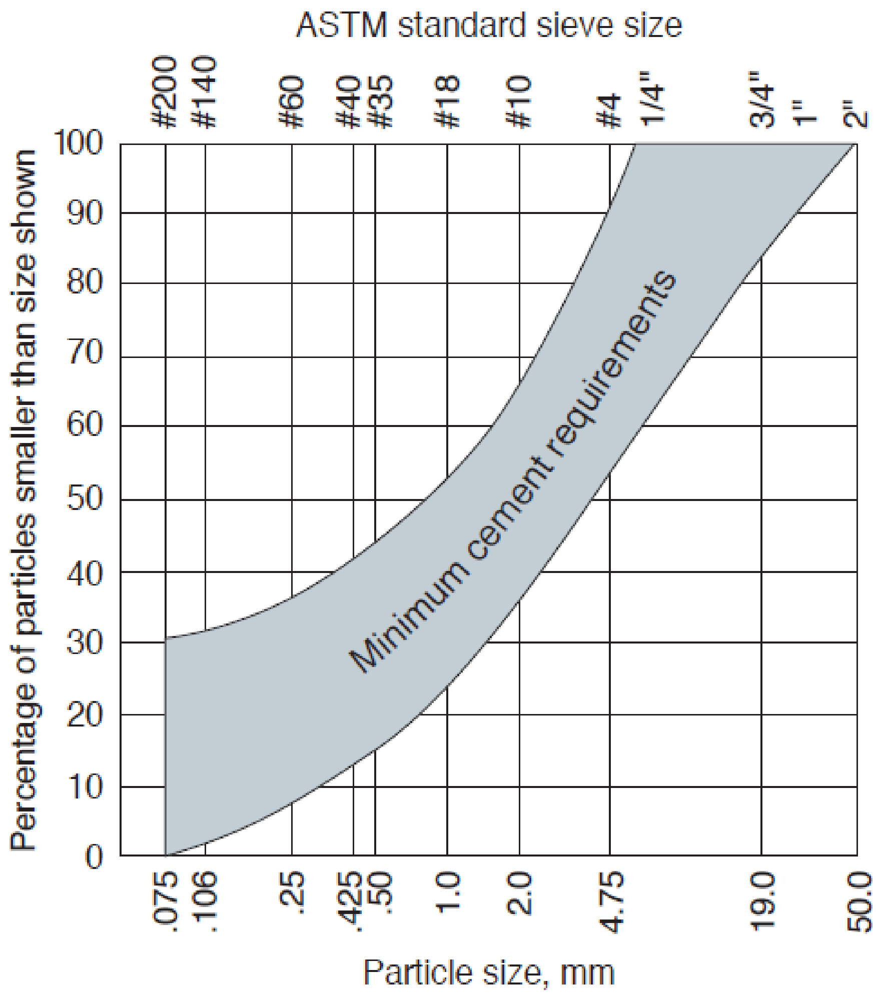

Figure 2.5: Aggregate gradation band for minimum cement requirements (Halsted 2006)

2.3.2 Portland Cement

Any type of portland cement can be used as along as it complies with ASTM C 150 (2016). Type I and Type II portland cement are the most commonly used for the construction of soil cement. The required amounts vary depending on the types of aggregates/soils and the desired properties (ACI 230 2009). Cement contents can range from 4 to 16 percent by dry weight of soil (ACI 230 2009). Table 1.1 shows the typical cement requirements for various types of soils. ACI 230 (2009) warns that the cement ranges are not mix-design recommendations but are initial estimates.

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

AASHTO Soil Classification	ASTM Soil Classification (USCS)	Typical range of cement requirement *Percent by weight
A-1-a	GW, GP, GM, SW, SP, SM	3 to 5
A-1-b	GM, GP, SM, SP	5 to 8
A-2	GM, GC, SM, SC	5 to 9
A-3	SP	7 to 11
A-4	CL, ML	7 to 12
A-5	ML, MH, CH	8 to 13
A-6	CL, CH	9 to 15
A-7	MH, CH	10 to 16

2.3.3 Water

Water is necessary to obtain maximum density by lubricating the soil grain and for hydration of the cement (PCA 1995). ASTM D 1632 (2007) suggests that "the mixing water shall be free of acids, alkalis, and oils, and in general suitable for drinking." ACI 230 (2009) states that "potable water or relatively clean water, free from harmful amounts of alkalis, acids, or organic matter, may be used." Typically, water from the city is acceptable. Seawater has been used, but the presence of chlorides may increase early strengths. For most applications, the water content ranges from 10 to 13 percent of oven dry soil cement (ACI 230 2009).

2.4 Properties

2.4.1 Density

The Proctor test, outlined in ASTM D 558 (2004), is used to determine the optimum moisture content and the maximum dry density. An example moisture-density curve is shown in

Figure 2.6.

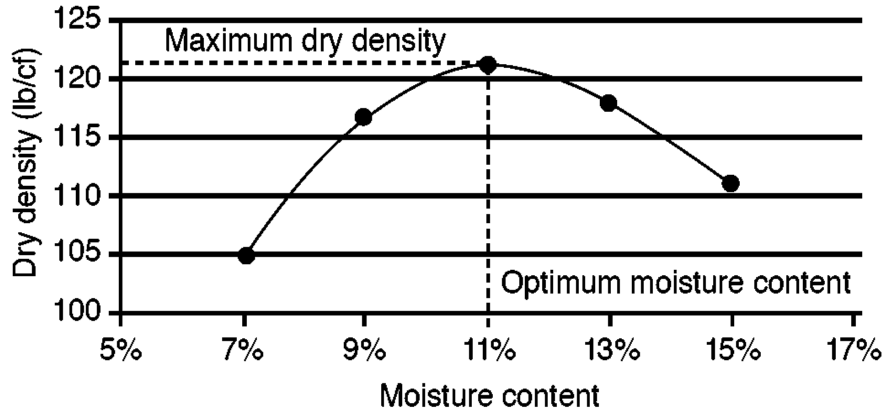

Figure 2.6: Maximum Dry Density and Optimum Moisture Content (Halsted et al. 2006)

ACI 230 (2009) notes that adding cement to a soil typically alters the optimum moisture content and maximum dry density but it cannot be predicted if it will increase or decrease these properties.

Research by Shen and Mitchell (1966) showed for a given cement content, density is directly related to the compressive strength of a cohesionless soil cement mixture. West (1959) showed that a delay of more than 2 hours results in a significant decrease in density and compressive strength. In addition, Felt (1955) showed that the effect of time delay could be minimized by mixing the soil cement several times an hour and if the moisture content at the time of compaction was at or slightly above optimum.

2.4.2 Compressive Strength

Unconfined compressive strength, f_c, is the most commonly used property of soil cement. It is typically measured in accordance to ASTM D 1633 (2007). It also provides a basis for determining the minimum cement requirements for proportioning soil cement (ACI 230 2009). Since strength is directly related to density, the compressive strength is affected the same as density by the degree of compaction and water content (ACI 230 2009). The curing time affects the strength gain differently depending on the soil type. Figure 2.7 shows that the strength increase is greater for granular soils than for fine-grained soils.

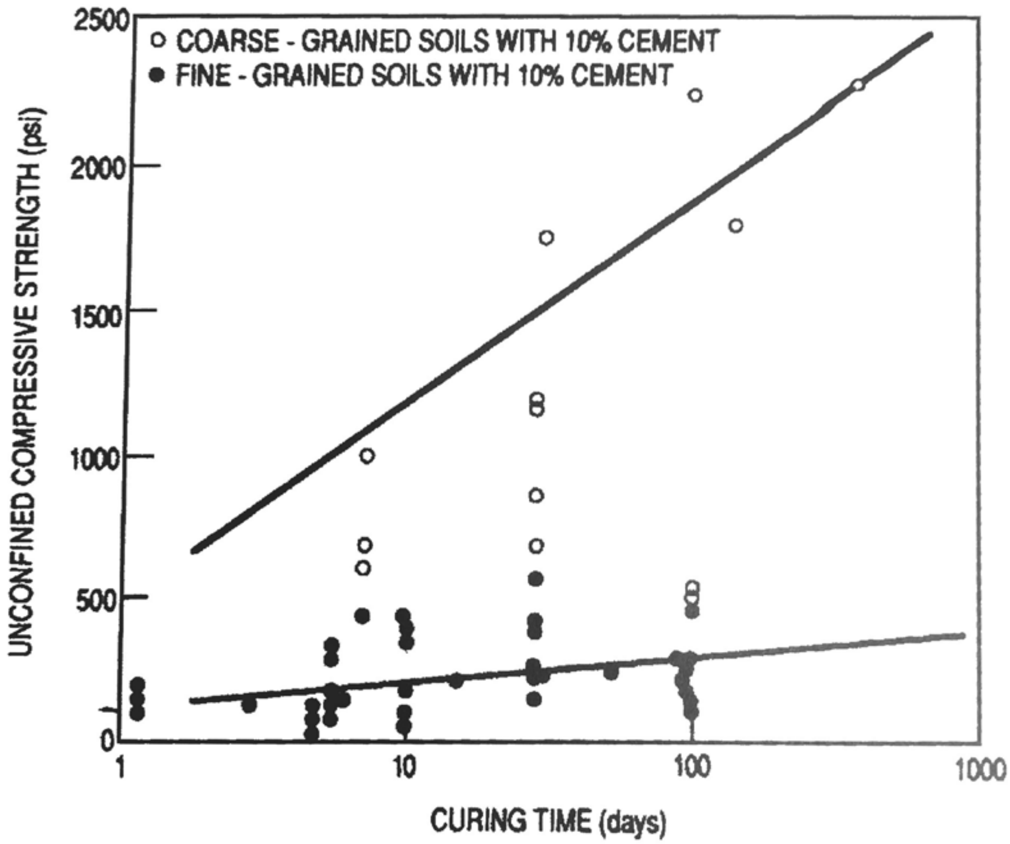

Figure 2.7: Effect of curing time on unconfined compressive strength of fine and coarse-grained soil cement mixtures (FHWA 1979)

2.4.3 Shrinkage and Reflective Cracking

Shrinkage cracking may develop in the soil cement base over time. This is dependent on the cement content, soil type, water content, degree of compaction, and curing conditions (ACI 230 2009). Soil cement made with clays develops a greater quantity of cracks but the widths were smaller and spaced closer together (Highway Research Board 1961). Also, the research showed that the soil cement made with granular soils produced less shrinkage but larger cracks spaced further apart (Highway Research Board 1961). Research performed by George (2002) showed that cracking is highly correlated to the following factors:

- Volume change resulting from drying, temperature change, or both,
- Tensile strength of the stabilized material,
- Stiffness and creep of the stabilized material, and
- Subgrade restraint.

Shrinkage cracking in the soil cement can lead to reflective cracking in the asphalt pavements. However, the reflective cracking may or may not be a performance problem, since pavements have performed well with narrow reflective cracks. When cracks remains narrow, load transfer can still occur and little water is introduced through the cracks to the base and subgrade (ACI 230 2009). When the cracks are wider, moisture can enter the sublayers which leads to the degradation of the base and subgrade. In addition, the cracks can cause raveling, pumping/loss of subgrade material, pavement faulting, surface deterioration, and poor ride qualities (ACI 230 2009). Methods of controlling cracks include proportioning of the soil cement constituents to minimize cracking, using secondary additives, implanting strict quality construction procedures, and controlling the cracking through the bituminous surface (ACI 230 2009).

2.4.4 Durability

Both strength and durability are important for a soil cement mixture to have a good service life. Cement is not only needed for strength but to hold the mass together and to maintain stability when shrinkage and expansive forces occur. ASTM D559 (2015), a test method for wetting and drying compacted soil cement mixtures, and ASTM D560 (2015), a test method for freezing and thawing compacted soil cement mixtures, are used to determine the durability of a mixture. Some agencies will use the results from these tests to determine a minimum compressive strength requirement. Figure 2.8 shows the relationship between the percent of samples passing these durability tests and the 7-day compressive strength based on PCA durability criteria.

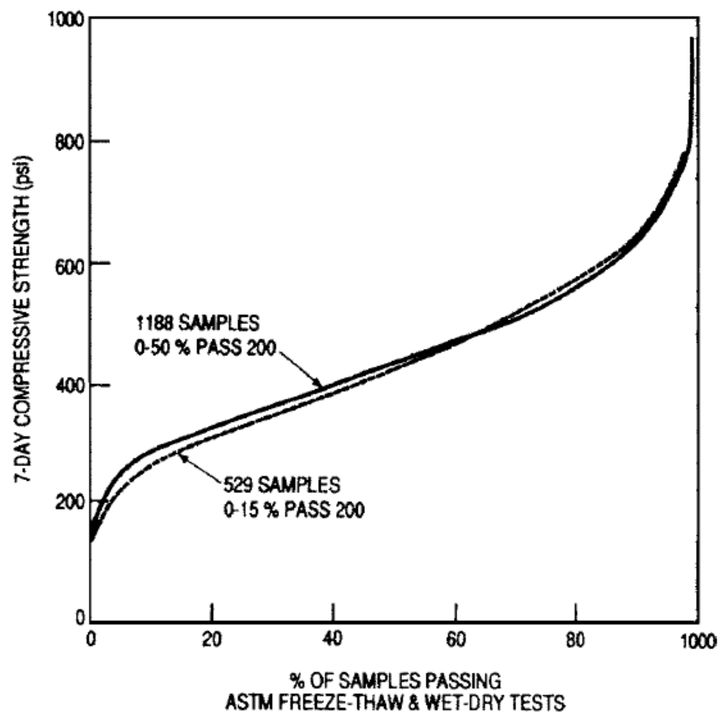

Figure 2.8: Relationship between the compressive strength and the durability of soil cement (PCA 1971)

2.5 Strength Evaluation

2.5.1 Dynamic Cone Penetrometer

The dynamic cone penetrometer (DCP) is an in-situ device used in field exploration and quality control of compacted soils during construction. It is simple to operate, inexpensive, and produces repeatable results. The DCP was originally developed in South Africa for in-situ evaluation of pavement layer strength (Scala 1956). It is now in used in South Africa, the United Kingdom, Australia, New Zealand, and several states in the United States such as California, Florida, Minnesota, Mississippi, Texas and North Carolina (Ashan 2014). The DCP has been correlated to engineering properties such as the California Bearing Ratio (Mohammadi et al. 2008), soil classification (Huntley 1990), and unconfined compressive strength (McElvaney and Djatnika 1991; Patel and Patel 2012).

Dynamic cone penetrometers can have various weights and drop heights depending on the use. A schematic of the DCP device is shown below in Figure 2.9. The ASTM-standard device for use in shallow pavement applications consists of a 17.6 lb (8 kg) or a 10.1 lb (4.6 kg) hammer with a 22.6 in. (575 mm) drop height (ASTM D 6951 2009). The device has a 5/8 in. (16 mm) diameter steel drive rod with a replaceable point or disposable cone tip, a coupler, a handle, and a vertical scale (ASTM D 6951 2009). Schematic drawings of a replaceable point tip and a disposable cone tip are shown in Figures 2.10 and 2.11. The tip has an included angle of 60 degrees and a diameter at the base of 20 mm.

To use the DCP, the device is held plumb and the hammer is raised to the maximum height and dropped. The penetration distance is read on the scale and recorded, typically after every 5 drops. The readings are then used to calculate the dynamic cone penetration index (DCPI) using Equation 2.1.

$$DCPI = \frac{PR_2 - PR_1}{BC_2 - BC_1} \qquad \text{(Equation 2.1)}$$

Where:

PR = the penetration reading (mm),

BC = the blow count,

$PR_2 - PR_1$ = the difference between two consecutive readings at different depths (mm), and

$BC_2 - BC_1$ = the difference between two consecutive blow counts.

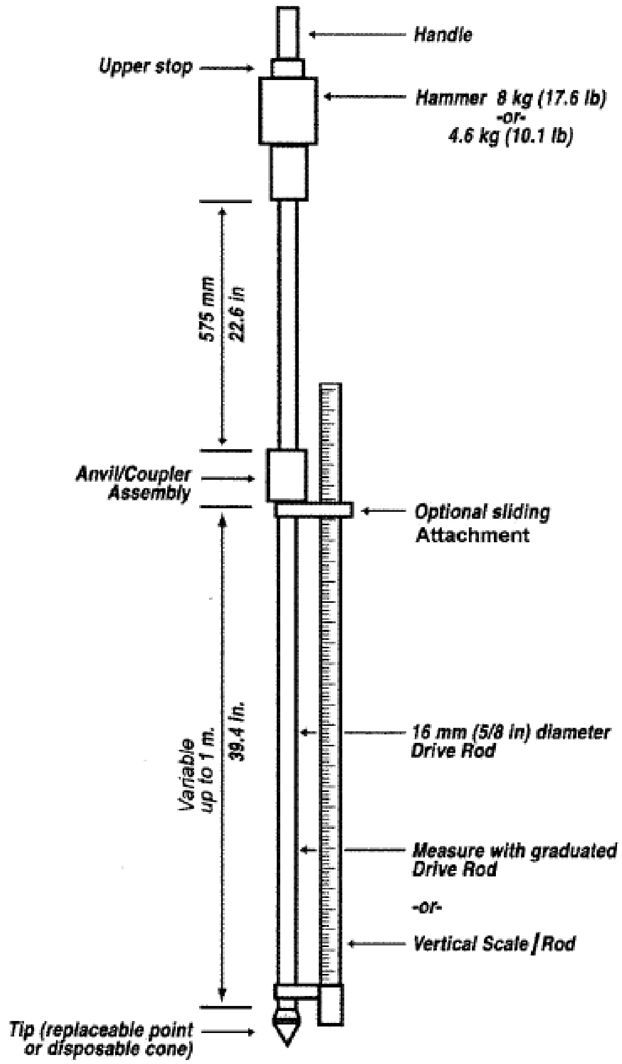

Figure 2.9: Schematic drawing of dynamic cone penetrometer (ASTM D 6951 2009)

The DCPI can be calculated after every 5 drops or can be calculated based on the total penetration depth and blow count. The unconventional units used were chosen for several reasons. When collecting the data using the dynamic cone penetrometer, it is more accurate and easier to record penetration in millimeters. This unit convention has been previously used by Ahsan (2014) during his investigation using the dynamic cone penetrometer to determine strength of stabilized soils.

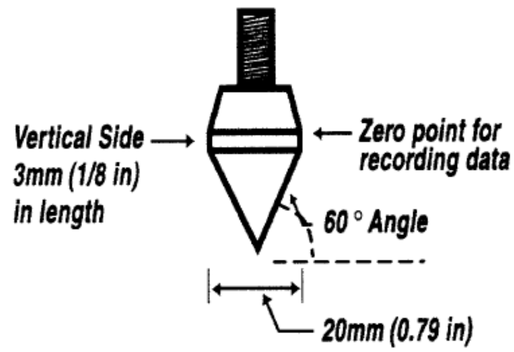

Figure 2.10: Replaceable point tip for dynamic cone penetrometer (ASTM D 6951 2009)

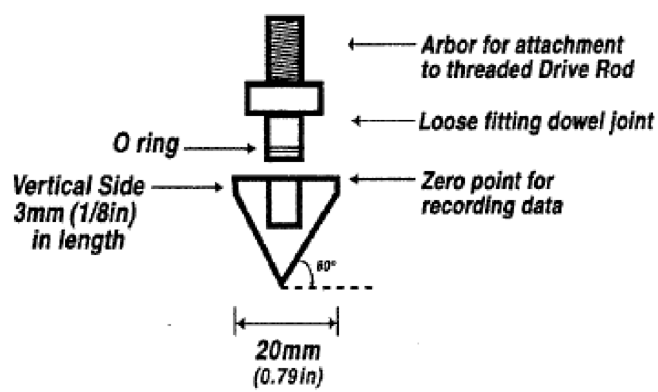

Figure 2.11: Disposable cone tip for dynamic cone penetrometer (ASTM D 6951 2009)

Extensive research has been performed to determine factors that can affect the measurements of the DCP on unstabilized materials. Kleyn and Savage (1982) concluded that the plasticity, density, moisture content and gradation affect the measurements. Hassan (1996) showed that the moisture content, AASHTO soil classification, confining pressures and dry density of fine grained soils. George (2000) concluded that the maximum aggregate size and the coefficient of uniformity could affect DCP results.

Additionally, researchers have found that the penetration slope of the DCP in penetration per blow is inversely related to the strength of the specimen being tested (Patel and Patel 2012; McElvaney and Djatnika 1991). Therefore, if a specimen has a very low strength the penetration rate with be much larger than a specimen with a very high strength.

2.5.1.1 Correlation between DCP and Unconfined Compressive Strength

Research has been performed to determine a relationship between the dynamic cone penetration index and the unconfined compressive strength on various unstabilized- and stabilized-soil types. McElvaney and Djatnika (1991) performed laboratory studies on silty clay, clay, and sandy clay with and without the addition of lime. The dynamic cone penetrometer tests were performed using the ASTM standard 17.6 lb hammer on specimens 5.98 in. (152 mm) in diameter and 4.57 in. (116 mm) high. The test specimens were only penetrated 50 mm. The unconfined compressive strength tests were conducted using BS 1924 (BSI 1975), on specimens with a L/D ratio of 2.0. They concluded that the dynamic cone penetrometer can be used to provide an estimate of the unconfined compressive strength of lime-stabilized soil mixtures. They also concluded that since the inclusion of data for material with zero lime content had negligible effects, the correlation is a function of strength not the way strength is obtained. They did caution that this might only apply to lower strength values. McElvaney and Djatnika (1991) developed three correlations.

50% probability of underestimation:

$$\log(UCS) = 3.56 - 0.807\log(DN) \qquad \text{(Equation 2.2)}$$

95% confident that probability of underestimation will not exceed 15 percent:

$$\log(UCS) = 3.29 - 0.809\log(DN) \qquad \text{(Equation 2.3)}$$

99% confident that probability of underestimation will not exceed 15 percent:

$$\log(UCS) = 3.21 - 0.809\log(DN) \qquad \text{(Equation 2.4)}$$

Where:

UCS = the unconfined compressive strength (kPa)

DN = the DCP reading (mm/blow)

Shown in Figure 2.12 is the correlation from McElvaney and Djatnika (1991) between the unconfined compressive strength and the dynamic cone penetrometer results. This figure includes both stabilized and unstabilized material.

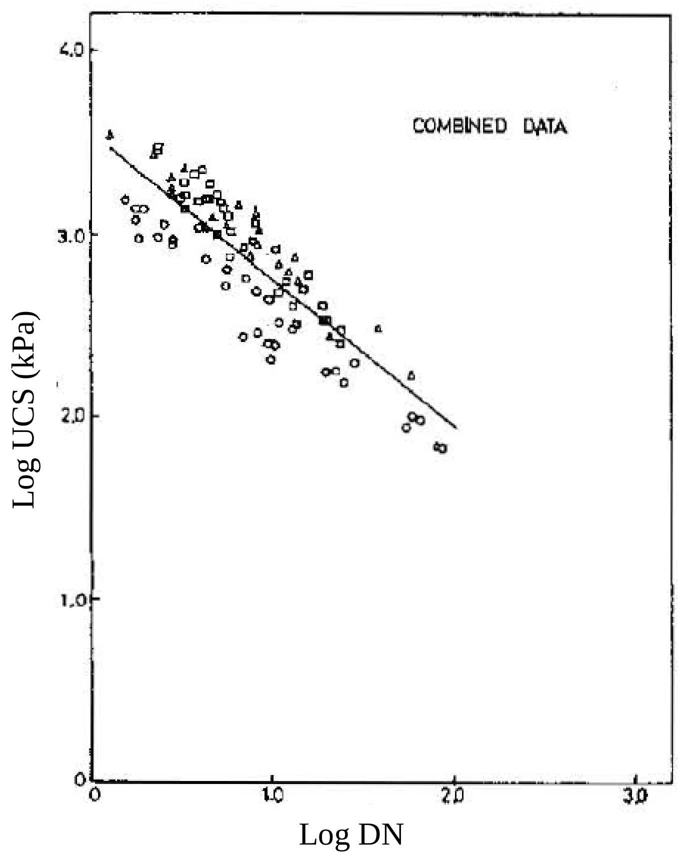

Figure 2.12: Correlation between UCS and DCP results from McElvaney and Djatnika (1991)

Patel and Patel (2012) conducted tests on in-situ conditions simulated in the laboratory on CH, CI, CL, SC, and SM-SC soils. They also conducted tests by stabilizing these soils with cement, lime, and flyash. The dynamic cone penetrometer tests were performed using an ASTM standard 17.6 lb hammer on soaked and unsoaked specimens using an automated DCP device. The penetration was recorded up to 300 mm. Unconfined compressive strength was tested in accordance with Indian Standard: 2720 (1980), using a L/D ratio of 2.0. Patel and Patel obtained the following equation for unstabilized and stabilized soils:

$$UCS = 3.1237 \times DCPI^{-0.865} \qquad \text{(Equation 2.5)}$$

Where:

UCS = the unconfined compressive strength (N/mm^2), and

DCPI = the dynamic cone penetration index (mm/blow).

Figure 2.13 shows the correlation between the unconfined compressive strength and the dynamic cone penetrometer index for stabilized and unstabilized soils. This figure includes a wide variety of soil types that were unstabilized and stabilized using cement, lime and flyash. Based on their results, Patel and Patel (2012) concluded that the correlation between the unconfined compressive strength and the dynamic cone penetrometer index was independent of soil type and the use of stabilizers.

Enayatpour et al. (2006) performed a series of laboratory tests on cement- and lime-stabilized soils to correlate the unconfined compressive strength with the dynamic cone penetrometer. Their results showed that the DCP could be calibrated to predict the unconfined compressive strength of subgrades. Enayatpour et al. (2006) concluded that a linear relationship existed between the DCP and the USC. They did stress that field studies needed to be conducted to provide reliable strength interpretations in real field conditions.

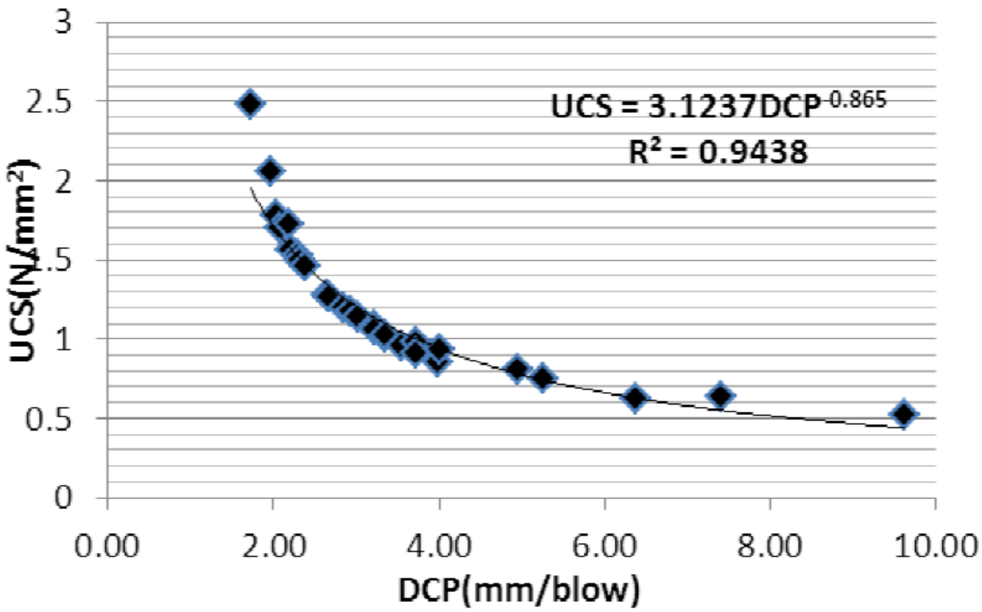

Figure 2.13: Correlation between UCS and DCP Results from Patel and Patel (2012)

2.5.2 Molded Cylinder Strength

2.5.2.1 Proctor Molded Specimens

The majority of past research concerning soil cement compressive strength was conducted using a specimen size of 4.0 in. in diameter and 4.58 in. in height with a length-diameter (L/D) ratio of 1.15 (ASTM D 559 2015). This method gives a “relative measure of the strength rather than a rigorous determination of compressive strength” (ASTM D 1633 2007). This mold size was used based on the availability of the molds in a soil testing laboratory.

To make a specimen, there are specific production techniques and procedures. The production of the 4.0 in. diameter specimens is described in ASTM D 698 (2012). This method utilizes a Proctor mold and a 5.5 lb hammer. Soil is placed in the mold in three equal lifts and the hammer dropped 25 times per lift around the specimen. After the three lifts are completed, the top portion of the mold is removed, and the surface is trimmed to the top edge of the bottom mold.

According to ASTM D 1633 (2007), this sized specimen remained in the mold in a continuously moist-curing room for a minimum of 12 hours or until the specimens could be extruded without damage. Once extruded, the specimens are placed back into the continuous moist-curing room. At the end of the moist-cure period, the specimens are immersed in water for 4 hours and tested immediately after.

2.5.2.2 Wilson (2013) Molded Specimens

Wilson (2013) studied the use of a modified version of ASTM D ASTM D 1632 (2007) to produce and cure soil cement specimens made in the laboratory and field. This method uses specimens that have a diameter of 2.8 in. and a height of 5.6 in. This diameter and height results in a L/D ratio of 2.0. This specimen size gives a better measure of the compressive strength since it reduces the complex stresses that may occur during the shearing of the smaller L/D ratio specimens (ASTM D 1633 2007).

Figures 2.14 and 2.15 show the dimensions and the equipment used for production. The cylindrical steel molds used had an inside diameter of 2.8 ± 0.01 in. and a height of 9 in. The mold also included a machined steel top and bottom pistons having a diameter 0.005 in. less than the mold, a 6 in. long mold extension, spacer clip, two aluminum separating disks 1/16 in. thick by 2.78 in. in diameter, and two ultra-high molecular weight polyethylene (UHMW) plugs with a diameter 0.005 in. less than the mold.

To produce a specimen, a small sample of the freshly mixed soil cement was tested to determine the moisture content. Based on this moisture content and the moisture-density curve previously produced, a target mass was determined using the Equation 2.6 to create a specimen with at least 98% density.

$$M_{sc} = 9.06\gamma_{dry}\frac{lb}{ft^3}$$ (Equation 2.6)

Where:

M_{sc} = mass of soil cement (g)

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

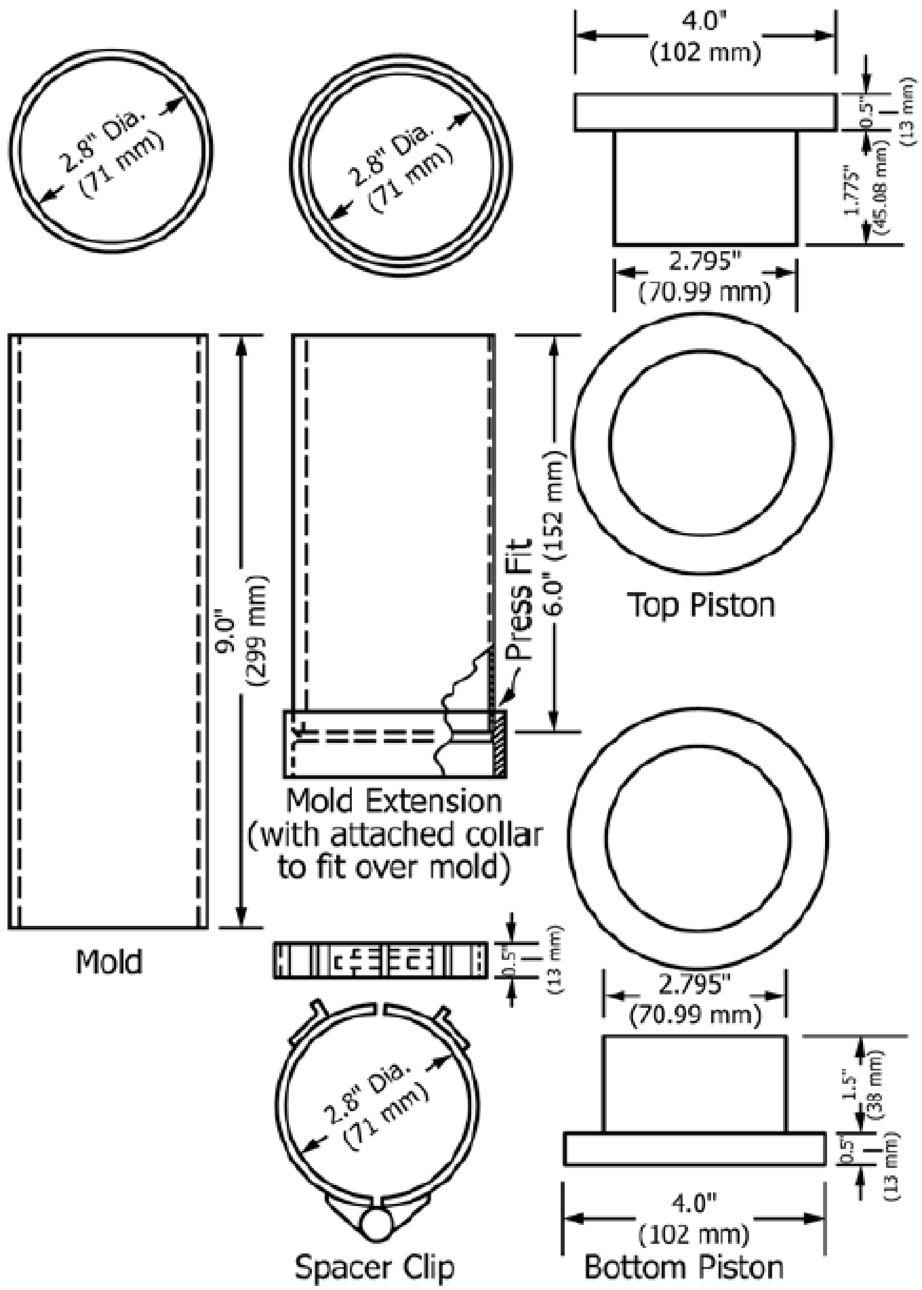

Figure 2.14: Soil cement cylinder mold (ASTM D 1632 2007)

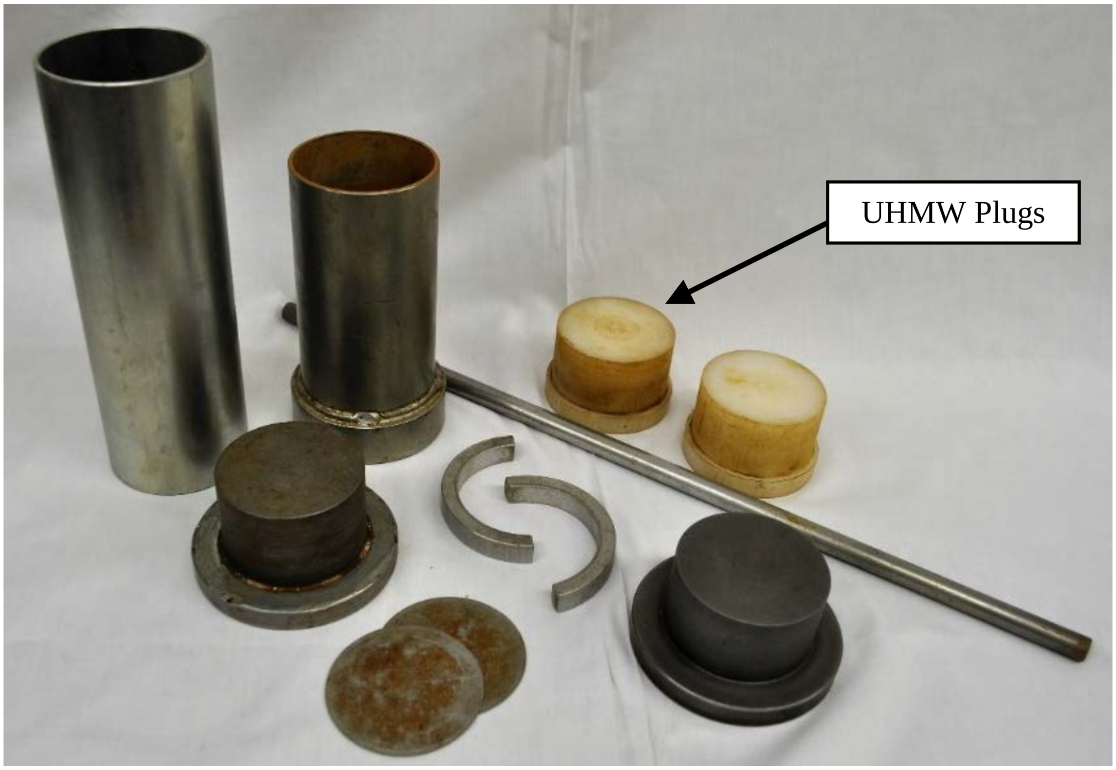

Figure 2.15: Soil cement molding equipment

Next, the mold and separating disks were lightly coated with a low-viscosity oil and placed on the bottom piston. Once assembled, the sleeve was placed on top of the mold. The predetermined amount of soil cement was then transferred into the mold. Next, the soil cement was compacted using a smooth steel rod until the specimen was below the level of the sleeve. Then the sleeve was removed and the separating disk and top piston placed on top of the mold. The specimen was compacted until the lip of the piston touched the end of the mold using a compacting drop-weight machine, shown in Figure 2.16. After compaction was completed, the pistons and separating disks were removed and a UHMW mold plug was placed on each end to reduce moisture loss. As an added barrier for moisture loss, metal foil tape, shown in Figure 2.17, was placed on the mold.

Figure 2.16: Soil cement compacting drop-weight machine (Wilson 2013)

Figure 2.17: Molded specimens during initial curing period (Wilson 2013)

Once the UHMW plug and metal foil tape were placed on the mold, the initial curing period began. Molds were transferred to a location in the laboratory or on-site where they had limited exposure to sun, wind, and other sources of rapid evaporation for at least 12 hours. After this period, specimens were transported to the laboratory where they were extruded using a vertical specimen extruder. Once extruded, the specimens were placed in a continuously moist curing room until the time of testing.

2.5.2.3 Strength Correction Factors for L/D ratios

For cylindrical concrete cylinders, ASTM C 39 (2016) states that if a specimen's length-to-diameter ratio is 1.75 or less, the compressive strength needs to be multiplied by the appropriate correction factor. These strength correction factors are suggested for use for soil cement specimens in ASTM D 1633 (2007). Wilson (2013) investigated these L/D correction factors commonly used for correcting the compressive strength of soil cement cylinders. Wilson (2013) showed that the ASTM C 39 (2016) L/D correction factors are not applicable to soil cement cylinders when made and tested using ASTM D1632 (2007) and ASTM D 1633 (2007). His recommendation was that no length to diameter ratios should be applied for L/D ratios between 1.0 and 2.0 (Wilson 2013).

Chapter 3

Experimental Plan

3.1 Introduction

The main objective of this research was to develop a method to reliably assess the strength of soil cement base. To accomplish this, a laboratory experimental testing program was developed. This chapter provides an overview of the laboratory experimental testing program. An outline of the soil cement mixtures from each borrow location is defined. In addition, a detailed specimen production and testing procedure is presented.

3.2 Experimental Testing Program

In order to develop a method to reliably assess the strength of soil cement base, an experimental testing program was developed. Figure 3.1 shows a summary of the laboratory testing plan. Two strength-testing methods were used: Modified ASTM D 1632 (Wilson 2013) for molded cylinders and ASTM D 6951 (2009) for DCP testing. The molded cylinders were tested for their unconfined compressive strength at 3 and 7 days. The DCP specimens were tested for penetration at 3 and 7 days.

A material and variable summary is presented in Figure 3.2. First, the two soils that were sampled and mixed are displayed with their respective AASHTO soil classification. Next, the strength ranges tested for both soil types are presented. The molded cylinder curing method is then shown. Finally, the strength testing age is presented for the both soil types and cylinder curing methods.

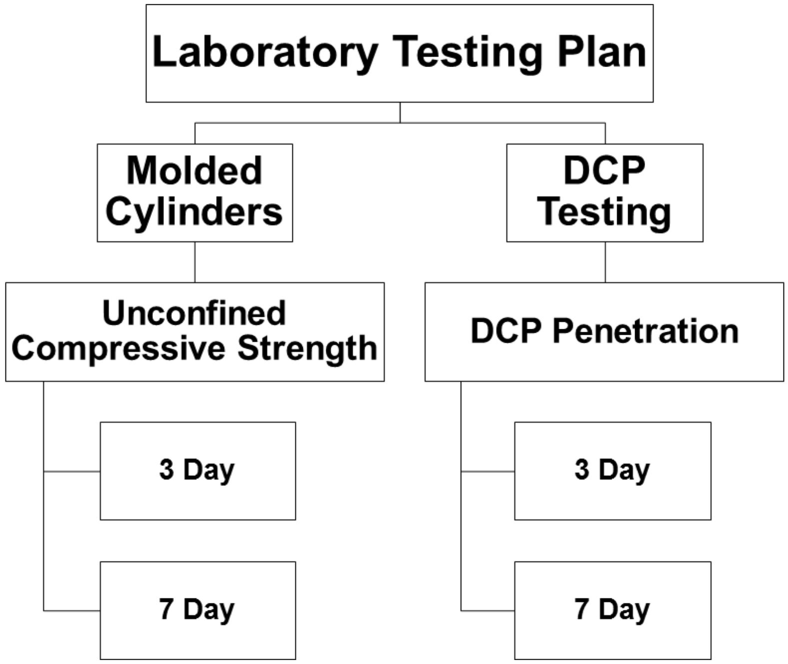

Figure 3.1: Summary of laboratory testing plan

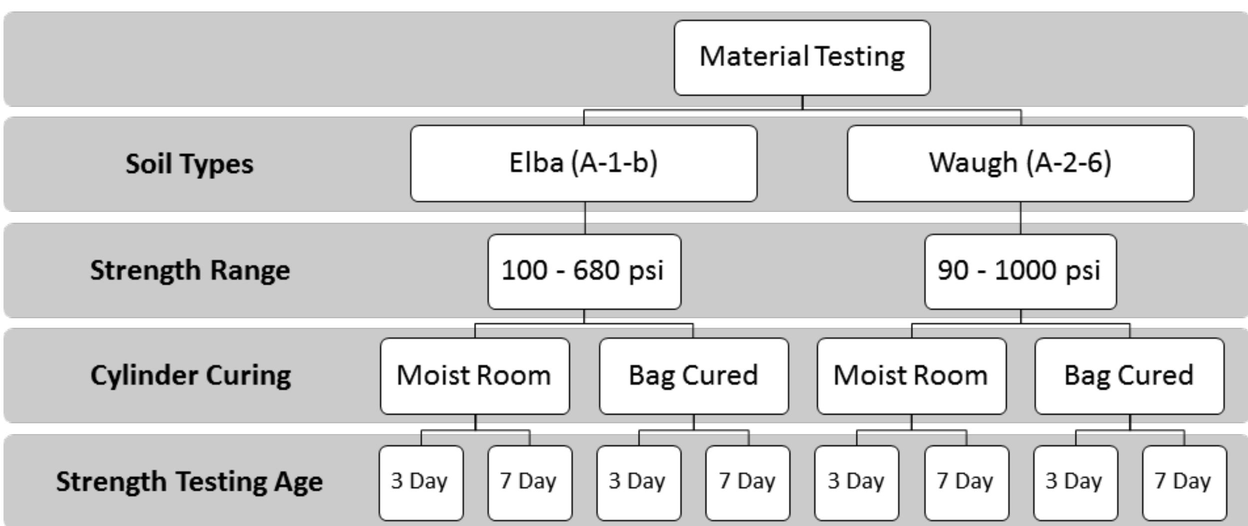

Figure 3.2: Material and variable testing summary

All mixtures tested consisted of soils sampled from borrow pits located near past or present soil cement projects to get the best representation of soils that could be used on construction sites. Each soil was tested to determine its properties and the soil classification using the USCS method and the AASHTO method. Each soil was mixed with a particular percentage of cement and the optimum moisture content and maximum dry unit weight was determined using a proctor test. The results from these tests were used to develop the mixture design. The percentage of cement used was determined to target three strength ranges: low (100 to 250 psi), moderate (250 to 600 psi), and high (600 to 800 psi). The moderate range is based on the strength requirements of ALDOT 304 (2014).

Once the soils were classified, an investigation was conducted to determine if the classification of soil had an impact on strength or cement content. Next, an appropriate curing method was developed for the molded cylinders by comparing two methods: moist-curing room method and sealed-bag method. A study was then conducted to determine the impact time had on the strength of soil cement. Next, the suitability of the DCP was tested to determine if it could penetrate specimens with a strength between 100 and 800 psi. Also, various penetration depths were investigated to determine which produced the most accurate results with the least amount of technician effort. Once the suitability of DCP was evaluated, three functions were compared to determine which produced the best fit for a correlation between the DCP and the molded cylinder strength. A total of 185 cylinders and 57 DCP specimens were produced and tested at 3 or 7 days.

3.2.1 Laboratory Mixtures Evaluated

Four types of soils sampled from central and south Alabama, shown in Figure 3.3, were evaluated in this study. These soils were selected based on their proximity to past and present soil cement projects in the state of Alabama. Each soil is labeled with the name that it is referred to throughout the research.

Figure 3.3: Soils used for testing

3.2.1.1 Elba Soil

The Elba soil was sampled from a borrow pit owned by Newell Construction in Elba, Alabama. The site location is shown in Figure 3.4, with the coordinates N 31.430253, W -86.125047.

In the laboratory, the Elba soil was mixed at 8, 11, and 14 percent cement content to target a range of strengths. The cement contents, optimum moisture contents, and maximum dry densities are shown in Table 3.1. This information was obtained through laboratory tests described in Section 3.2.2.

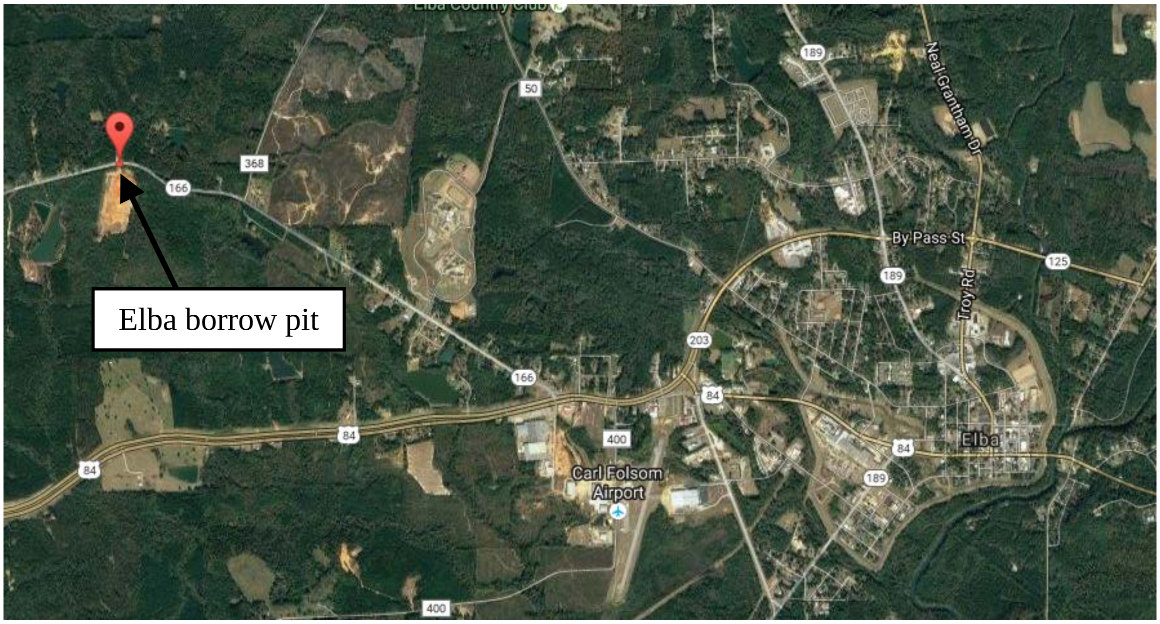

Figure 3.4: Map of Elba Borrow Pit (Google Maps)

Table 3.1: Mixture properties of Elba laboratory mixtures

Mixture properties of Elba laboratory mixtures		
Cement Content, %	Optimum Moisture Content, %	Maximum Dry Density, lb/ft^3
8	12.0	110.5
11	11.5	113.5
14	10.5	115.5

3.2.1.2 Waugh Sand and Waugh Clay

Two types of soil were sampled to later be mixed together from a borrow pit owned by Newell Construction in Waugh, Alabama. The coordinates of the borrow pit are N 32.365992, W -86.041644. A map of the location is shown in Figure 3.5.

Figure 3.5: Map of Waugh Borrow Pit (Google Maps)

3.2.1.3 Waugh Soil

To create a mixture with a fines content between 5% and 35% (ACI 230 2009), the Waugh Clay and the Waugh Sand were mixed together to create a soil blend. The mixture proportions were 80% of the Waugh Sand and 20% of the Waugh Clay. For the remainder of this paper this mixture will be referred to as the Waugh soil.

To create a wide range of strengths for testing, the Waugh soil was mixed at 4, 6, 8, 10, and 12 percent cement content. The cement contents, optimum moisture contents, and maximum densities are shown in Table 3.2. This information was obtained through laboratory tests described in Section 3.2.2.

Table 3.2: Mixture properties of Waugh laboratory mixtures

Mixture properties of Waugh laboratory mixtures		
Cement Content, %	Optimum Moisture Content, %	Maximum Dry Density, lb/ft^3
4	11.5	116.0
6	9.75	117.0
8	10.5	116.0
10	10.0	123.0
12	10.5	124.0

3.2.2 Material Classification

To better understand the soils used and to create the mixture designs, standard soil classification tests were run to determine geotechnical properties. First, a grain size distribution was run using ASTM D 422 (2007). This was used to determine the percentage of coarse- and fine-grained particles. The optimum moisture content and maximum dry density was determined using ASTM D 698 (2012): *Standard Test Methods for Laboratory Compaction Characteristics of Soil Using Standard Effort*. This test was important when creating the mixture designs. The raw soil was classified using both the American Association of State Highway and Transportation Officials (AASHTO) method and the Unified Soil Classification System (USCS) method.

3.2.3 Soil Classification Impact

The soil classification impact on soil cement was evaluated to determine the effects of coarse- and fine- particle percentages on the strength of soil cement. Two laboratory mixtures were developed, one with a low fines content and one with a higher fines content. The strengths of the soil cement specimens were compared when mixed with the same cement contents. In addition, the impact of the required cement content to stabilize the two soil types was evaluated.

3.2.4 Curing Method Impact

After seeing virtually no gain in strength between 3 and 7 days of curing, the final curing method of the molded cylinders was evaluated. During the first portion of testing, after removal from the mold, the cylindrical specimens were cured continuously in a moist-curing room until the time of testing. An alternative method, based on ASTM C 42 (2016), was suggested in which the molded cylinders were cured in sealed plastic bags inside the moist-curing room immediately after removal from the mold. This method was chosen since it reflected the curing method of the dynamic cone penetrometer specimens and is used for concrete cores (ASTM C 42 2016). The compressive strength, strength gain, and variability of these two curing methods were compared and evaluated.

3.2.5 Curing Time Impact

The impact of curing time was evaluated to determine the effect after 3 and 7 days of curing on the strength of the soil cement. Both the molded cylinders and the DCP specimens were made and tested at 3 and 7 days.

3.2.6 Suitability of the Dynamic Cone Penetrometer

The suitability of the dynamic cone penetrometer (DCP) to determine the strength of soil cement base was evaluated. During this evaluation, modifications such as altering the drop weight and height were considered. To evaluate the suitability, the DCP was tested at strengths ranging from 100 psi to 1000 psi. This range encompasses 200 to 650 psi, which is the minimum and maximum accepted by ALDOT 304 (2014) before replacement is required. Next, testing was performed to determine an accurate yet practical DCP penetration depth. DCP penetration depths between 1 in. and full-depth penetration were tested to determine which would be the most efficient.

3.2.7 Establishing the Correlation between MCS and DCP

Once the suitability of the DCP was completed, a study began to determine if a statistically significant correlation could be established between the molded cylinder strength and the dynamic cone penetrometer. This study consisted of testing various mixtures of soil cement with varying soil types and amounts of cement to produce a wide range of strengths. Each pair of companion MCS and DCP specimens were made from the same soil cement batch and tested at the same age.

3.3 Laboratory Experimental Procedures

3.3.1 Production in Laboratory

Multiple 55-gallon drums of soil were collected from borrow pits that were used in different aspects of the project. The portland cement was Cemex Type I. The water used was obtained from the City of Auburn's public water supply.

3.3.1.1 Moisture-Density Curve

The first step in the production of soil cement was to create the moisture-density curves with the soil cement for each mixture design. This information was necessary when batching the material for production. For this research, the optimum moisture content and maximum dry density was determined using ASTM D 698 (2012): *Standard Test Methods for Laboratory Compaction Characteristics of Soil Using Standard Effort*. Method A was used which utilizes a 4 in. diameter mold. For this mold, the specimen is compacted in three equal lifts using 25 blows per lift. Once compacted, the weight of the mold and soil cement was weighed and a sample taken to determine the moisture content. The results were then plotted to create the moisture-density curve.

3.3.1.2 Batching

Before batching began, a portion of the soil was removed from the drum and used to obtain the moisture content of the sampled soil using ASTM D 2216 (2010). Based on the moisture-density relationship curve and the current moisture content of the soil, the weight of soil, water, and cement was batched based on 100% density. Each component was weighed in 5-gallon buckets to the nearest hundredth of a pound and covered to minimize moisture loss.

3.3.1.3 Mixing

As a first attempt, mixing was to be performed in a laboratory-sized pugmill. Unfortunately, the pugmill was unable to handle the 2 cu. ft batch sizes. A 2 cu. ft batch was necessary to produce enough material to create the molded cylinders and the DCP specimens using the same batch. Next, an 8 cu. ft mortar mixer was tested to determine if the size was suitable. Figure 3.6 shows the mortar mixer used. This mixer also was not able to handle the batch size. This machine lacked the power to turn the paddles under the weight of the material.

Figure 3.6: 8 cu. ft Mortar Mixer evaluated for Soil Cement Mixing

Finally, a mortar mixer with a drum capacity of 12 cu. ft. was found to be sufficient. This mixer has enough power and volume to uniformly mix all the material. Mixing was performed in a Multiquip/Whiteman WM120PHD mortar mixer, as shown in Figure 3.7.

Figure 3.7: 12 cu. ft Mortar Mixer used for Soil Cement Mixing (Single Cylinder Repair 2016)

3.3.1.4 Molded Cylinder Production

The molded cylinders were made using the modified ASTM D 1632 method created by Wilson (2013). An outlined procedure is given in Section 2.5.2.2.

3.3.1.5 DCP Specimen Production

The molds used to make the dynamic cone penetrometer specimens were cylindrical plastic 5-gallon buckets, with a 12-inch diameter and 14-inch height. These buckets were chosen based on research performed by Enayatpour et al. (2006). The 5-gallon bucket allowed a 10-inch tall specimen to be produced and provided a large enough diameter for the dynamic cone penetrometer to collect data. Since a plastic bucket was chosen as the mold for the specimen, a concrete block was designed to create confinement during production and testing. A schematic of the confinement block is shown in Figure 3.8. Figure 3.9, shows the concrete confinement block built with and without a DCP specimen in the hole. This confinement was necessary to replicate field conditions when testing an in-situ base. The size of the reinforced concrete confinement block used was 30 in. by 36 in. by 13 in. deep. In the center of the confinement block was a hole that would allow the plastic mold to slide in. At the bottom of the hole was a ½ in. steel plate cast into the confinement block with grooves that matched the underside of the 5-gallon bucket. Surrounding the hole in the center of the block was spiral reinforcing steel to help with confinement. In addition, 0.018 percent temperature and shrinkage reinforcing steel was placed throughout the block.

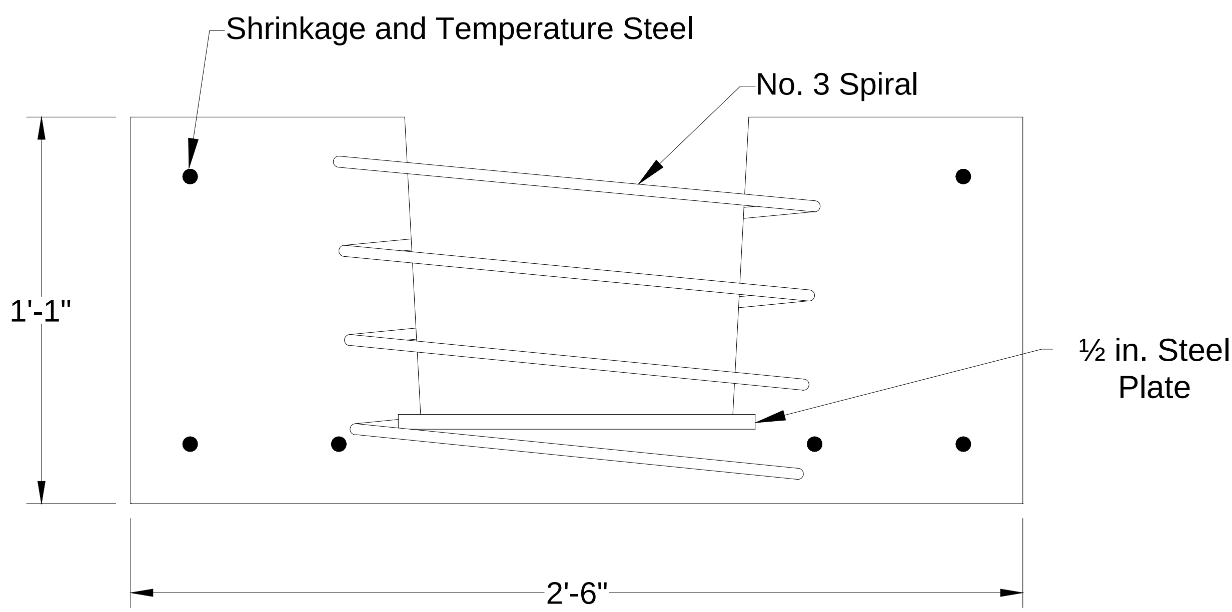

Figure 3.8: Reinforced concrete confinement block schematic

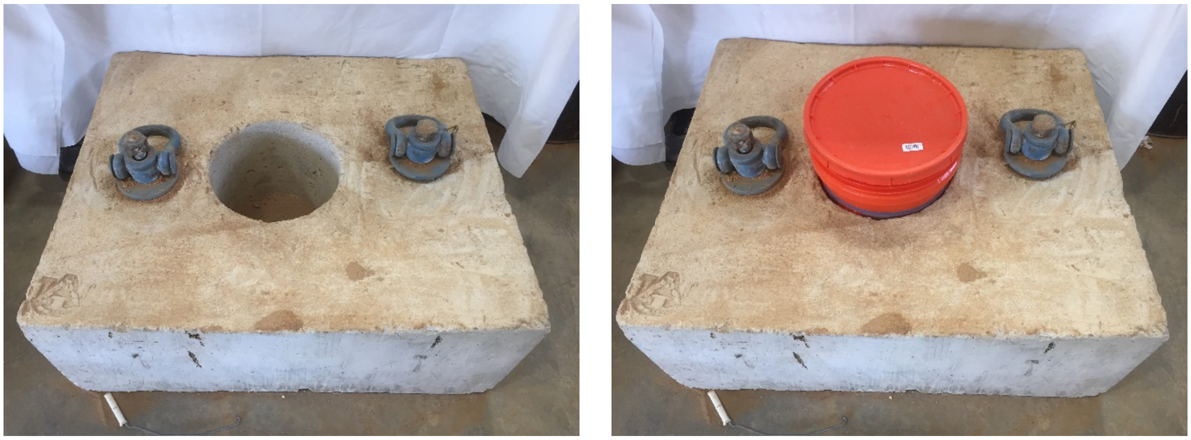

Figure 3.9: Reinforced concrete confined block with and without DCP specimen

To compact the soil cement in the mold a vibrating compaction hammer was used. For this research a Kango 900B ¾ in. Hex Demolition Hammer was chosen. This hammer was chosen based on the recommendations of ASTM C 1435 (2014): *Standard Practice for Molding Roller-Compacted Concrete in Cylinder Molds using a Vibrating Hammer*. This hammer was selected to simulate the vibrating roller used to compact soil cement during field construction. A circular steel tamping plate welded to a steel shaft was attached to the vibrating compaction hammer. The plate had a diameter of 5 ¾ ± 1/8 in. The mass of the plate and shaft were 6.6 ± 2.2 lb. as per ASTM C 1435 (2014). Figure 3.10 shows the vibrating compaction hammer used during production.

The production of the dynamic cone penetrometer specimens started immediately after mixing finished. An empty 5 gal. bucket was placed inside the concrete block with marks 4.5 in., 7.5 in., and 11.5 in. from the bottom. The soil cement was compacted in three equal lifts to ensure that the entire specimen was equally compacted, which is similar to the compaction method used in ASTM D 1557 (2012). Soil cement was shoveled from the mixer into the empty bucket until it reached the 4.5 in. mark. The vibrating hammer with the tamping plate assembly attached was placed on the surface of the soil cement in position 1, as shown in Figure 3.11a. For positions 1 through 4, the vibrating hammer was run in each position for 3 seconds. The hammer was stopped after each position and moved before resuming compaction. Then with the hammer on, a circular pattern, shown in Figure 3.11b, was followed making one revolution every 14 seconds. Three complete revolutions were made before stopping the vibratory compactor. This compaction method was chosen after trials to determine the amount of effort required to produce specimens with 98% density. Figure 3.12 shows the DCP specimen being compacted with the vibrating hammer in the concrete compaction block.

Figure 3.10: Vibrating compaction hammer with plate

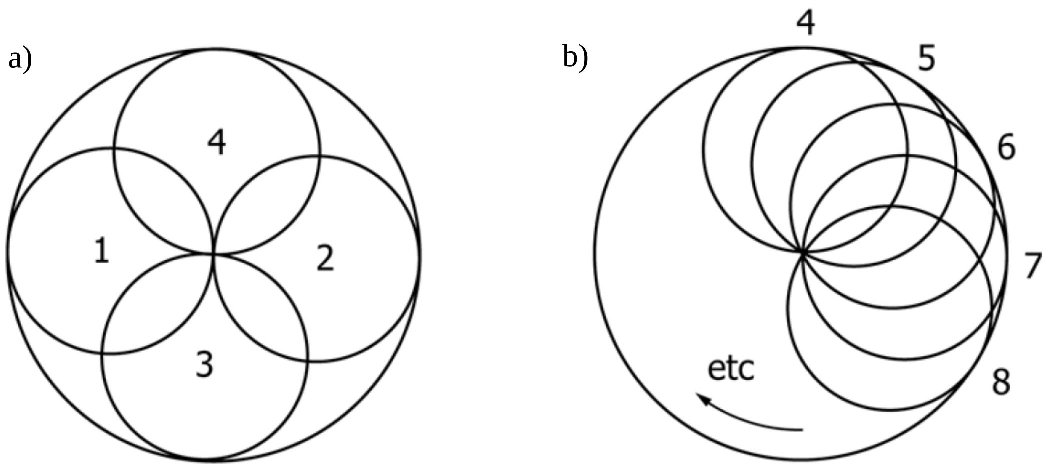

Figure 3.11: DCP specimen compaction pattern (ASTM D 1557)

Figure 3.12: DCP specimen compaction in the concrete compaction block

After three complete revolutions, the hammer was stopped. Soil cement was added to the next line inside the bucket and the compaction process was repeated for a total three of lifts. Next, the bucket was removed from the concrete block and the lid sealed on top. This process was repeated until three buckets were made for each mixture design and strength testing date.

3.3.2 Initial Curing

3.3.2.1 Molded Cylinders

Research performed by Wilson (2013), showed that specimens were too weak to be removed from the steel cylindrical mold immediately after production and thus the soil cement needed to remain in the mold until initial curing was complete. As per Wilson (2013), the specimens were allowed to cure under standard air conditions in the laboratory in their undisturbed location for a minimum of 12 hours, as shown in Figure 3.13. Typically, the specimens remained in the molds for initial curing overnight and between 12 and 48 hours (Wilson 2013).

Figure 3.13: Initial curing of molded cylinders

3.3.2.2 DCP Specimens

Before initial curing began, measurements were taken to determine the density of the DCP specimens. To determine the volume, five measurements were made from the top of the bucket to the top of the specimen and the results averaged. Next, the diameter of the specimen and weight was measured and recorded. Using these results, the dry density of the specimen was calculated to ensure that the specimen was no less than 98 percent.

The DCP specimens then were immediately transferred after completion to a moist-curing room, as shown in Figure 3.14. The lid was removed for a few minutes to allow moist air to enter the mold. The lid was then placed back onto the bucket. The specimens were allowed to cure in their initial curing state for 12 to 48 hours, but typically were not disturbed until the following day.

Figure 3.14: Initial curing of DCP specimens

3.3.2.3 Extrusion of Molded Cylinders

Once the initial curing was complete, the UHMW mold plugs were removed from the steel cylindrical molds and the specimens extruded. The specimens were extruded using a vertical hand-jack. This jack showed minimal signs of causing edge cracking during extrusion, which was a problem when a horizontal jack was used (Wilson 2013). Figure 3.15, shows the vertical hand jacking machine used for extrusion of the molded cylinders.

Figure 3.15: Vertical, hand jacking machine used to extract specimens

Once the molds were extruded, each cylinder was weighed and measurements taken to determine the density of the specimen. This was performed to ensure that the specimen had at least 98% of the maximum dry density.

3.3.3 Final Curing

3.3.3.1 Molded Cylinders

Final curing began as soon as the specimens were extruded from the mold. To simulate the curing process of the DCP specimens, the cylinders were placed in sealed plastic bags. All of the air was removed from the bags and the bag was sealed. By sealing the bags, no moisture was added or lost from the specimen. The specimens were then placed in the moist-curing room, which was kept at a temperature of 73 ºF ± 3 ºF, as shown in Figure 3.16, and remained there until it was time to test.

Figure 3.16: Final curing of the molded cylinders in the moist-curing room

Some specimens were removed from the mold and placed in the moist-curing room without the sealed bags for the purpose of exploring different curing methods. More details can be found in Section 3.2.4 about this part of the study.

3.3.3.2 DCP Specimens

When the molded cylinders were extruded and began their final curing, the final curing also began for the DCP specimens. While in the curing room, the lid was removed from the bucket and a sizeable piece of 6 mil plastic sheeting was placed in the bucket down to the surface of the soil cement. Special attention was made to ensure that the surface of the soil cement was completely covered by the plastic sheet. The process of placing a piece of plastic on top was chosen to simulate the asphalt emulsion that is placed on the surface of the soil cement in ALDOT field construction of soil cement base. Next using plastic clips, the plastic sheet was clipped to the bucket to avoid excessive amounts of water from entering the bucket. The DCP specimens remained in the moist-curing room with the plastic covering on until it was removed for testing. The final assembly of the final curing stage of the DCP specimen inside the moist-curing room is shown in Figure 3.17.

Figure 3.17: Final curing of DCP specimens in moist-curing room

3.3.4 Testing

3.3.4.1 Molded Cylinder Strength

Compression testing followed the modified ASTM D 1633 (2007) method created by Wilson (2013) during previous research at Auburn University. The differences include

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

The molded cylinder specimens were not immersed in water for 4 hours prior to testing based on recommendations made by Wilson (2013) and to simulate the curing in the DCP specimens. Specimens were not capped because of the recommendations from Wilson (2013) that showed that the method of making the soil cement cylinders provided the planeness and perpendicularity tolerances necessary to meet the criteria of ASTM C 1633 (2007). The loading rate was reduced to 10 ± 5 psi/s due to the recommendation from Wilson (2013) that suggested that the lower rate was more suitable for the low strength requirements of soil cement. With the reduced load rate, failure occurred between 15 seconds and 2 minutes for 100 and 1000 psi specimens, respectively.

For compression testing, a 100-kip compression testing machine was used to allow for more precise control of the loading rate. The compression testing machine used in this study is shown in Figure 3.18.

Upon removal from the moist-curing room, the molded cylinder was removed from the sealed plastic bag and placed in the compression machine. Special attention was paid to ensure that the vertical axis of the specimen was aligned with the center of thrust of the upper plate. Figure 3.19 shows the proper alignment of the cylinder in the compression machine.

Figure 3.18: Compression Testing Machine

The load was continuously applied at a rate of 10 ± 5 psi/sec. until failure. The total load at failure was recorded to the nearest 10 lb. The compressive strength was calculated by dividing the failure load by the cross-sectional area of the specimen.

To determine if there were outliers in each mixture, the acceptable range among results method outlined in ASTM C 670 (2015): *Standard Practice for Preparing Precision and Bias Statements for Test Methods for Construction Materials* was used. A coefficient of variation of 7.1% for no capping for strength was used, which was determined by Wilson (2013). The multiplier of coefficient of variation from Table 3.3 was multiplied by this coefficient of variation to produce the acceptable range of results.

Figure 3.19: Soil cement cylinder during testing

Table 3.3: Maximum Acceptable Range of Test Results (Adapted from ASTM C 670 2015)

Number of Test Results	Multiplier of Standard Deviation or Coefficient of Variation
2	2.8
3	3.3
4	3.6
5	3.9
6	4
7	4.2
8	4.3
9	4.4
10	4.5

3.3.4.2 DCP Testing

Testing of the dynamic cone penetrometer specimens followed the procedure of ASTM D 6951 (2009). Following the DCP requirements of ASTM D 6957, a 17.6 lb dynamic cone penetrometer with a 5/8 in. diameter steel rod with a 22.6 in. drop height was used. All tests were completed using a replaceable point tip with a 60° angle, which was replaced after every 100 tests. Figure 3.20 shows a schematic of the DCP device used for testing.

Once final curing was complete, the plastic and clips were removed from the DCP specimens while in the curing room. Before the DCP specimens were removed, a lid was secured to the bucket to avoid moisture loss during transportation to the testing location. The DCP specimens were transported back to the laboratory that they were made in and placed inside the concrete confinement block that they were prepared in. The lid was then removed to allow for testing.

Before testing began, the DCP was assembled and checked for any damaged parts. The DCP was placed on the soil cement surface roughly in the center of the specimen. While the device was held vertically, the tip was seated, by 25 mm (1 in.) of penetration, such that the top of the widest part of the tip was flush with the surface of the soil cement. Figure 3.21 shows the DCP hammer after seating in the DCP specimens. At this point, an initial reading was taken and recorded. The DCP remained in a vertical or plumb position while the operator raised the hammer until it made light contact with the handle. After reaching the top, the hammer was let go and dropped to initiate a blow. After every five blows, the penetration was read from the millimeter scale and recorded. This process continued until a total penetration of at least 150 mm. In accordance with ASTM D 6951 (2009), if the penetration was less than 2 mm after 5 blows or the handle deflected more than 3 in. from the vertical position, the testing was stopped.

Once the test was completed, the DCP was removed by driving the hammer upwards against the handle.

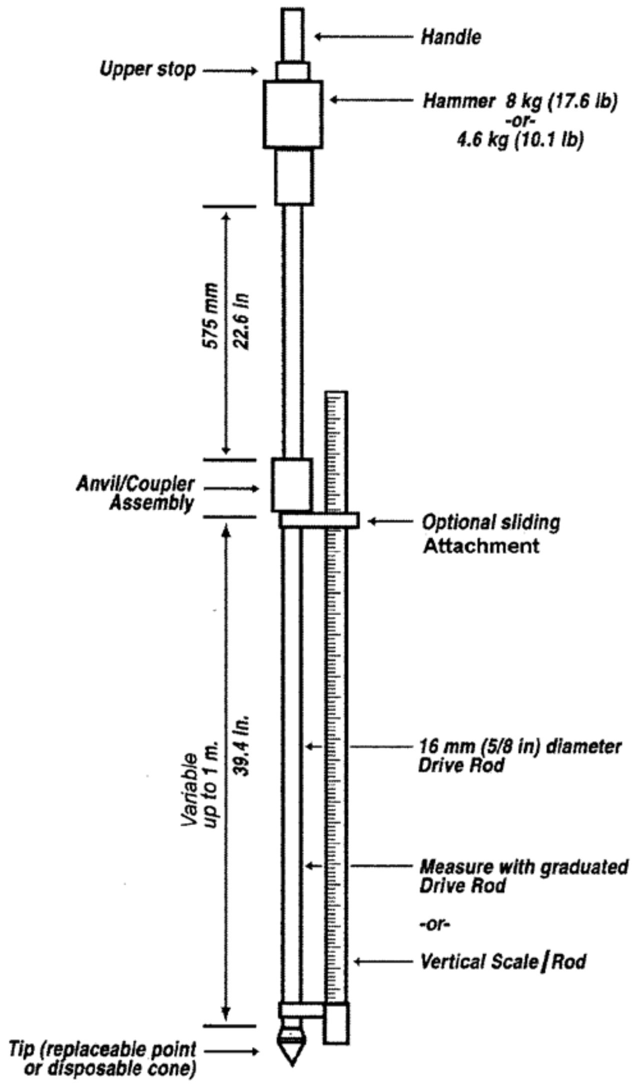

Figure 3.20: Dynamic cone penetrometer schematic (ASTM D 6951)

Figure 3.21: DCP testing assembly

Chapter 4

Presentation and Analysis of Results

4.1 Introduction

In this chapter, results from the laboratory testing program, which is described in Chapter 3, are presented and discussed. An in-depth analysis of the dynamic cone penetrometer results with respect to molded cylinder strength results, and their correlation is discussed. A summary of all data collected for each soil cement mixture can be found in Appendices A through J.

4.2 Material Classification

Using the methods described in Section 3.2.2, each soil was classified in accordance with AASHTO and USCS. Table 4.1 presents a summary of the findings from these tests. The Atterburg limit tests were performed by Matt Barr.

Table: 4.1: Summary of soil classifications

Soil	Percent Passing No. 200 Sieve	LL	PI	USCS Classification	AASHTO Classification
Elba	0.05	N/A	N/A	SP	A-1-b
Waugh Clay	38.4	21	18	SC	A-6b
Waugh Sand	0.71	N/A	N/A	SP	A-1-b
Waugh	12.0	14	12	SP-SC	A-2-6

4.3 Soil Classification Impact

As discussed in Section 3.2.3, a soil classification study was conducted to determine the effects of particle size and soil classification on the strength of soil cement and results obtained from the DCP and molded cylinders.

Figure 4.1 shows a comparison of the 7-day molded cylinder strength results versus cement content for the soil with 0.05% passing the No. 200 sieve and the soil with 12% passing the No. 200 sieve. The 7-day molded cylinder strength presented in this figure is the average of seven specimens.

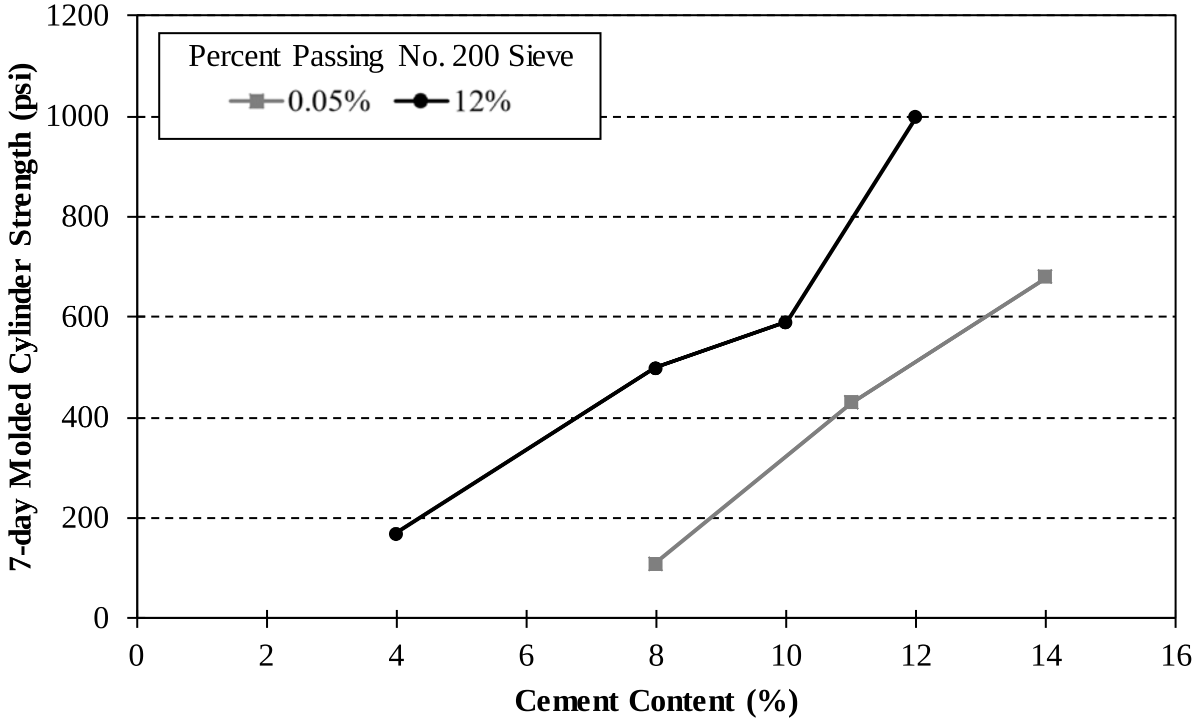

Figure 4.1: Effect of fines content and cement content on 7-day molded cylinder strength

Figure 4.2 shows a similar comparison of the 7-day DCP slope results versus the cement content for the soil with 0.05% passing the No. 200 sieve and the soil with 12% passing the No. 200 sieve. The DCP slope was obtained by penetrating the soil cement specimen, based on the procedure in Section 3.3.4.2, and analyzing the millimeters per blow based on a penetration distance of 75 mm (3 in.). As previously discussed in Section 2.5.1, the DCP slope is inversely related to the strength of the specimen. For both the molded cylinder strength and the DCP slope, the soil cement mixtures with the higher fines content not only had higher strengths, but also required less cement content to achieve the same strength level. These results are similar to literature from ACI 230 (2009) that states that “soils containing between 5% and 35% fines passing a No. 200 sieve produce the most economical soil cement.”

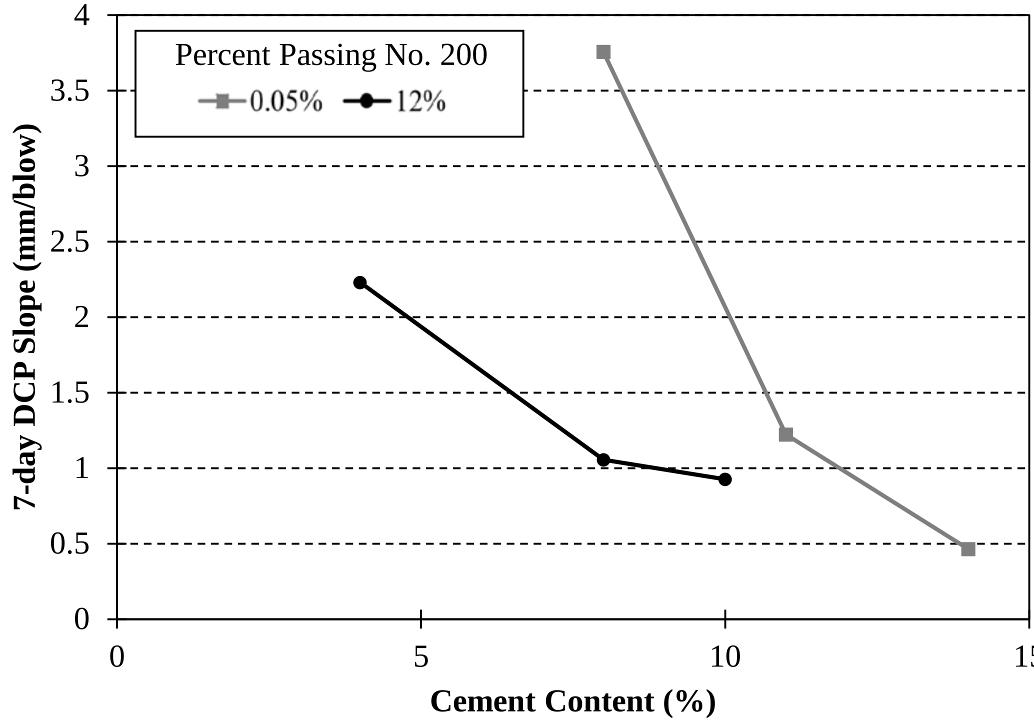

Figure 4.2: Effect of fines content and cement content on 7-day DCP slope

4.4 Curing Method Impact

As previously discussed in Section 3.2.4, variable results were seen when the molded cylinders were openly cured in a moist-curing room during the final curing period. To determine if the variability was due to the curing method, the results were compared to a sealed plastic bag curing method, which is used for concrete cores (ASTM C 42 2016). The results of this part of the study are shown in Figure 4.3. The label indicates the location where the soil source, the percent cement that was used, and the length of curing time. For example, “Elba-8-3d” is a sample using soil from Elba with 8% cement that was cured for 3 days. As shown, the sealed-bag cured specimens consistently produced higher strength specimens at a variety of cement contents and strengths. The variation in strength between sealed-bag and moist curing could be due to swelling of the clay particles and the soil-water interaction that occurs during moist curing. Patel and Patel (2013) performed research on soaked and unsoaked UCS specimens. The unsoaked specimens from Patel and Patel (2013) produced approximately 40% higher strengths than the soaked specimens.

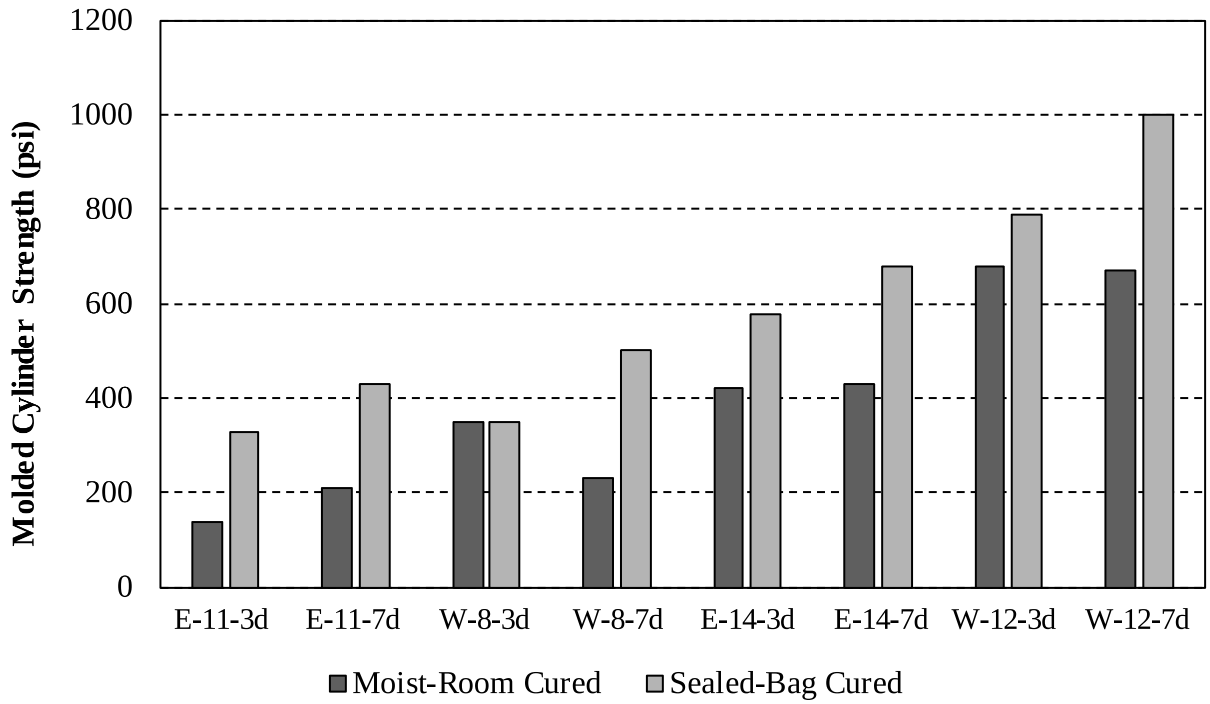

Figure 4.3: Comparison of moist room cured and bag cured specimens

The percent gain in strength between three and seven days of curing was evaluated to determine if one curing method captured the increase in strength with age due to the continued hydration of the cement. Figure 4.4 shows the results of this evaluation. As shown, the moist-room curing method was inconsistent and produced specimens that either showed little increase in strength or decrease in strength over time. The average gain is strength for the moist-room curing method was 4%, while the average gain in strength for the sealed-bag cured specimens was 30%.

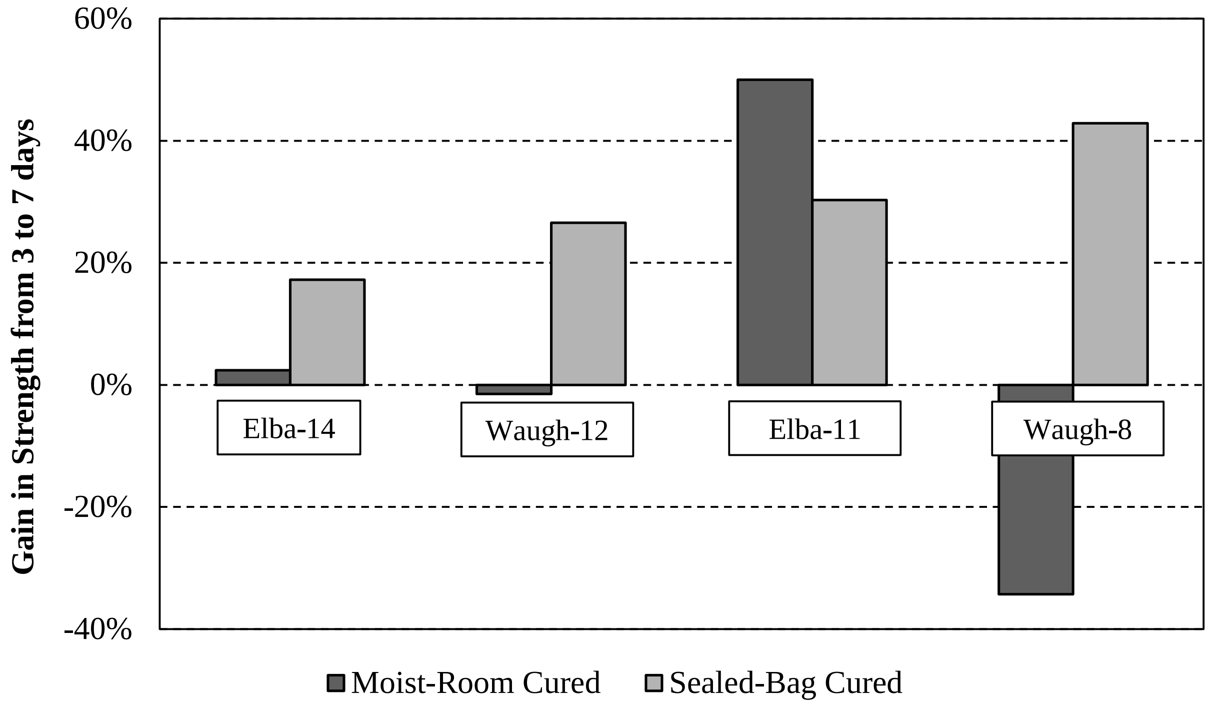

Figure 4.4: Comparison of the percent gain in strength

When the molded cylinders were cured in the moist room the coefficient of variation was 11%, while the molded cylinders cured in sealed bags had a coefficient of variation of 9%. This decreased in variability reflected more reliable and consistent results when curing the cylinders in sealed bags.

4.5 Curing Time Impact

As discussed in Section 3.2.5, a curing impact study was conducted to evaluate the impact of curing time on three and seven day strengths. In an effort to evaluate the impact, the molded cylinders and DCP specimens were cured for three and seven days and the results compared. Figure 4.5 shows the comparison of molded cylinder strength that were cured for 3 and 7 days using the sealed-bag curing method. The nomenclature indicates the location where the soil was sampled from and the percent cement that was used. For example, “Elba-8” is a sample using soil from Elba with 8% cement. The molded cylinder strength presented is the average strength of seven cylinders that were cured using the sealed plastic bag curing method. Additionally, the results include data from Waugh and Elba with varying amounts of cement content. The average gain in strength between three and seven days of curing was approximately 45%.

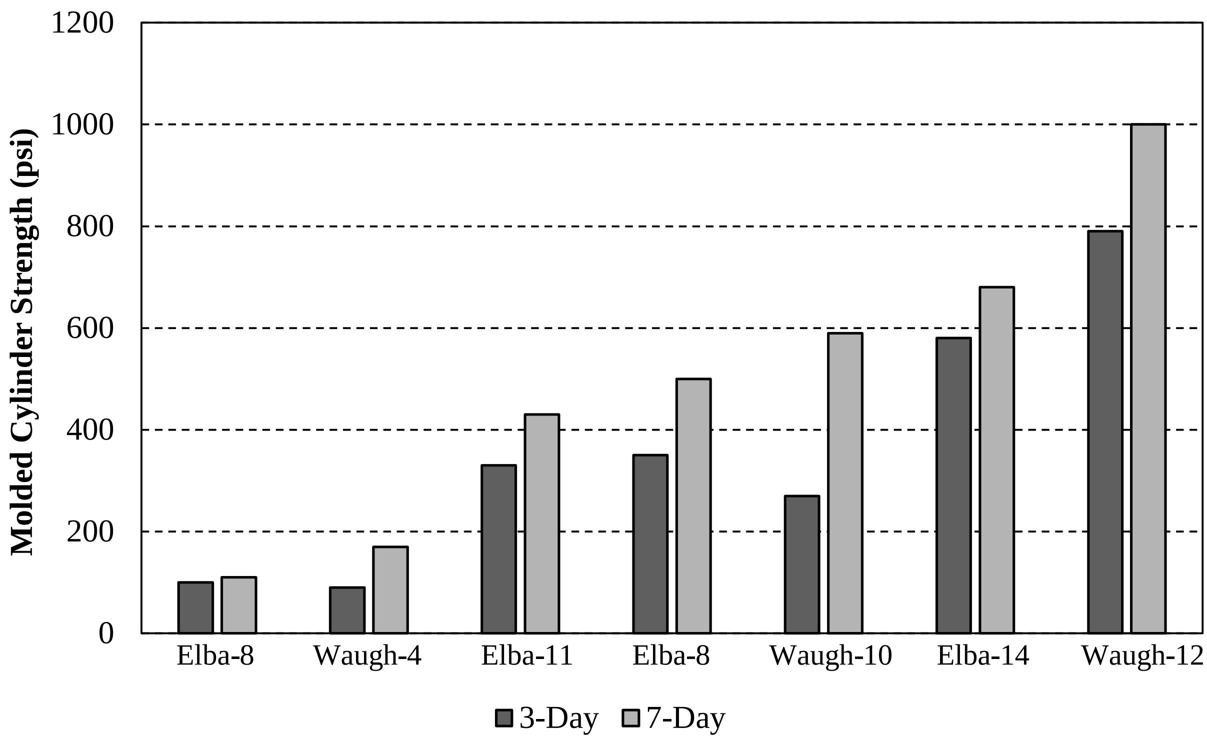

Figure 4.5: Comparison of molded cylinder strength over time

Since the gain in strength from 3 to 7 days was observed for the molded cylinders, the gain in strength from 3 to 7 days was analyzed for the DCP results. Figure 4.6 shows the difference in the DCP slope from three to seven days. Not only did the molded cylinders show an increase in strength between three and seven days, but so did the DCP results. The DCP slope was obtained by penetrating the soil cement specimen, based on the procedure in Section 3.3.4.2, and analyzing the millimeters per blow based on a penetration distance of 75 mm (3 in.). The average decrease in slope between three and seven days is approximately 35%. This increase in strength over time for both the molded cylinders and the DCP results was expected based on research performed by Patel and Patel (2013).

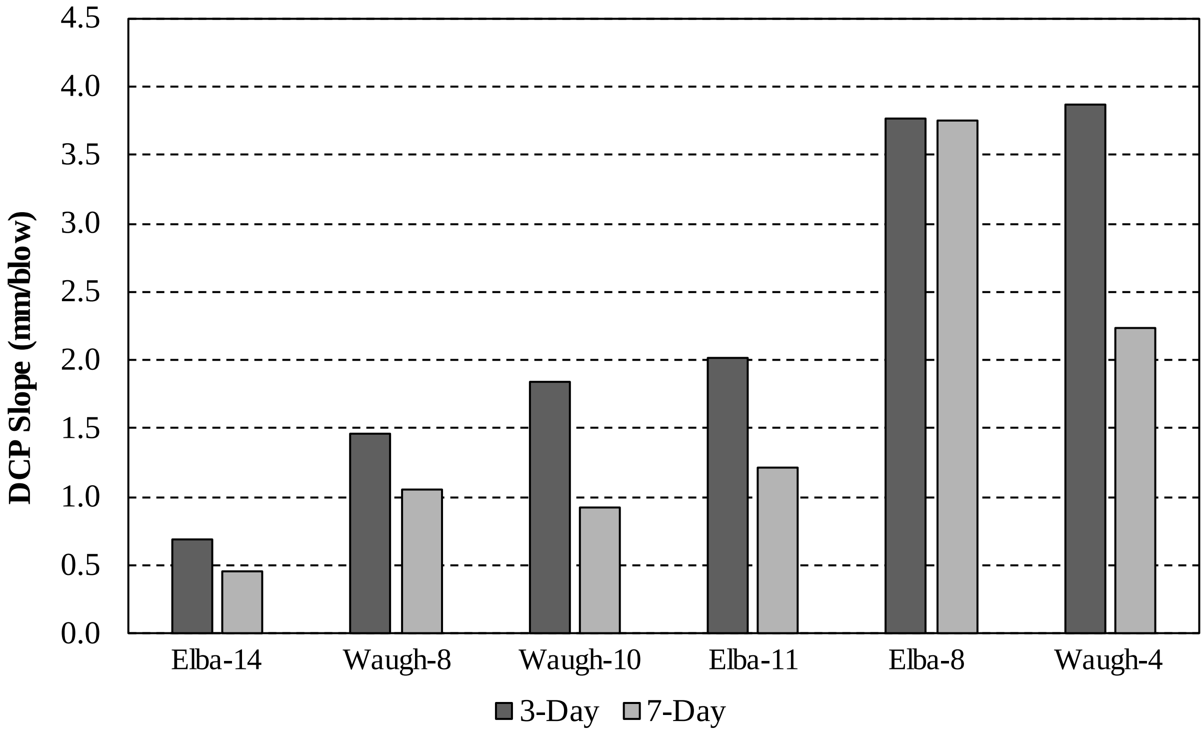

Figure 4.6: Comparison of DCP slope over time

4.6 Suitability of Dynamic Cone Penetrometer

The suitability of the dynamic cone penetrometer was assessed to ensure that it could penetrate the soil cement once it had cured. The dynamic cone penetrometer was tested at a wide range of strengths from 100 psi to 1000 psi. As mentioned in 3.3.4.2, a 17.6 lb hammer, with a 22.6 in. drop height and a 60° replaceable point tip. In accordance with ASTM D 6951 (2009), if the penetration was less than 2 mm after 5 blows or the handle deflected more than 3 in. from the vertical position, the testing was stopped. The results of this investigation are given in Table 4.2.

Table: 4.2: Summary of the penetration versus strength investigation

Strength (psi)	Refusal
90	No
100	No
110	No
170	No
230	No
260	No
270	No
330	No
350	No
430	No
500	No
580	No
590	No
680	No
790	No
1000	Yes

As shown, the DCP was able to penetrate without meeting the ASTM refusal criterial when the strength when the strength of the samples ranged from 90 psi to 790 psi. However, the DCP was not able to penetrate the sample with a strength of 1000 psi. Since the dynamic cone penetrometer was able to penetrate strengths well above 650 psi—the maximum ALDOT requires before replacement—the weight of the hammer and the height of the drop were not changed from what is specified in ASTM D 6951 (2009).

Based on ALDOT 304 (2014) and the results from this study, Figure 4.7 was developed to show a comparison of the ranges of ALDOT strengths and the DCP range. “100% Pay” represents the range that the contractor receives full payment. “ALDOT Acceptance” represents the range that the contractor is not required to remove and replace but may receive a pay reduction if the range is not between 250 and 600 psi. “DCP Range” represents the ranges of strengths tested during this research where the DCP was able to penetrate and not meet refusal. The DCP was able to accurately penetrate well outside the range that could be used in field construction.

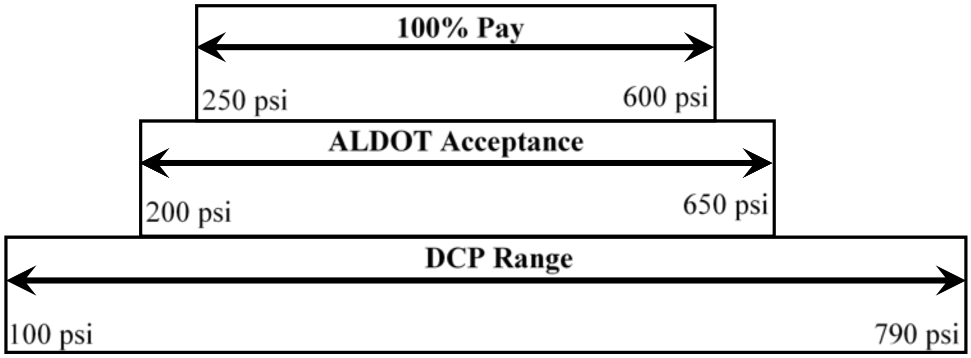

Figure 4.7: Comparison of the DCP range and ALDOT acceptance range

4.6.1 Penetration Depth Analysis

An extensive analysis was performed to determine the depth of penetration over which the data is analyzed for the dynamic cone penetrometer. For ease of presentation, all graphs shown are for the same soil cement mixture; however, overall conclusions are based on all the tests performed. The figures presented in Sections 4.6.1.1 through 4.6.1.5 are meant to be shown as a demonstration of the process used to analyze each soil cement mixture.

For each mixture design, the data from the three DCP specimens were plotted. The blow count was plotted on the x-axis against the DCP penetration in mm on the y-axis. As previously mentioned, the DCP data were recorded in millimeters instead of inches because it is easier and more accurate to record. A linear-regression analysis was performed on each set of data to determine the slope of the line. The y-intercept was restricted to zero to make the comparison easier between all of the results. Five penetration depths were evaluated—full-depth, 100 mm, 75mm, 50 mm, and 25mm. Full depth was a minimum of 150 mm in penetration. A summary of the penetration depths is shown in Figure 4.8.

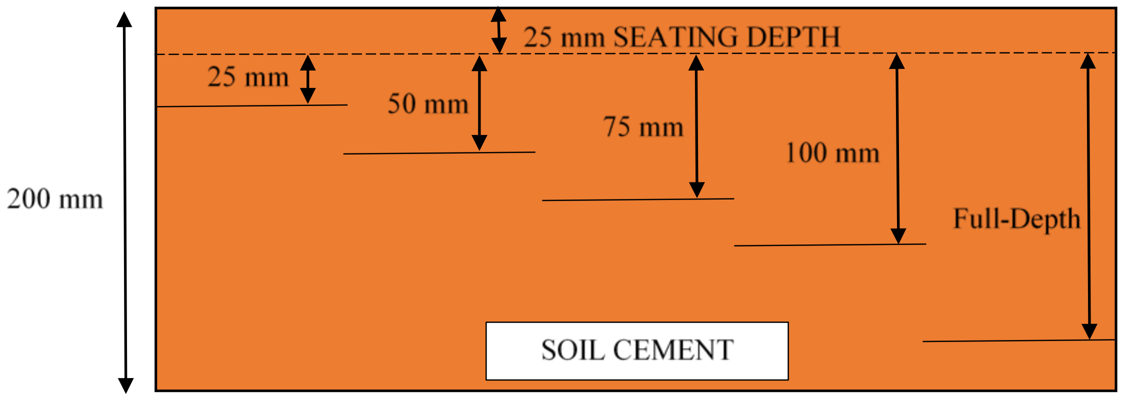

Figure 4.8: Penetration Depth Summary

These penetration depths were analyzed and compared to determine which penetration depth produced the most sufficiently accurate results with the least amount of technician effort when performing the test. The concept of penetrating shallower depths was based upon research performed by McElvaney and Djatnika (1991) that used a penetration depth of only two inches (51 mm). There was no indication that penetrating smaller distances produced less reliable results (McElvaney and Djatnika 1991). In addition, Webster et al. (1992) suggested that a minimum of one inch (25 mm) of penetration was required to avoid inaccurate strength determination. A summary of the data from all of the mixture designs can be found in Appendices E through I.

4.6.1.1 Full-Depth Analysis

First, the full set of data collected over a penetration ranging from 0 to approximately 160 mm was plotted to determine if there was a strong linear relationship between the blow count and the DCP penetration depth. An example of full-depth penetration data of the DCP is presented in Figure 4.9. As shown, there is a strong linear relationship between the blow count and the penetration. This strong relationship is shown in laboratory research performed by Enayatpour et al. (2006) using uniformly mixed soil cement and lime-stabilized soil.

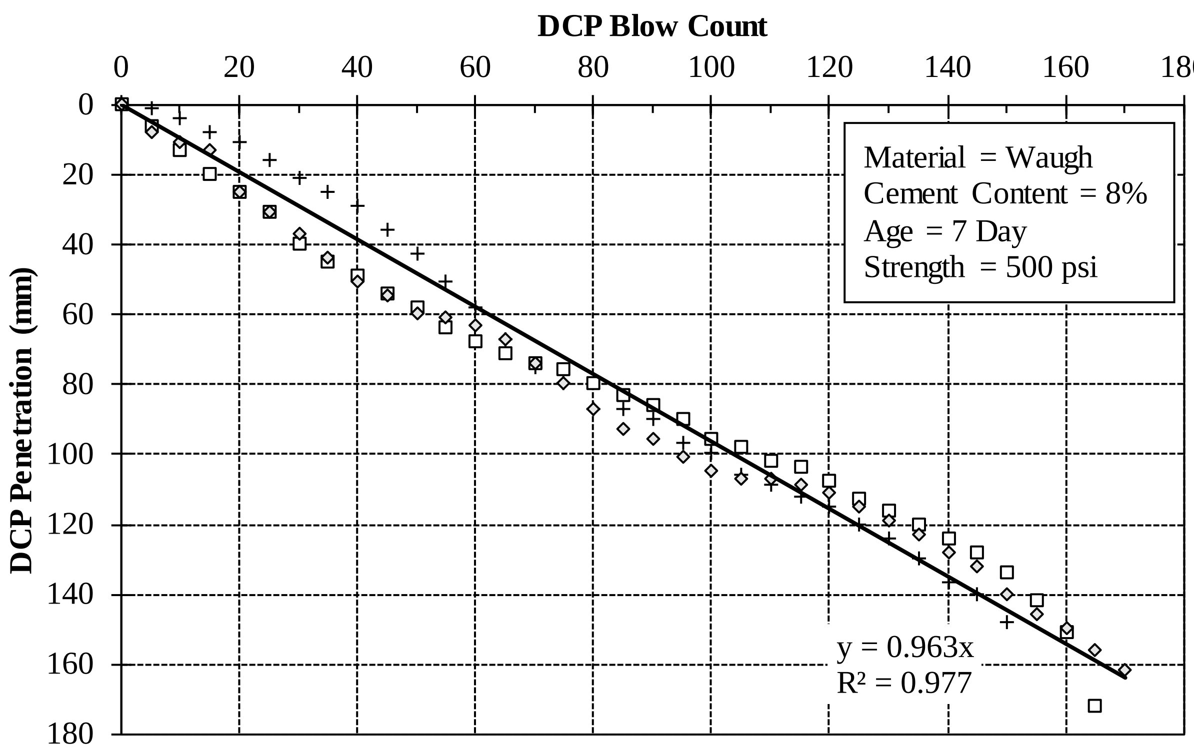

Figure 4.9: Full depth penetration relationship between 0 and 170 mm

4.6.1.2 One Hundred Millimeter Penetration Depth Analysis

The next penetration depth that was analyzed was 100 mm (4 in.). A 100 mm penetration depth was chosen as the starting point because it was approximately 60% of the total overall penetration, not including the seating distance. Shown in Figure 4.10, is the relationship developed for a penetration depth of 100 mm for this particular soil cement. It should be noted that at least one data point after the 100 mm mark was recorded to ensure a full reading. As suspected, the relationship remained linear even though fewer data points were used. The percent error of the slope is only 6.4% when compared to the full-depth penetration slope. This percent error was calculated by finding the difference between the full-depth slope and the 100 mm slope, dividing it by the full-depth slope, and multiplying this number by 100 to convert it to a percentage. The coefficient of determination (R^2) did decrease but the relationship still remained very strong.

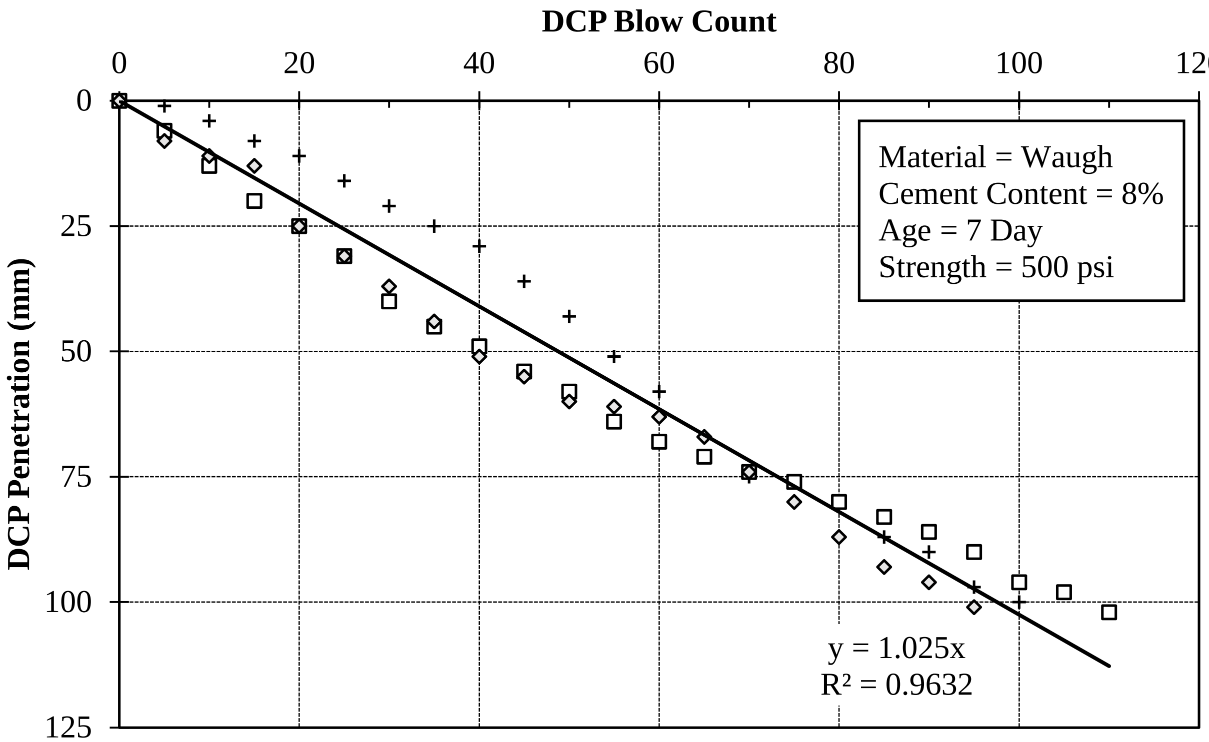

Figure 4.10: One hundred millimeter penetration depth relationship

4.6.1.3 Seventy-Five Millimeters Penetration Depth Analysis

Next, a penetration depth of 75 mm (3 in.) was analyzed to determine if less technician effort will still produce sufficiently accurate results. A 75 mm penetration depth was chosen since it is exactly half of the typical 200 mm (8-inches) soil cement base layer thickness when the 25 mm (1-inch) seating depth is included. An example of a relationship for 75 mm of penetration for this strength is given in Figure 4.11. It should be noted that at least one data point after the 75 mm mark was recorded to ensure a full reading. The penetration slope increased by 9.5% compared to the full-depth penetration slope. This percent error was calculated by finding the difference between the full-depth slope and the 75 mm slope, dividing it by the full-depth slope, and multiplying this number by 100 to convert it to a percentage. The coefficient of determination decreased by 3.3%, but an R^2 value of 0.9445 still indicates that a strong linear relationship exists between DCP blow count and its penetration.

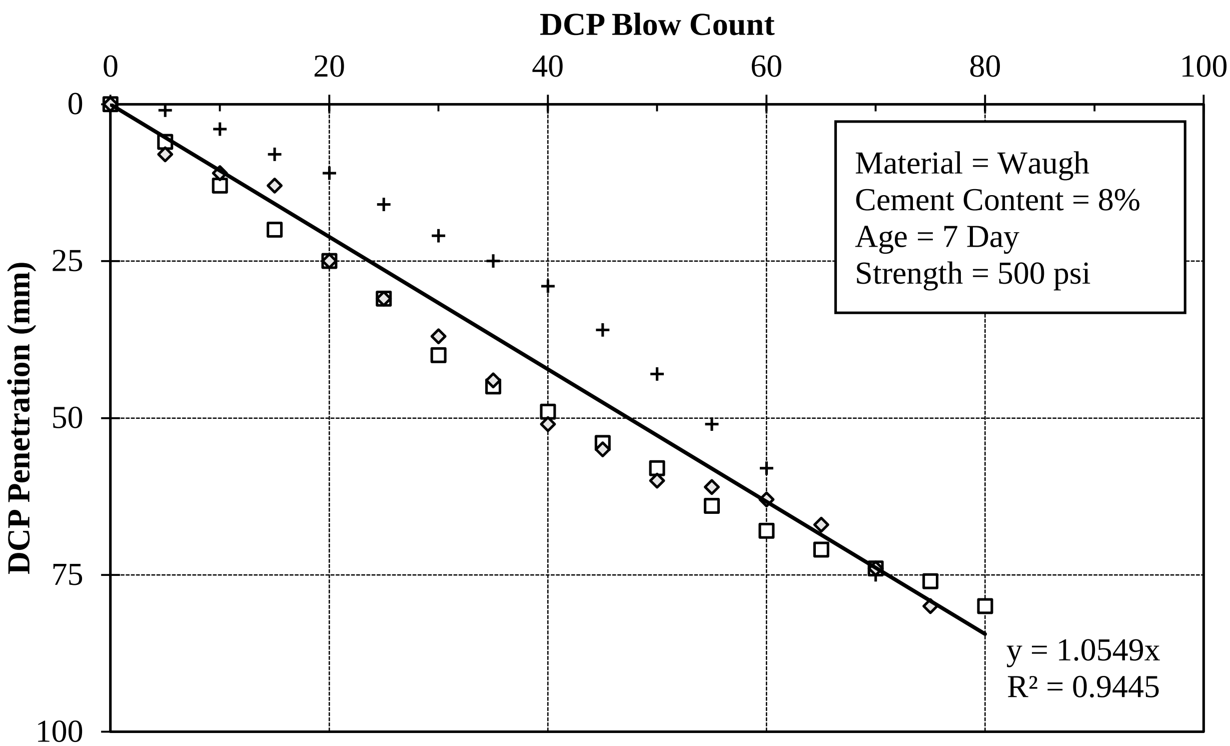

Figure 4.11: Seventy-five millimeter penetration depth relationship

4.6.1.4 Fifty Millimeters Penetration Depth Analysis

Since a penetration depth of 75 and 100 mm produced similar results, an analysis was performed on a penetration depth of 50 mm to determine if it had a sufficiently accurate linear relationship between 0 and 50 mm. The results from this analysis can be found in Figure 4.12 for one of the mixtures tested at 7 days. It should be noted that at least one data point after the 50 mm mark was recorded to ensure a full reading. Though the slope of the line did not change significantly, the coefficient of determination dropped significantly by 14.5%. This indicates that a linear relationship less accurately characterizes the DCP blow count versus penetration depth up to 50 mm.

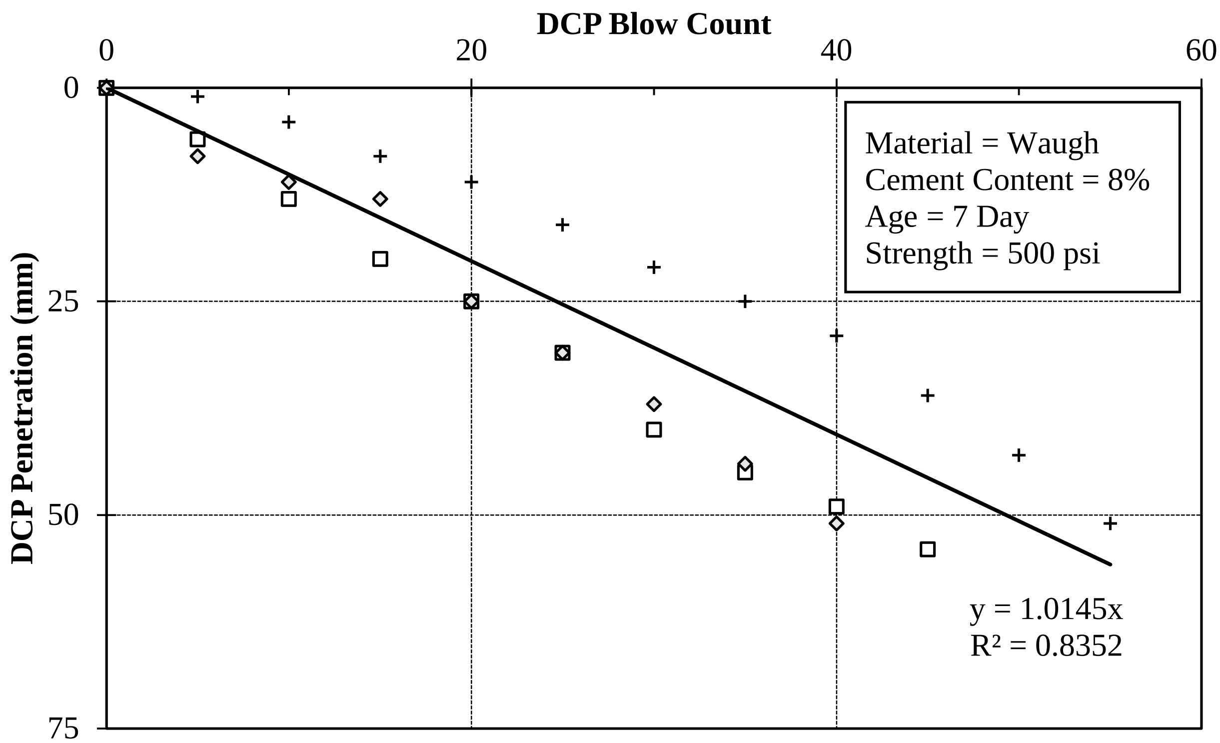

Figure 4.12: Fifty millimeter penetration depth relationship

4.6.1.5 Twenty-Five Millimeter Penetration Depth Analysis

Lastly, for the purpose of research, an analysis was performed on only 25 mm (1 in.) of penetration. As previously mentioned, Webster et al. (1992) suggested that a minimum penetration of 25 mm (1 inch) was required. This depth is approximately 20% of the full penetration depth, not including the seating depth. The results based on 25 mm of penetration are shown in Figure 4.13. It should be noted that at least one data point after the 25 mm mark was recorded to ensure a full reading. Not only did the slope for 25 mm change significantly from the other penetration depths, but also the coefficient of determination also significantly decreased for this example. This could be attributed to the small amount of data points in this range. A 25 mm penetration depth does not produce enough reliable data points when readings are only taken every five blows. This problem is shown more with the lower strength specimens.

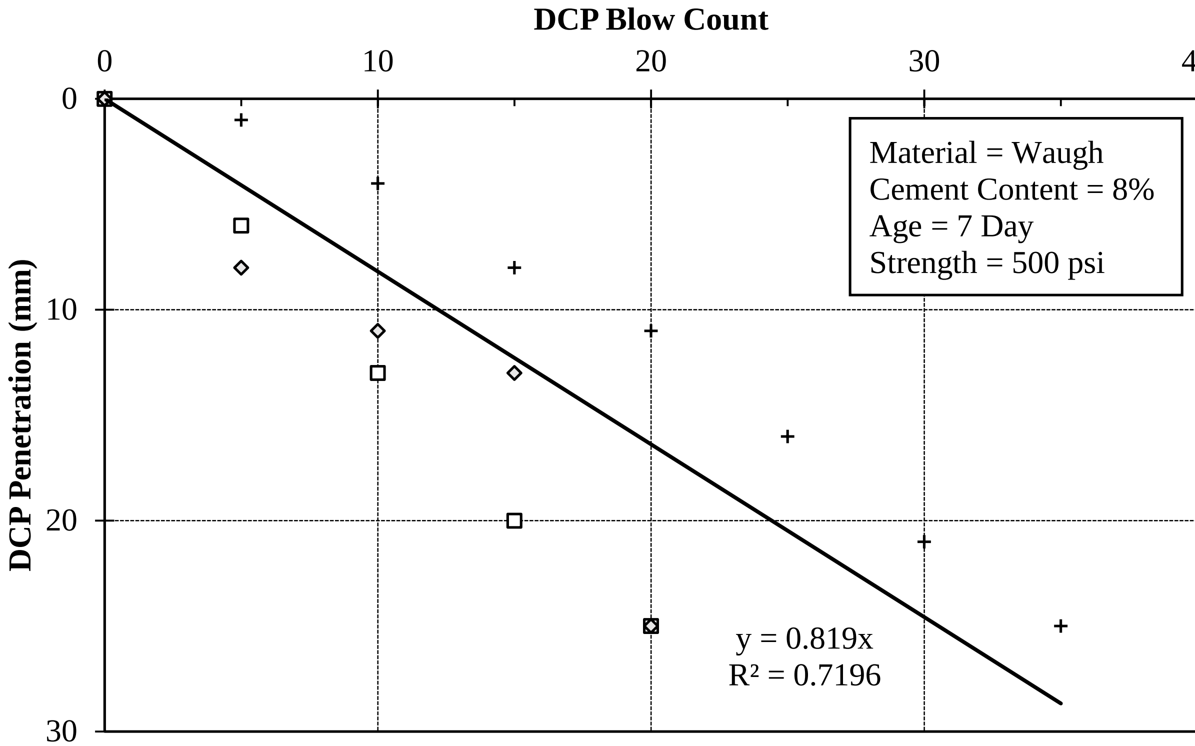

Figure 4.13: Twenty-five millimeters depth penetration relationship

4.6.2 Penetration Depth Analysis

The average coefficient of determination for each penetration depth for all data analyzed for this research is shown in Figure 4.14. Also shown are range bars that show the minimum and maximum coefficient of determination obtained for each case. The penetration depth with the highest value was the 75 mm penetration depth suggesting that it is the most consistent penetration depth.

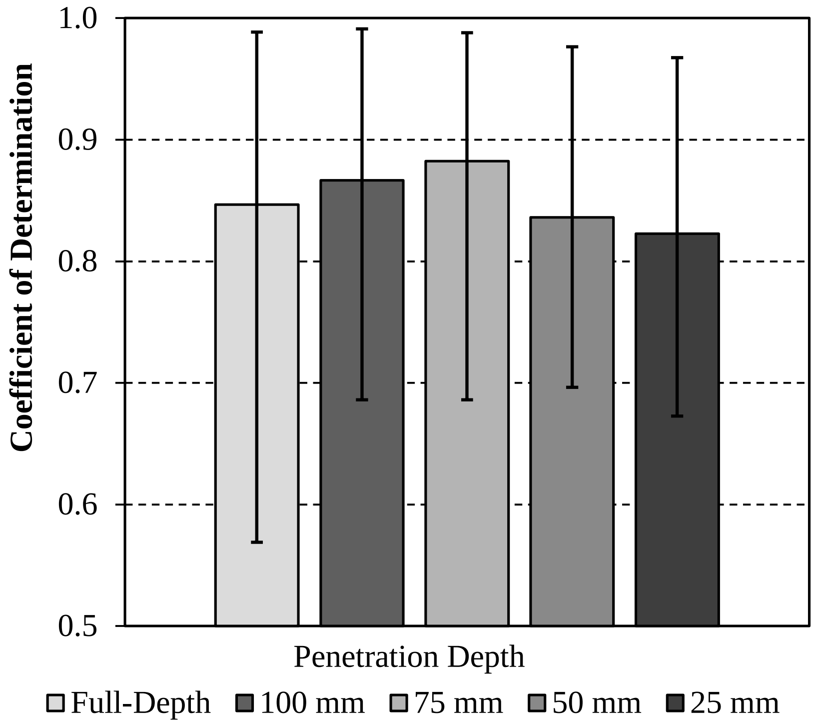

Figure 4.14: Coefficient of determination for all DCP data collected based on penetration depth

Using the analysis performed during this research, Table 4.3 was compiled to summarize the quantity of DCP blows needed to penetrate a certain distance depending on the strength of the soil cement. This strength range was chosen based on the ALDOT 304 (2014) specification requirements for in-place strength of soil cement base. As shown, with increased strength and penetration depth, the required number of blows increase, thus requiring more effort and time to complete a DCP test. Based on the average coefficient of determination and the required effort and time to run a test, it was determined that a 75 mm (3 inch) penetration depth was the best option for future DCP testing. The ease of this penetration depth should be evaluated during the site testing of soil cement base.

Table: 4.3: Summary of blow counts for each penetration depth

Penetration Depth	Blow Count		
	250 psi	425 psi	600 psi
25 mm	10	14	28
50 mm	20	29	63
75 mm	31	44	95
100 mm	42	63	127

4.7 DCP to MCS Correlation

Since the dynamic cone penetrometer was able to penetrate throughout the desired strength range of 250 psi to 600 psi, an investigation was done to determine whether a correlation could be developed between the dynamic cone penetrometer and the molded cylinder strength. Three different types of mathematical functions were considered for the correlation between the DCP results and the molded cylinder strength. The three functions considered were linear, power, and logarithmic functions. Based on the results from the penetration depth analysis discussed in Section 4.6.1, these correlations were developed only for the 75 mm penetration depth.

4.7.1 Linear Function for DCP to MCS Correlation

Based on research performed by Enayatpour et al. (2006), a linear function between the molded cylinder strength and the slope of the DCP penetration was developed. This correlation and the coefficient of determination are shown in Figure 4.15. This relationship produces a good correlation, but the line indicates that the DCP should have not penetrated if the strength is above 750 psi. The data shown does not match that since it is still penetrating at 790 psi. In addition, based on this relationship, the ASTM D 6951 (2009) refusal limit would be 675 psi. For these reasons, it was determined that a linear correlation was not accurate enough to be used.

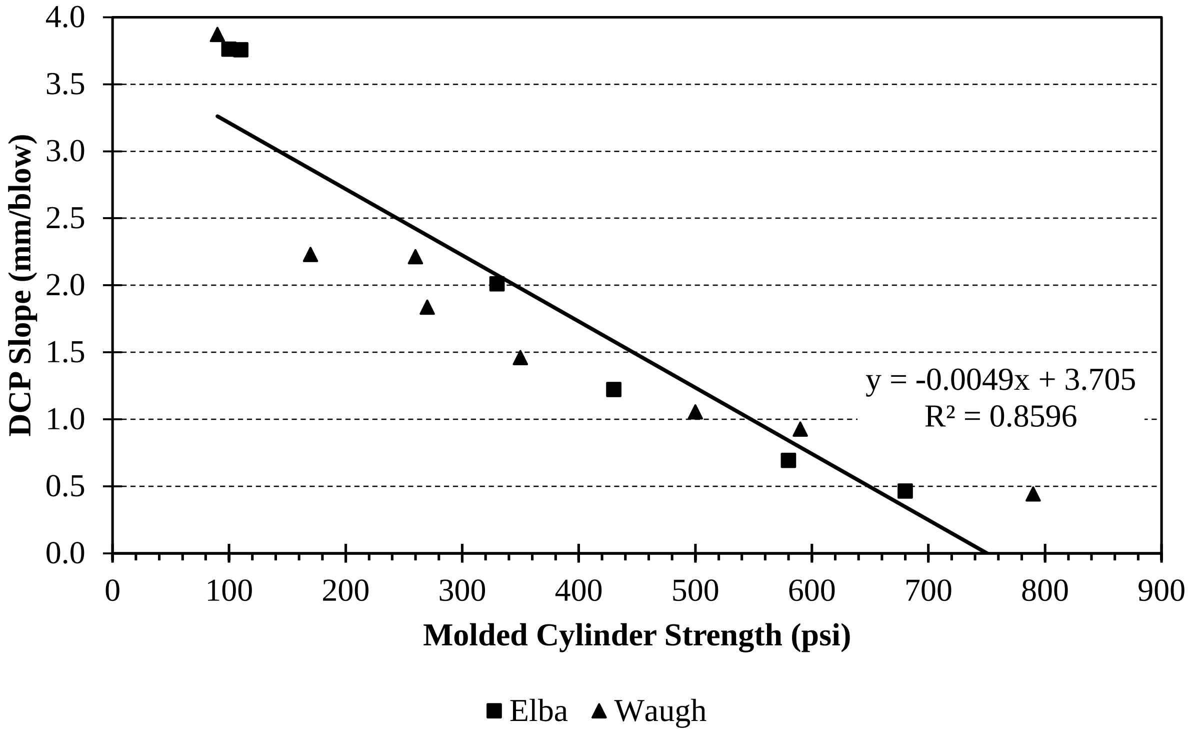

Figure 4.15: Linear function for DCP slope to molded cylinder strength correlation

4.7.2 Power Function for DCP to MCS Correlation

A power correlation was chosen for the next relationship based on the research by Patel and Patel (2013) and McElvaney and Djatnika (1991), who utilized a power function for their correlation. In addition, some geotechnical applications such as the CBR (Mohammadi et al. 2008) utilize a power function plotted on logarithmic axes. The correlation and the coefficient of determination developed for the data collected during this research are presented in Figure 4.16. The relationship produced resulted in a very strong correlation, which is similar to the findings by Patel and Patel (2013) and McElvaney and Djatnika (1991) when tested on a variety of natural and stabilized soils.

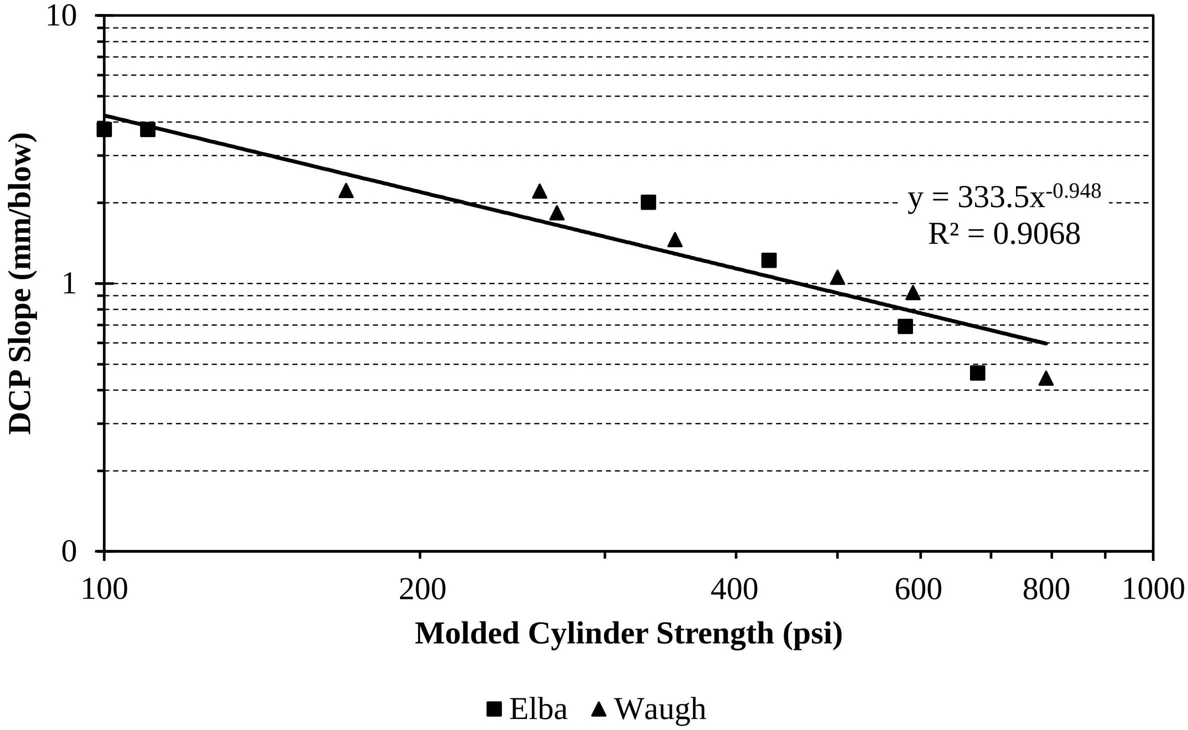

Figure 4.16: Power function for DCP slope to molded cylinder strength correlation

4.7.3 Logarithmic Function for DCP to MCS Correlation

Since there was a strong correlation for the power relationship, a logarithmic function was developed for DCP to MCS correlation. The logarithmic function and the coefficient of determination developed for the collected data are presented in Figure 4.17. As shown, it produces a very strong correlation. As discussed in Section 4.6, the DCP could penetrate specimens with a strength of 790 psi, but could not penetrate specimens with a strength of 1000 psi. Using the logarithmic equation developed with this research, the DCP would no longer penetrate specimens with a strength of 950 psi. This is a very close approximation to what was discovered during this research. Based on ASTM D 6951 (2009) refusal limit of less than 2 mm after 5 blows, refusal would be met at a strength of 740 psi.

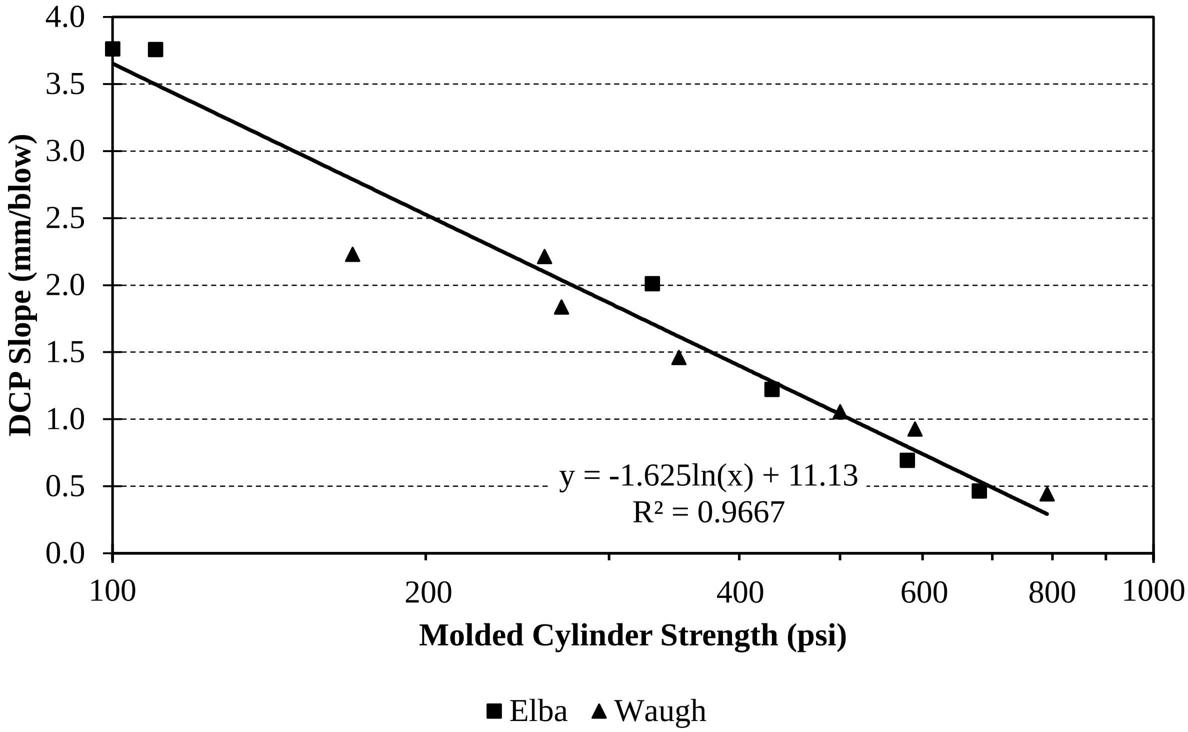

Figure 4.17: Logarithmic correlation of slope and strength

4.7.4 Correlation Analysis and Conclusions

Based on the data collected in this study, it was determined that the best relationship between the DCP penetration results and the molded cylinder strengths was obtained with a logarithmic function. For the ease of calculating the strength from known DCP results, the best-fit logarithmic function shown in Figure 4.17 was rearranged.. The final relationship recommended is presented in Equation 4.1. This equation is valid for a strength range between 100 and 800 psi.

$$MCS = 926e^{-0.615DCP} \quad \text{(Equation 4.1)}$$

Where:

MCS = molded cylinder strength (psi), and

DCP = dynamic cone penetrometer slope (mm/blow).

As previously discussed, the unconventional units in this equation were chosen for several reasons. When collecting the data using the dynamic cone penetrometer, it is more accurate and easier to record penetration in millimeters. Ahsan (2014) used both mm/blow and psi during his investigation using the dynamic cone penetrometer to determine strength of stabilized soils. Both Patel and Patel (2012) and McElvaney and Djatnika (1991) research utilized millimeters to collected DCP results. Also, ASTM D 6951 (2009) recommends recording DCP penetration in millimeter.

4.7.5 Comparison of Equation 4.1 to Other Published Correlations

To compare the correlation created for this research to correlations recommended by other researchers, each correlation was plotted on one graph. This comparison of these functions is shown in Figure 4.18.

Each correlation is plotted using the range of strengths tested. The McElvaney and Djatnika (1991) function, which was a correlation created for lime-stabilized soils. The function created by Patel and Patel (2012), which was a function made using a variety of stabilized soils, reasonably predicts the strength between 200 and 360 psi. The percent difference was 12% when the strength was greater than 250 psi. The Patel and Patel (2012) correlation does not cover the full strength range tested during this research, but seems as though that it could be a good indication of strength for soil cement base. The fact that the relationship shown in Equation 4.1 is reasonably similar to that of Patel and Patel (2012) from 200 to 360 psi is encouraging because the data Patel and Patel (2012) collected is completely independent from the data analyzed in this study. This indicates that Equation 4.1 should be evaluated for full scale soil cement projects to validate if the data collected under laboratory conditions are applicable to field conditions.

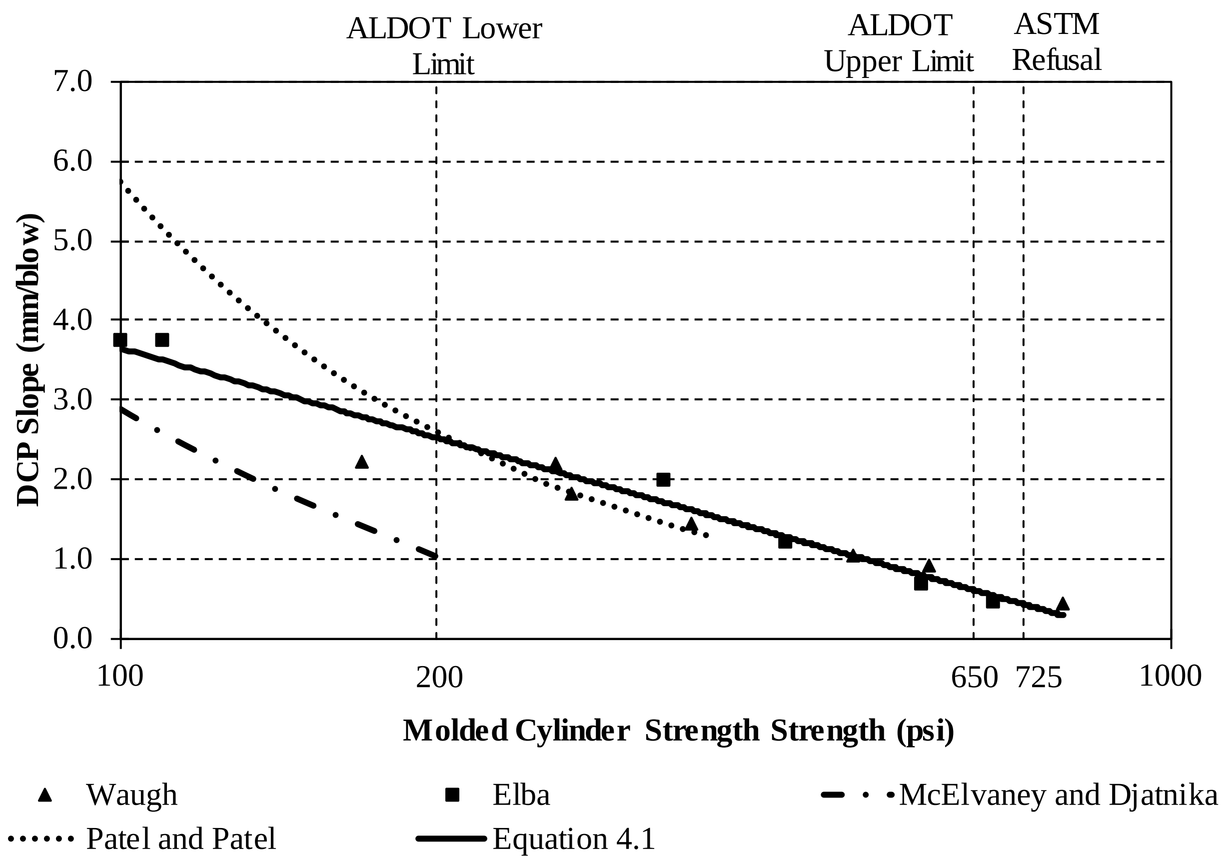

Figure 4.18: Comparison of Equation 4.1 to other published correlations

Chapter 5

Summary, Conclusions, and Recommendations

5.1 Summary

Soil cement base is a mixture of native soils with measured amounts of portland cement and water that forms a strong, durable, frost-resistant paving material. During this research, an assortment of variables were tested to determine their impact on soil cement strength. These variables were the soil classification, the curing time, and the curing method. Also the suitability of the DCP for use in determining the strength of soil cement was evaluated. Finally, a correlation was established between the MCS and the DCP. Approximately 185 molded cylinders and 57 DCP specimens were made and tested over the course of this research.

5.2 Conclusions

The study yielded the following key findings:

- Soils with virtually no fines content require more cement than soils with fines contents between 5% and 35%,
- The average gain in strength from three to seven days was 45% for the molded cylinders and 35% for the DCP specimens,
- Cylinders should be cured in sealed plastic bags to match the strength development of the larger-scale specimens in 5-gallon buckets. Molded cylinders cured inside a sealed plastic bag produced an average of 34% stronger specimens. In addition, molded cylinders cured in a moist room only gained an average of 4% in strength from three to seven days, while molded cylinders cured in sealed plastic bags gained an average of 30% in strength,
- The dynamic cone penetrometer is able to efficiently penetrate uniformly mixed soil

cement bases with strengths less than approximately 800 psi.

- The ideal penetration depth of the DCP is 75 mm (3 in.) because it produces the best results with the least amount of technician effort.
- The most practical molded cylinder strength to DCP slope correlation based on ease of use for field applications and best fit was the logarithmic function. The most appropriate equation is presented in Equation 5.1. This equation is valid for a strength range between 100 and 800 psi.

$$MCS = 926e^{-0.615DCP} \quad \text{(Equation 5.1)}$$

Where:

MCS = molded cylinder strength (psi), and

DCP = dynamic cone penetrometer slope (mm/blow).

5.3 Recommendations for Future Work

A few recommendations can be made for future work. First, how the molded cylinder strength data compares to DCP results when collected under field conditions needs to be evaluated. Also, the technician friendliness of the both the DCP and the method to make molded cylinders under field conditions should be assessed under field conditions. The correlation developed between the DCP and the molded cylinder strength requires field testing to validate the results. Also, to gain further knowledge on the strength assessment of soil cement base, additional testing should be conducted to identify potential variability in strength data. Lastly, the molded cylinder method should be compared to the plastic mold method (Sullivan et al. 2014).

References

ACI 230. 2009. *Report on Soil Cement*. (ACI 230.1R-09), American Concrete Institute, Farmington Hills, MI.

Alabama Department of Transportation. 2012. Standard Specifications for Highway Construction. Alabama Department of Transportation.

ALDOT 304. 2014. *Soil-Cement*. Alabama Department of Transportation, Special Provision No. 12-1167.

ALDOT 419. 2008. *Extracting, Transporting, and Testing Core Samples from Soil-Cement*, Alabama Department of Transportation.

Ashan, Ahmed. 2014. "Pavement Performance Monitoring Using Dynamic Cone Penetrometer and Geogauge During Construction." Masters Thesis, The University of Texas at Arlington.

ASTM C 39. 2016. *Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens*. ASTM International. West Conshohocken, PA.

ASTM C 42. 2013. *Standard Test Method for Obtaining and Testing Drilled Cores and Sawed Beams of Concrete*. ASTM International. West Conshohocken, PA.

ASTM C 150. 2016. *Standard Specification for Portland Cement*. ASTM International. West Conshohocken, PA.

ASTM C 1435. 2014. *Standard Practice for Molding Roller-Compacted Concrete in Cylindrical Molds using a Vibrating Hammer.* ASTM International. West Conshohocken, PA.

ASTM D 422. 2007. *Standard Test Method for Particle-Size Analysis of Soils.* ASTM International. West Conshohocken, PA.

ASTM D 558. 2004. *Standard Test Methods for Moisture-Density (Unit Weight) Relations of Soil-Cement Mixtures.* ASTM International. West Conshohocken, PA.

ASTM D 559. 2015. *Standard Test Method for Wetting and Drying Compacted Soil-Cement Mixtures*. ASTM International. West Conshohocken, PA.

ASTM D 560. 2015. *Standard Test Methods for Freezing and Thawing Compacted Soil-Cement Mixtures*. ASTM International. West Conshohocken, PA.

ASTM D 698. 2012. *Standard Test Methods for Laboratory Compaction Characteristics of Soil Using Standard Effort.* ASTM International. West Conshohocken, PA.

ASTM D 806. 2011. *Standard Test Method for Cement Content of Hardened Soil-Cement Mixtures.* ASTM International. West Conshohocken, PA.

ASTM D 1556. 2015. *Standard Test Method for Density and Unit Weight of Soil in Place by Sand-Cone Method.* ASTM International. West Conshohocken, PA.

ASTM D 1557. 2012. *Standard Method for Laboratory Compaction Characteristics of Soil Using Modified Effort*. ASTM International. West Conshohocken, PA.

ASTM D 1632. 2007. *Standard Practice for Making and Curing Soil-Cement Compression and Flexure Test Specimens in the Laboratory*. ASTM International. West Conshohocken, PA.

ASTM D 1633. 2007. *Standard Test Methods for Compressive Strength of Molded Soil-Cement Cylinders*. ASTM International. West Conshohocken, PA.

ASTM D 2167. 2015. *Standard Test Method for Density and Unit Weight of Soil in Place by the Rubber Balloon Method.* ASTM International. West Conshohocken, PA

ASTM D 2216. 2010. *Standard Test Method for Laboratory Determination of Water (Moisture) Content of Soil and Rock by Mass*. ASTM International. West Conshohocken, PA.

ASTM D 2922. 2005. *Standard Test Methods for Density of Soil and Soil-Aggregate in Place by Nuclear Methods (Shallow Depth).* ASTM International. West Conshohocken, PA

ASTM D 3017. 2005. *Standard Test Methods for Water Content of Soil and Rock in Place by Nuclear Methods (Shallow Depth).* ASTM International. West Conshohocken, PA

ASTM D 5982. 2015. *Standard Test Method for Determining Cement Content of Fresh Soil-Cement (Heat of Neutralization Method).* ASTM International. West Conshohocken, PA.

ASTM D 6951. 2009. *Standard Test Method for Use of the Dynamic Cone Penetrometer in Shallow Pavement Applications.* ASTM International. West Conshohocken, PA.

Catton, M.D. and E.F. Felt. 1943. “Effect of Soil and Calcium Chloride Admixtures on Soil-Cement Mixtures.” *Proceedings*, V. 23, Highway Research Board, pp. 497-529.

Enayatpour, Saeid, Anand J. Puppala, and Hariharan Vasudevan. 2006. “Dynamic Cone Penetrometer to Evaluate Unconfined Compressive Strength of Stabilized Soils.” *Geotechnical Special Publication*, American Society of Civil Engineers, pp.285-292.

Felt, E. J. 1955. “Factors Influencing Physical Properties of Soil-Cement Mixtures.” *Bulletin No. 108,* Highway Research Board, Washington, D.C., pp. 138-162.

Federal Highway Administration (FHWA). 1979. *Soil Stabilization in Pavement Structures: A User’s Manual*, V.2. Report No. FHWA-IP-80-2, Washington, DC.

George, K.P. and W. Uddin. 2000. *Subgrade Characterization for Highway Pavement Design Final Report*, Mississippi Department of Transportation, Jackson, MS.

George, K.P. 2002. “Minimizing Cracking in Cement-Treated Material for Improved Performance.” *Research and Development Bulletin RD123,* Portland Cement Association. Skokie, IL.

Google Maps. 2016. https://www.google.com/maps/

Halsted, G.E., Luhr, D.R., Adaska, W.S. 2006. *Guide to Cement-Treated Base (CTB). Portland Cement Association.* Skokie, IL.

Hassan, A.B. 1996. "The Effects of Material Parameters on Dynamic Cone Penetrometer Results for Fine-Grained Soils and Granular Materials." PhD diss., Oklahoma State University.

Highway Research Board. 1961. "Soil Stabilization with Portland Cement." *Bulletin* 292, 212, Washington, DC.

Huntley, S.L. 1990. "Use of a dynamic penetrometer as a ground investigation and design tool in Hertfordshire." *Field Testing in Engineering Geology*. Geological Society Engineering Geology Special Publications No. 6.

Kleyn, E. G. 1975. *The Use of the Dynamic Cone Penetrometer (DCP)*. Report 2/74. Transvaal Roads Department, Pretoria.

Kleyn, E.G. and P.E. Savage. 1982. "The Application of the Pavement DCP to Determine the Bearing Properties and Performance of the Road Pavements". *International Symposium on Bearing Capacity of Roads and Airfields*, Trondheim, Norway.

McCarthy, D. 2007. *Essentials of Soil Mechanics and Foundations: Basic Geotechnics.* Seventh Edition. New Jersey: Pearson.

McElvaney, J. and IR. Bunadi Djatnika. 1991. “Strength Evaluation of Lime-Stabilized Pavement Foundations Using the Dynamic Cone Penetrometer.” *Australian Road Research*, Vol. 21, No. 1, pp. 40-52.

Mohammadi, S.D., M. R. Nikoudel, H. Rahimi, and M. Khamechchiyan. 2008. “Application of the Dynamic Cone Penetrometer (DCP) for determination of the engineering parameters of sandy soils.” *Engineering Geology*, 101 (3): 195-203.

Patel, Mukesh A. and H.S. Patel. 2012. “Experimental Study to Correlate the Test Results of PBT, UCS, and CBR with DCP on Various Soils in Soaked Condition.” *International Journal of Engineering*, Vol. 6, Issue 5, pp. 244-261.

Portland Cement Association (PCA). 1971. “Soil Cement Laboratory Handbook.” *Engineering Bulletin*, Portland Cement Association. Skokie, IL.

Portland Cement Association (PCA). 1995. “Soil-Cement Construction Handbook.” Engineering Bulletin, *Portland Cement Association.* Skokie, IL.

Robbins, E.G., and Mueller P.E. 1960. “Development of a Test for Identifying Poorly Reacting Sandy Soils Encountered in Soil-Cement Applications.” Highway Research Board, *Bulletin 267*, pp.46-49.

Scala, A.J. 1956. “Simple Methods of Flexible Pavement Design Using Cone Penetrometer.” *N.Z. Eng.* 11 (2).

Shen, C.K. and J.K. Mitchell. 1966. “Behavior of Soil-Cement in Repeated Compression and Flexure.” Highway Research Board, *Highway Research Record*, No. 128. Washington, DC., pp. 68-100.

Single Cylinder Repair. 2016. https://www.singlecylinderstore.com/Multiquip-WM120PHD-Mortar-Mixer. Accessed on September 16, 2016.

Sullivan, W, I. Howard, and B. Anderson. 2014. “Development of Equipment for Compacting Soil-Cement into Plastic Molds for Design and Quality Control Purposes.” 94th Annual Meeting of the Transportation Research Board.

Webster, S., R. Grau, and T. Williams. 1992. *Description and Application of Dual Mass Dynamic Cone Penetrometer*. Project AT40. US Army Corps of Engineers, Washington, DC.

West, G. 1959. “A Laboratory Investigation into the Effect of Elapsed Time After Mixing on the Compaction and Strength of Soil-Cement.” *Geotechnique,* Vol. 9, No. 1, pp. 22-28.

Wilson, William Herbert Jr. 2013. Strength Assessment of Soil Cement. Master’s Thesis, Auburn University.

Appendix A

Design Curves and Gradations

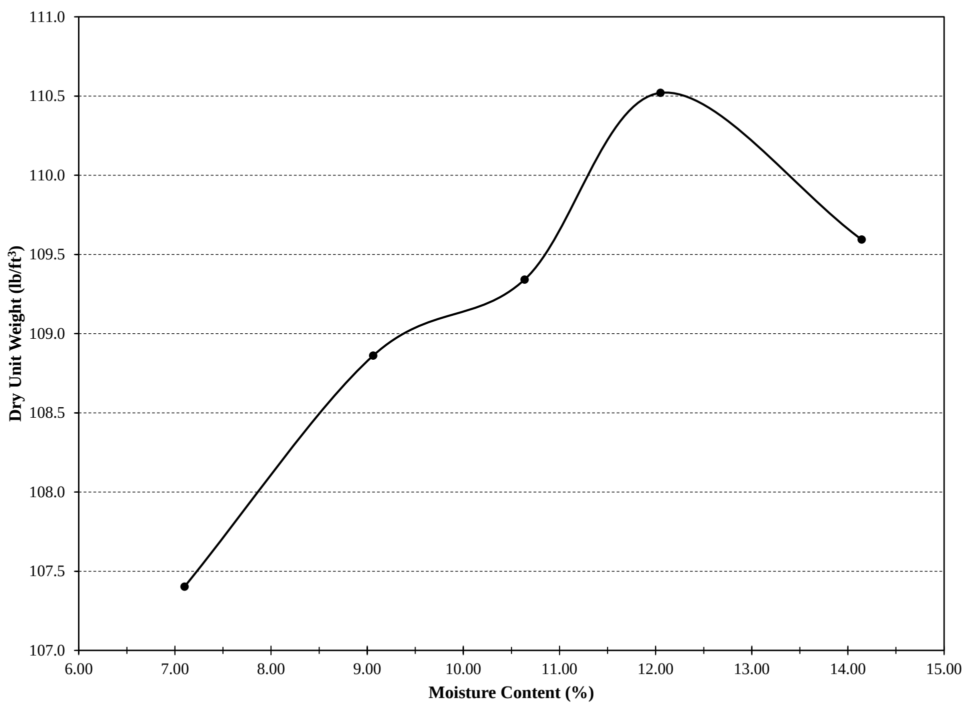

Figure A.1: Design curve for Elba soil with eight percent cement content

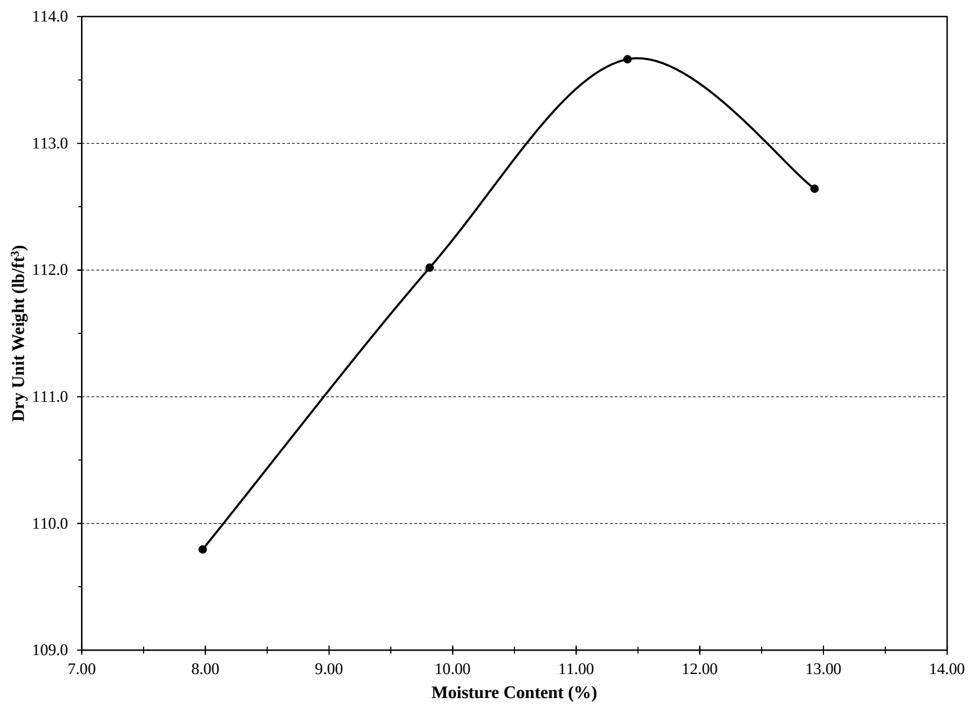

Figure A.2: Design curve for Elba soil with eleven percent cement content

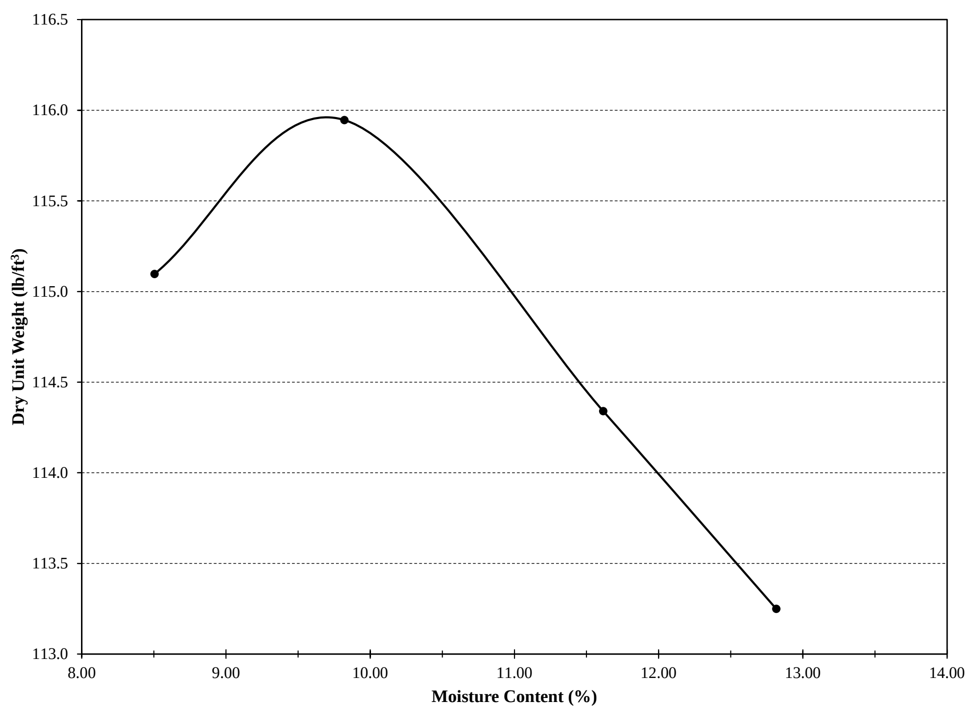

Figure A.3: Design curve for Elba soil with fourteen percent cement content

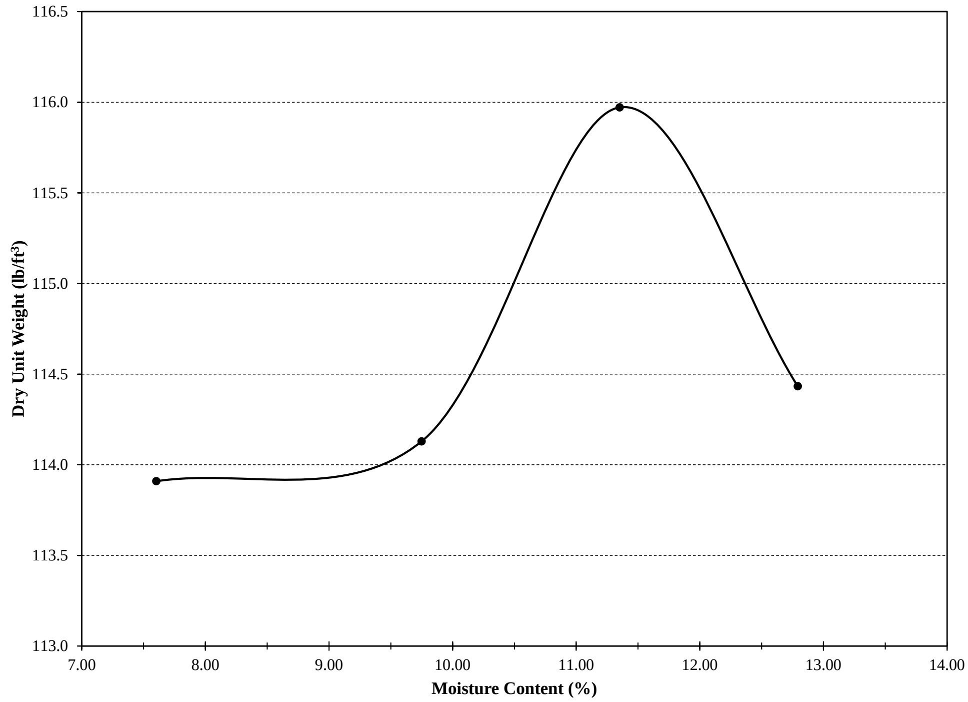

Figure A.4: Design curve for Waugh soil with four percent cement content

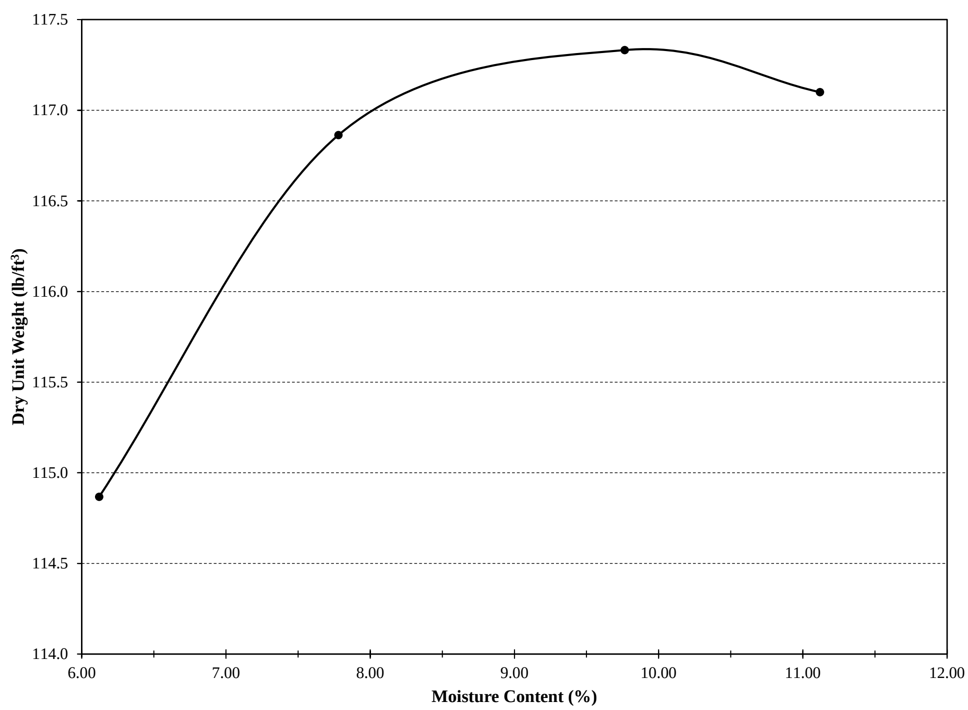

Figure A.5: Design curve for Waugh soil with six percent cement content

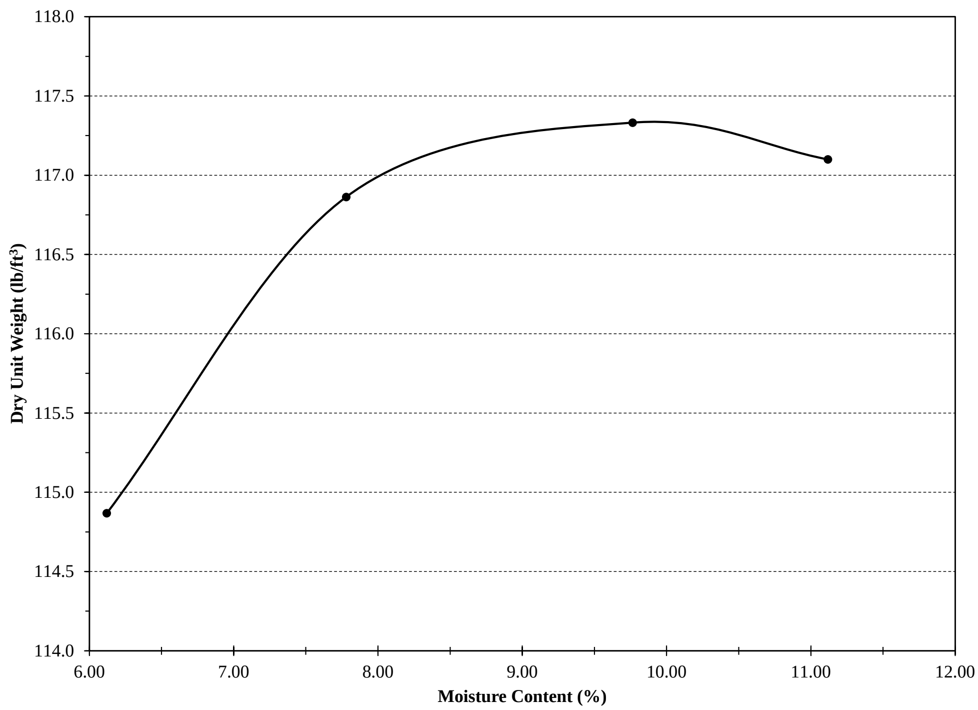

Figure A.6: Design curve for Waugh soil with eight percent cement content

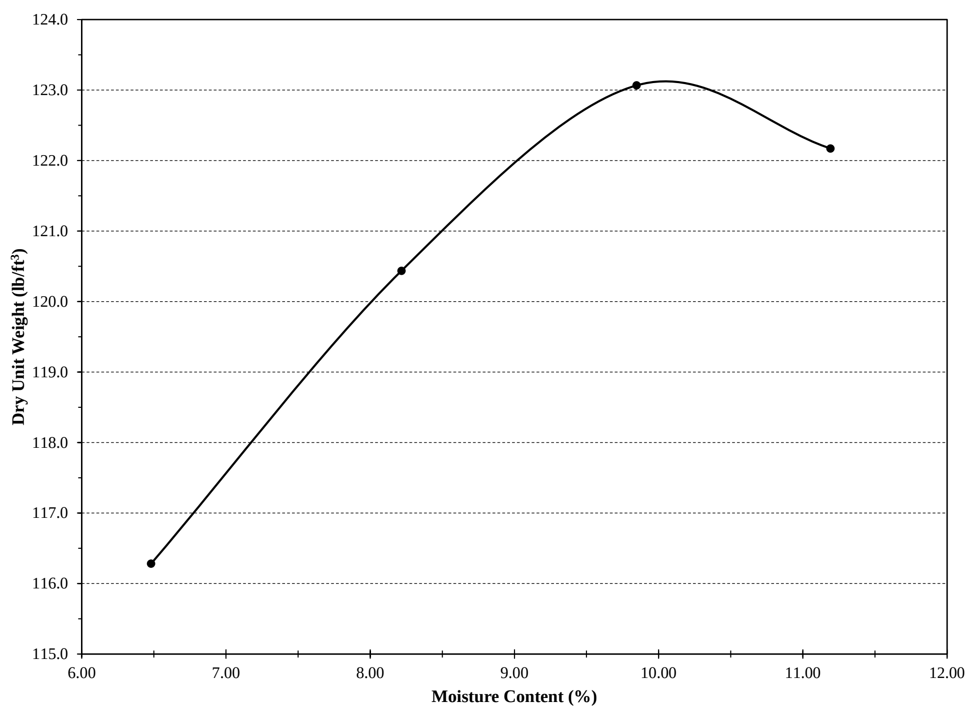

Figure A.7: Design curve for Waugh soil with ten percent cement content

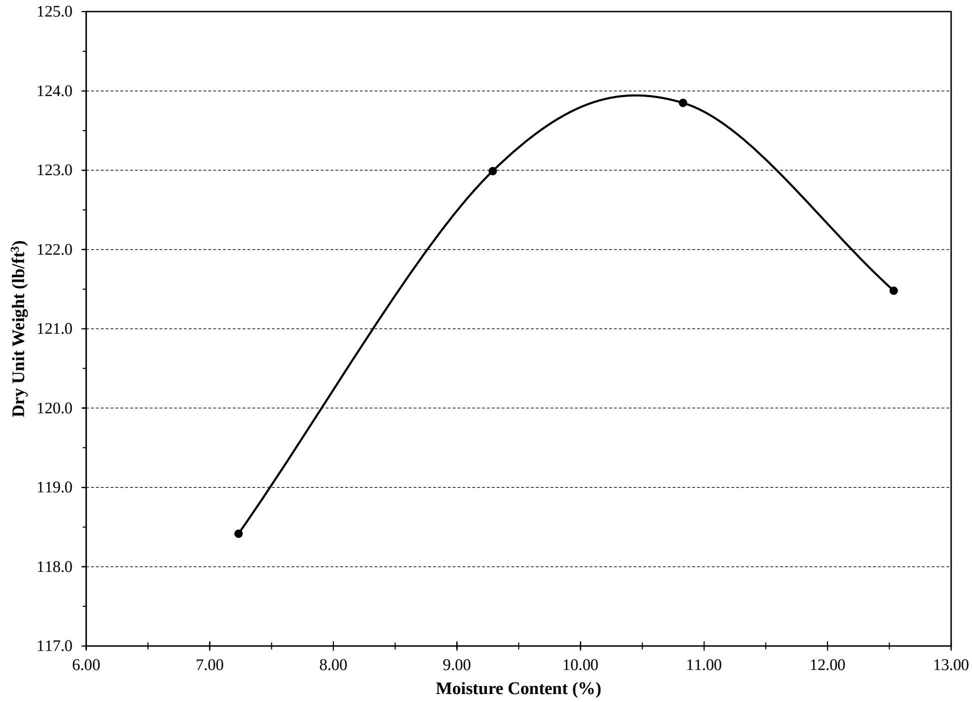

Figure A.8: Design curve for Waugh soil with twelve percent cement content

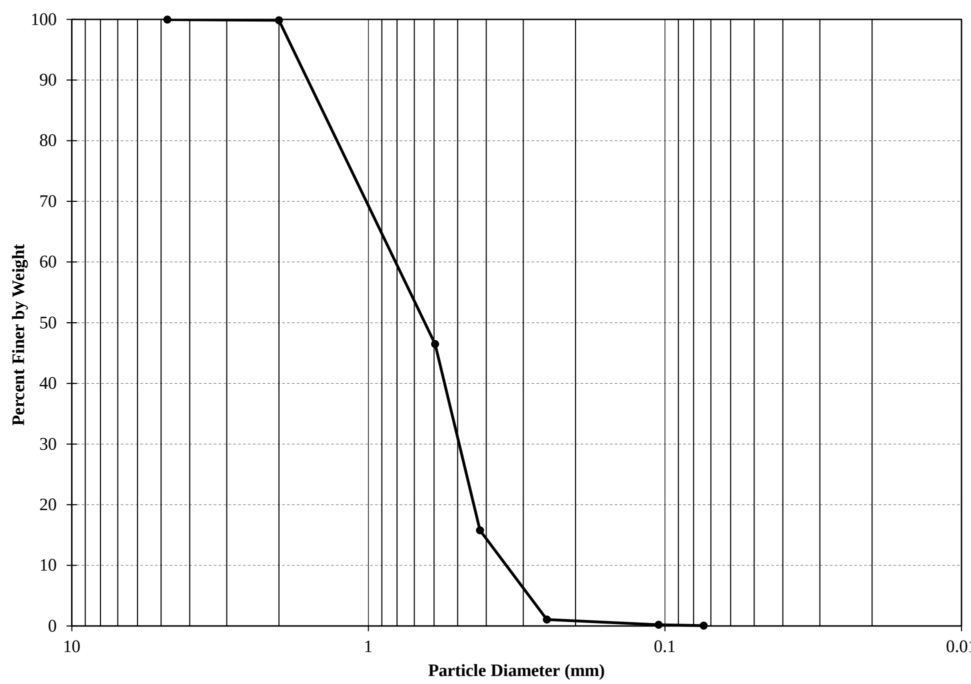

Figure A.9: Grain distribution for Elba soil

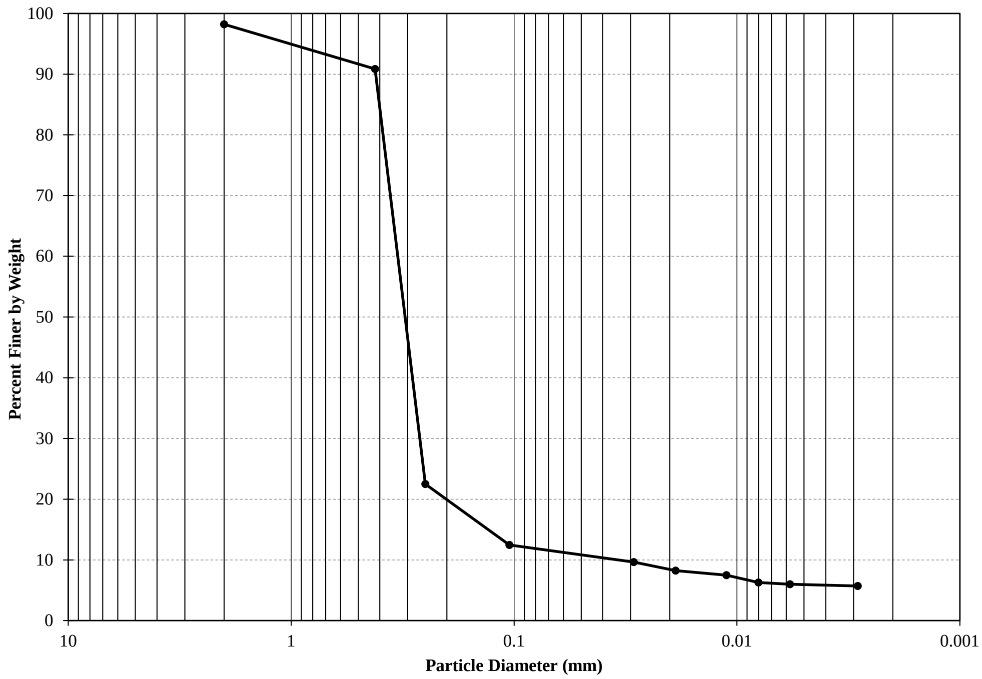

Figure A.10: Grain distribution for Waugh soil

Appendix B

Soil Classification Impact Data

Table B.1: Data for effect of fines content and cement content on 7-day molded cylinder strength

Fines Percentage (%)	Cement Content (%)	Strength (psi)
0.05	8	110
	11	430
	14	680
12	4	170
	8	500
	10	590
	12	1000

Table B.2: Data for effect of fines content and cement content on 7-day DCP slope

Fines Percentage (%)	Cement Content (%)	DCP Slope (mm/blow
0.05	8	3.76
	11	1.22
	14	0.46
12	4	2.23
	8	1.05
	10	0.93

Appendix C

Curing Method Impact Data

Table C.1: Curing Method Data for Elba Material

Elba Material			
Cement Content (%)	**Curing Time (days)**	**Moist-Room Cured Strength (psi)**	**Bag Cured Strength (psi)**
11	3	140	330
11	7	210	430
14	3	420	580
14	7	430	680

Table C.2: Curing Method Data for Waugh Material

Waugh Material			
Cement Content (%)	**Curing Time (days)**	**Moist-Room Cured Strength (psi)**	**Bag Cured Strength (psi)**
8	3	350	350
8	7	230	500
12	3	680	790
12	7	670	1000

Table C.3: Percent gain in strength between 3 and 7 days data

Percent Gain in Strength between 3 and 7 Days			
Cement Content (%)	**Material**	**Moist-Room Cured (%)**	**Bag Cured (%)**
8	Waugh	-34	43
11	Elba	50	30
12	Waugh	2	17
14	Elba	-1	27

Appendix D

Curing Time Impact Data

Table D.1: Molded cylinder strengths at 3 and 7 days

	Molded Cylinder Strength	
Mixture Design	**3 Day Strength**	**7 Day Strength**
Elba-8	100	110
Waugh-4	90	170
Elba-11	330	430
Waugh-8	350	500
Waugh-10	270	590
Elba-14	580	680
Waugh-12	790	1000

Appendix E

Full-Depth Penetration Data

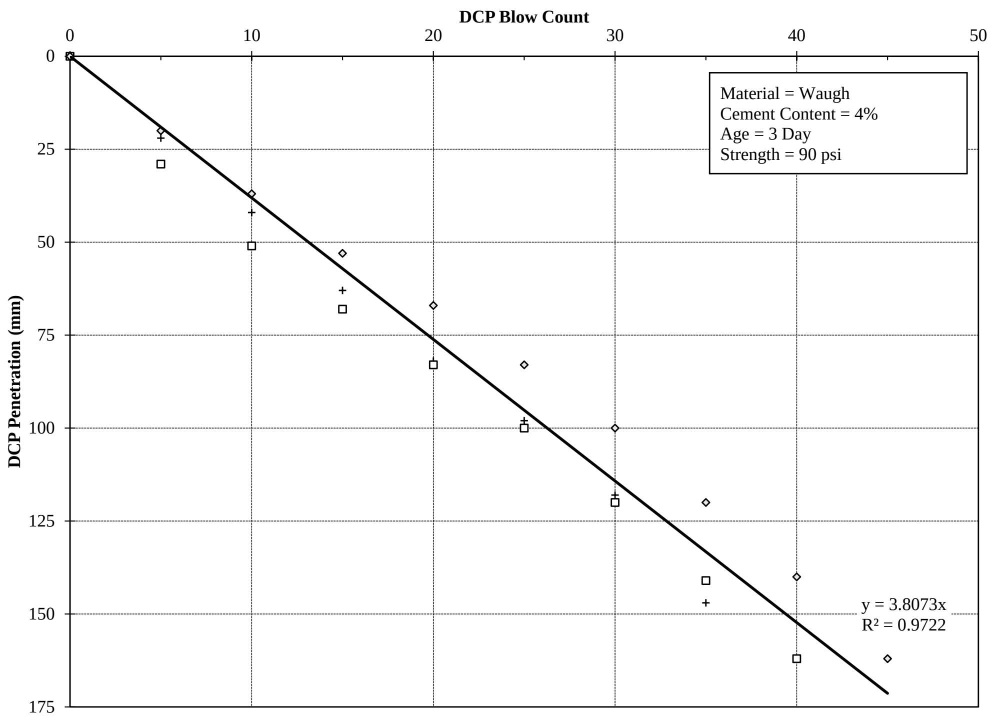

Figure E.1: Waugh 4% 3 day

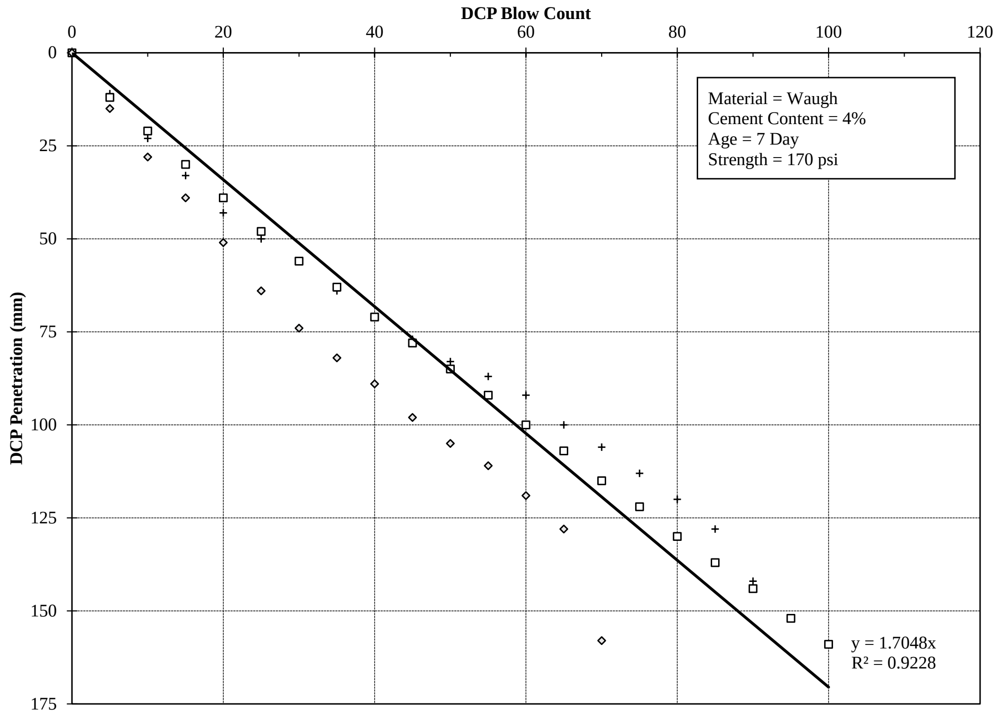

Figure E.2: Waugh 4% 7 day

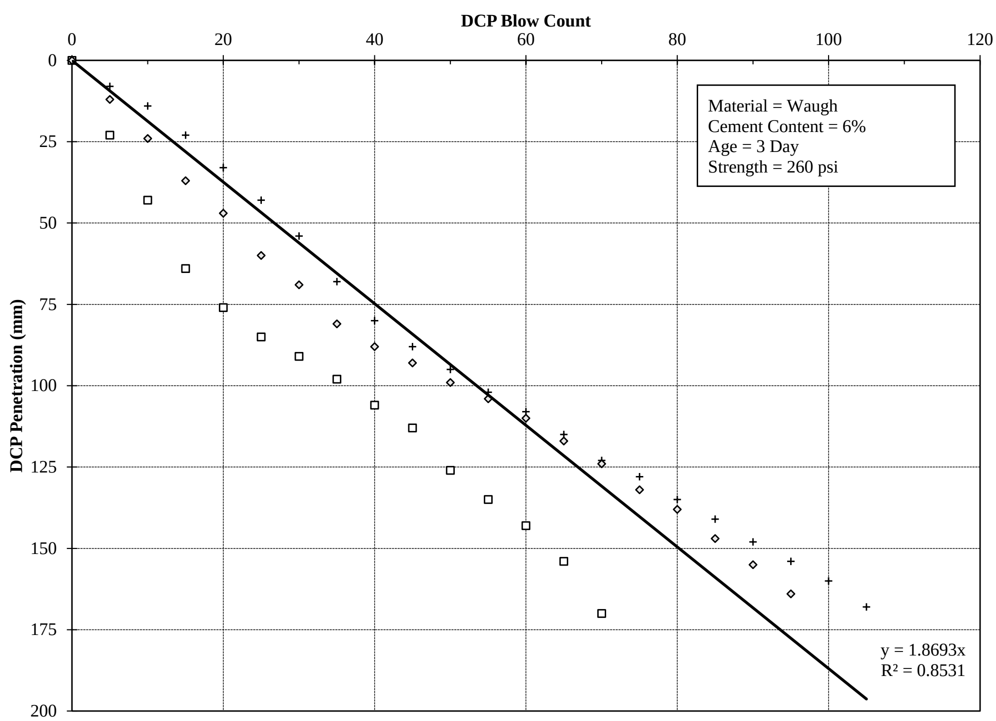

Figure E.3: Waugh 6% 3 day

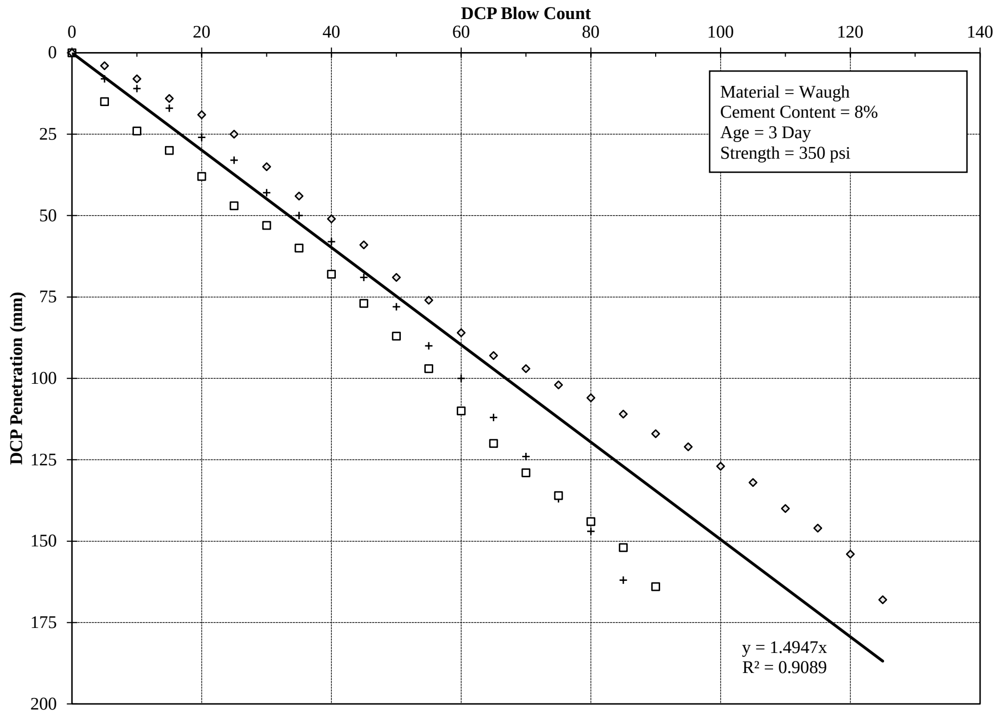

Figure E.4: Waugh 8% 3 day

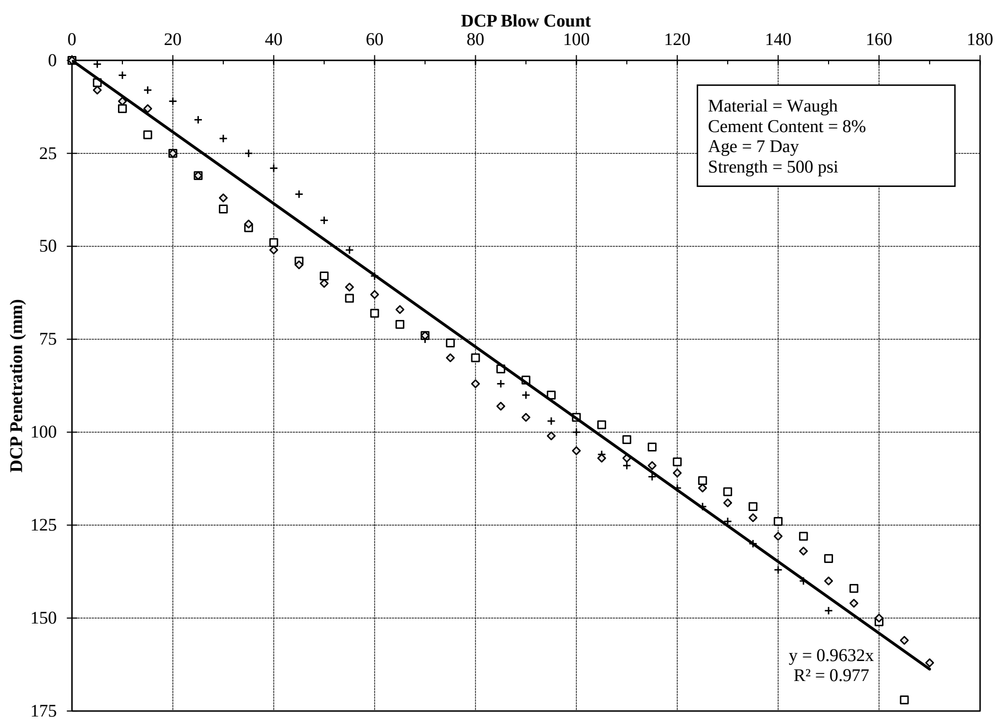

Figure E.5: Waugh 8% 7 day

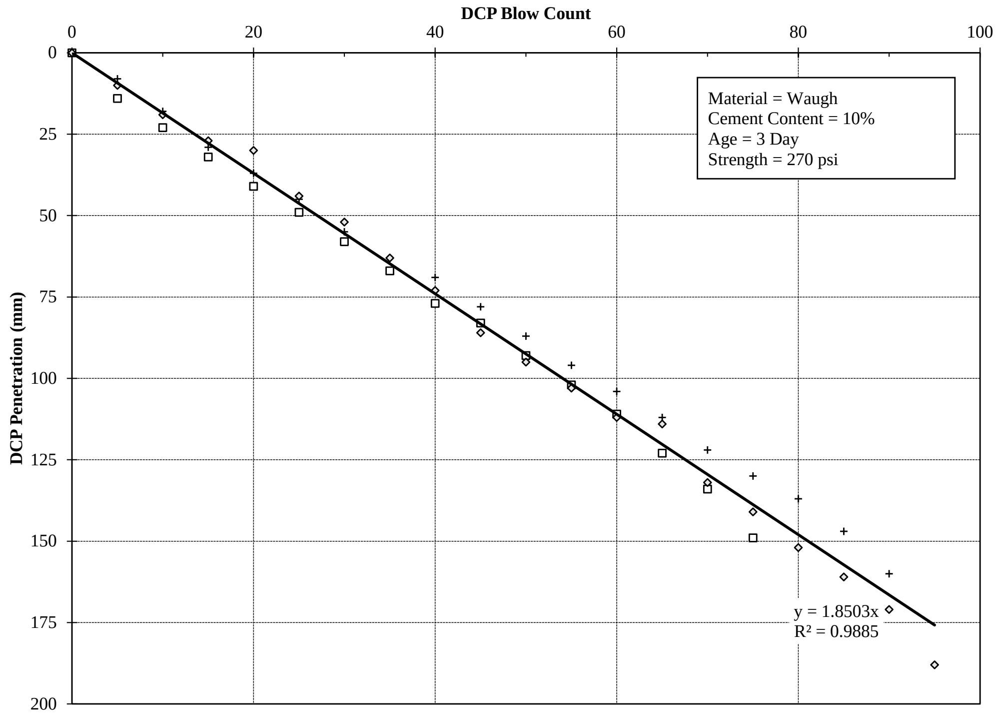

Figure E.6: Waugh 10% 3 day

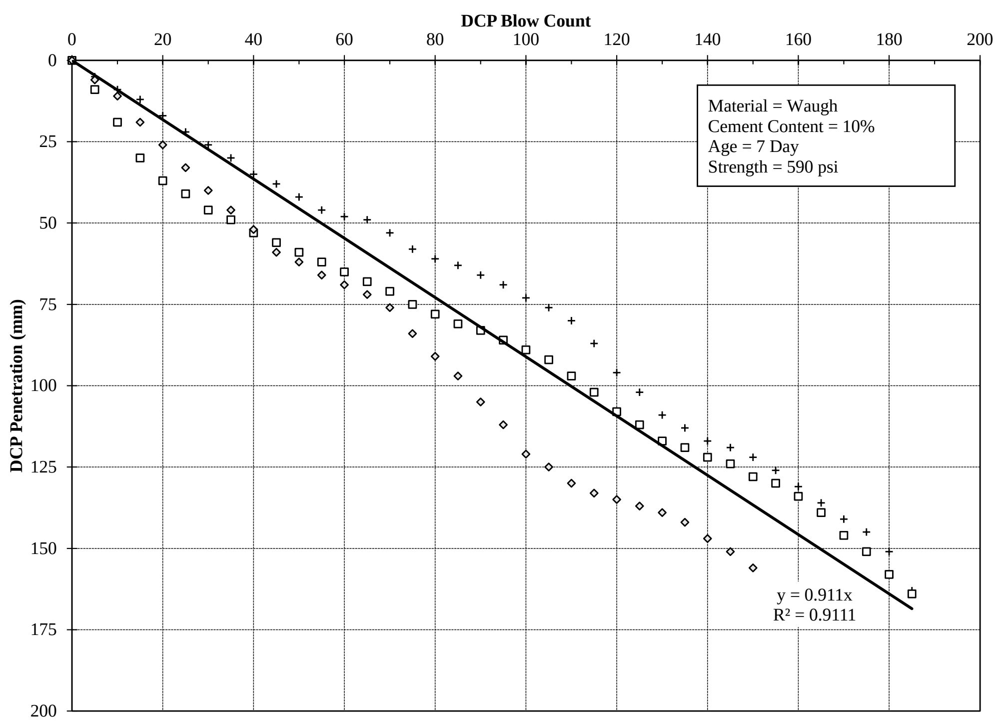

Figure E.7: Waugh 10% 7 day

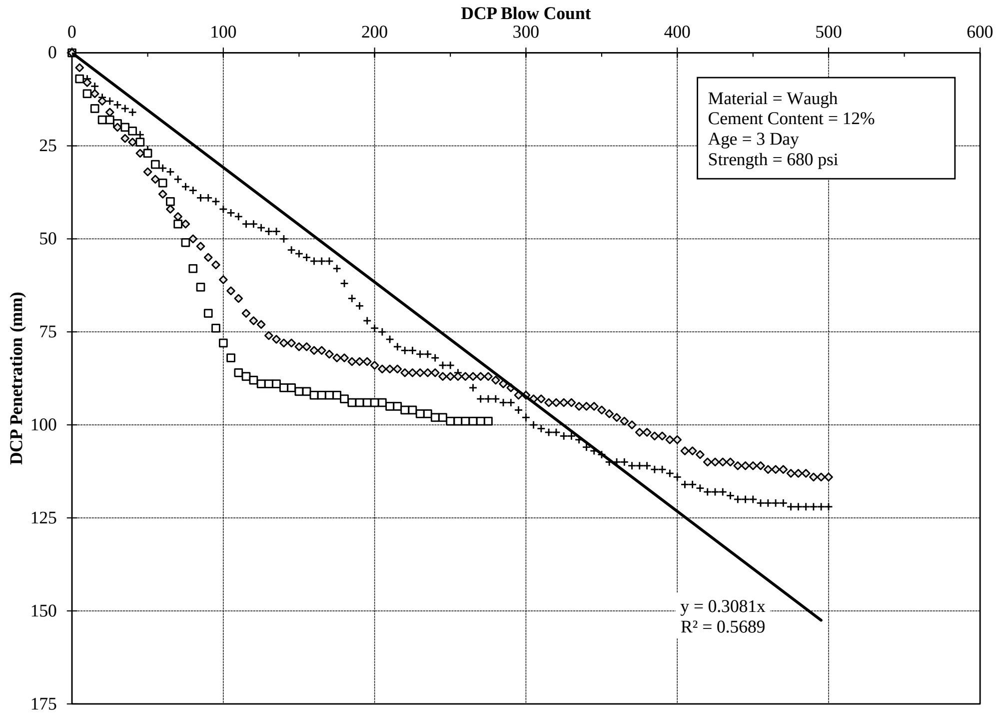

Figure E.8: Waugh 12% 3 day

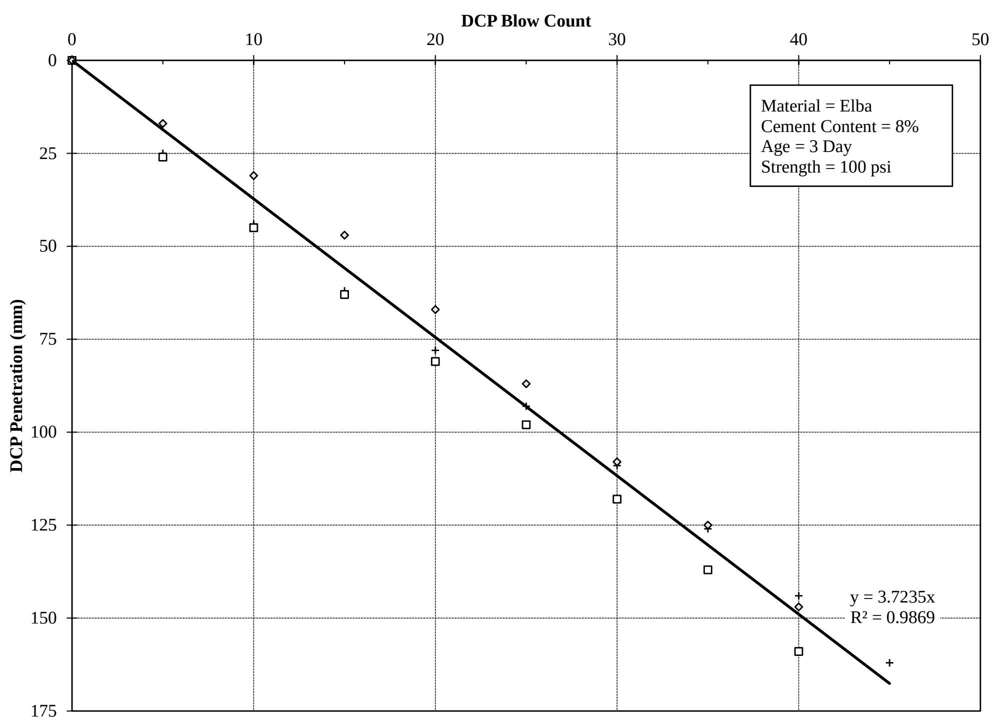

Figure E.9: Elba 8% 3 day

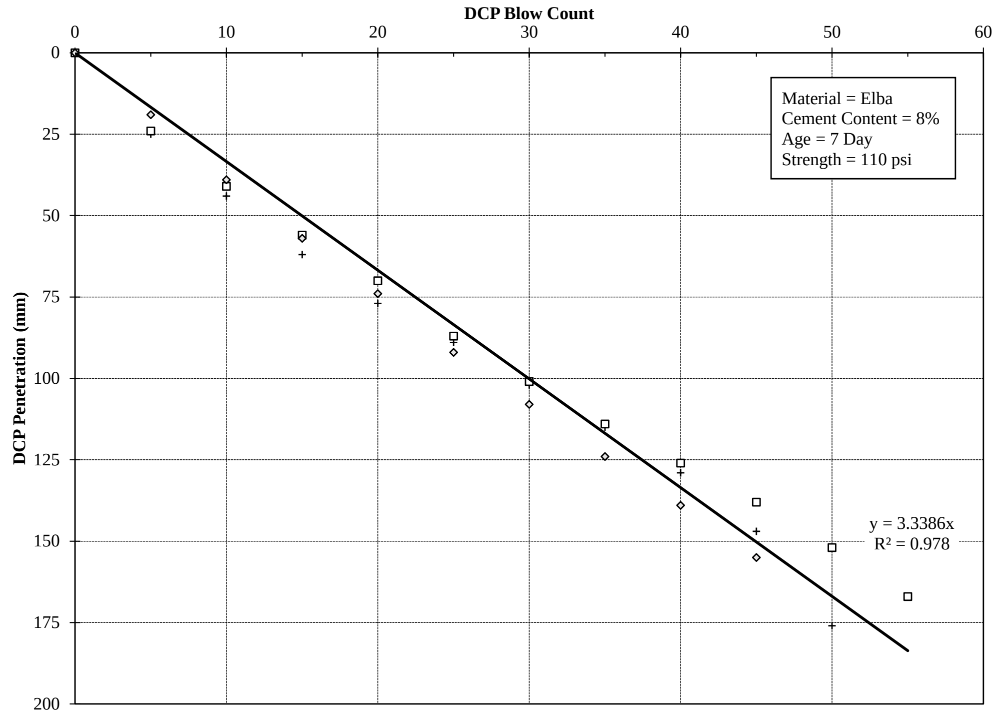

Figure E.10: Elba 8% 7 day

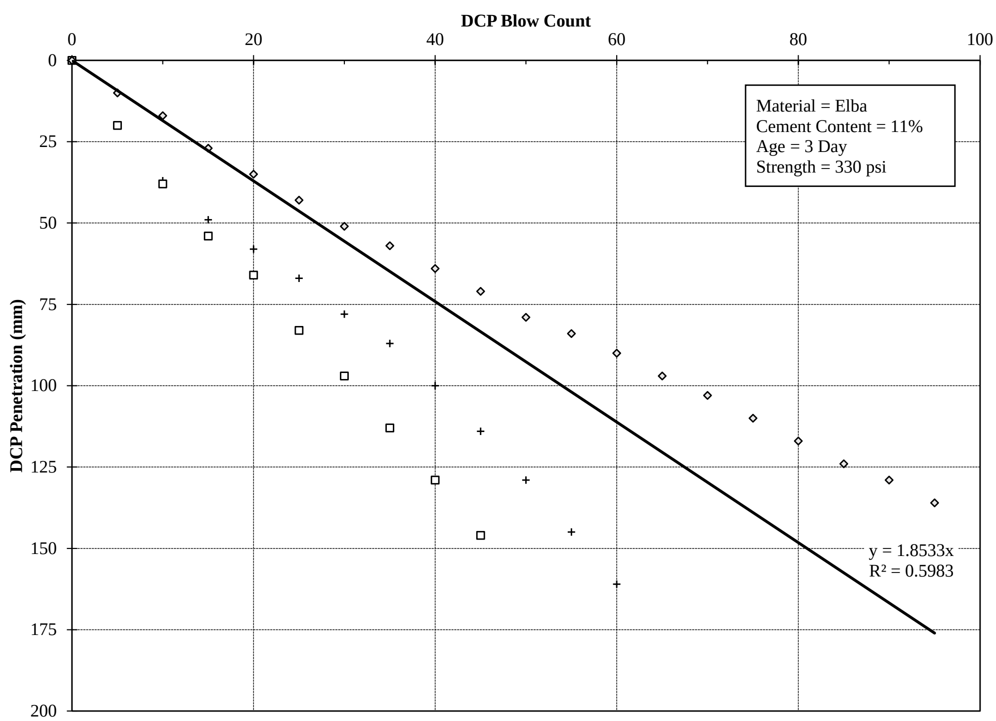

Figure E.11: Elba 11% 3 day

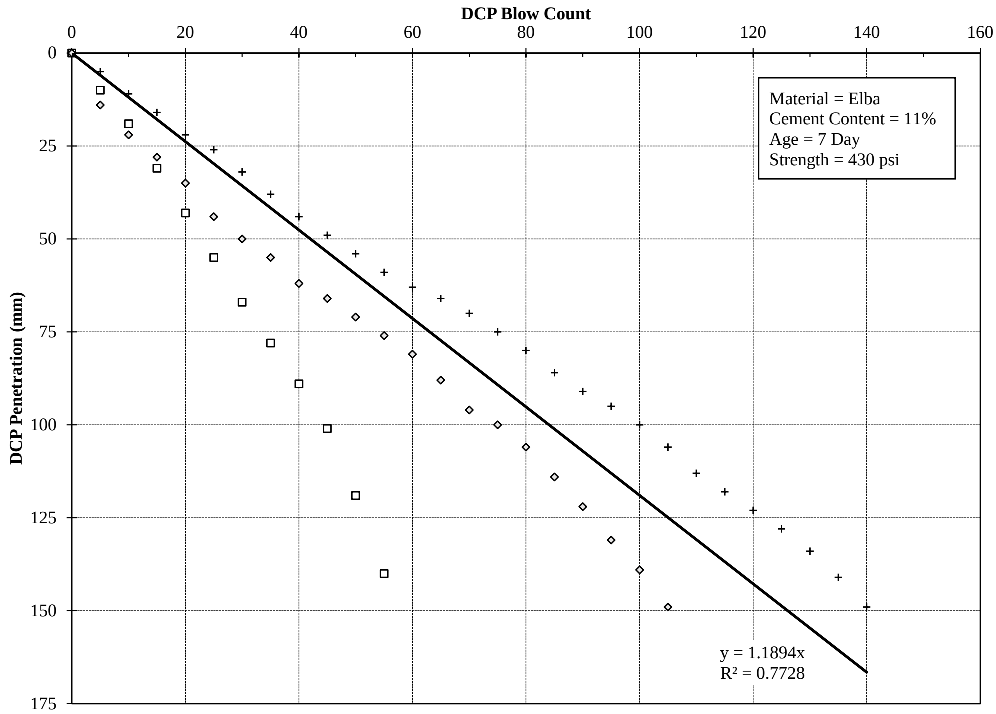

Figure E.12: Elba 11% 7 day

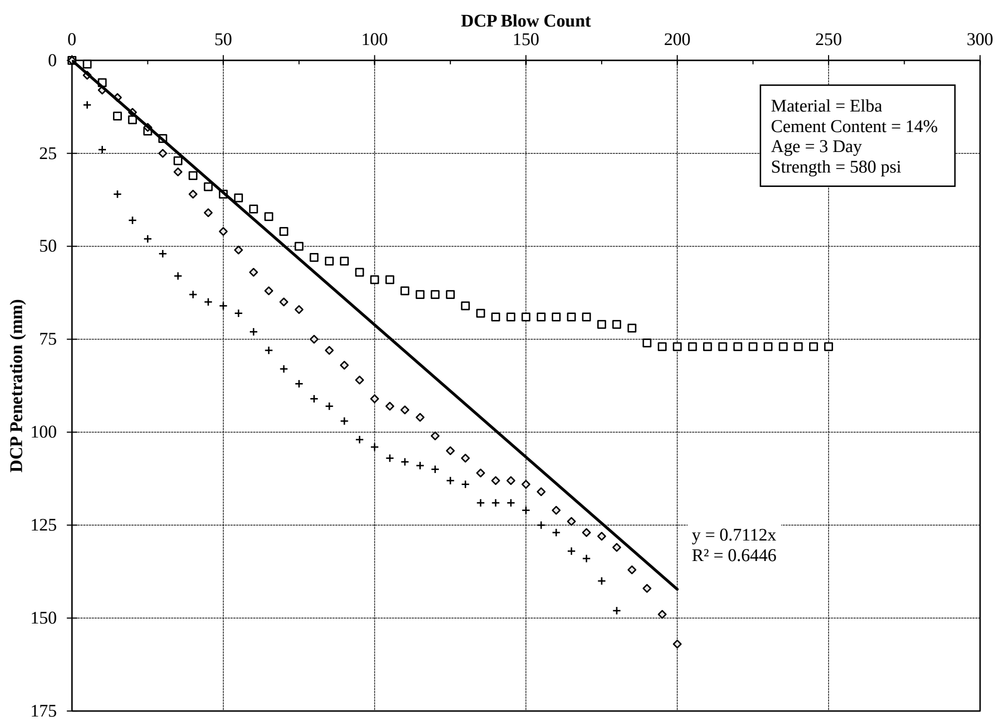

Figure E.13: Elba 14% 3 day

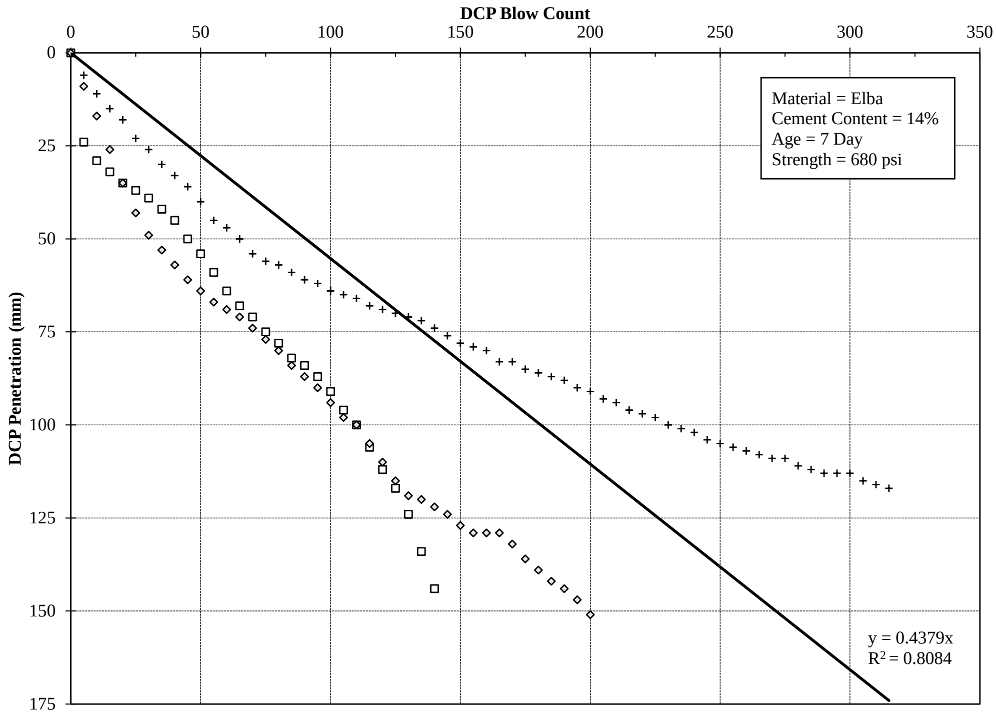

Figure E.14: Elba 14% 7 day

Appendix F

100 mm Penetration Depth Data

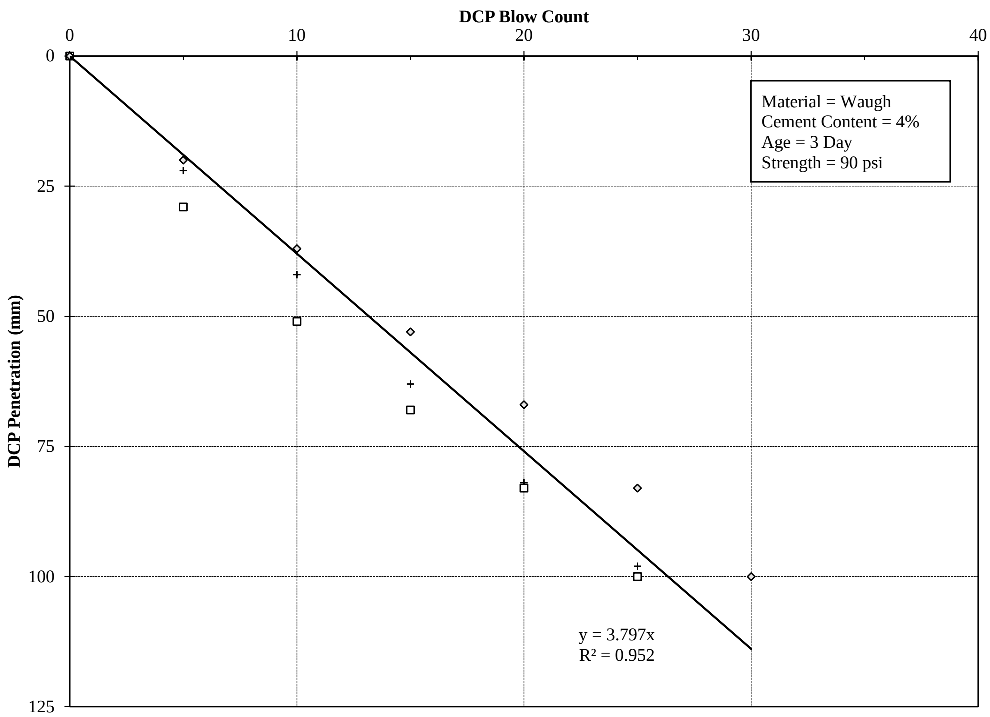

Figure F.1: Waugh 4% 3 Day

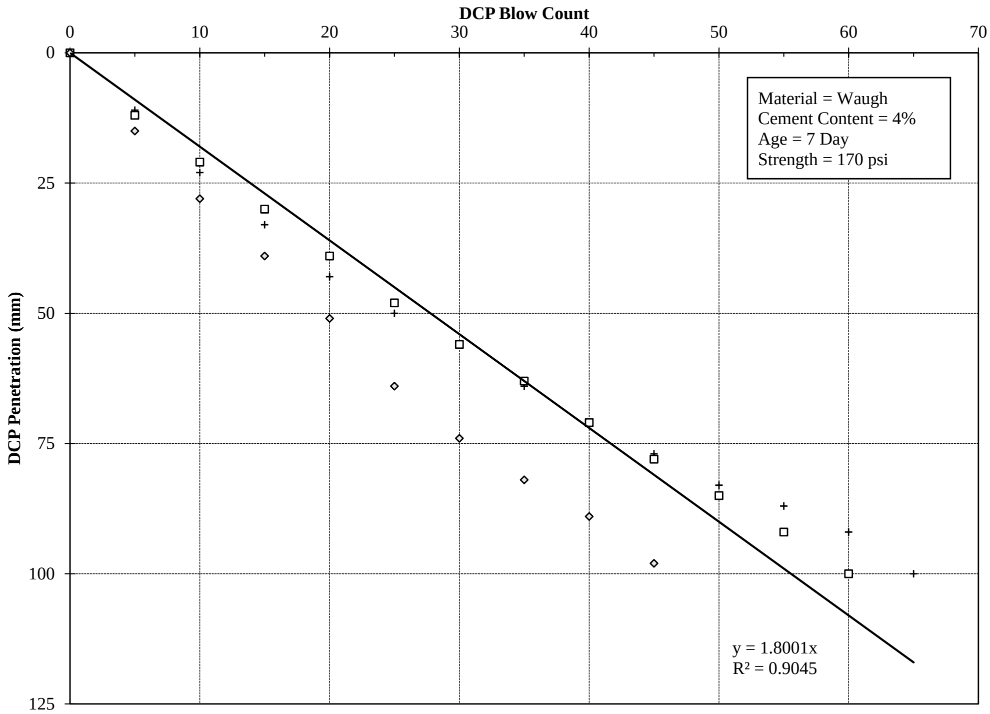

Figure F.2: Waugh 4% 7 Day

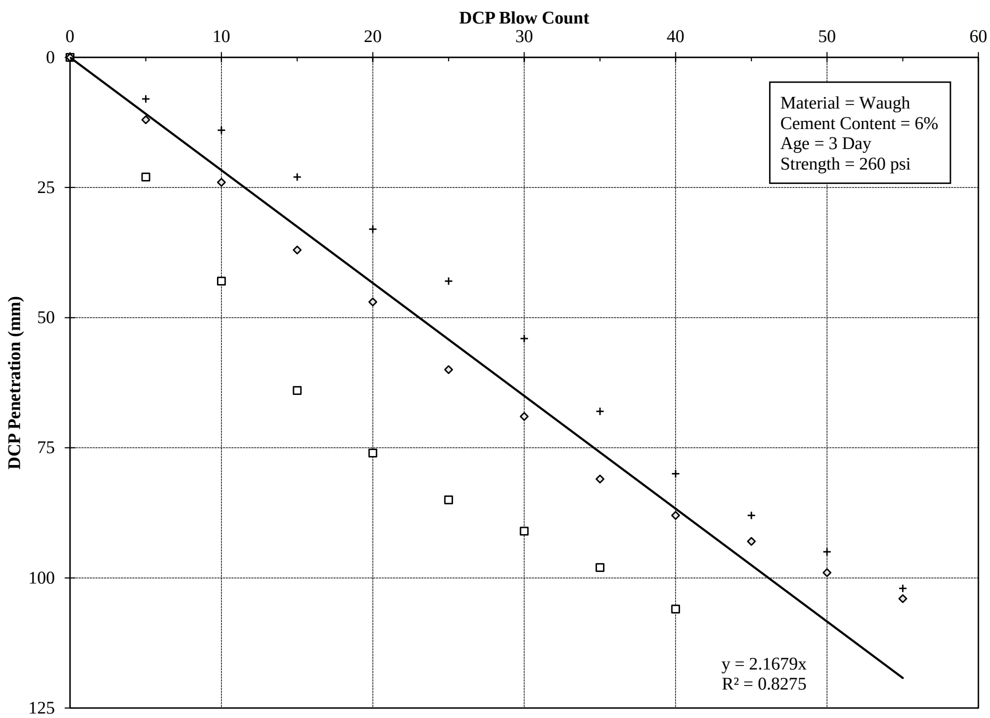

Figure F.3: Waugh 6% 3 Day

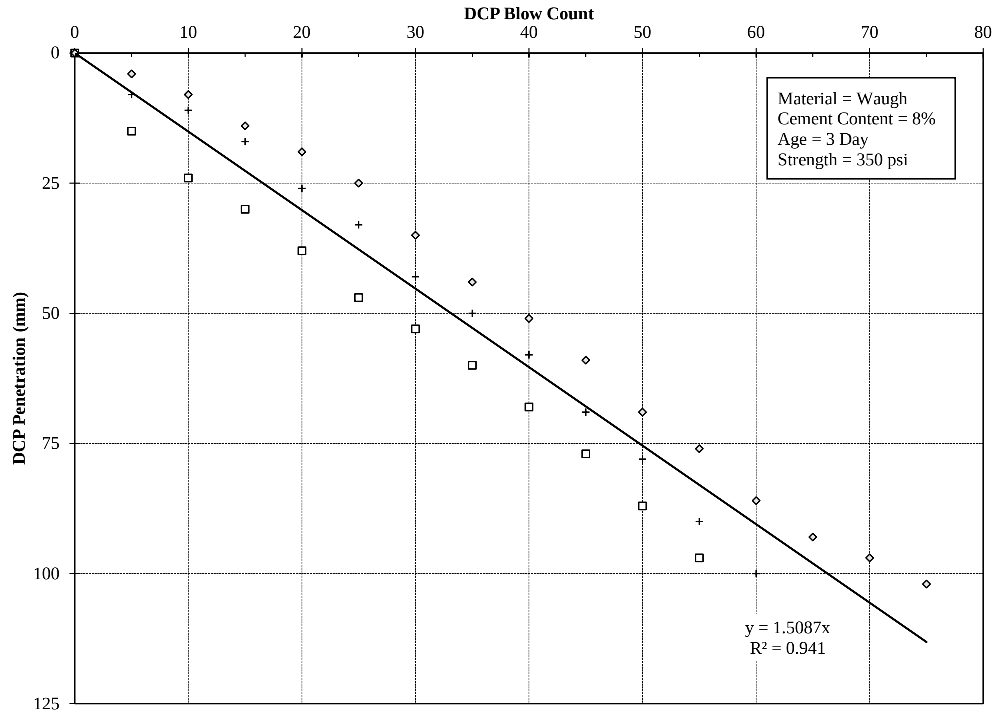

Figure F.4: Waugh 8% 3 Day

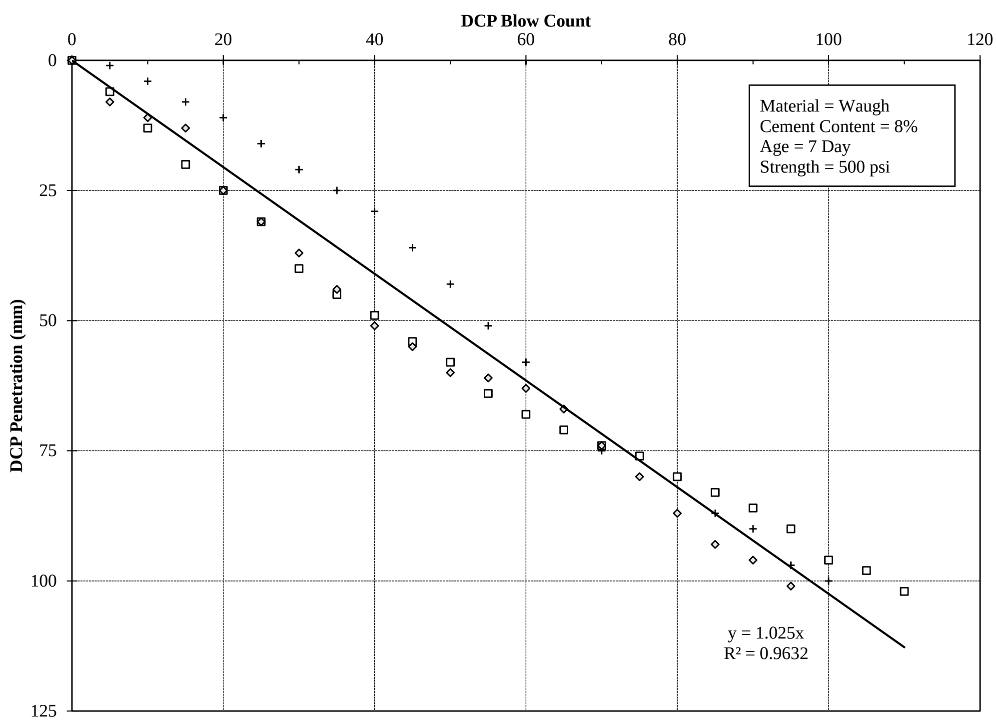

Figure F.5: Waugh 8% 7 Day

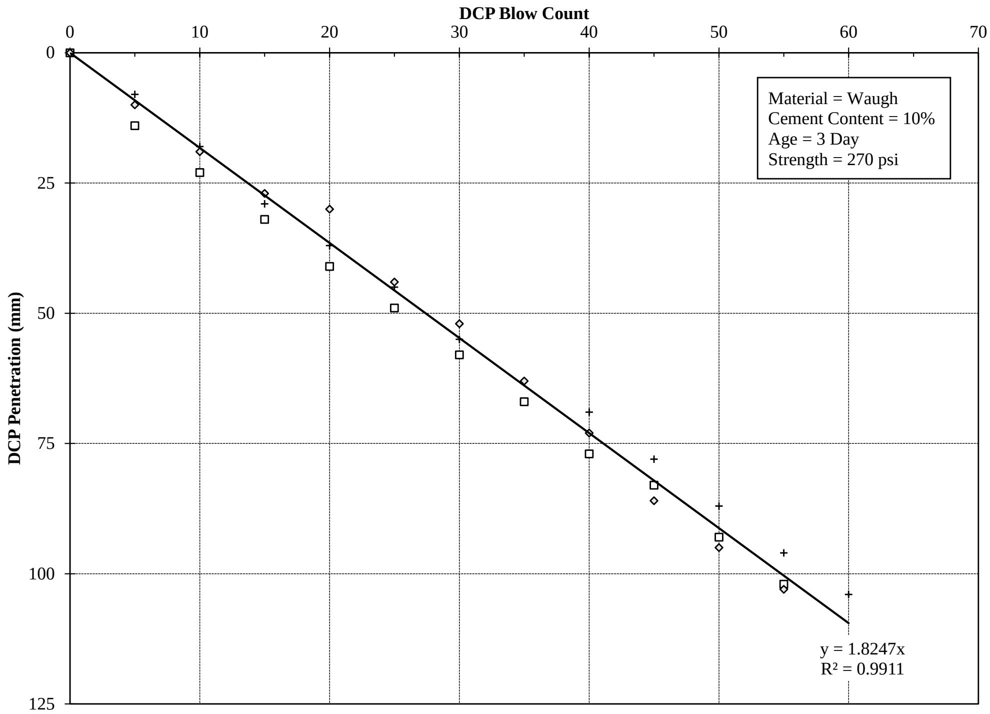

Figure F.6: Waugh 10% 3 Day

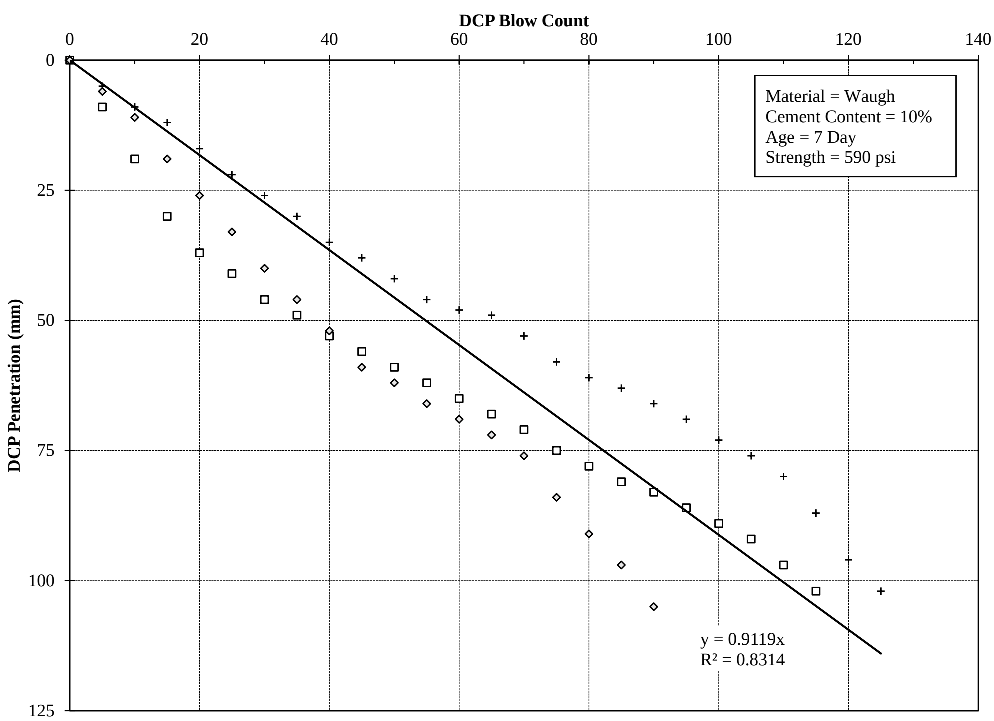

Figure F.7: Waugh 10% 7 Day

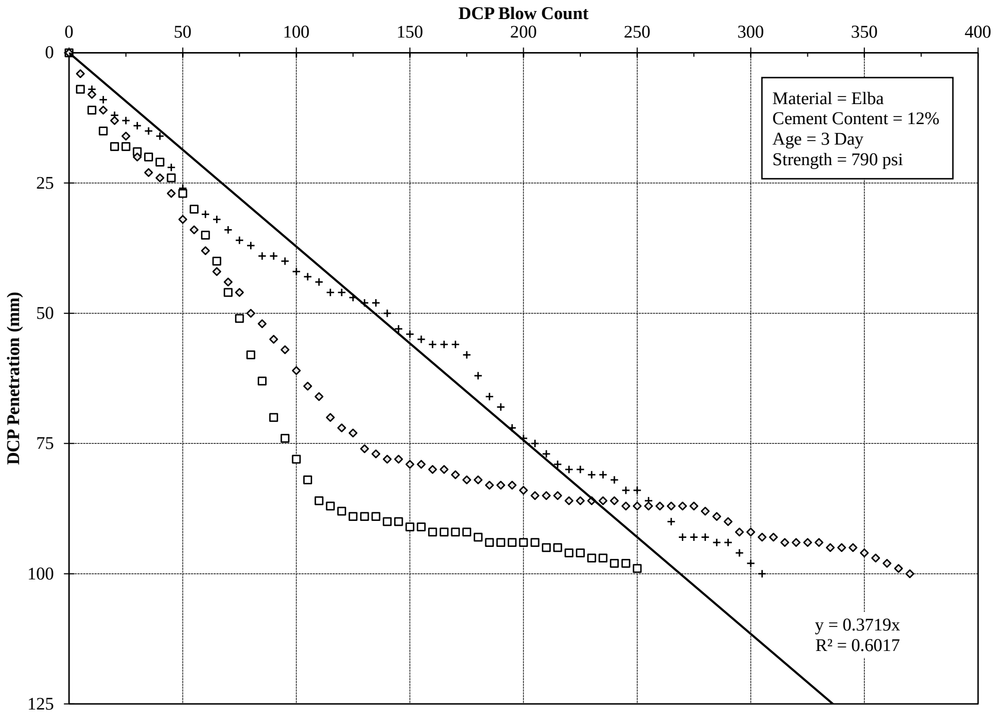

Figure F.8: Waugh 12% 3 Day

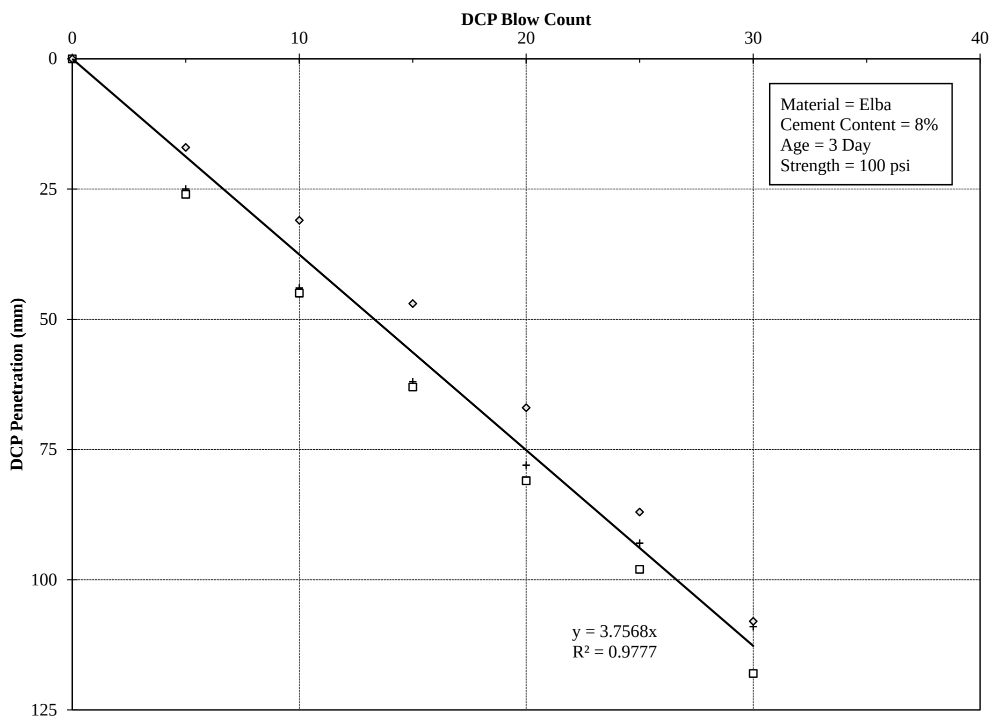

Figure F.9: Elba 8% 3 Day

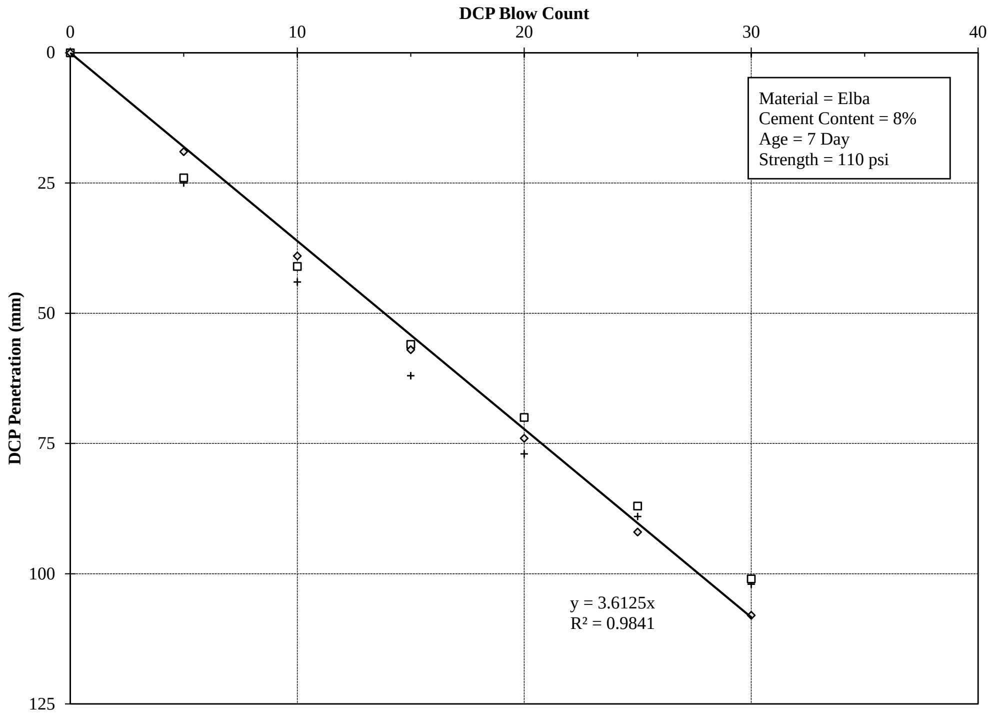

Figure F.10: Elba 8% 7 Day

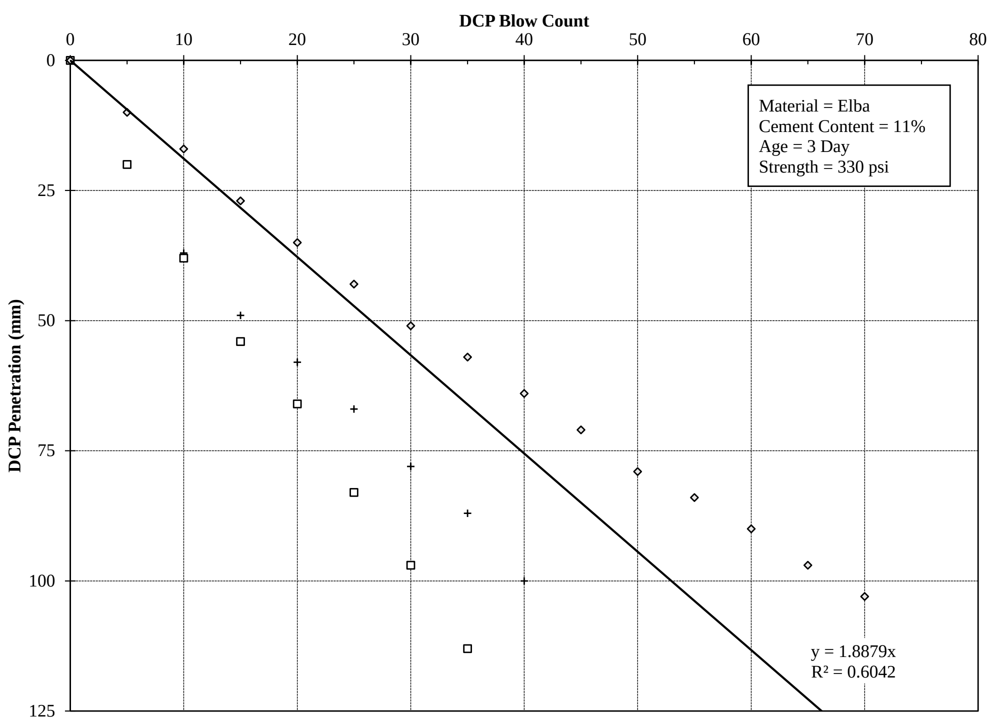

Figure F.11: Elba 11% 3 day

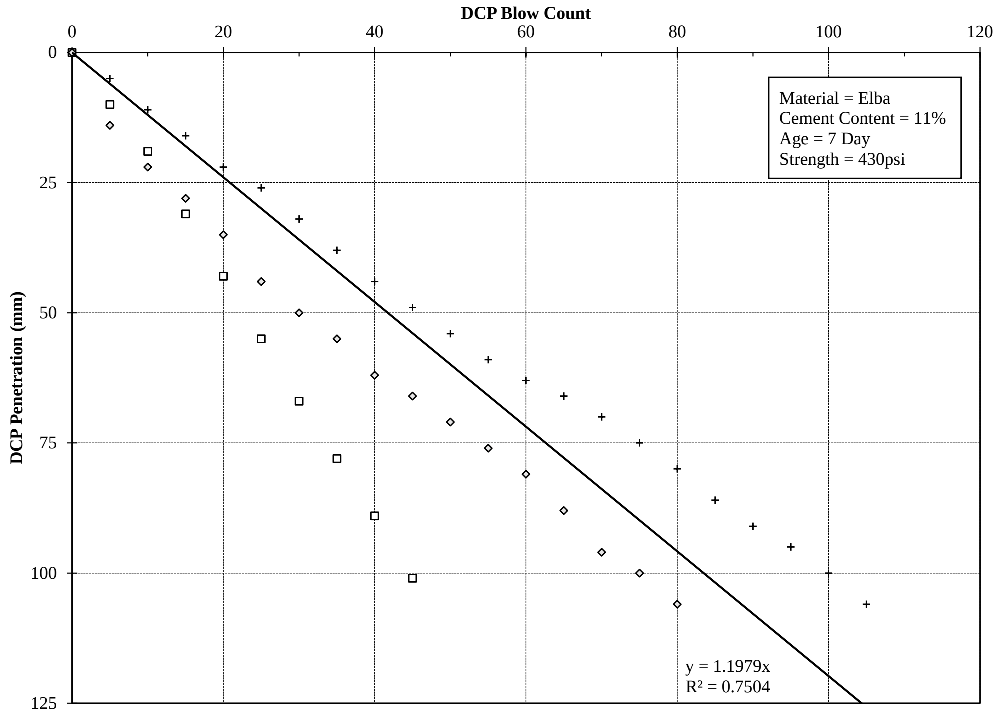

Figure F.12: Elba 11% 7 Day

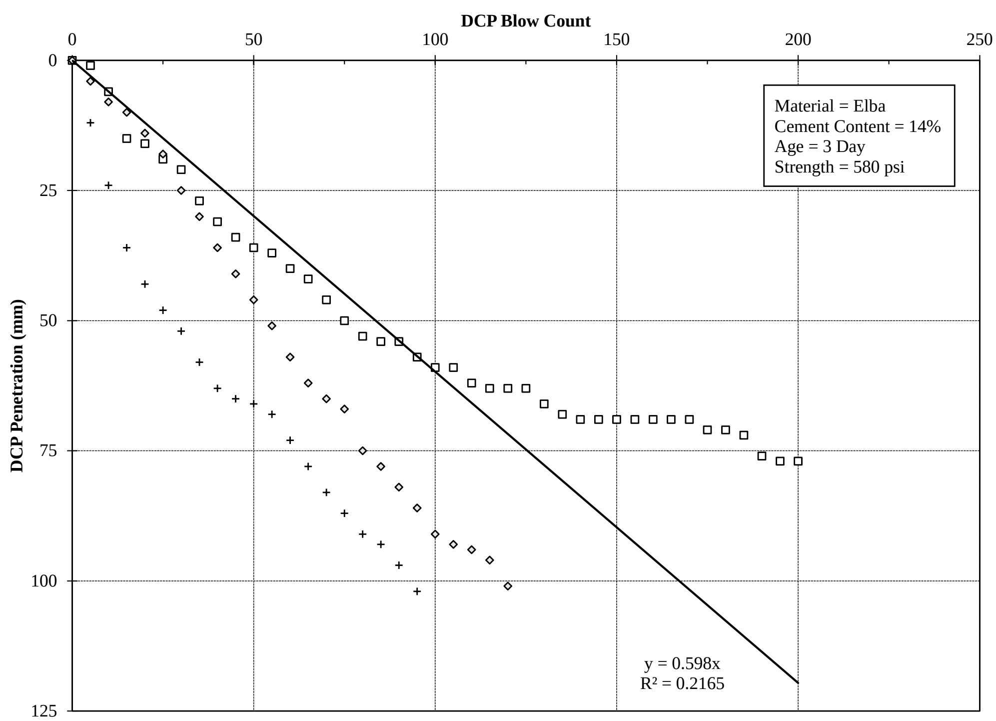

Figure F.13: Elba 14% 3 Day

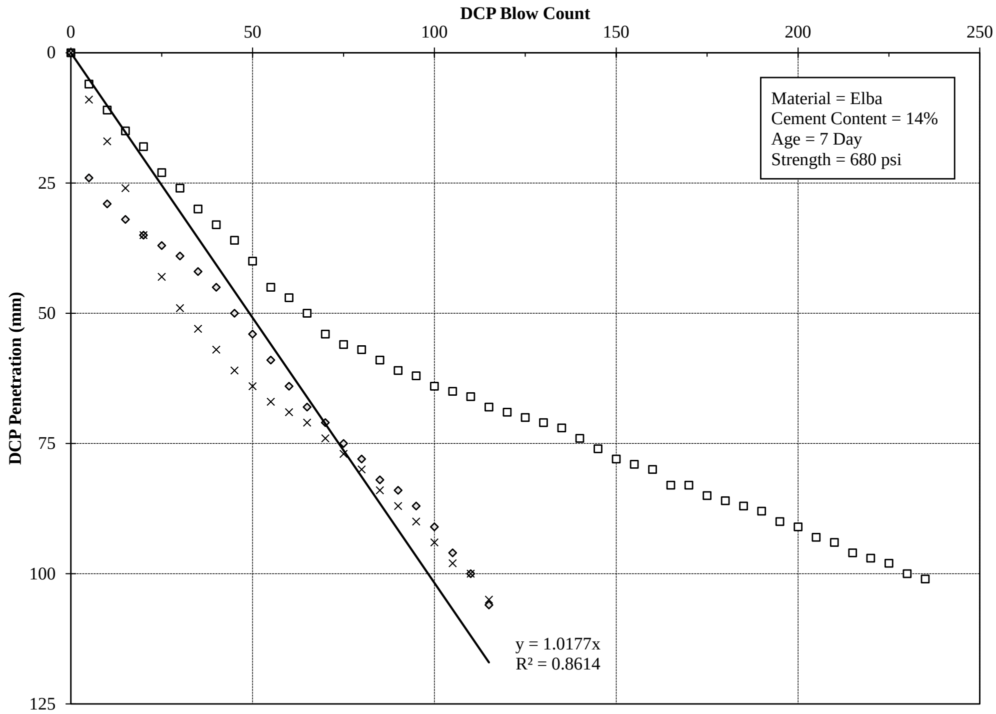

Figure F.14: Elba 14% 7 Day

Appendix G

75 mm Penetration Depth Data

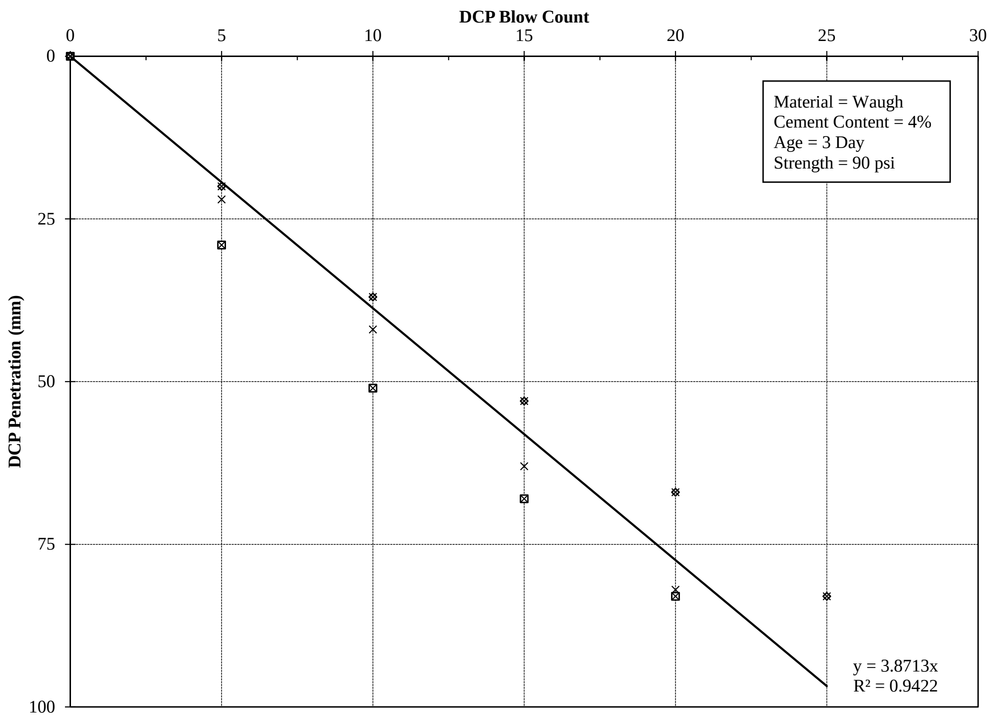

Figure G.1: Waugh 4% 3 Day

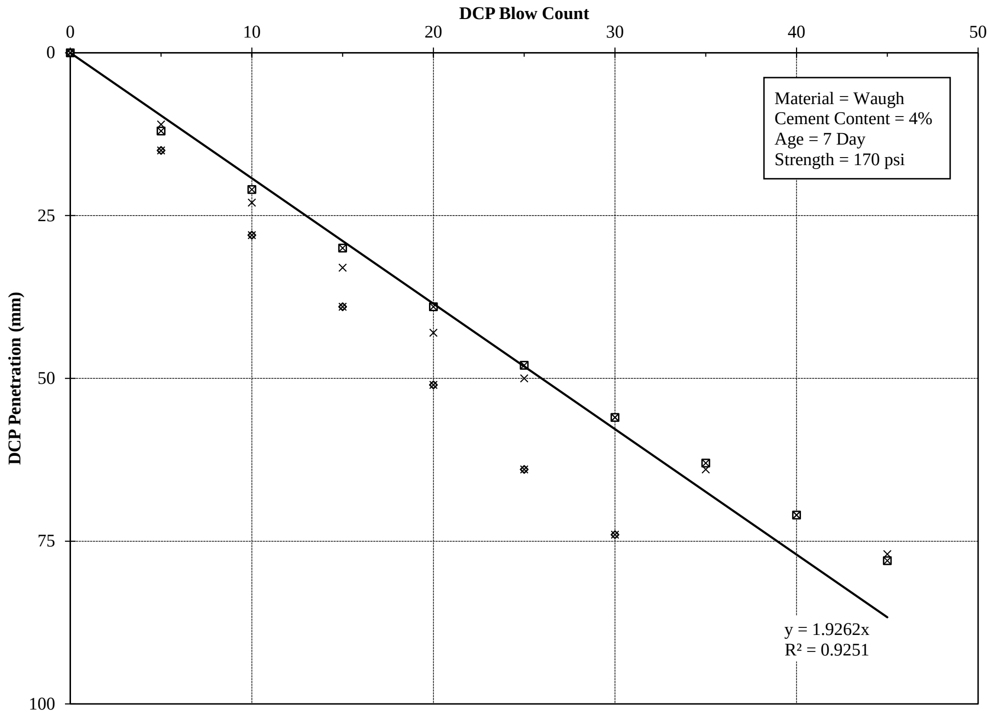

Figure G.2: Waugh 4% 7 day

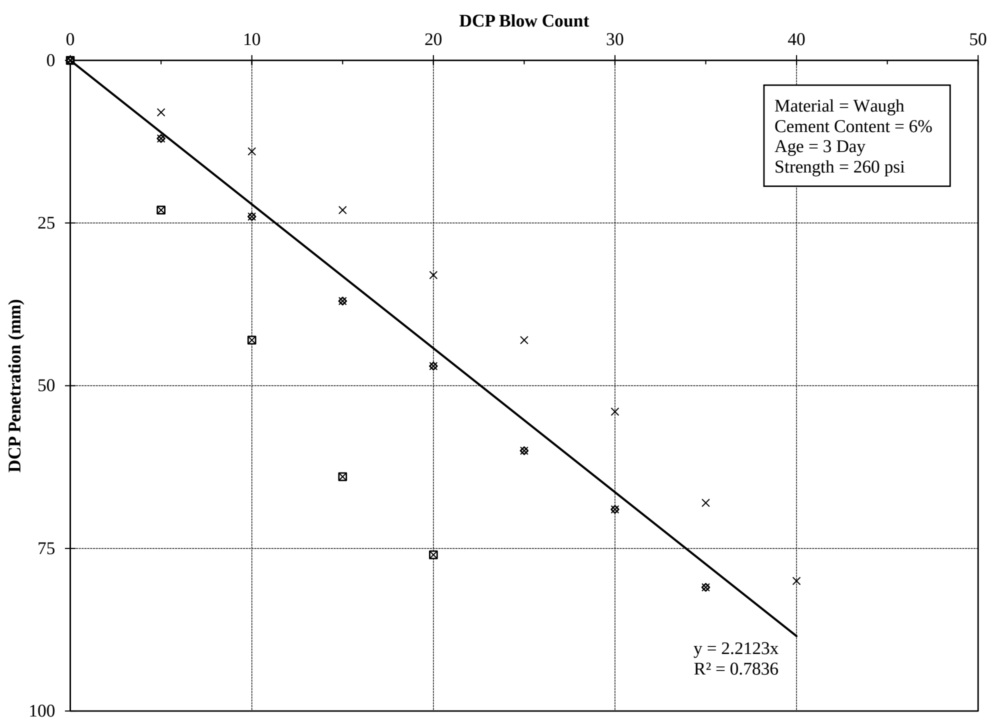

Figure G.3: Waugh 6% 3 Day

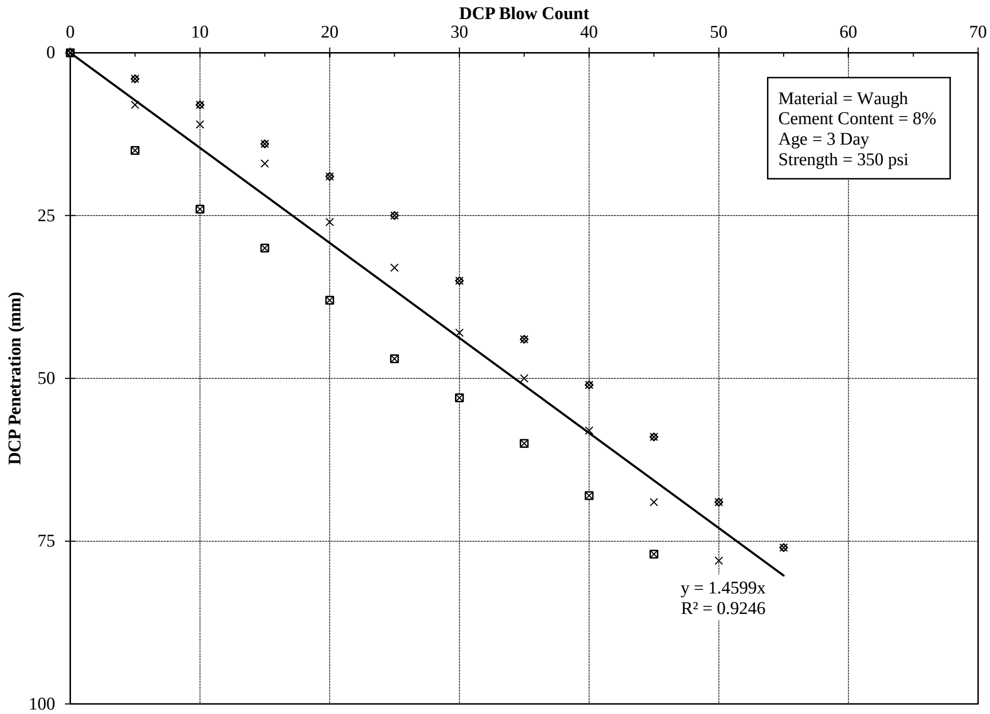

Figure G.4: Waugh 8% 3 Day

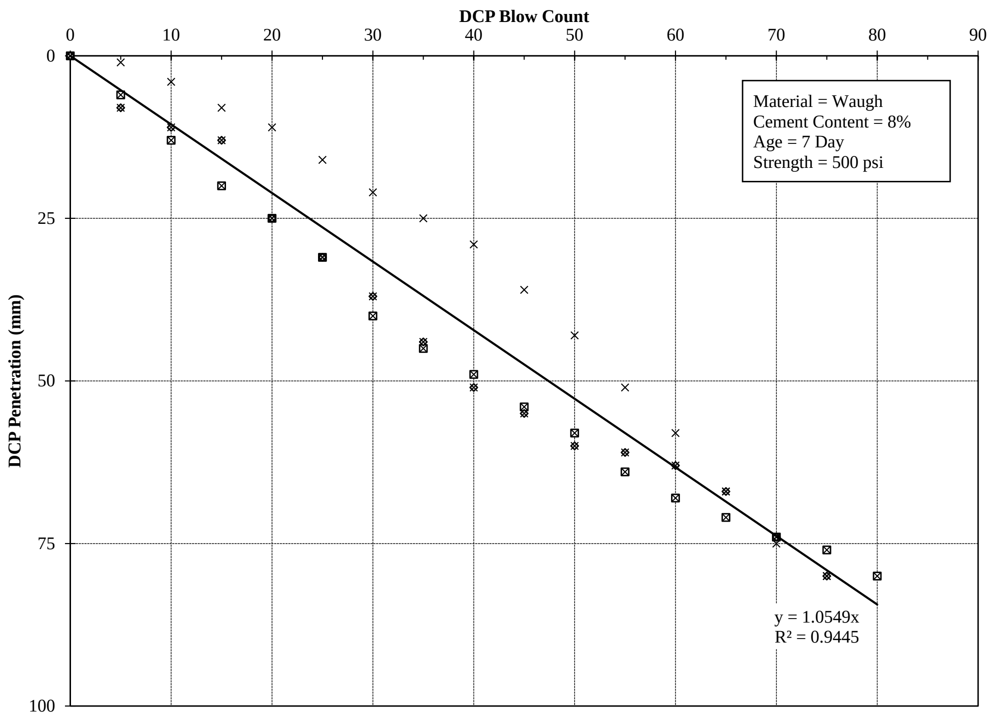

Figure G.5: Waugh 8% 7 Day

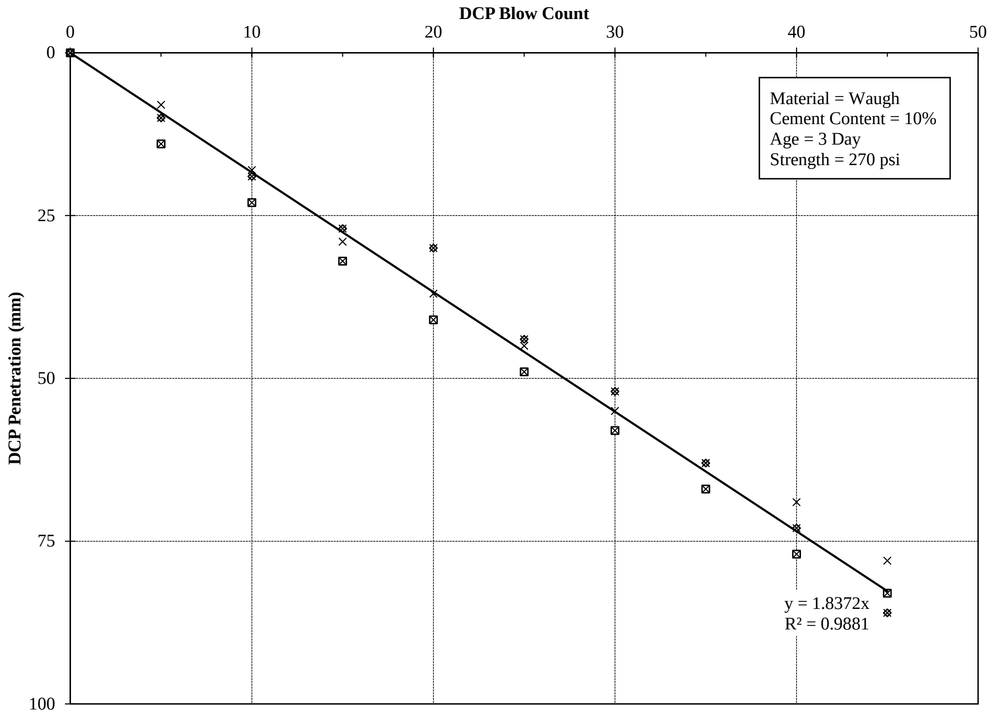

Figure G.6: Waugh 10% 3 Day

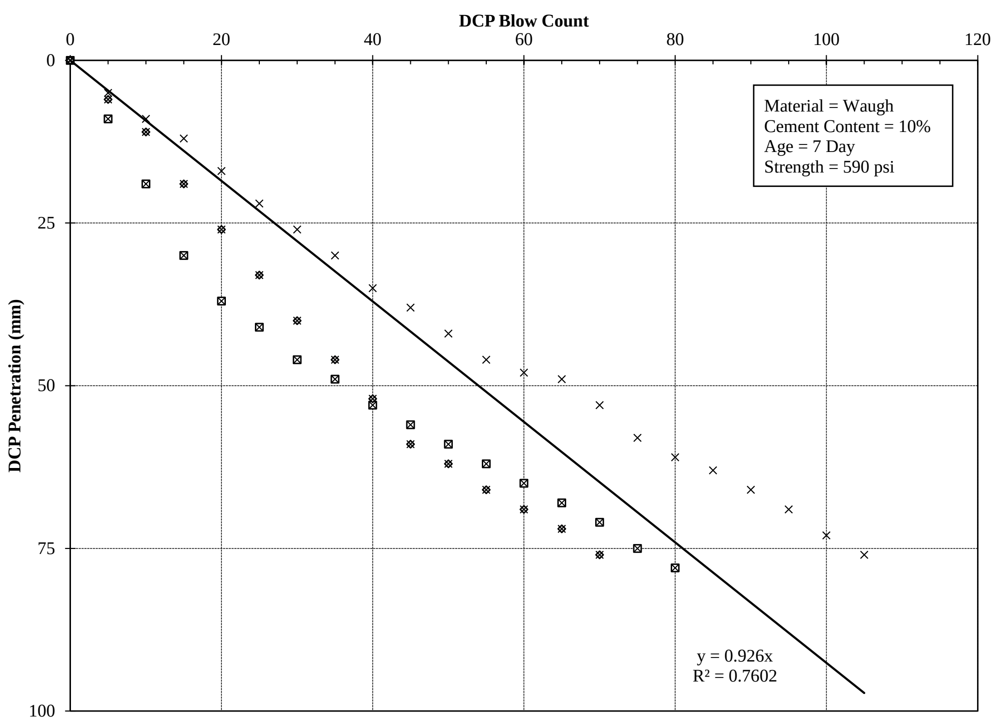

Figure G.7: Waugh 10% 7 Day

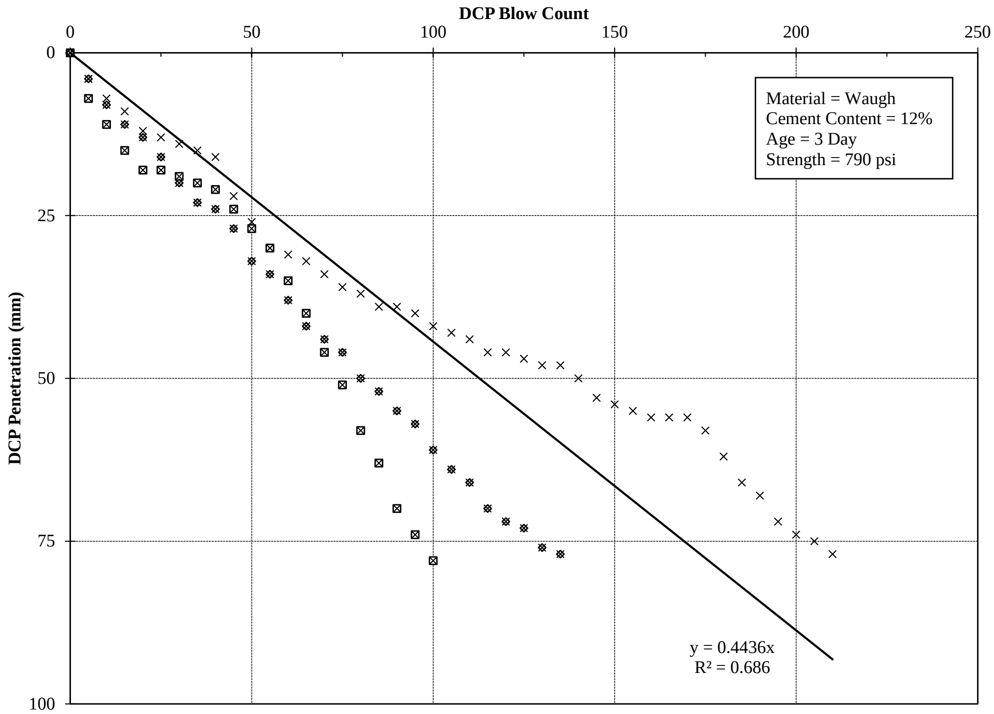

Figure G.8: Waugh 12% 3 Day

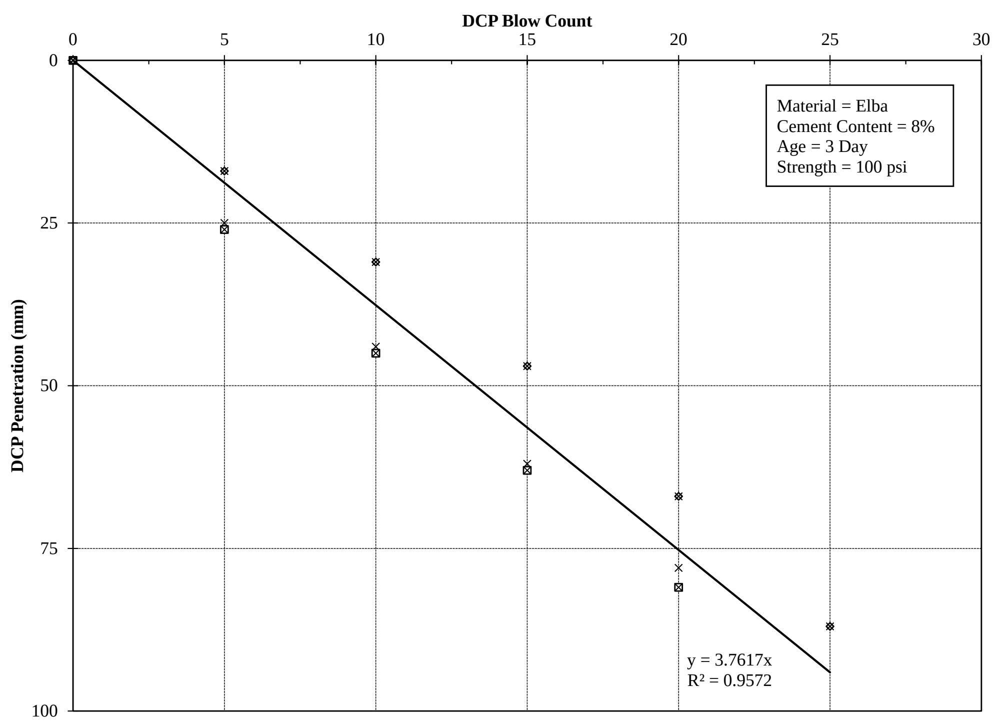

Figure G.9: Elba 8% 3 Day

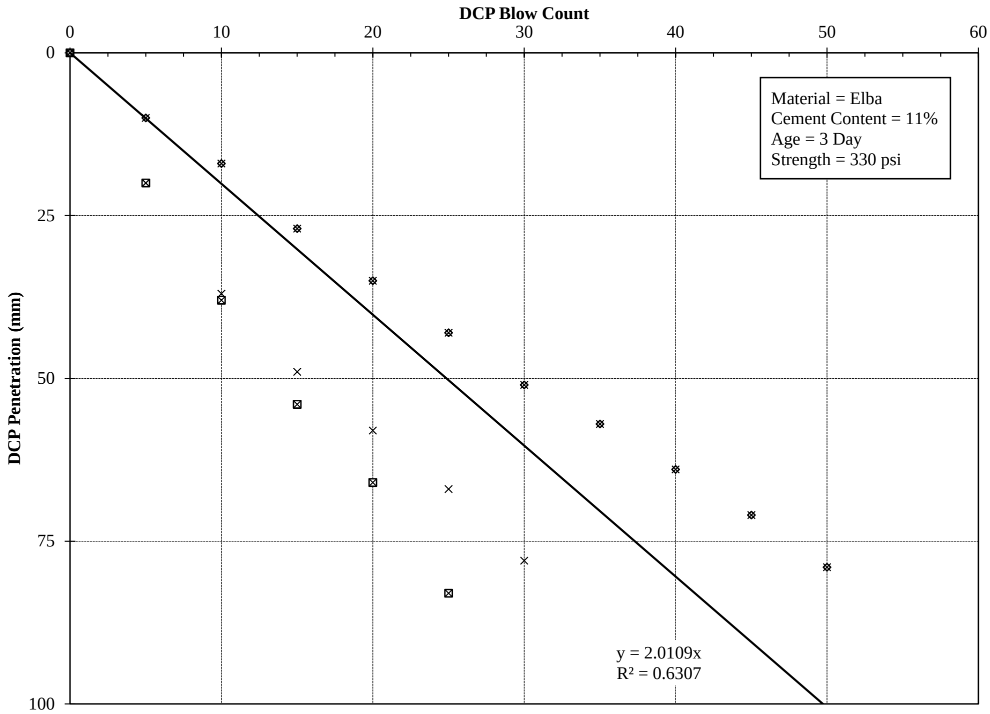

Figure G.10: Elba 11% 3 Day

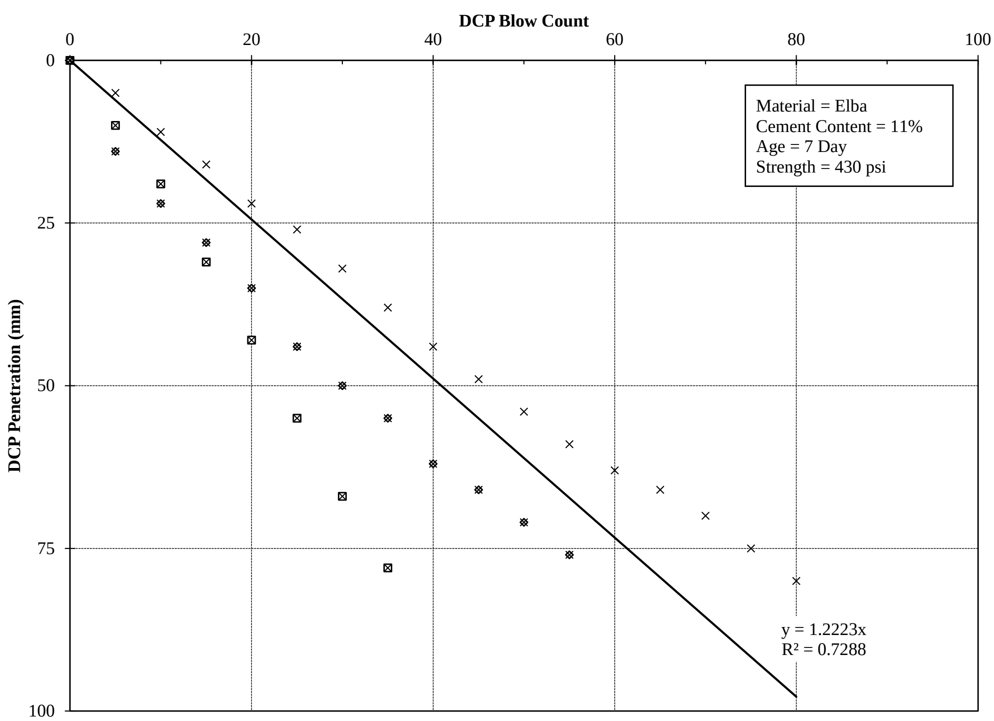

Figure G.11: Elba 11% 7 Day

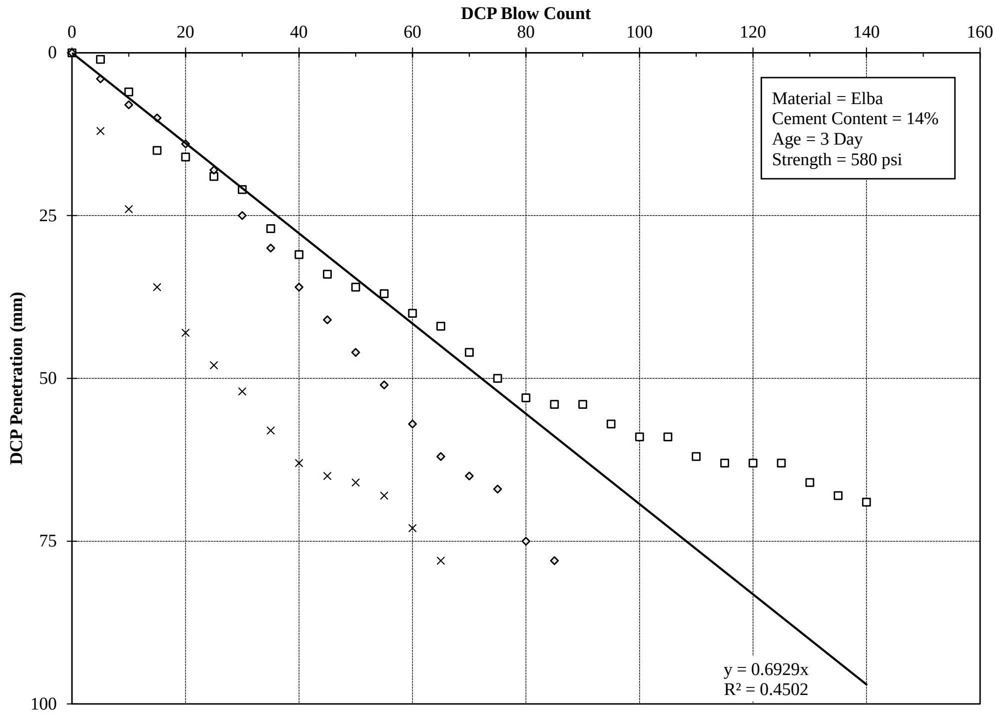

Figure G.12: Elba 14% 3 Day

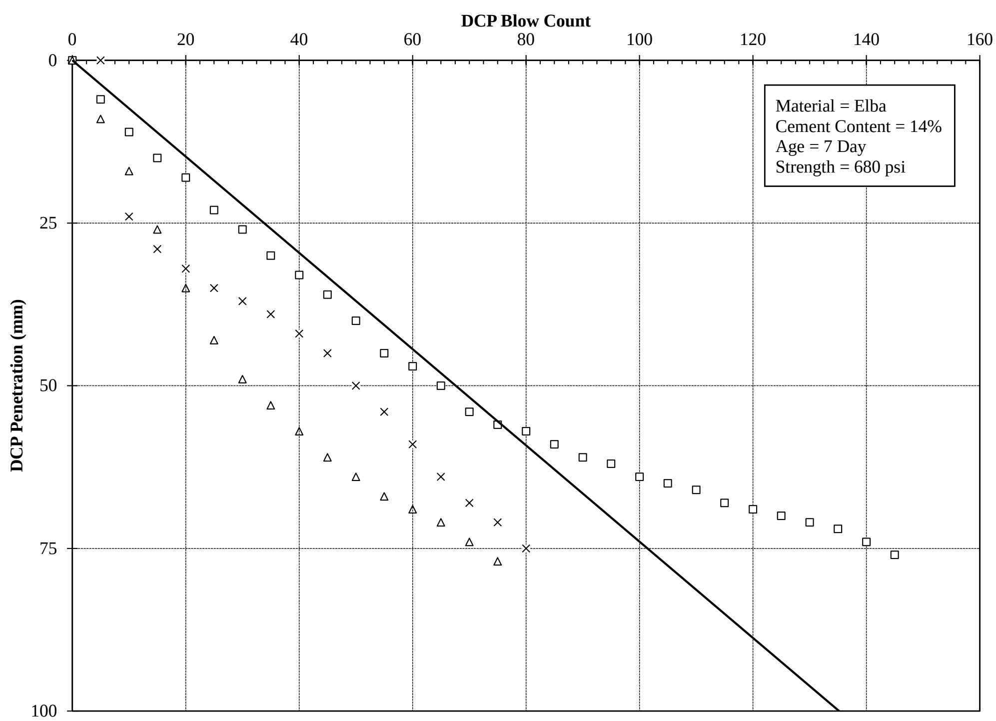

Figure G.13: Elba 14% 7 Day

Appendix H

50 mm Penetration Depth Data

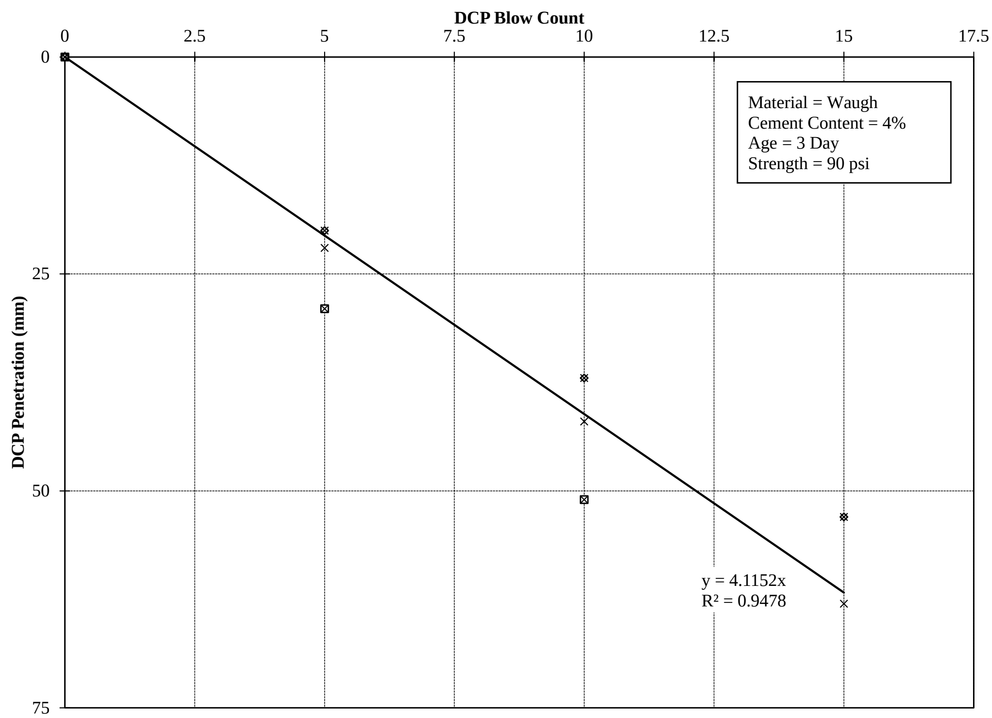

Figure H.1: Waugh 4% 3 Day

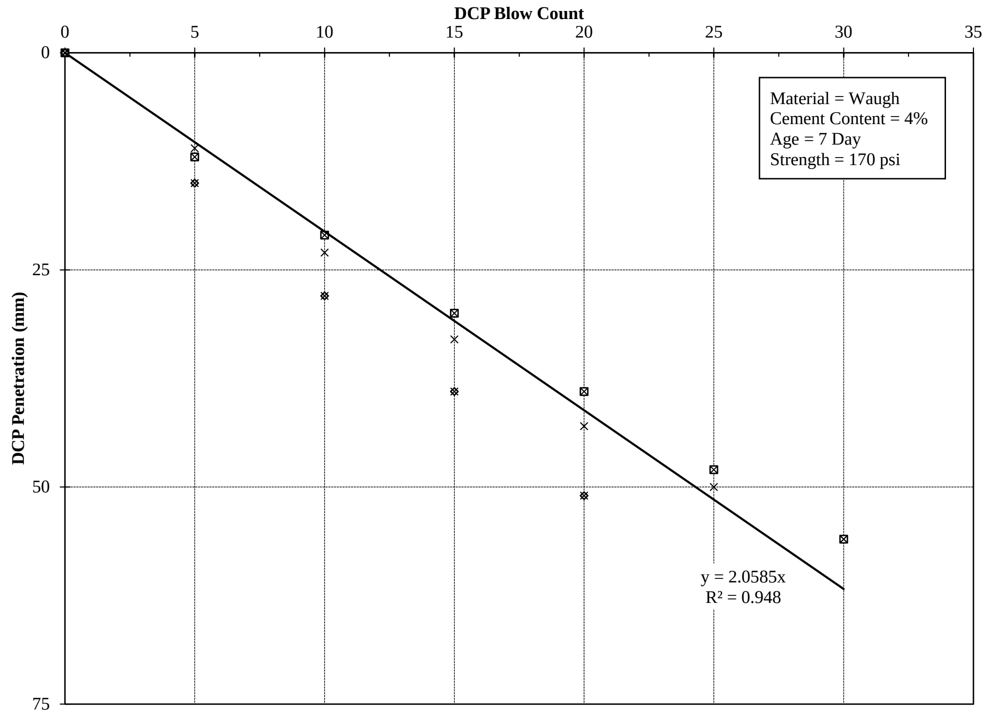

Figure H.2: Waugh 4% 7 Day

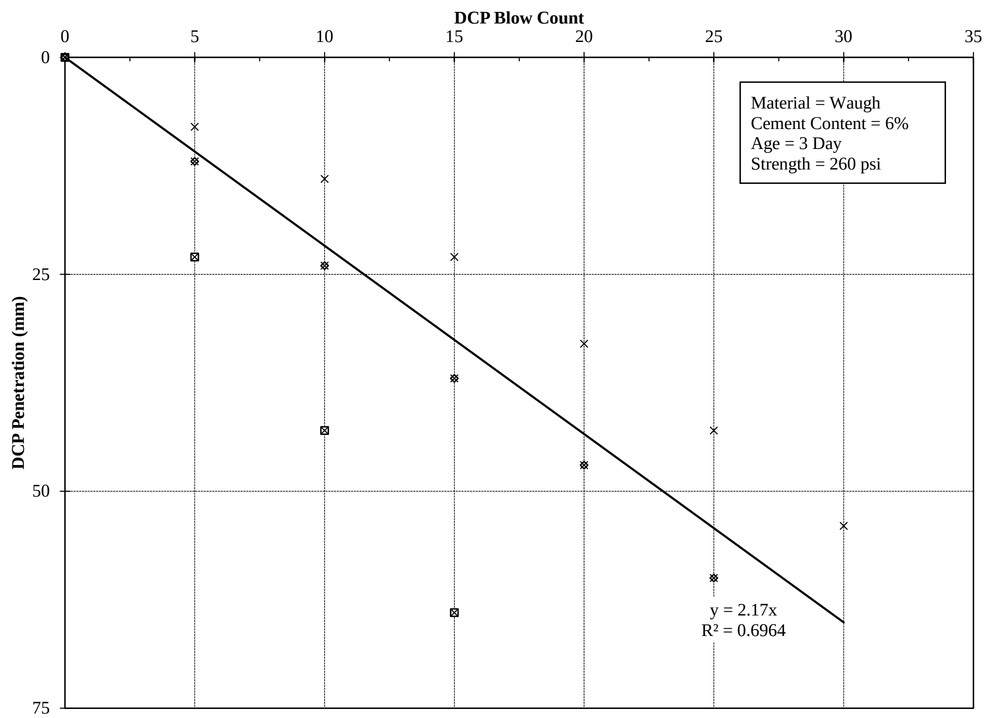

Figure H.3: Waugh 6% 3 Day

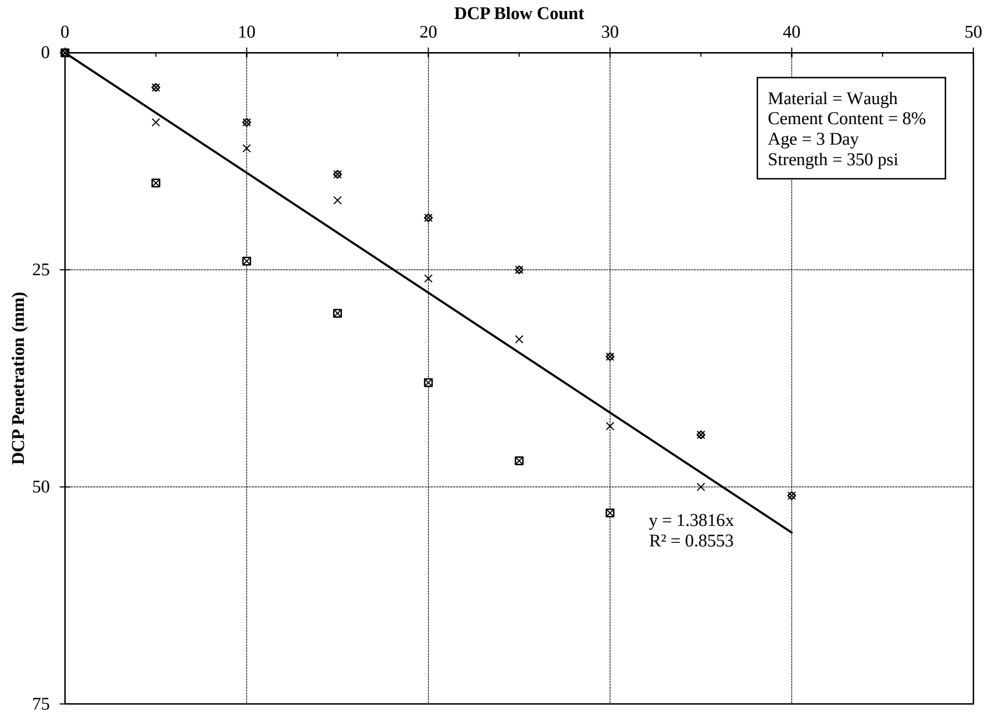

Figure H.4: Waugh 8% 3 Day

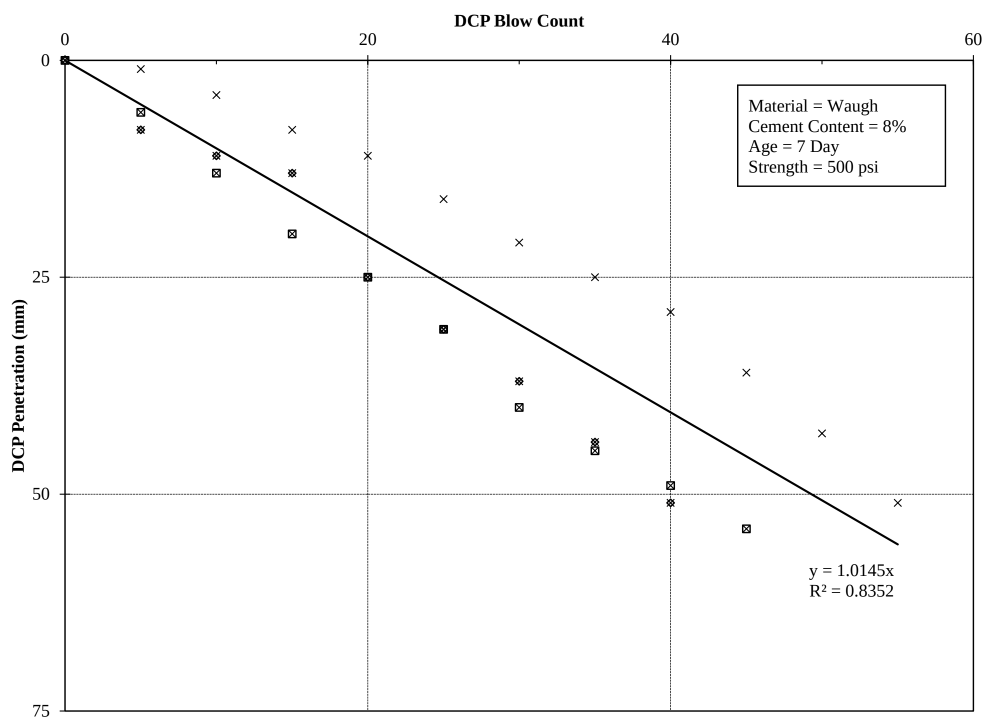

Figure H.5: Waugh 8% 7 Day

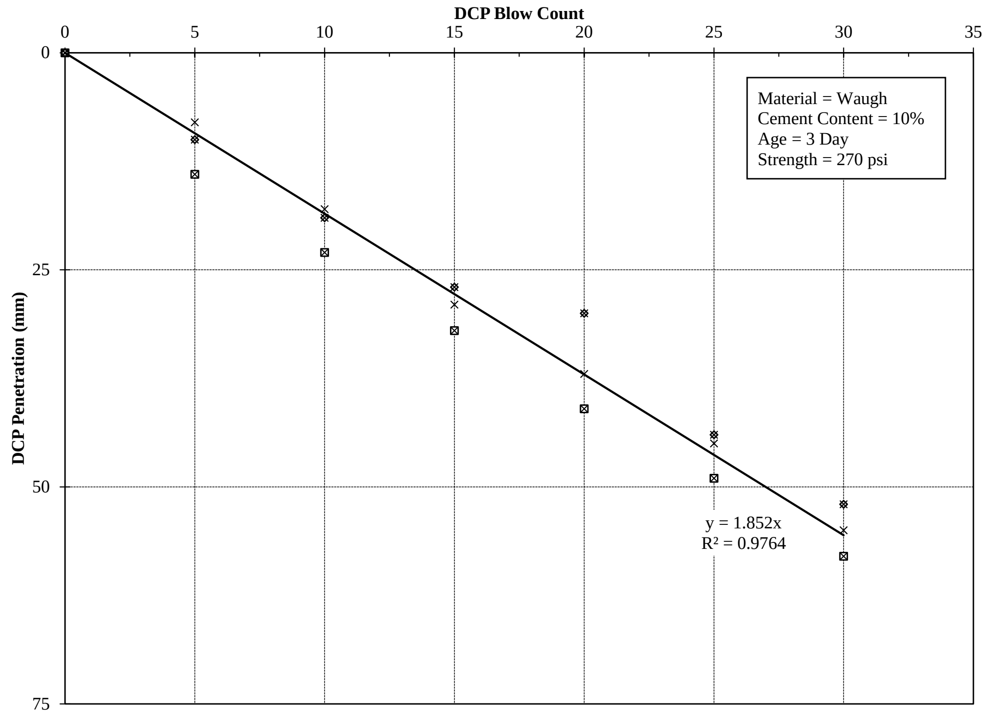

Figure H.6: Waugh 10% 3 Day

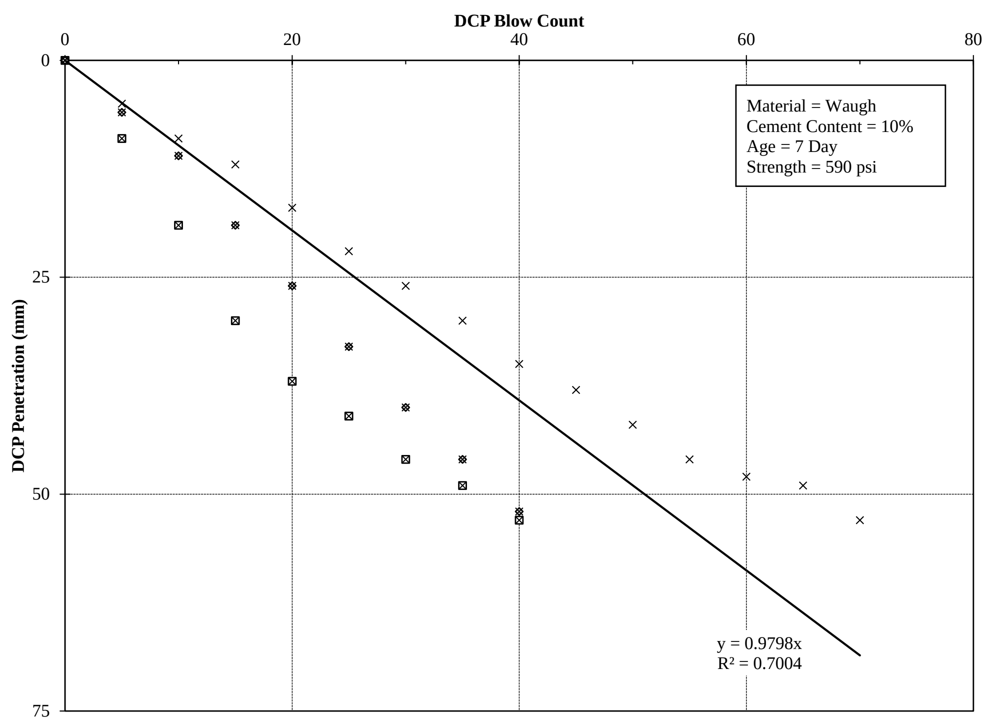

Figure H.7: Waugh 10% 7 Day

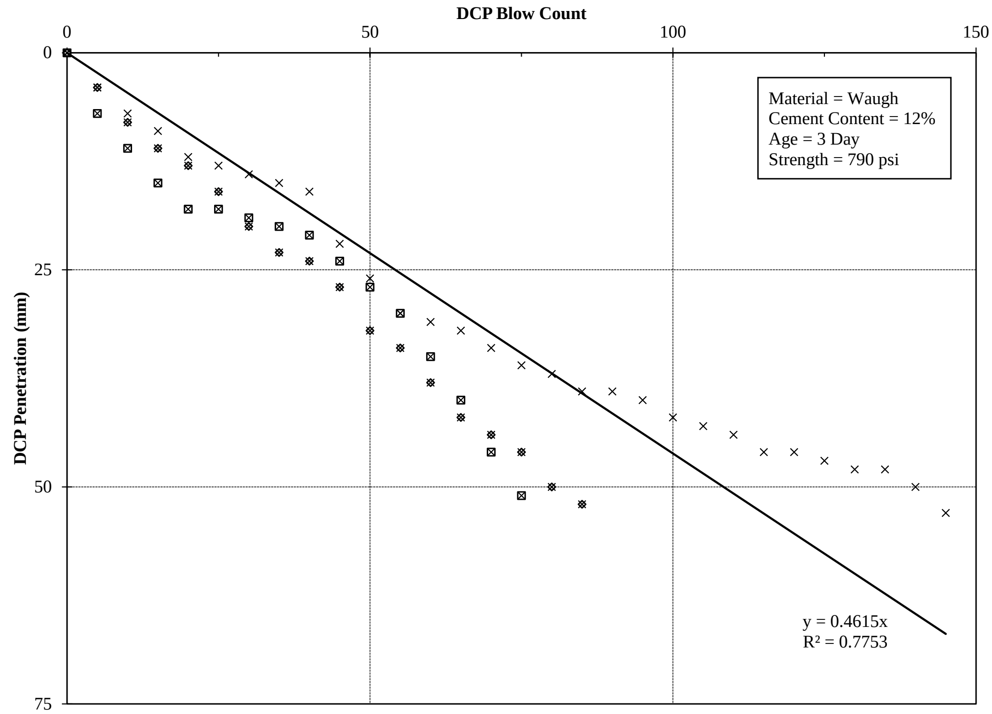

Figure H.8: Waugh 12% 3 Day

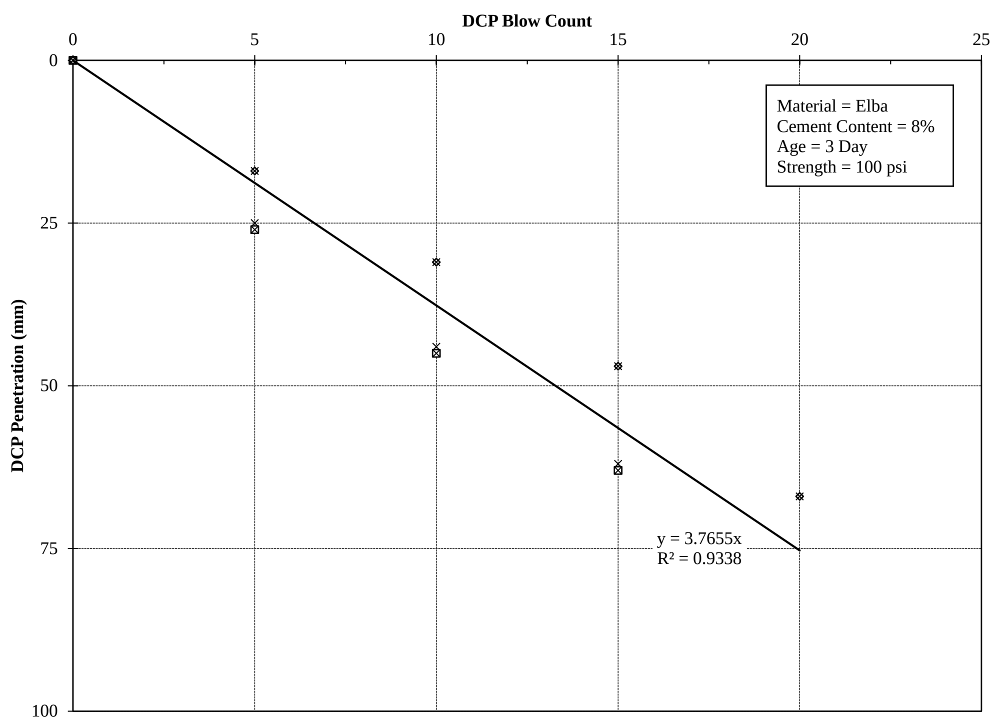

Figure H.9: Elba 8% 3 Day

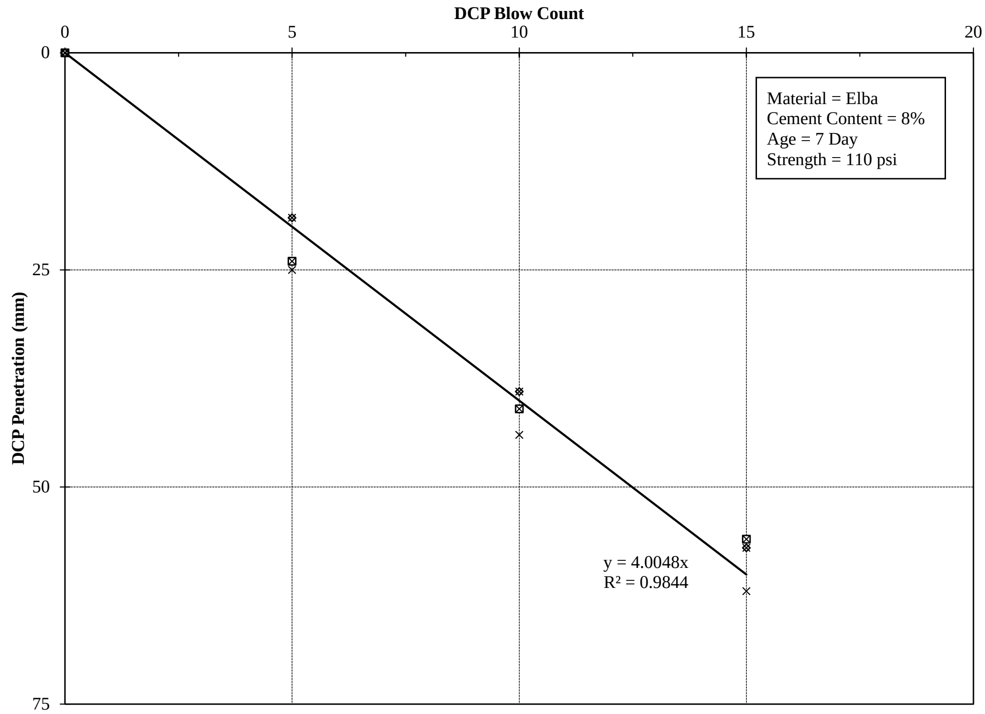

Figure H.10: Elba 8% 7 Day

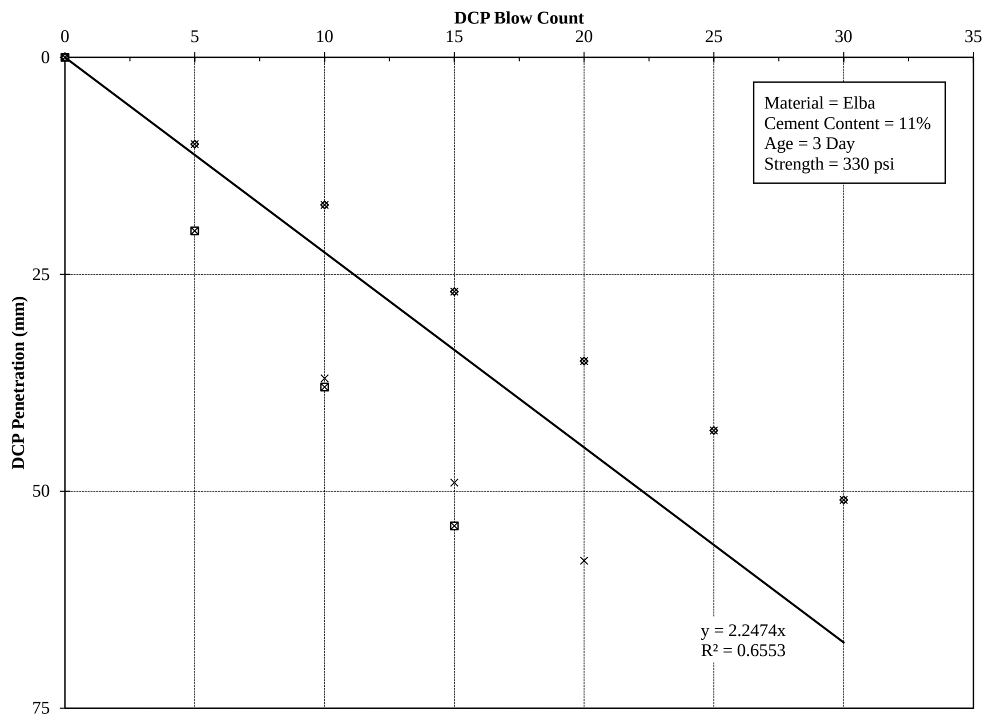

Figure H.11: Waugh 11% 3 Day

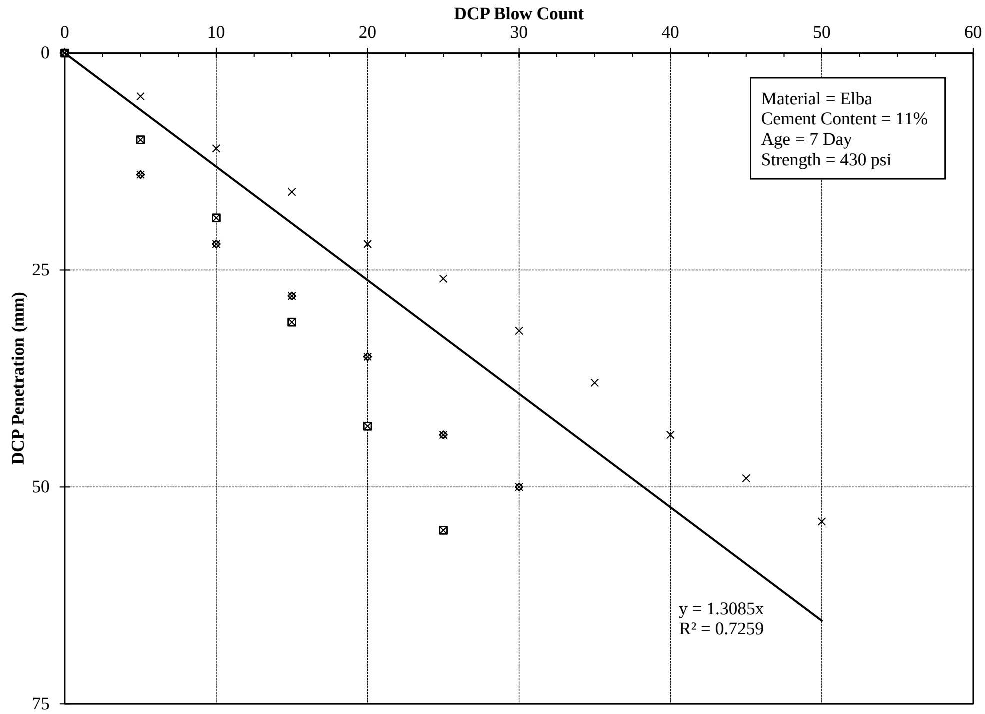

Figure H.12: Elba 11% 7 Day

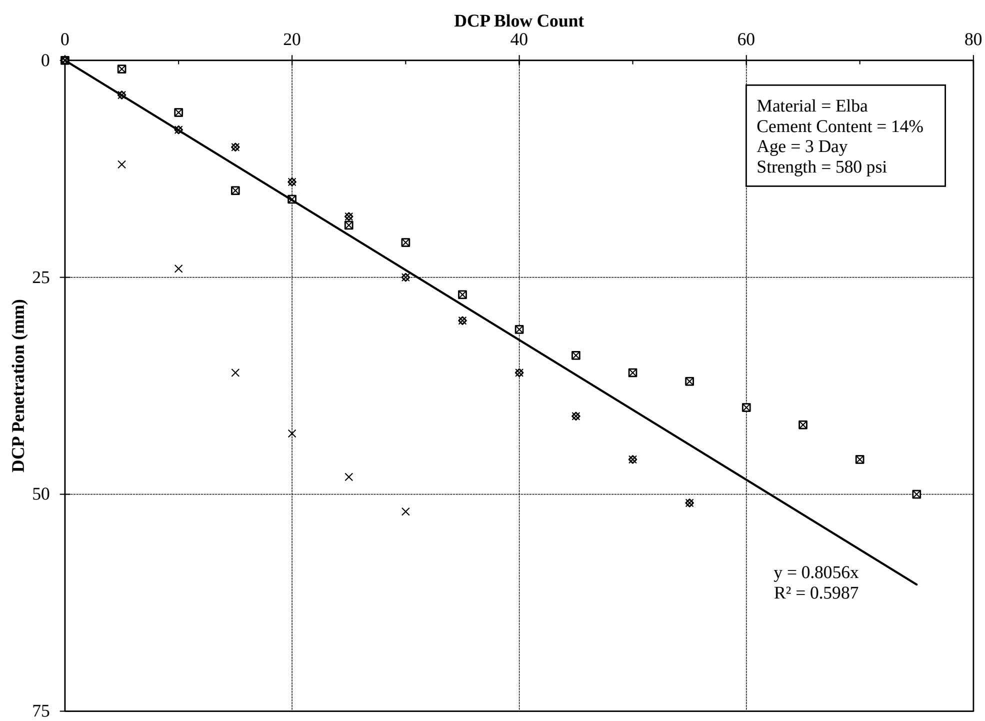

Figure H.13: Elba 14% 3 Day

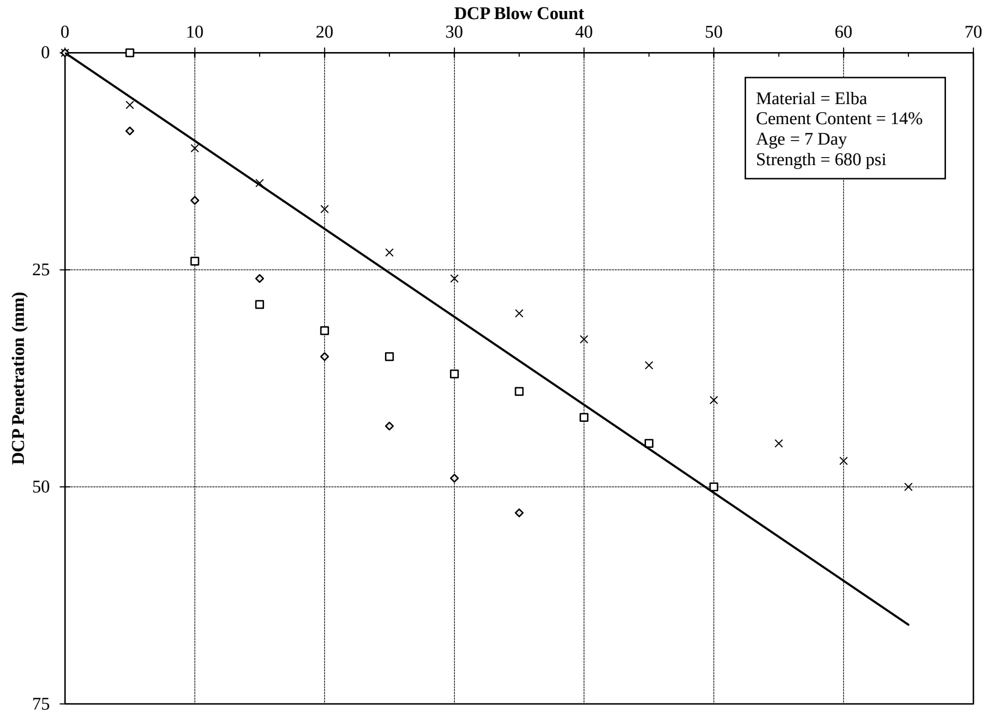

Figure H.14: Elba 14% 7 Day

Appendix I

25 mm Penetration Depth Data

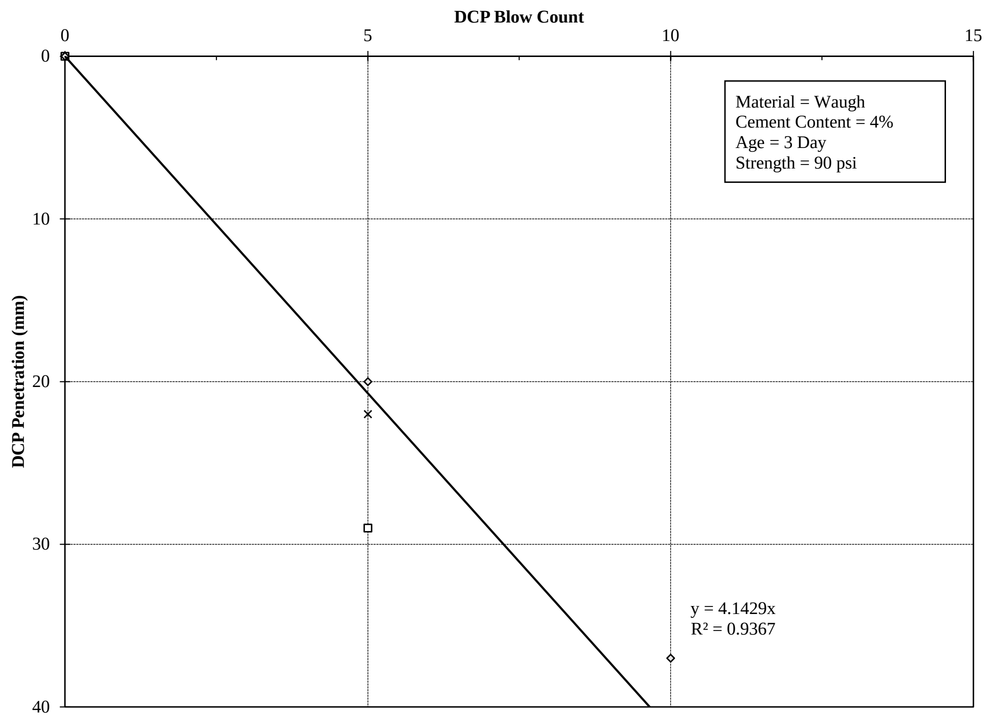

Figure I.1: Waugh 4% 3 Day

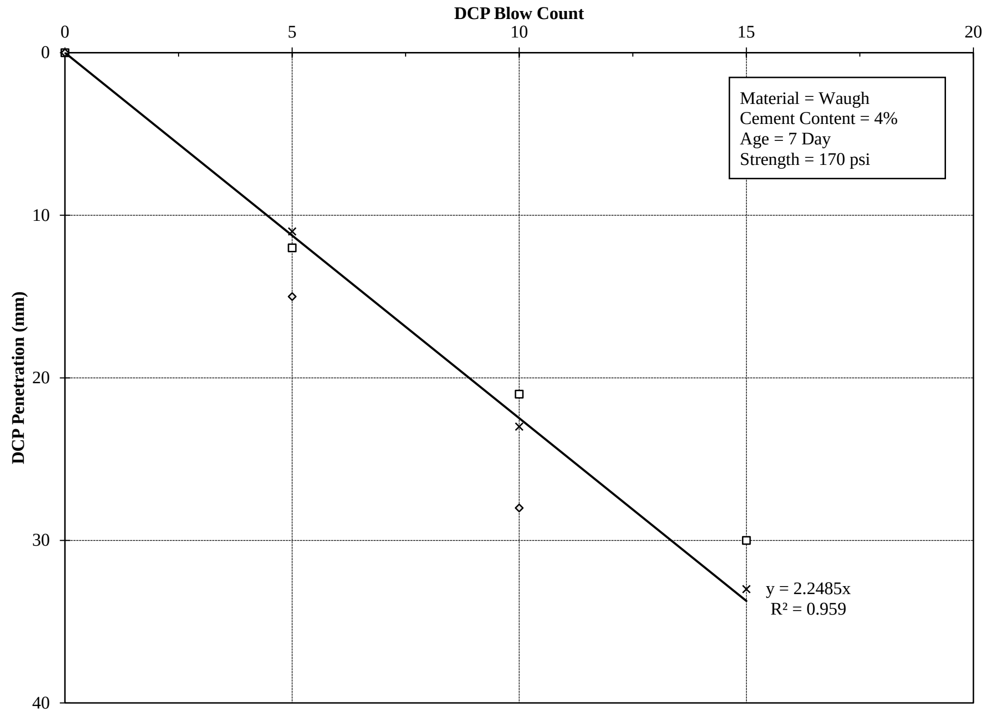

Figure I.2: Waugh 4% 7 Day

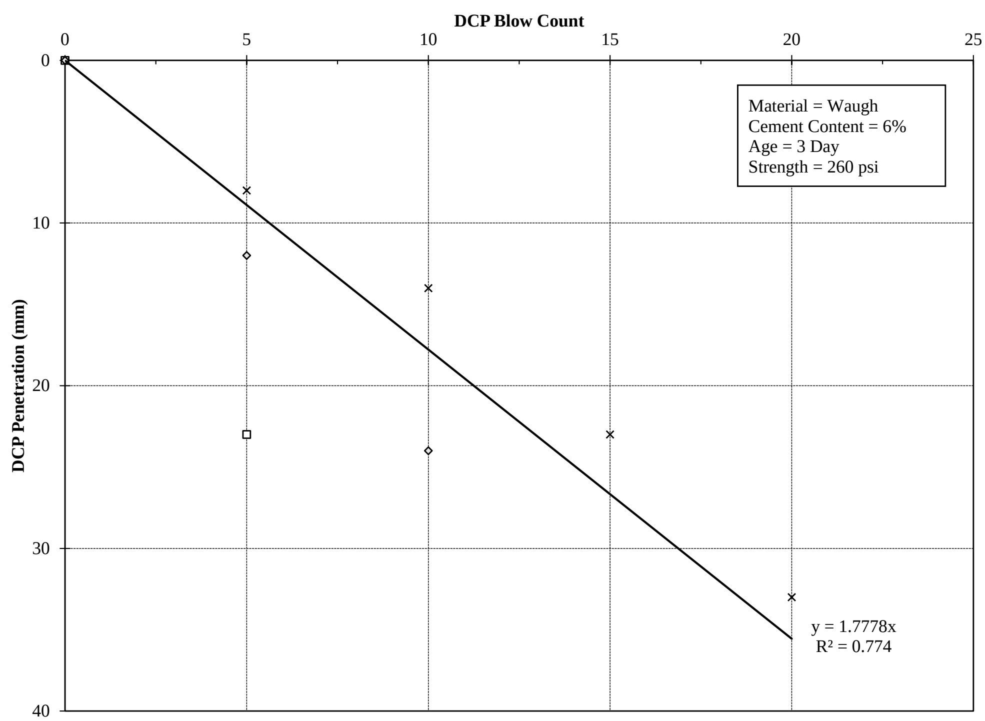

Figure I.3: Waugh 6% 3 Day

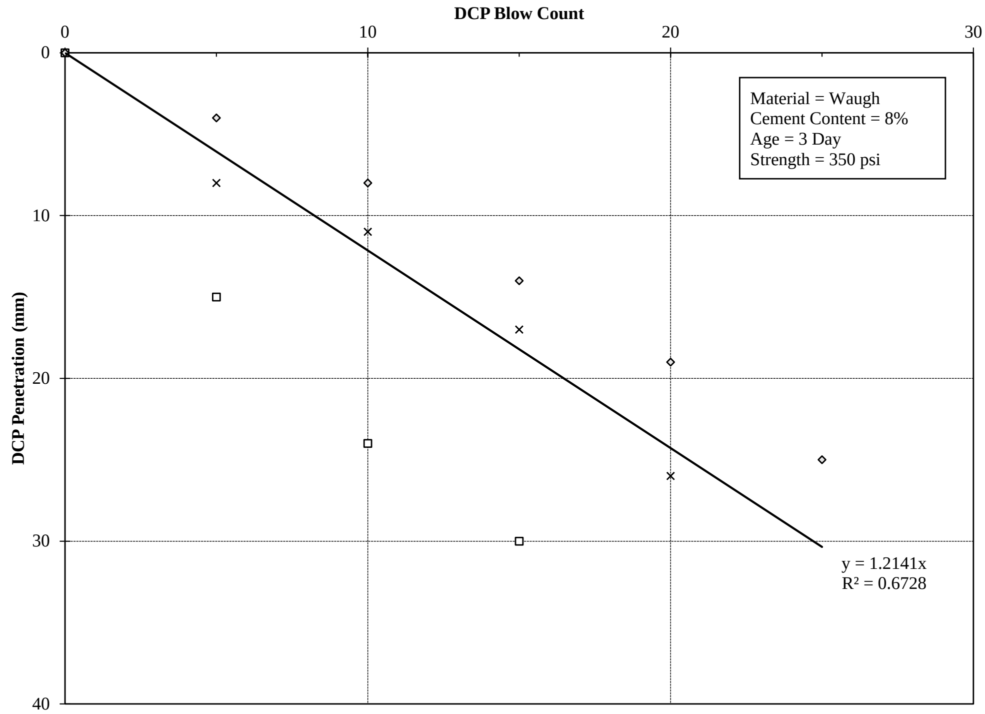

Figure I.4: Waugh 8% 3 Day

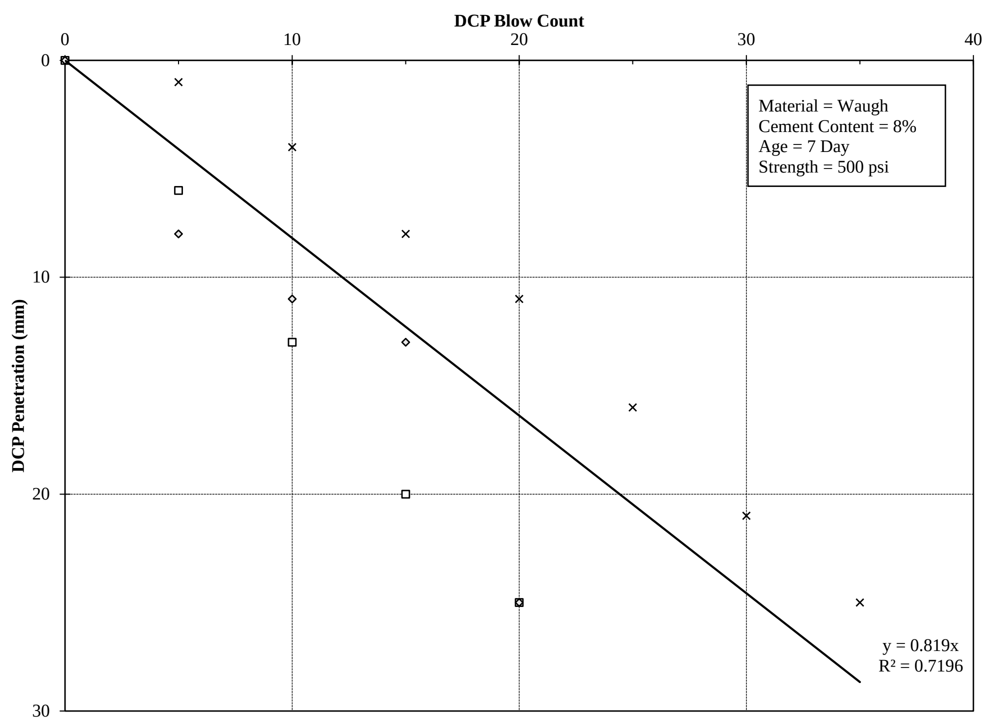

Figure I.5: Waugh 8% 7 Day

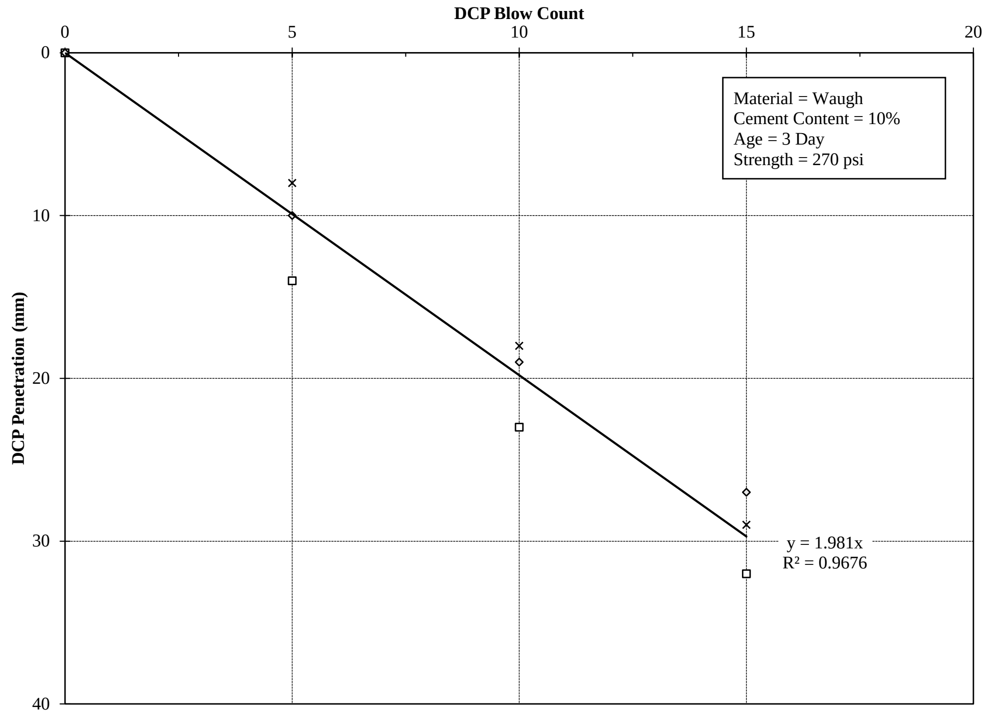

Figure I.6: Waugh 10% 3 Day

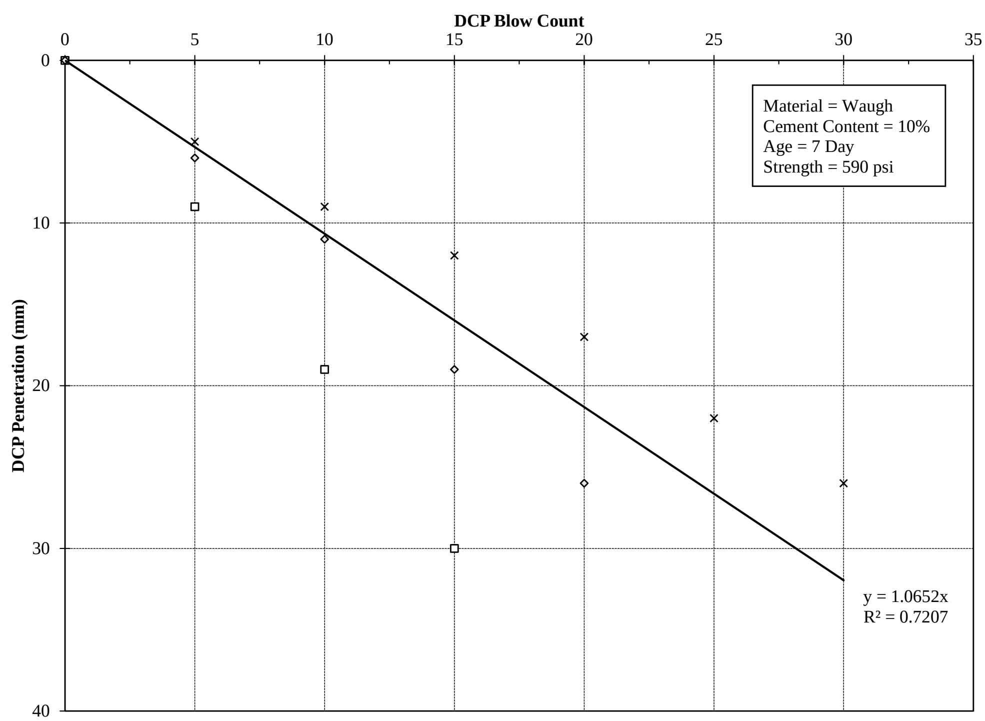

Figure I.7: Waugh 10% 7 Day

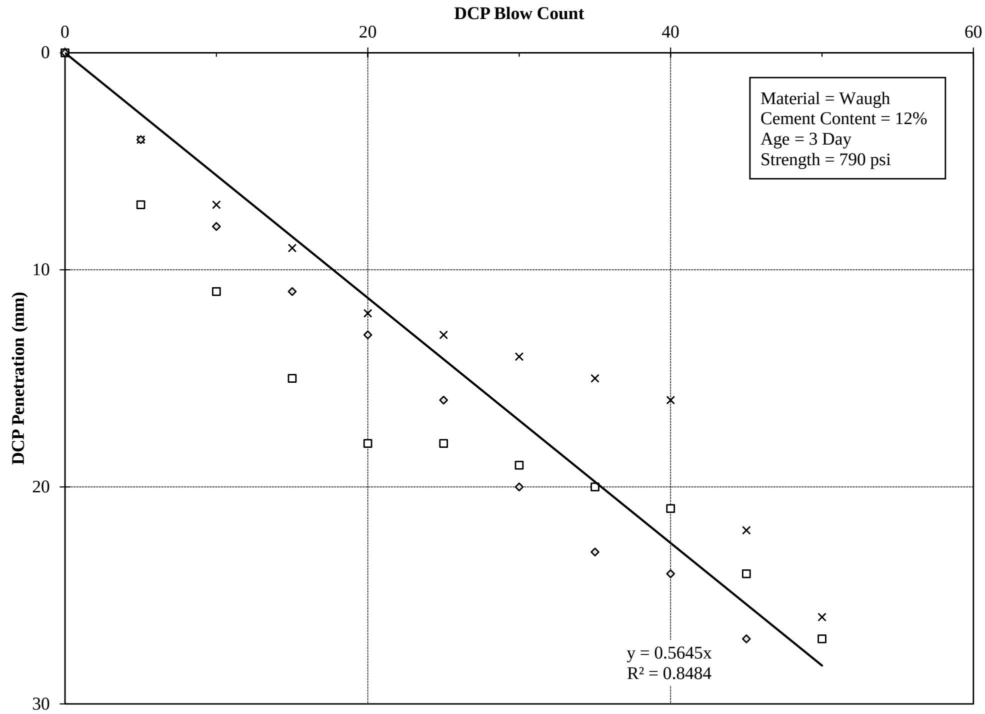

Figure I.8: Waugh 12% 3 Day

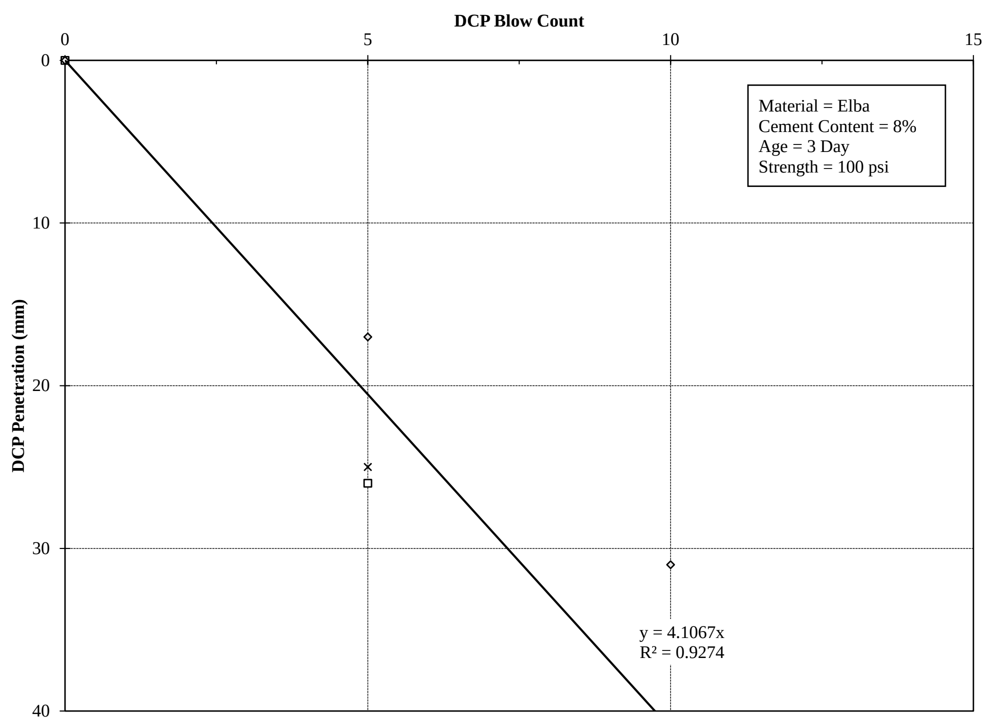

Figure I.9: Elba 8% 3 Day

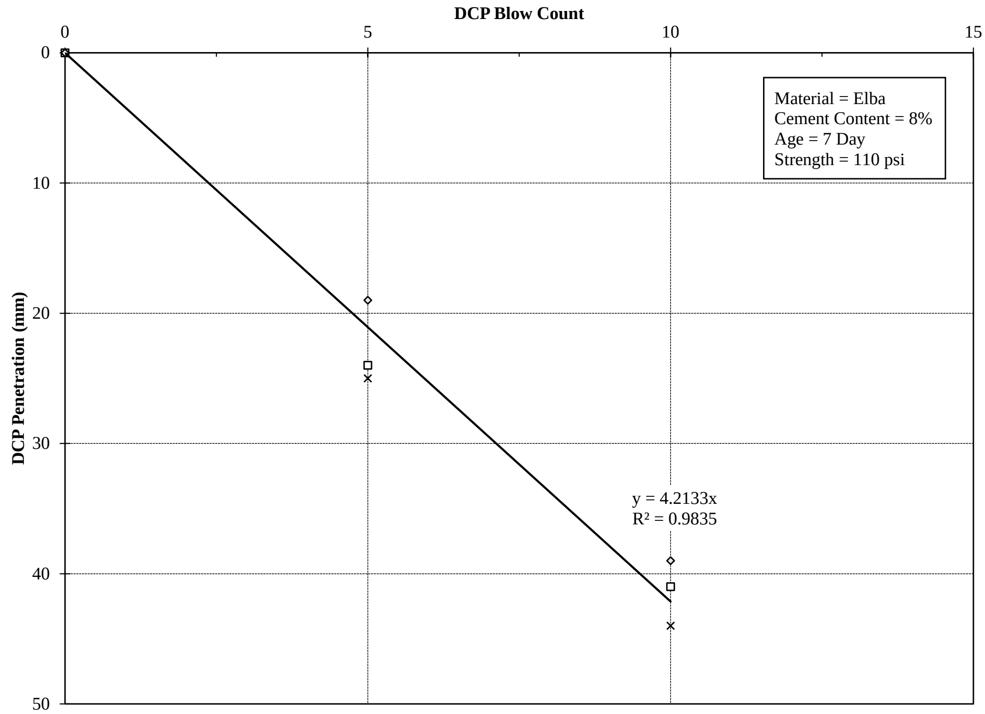

Figure I.10: Elba 8% 7 Day

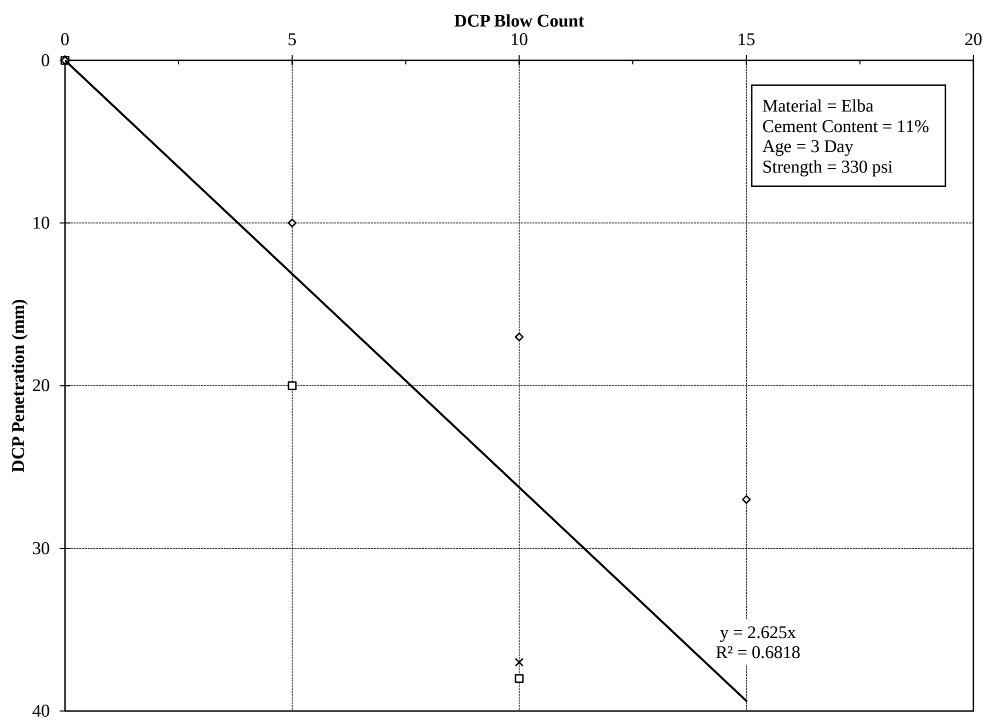

Figure I.11: Elba 11% 3 Day

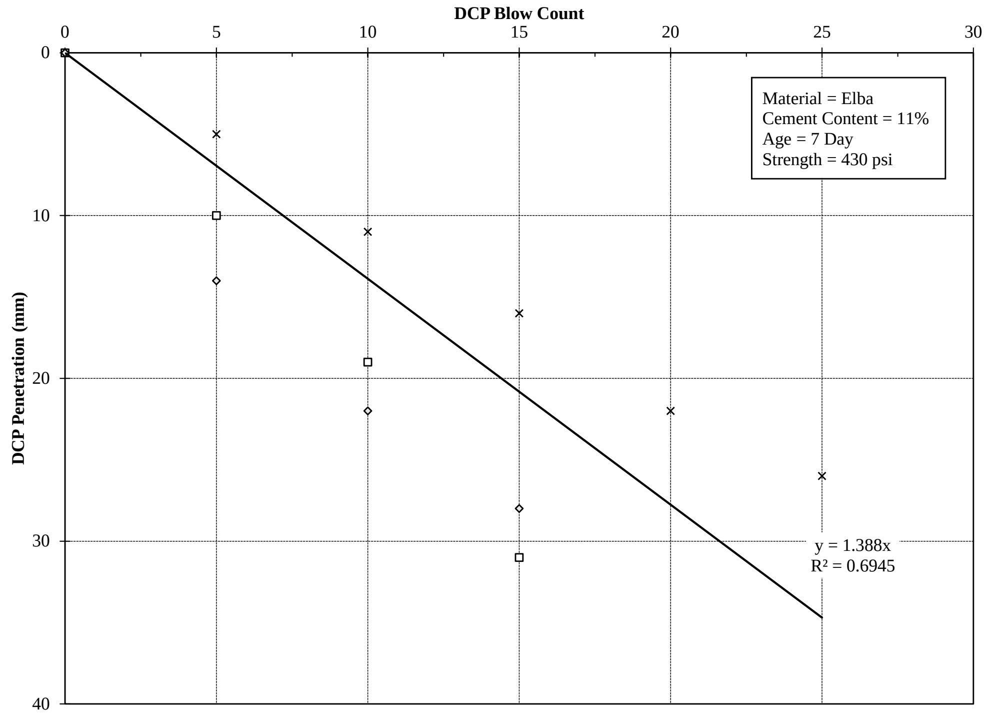

Figure I.12: Elba 11% 7 Day

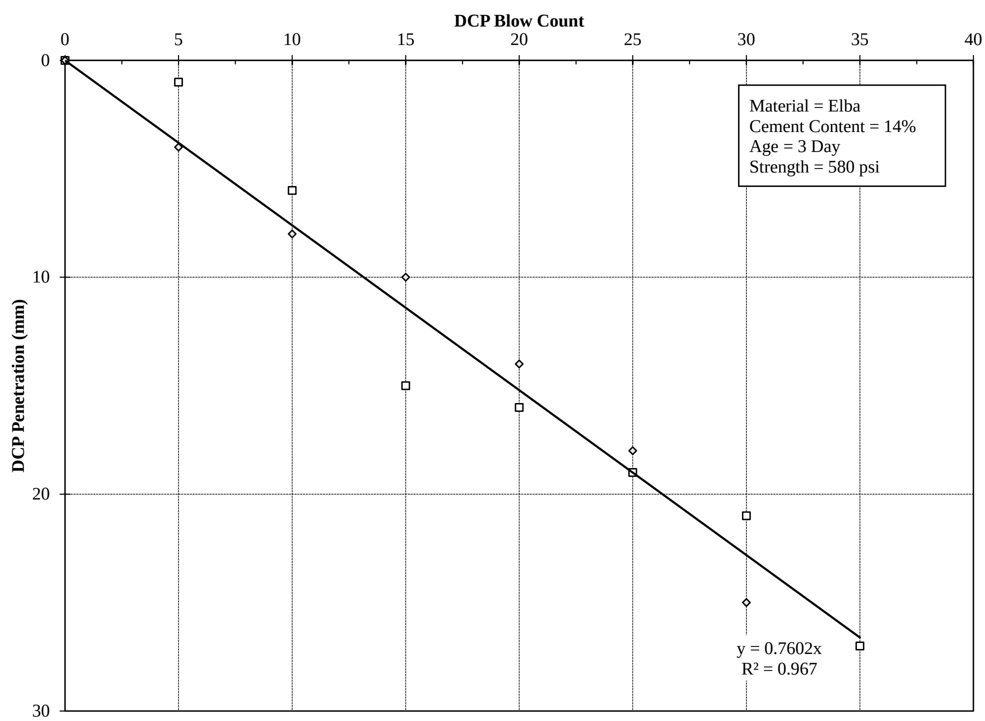

Figure I.13: Elba 14% 3 Day

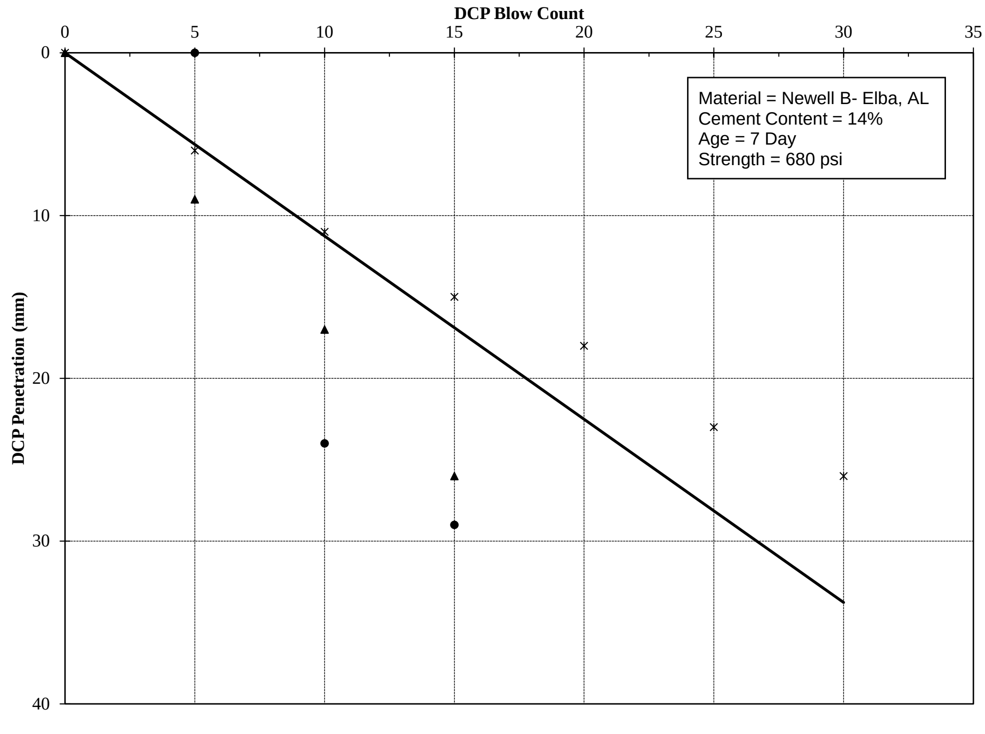

Figure I.14: Elba 14% 7 Day

Appendix J

DCP to MCS Correlation Data

Table J.1: Data for McElvaney and Djatnika (1991) DCP to UCS Correlation

UCS	DCP
psi	mm/blow
6	100
10	50
21	20
27	15
37	10
40	9
44	8
49	7
55	6
64	5
77	4
97	3
135	2
203	1

Table J.2: Data for Patel and Patel (2012) DCP to UCS Correlation

UCS	DCP
psi	**mm/blow**
361	1.3
339	1.4
260	1.9
249	2
175	3
137	4
113	5
96	6
84	7
75	8
68	9
62	10