ENGINEERING BEHAVIOR OF SOFT CLAYS TREATED WITH CIRCULATING FLUIDIZED BED COMBUSTION FLY ASH

by

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Abstract

This thesis presents results from a comprehensive laboratory study carried out to investigate the feasibility of using Circulating Fluidized Bed Combustion fly ash for improvement of engineering properties, particularly strength and stiffness, of soft clays. The CFBC fly ash was obtained from the AES power plant in Guayama, P.R. A soft clay from Hormigueros, P.R. was treated with different admixture percentages of this fly ash. Improvement levels were evaluated based on unconfined compression test carried out at different curing times. Other soil characteristics like plasticity, compaction properties, and expansion were monitored. A comparative analysis was also presented using class C fly ash and Hydrated lime. In general, results indicate that the soil treated with CFBC fly ash showed improvement. However class C fly ash produced a superior effect in the levels of improvement when compared with CFBC fly ash and hydrated lime. Soil samples treated with CFBC fly ash were found to develop crystal formation at 35 days of curing. Recommendations for future works are presented.

Resumen

Este trabajo presenta los resultados de un estudio minucioso de laboratorio realizado para investigar la viabilidad de usar cenizas de carbón que resultan del proceso de cama circulante fluidizada (CCF) para mejorar las propiedades ingenieriles, particularmente resistencia y rigidez, de una arcilla. Las cenizas CCF fueron obtenidas de la planta AES en Guayama, P.R. Arcilla proveniente de Hormigueros fue tratada con diferentes porcentajes de estas cenizas. Niveles de mejoramiento fueron evaluados basados en pruebas de resistencia sin confinamiento a diferentes tiempos de curado. Otras características del suelo como plasticidad, compactación y expansión fueron monitoreadas. Se presenta un análisis comparativo que incluye cenizas de carbón clase C y cal hidratada. En general los resultados indican que el suelo tratado con las cenizas CCF mostró mejoría. Las cenizas clase C causaron un efecto superior en los niveles de mejoría cuando se comparan con las cenizas CCF y la cal hidratada. Se encontró desarrollo de cristales en muestras de suelo tratadas con cenizas CCF a los 35 días de curado. Al final se presentan recomendaciones para trabajos futuros.

to my family…

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1 INTRODUCTION

1.1 General Introduction

Often project sites are located in areas with soft or weak soils. Depending on the nature of the project the design solution may involve the expensive option of removal and replacement of the weak/compressible soils. The replacement option typically entails use of crushed rock, gravel or lightweight aggregates which implies higher cost and involves the use of limited natural resources which is particularly critical for Puerto Rico. Other designs options involve using ground improvement alternatives such as stone columns, grouting, wick drains and chemical admixtures such as cement or lime. This thesis focuses on studying the feasibility of improving weak or compressible soils with chemical admixtures obtained from byproducts of coal-based power plants. Specifically the project will study the improvement of characteristics in terms of strength and stiffness of soils treated with fly ash produced by a local power plant in Puerto Rico.

Recent research has provided evidence that coal combustion by products, such as coal fly ash, are a cost-effective and environmentally friendly ground improvement alternative. This study was motivated due to the existence of a power plant in Puerto Rico that generates large amounts of fly ash with unique chemical and physical properties that could be recycled using this application.

Past research has established the potential of using fly ash for a variety of construction applications, such as structural fills, concrete admixtures, liners and to stabilize expansive soils (e.g., Lane and Best, 1982; Edil et al., 1987; Usmen et al.,1992; Cokca, 1997; Cokca, 2001). Most of this research has involved the class C fly ash, however the Puerto Rico power plant produces CFBC fly ash. This one has different properties than class C. Despite the existing body of knowledge body of knowledge, little has been published regarding the applicability of CFBC fly ash for ground improvement applications. This research proposes an experimental program to determine the suitability of using CFBC fly ash from AES Puerto Rico Power Plant to improve the properties of high plasticity soft clays.

This chapter presents the motivation for this thesis research project, the objectives, and a description of the organization of this thesis.

1.2 Motivation

CFBC fly ash has important physical and chemical differences compared to conventional or pulverized coal fly ash (typically class C or F) obtained from other combustion processes. Pulverized fly ash has been successfully used in several countries around the world for the engineering application of stabilization or strengthening of poor soils. However these previous experiences or studies are not directly transferable to improvement of poor or compressible soils using CFBC fly ash. This investigation will try to fill this gap. This research is motivated due to the many structural damages that arise when foundations or roadways are built over weak compressible soils. Furthermore if CFBC fly ash obtained from AES power plant were proven to be adequate to improve soil or roads over weak subgrades this would offer a solution with both economic and environmental advantages. The environmental motivation for this study is to help find recycling applications for this coal combustion by-product and avoid disposal options in the small island of Puerto Rico which are limited and/or expensive.

1.3 Objectives

The main purpose of this study is to determine if CFBC fly ash from AES Puerto Rico is suitable for engineering ground improvement of soft clays. The evaluation will be made using a high plastic clay soil from Hormigueros, Puerto Rico.

More specific objectives of this work are as follows:

- Evaluate the changes in the engineering properties (e.g., strength, stiffness, compaction, plasticity) of a soft clayey soil when different percents of CFBC fly ash are added.
- Determine the influence that curing time has in the levels of ground improvement achieved.
- Compare the ground improvement levels achieved using CFBC fly ash with class C fly ash and lime.

1.4 Organization of thesis

This thesis is organized into six chapters and three appendices. Chapter 1 provides a general introduction of the research problem, the motivation and the research objectives. Chapter 2 presents background information about fly and lime in general and also regarding engineering ground improvement using admixtures. Chapter 3 presents a literature review regarding previous studies related to ground improvement using fly ash. The description of the materials used in this thesis is presented in Chapter 4. The fifth chapter describes the experimental program carried out as well as the test results. The test results are discussed in terms of changes in the engineering properties of soft clays. Chapter 6 finally presents the conclusions drawn from this study and provides recommendations for future works.

2 BACKGROUND

2.1 Introduction

The purpose of this chapter is to present information related to the classification, applications and processes of fly ash and some statistics about the utilization of this material since 1981 until 2004. It also present information related to lime and ground improvement.

2.2 Fly Ash

Ground modification techniques have become a major part of civil engineering practice over the last 30 years (Hausmann, 1990). Improvement of sites with weak or compressible clay foundations is commonly done by removing the low bearing soils and replacing them with more competent ones such as compacted gravel, crushed rock, or lightweight aggregates to increase the load bearing capacity (Kukko, 2000). Although this is considered a good solution, usually has the drawback of high cost due to the cost of the replacement materials. The use of admixtures derived from coal combustion by products (CCPs) such as fly ash is considered a more cost-effective solution which can result in adequate improved engineering properties of the treated foundation soils.

In many countries around the world (e.g., USA, India, Japan, China, Europe) coal combustion byproducts (CCPs) are used in many different applications (IEA, 2005). According to the American Coal Ash Association (ACAA), in 2003 over 121 million tons of CCPs were generated as follows:

- Fly ash – 70 million tons
- Bottom ash – 18.1 million tons

- Boiler slag – 1.8 million tons
- FGD material and other by-products – 31.6 million tons

Approximately 46.3 million tons (i.e., 38%) of the 2003 CCPs were recycled into useful applications through re-utilization programs. The above quantities indicate that approximately 58% of the CCP's produced are fly ash. In the United States, fly ash production has steadily increased from 1981 through 2004, as shown in Figure 2.1. This figure also shows metric tones of fly ash reutilized each year. It can be seen that fly ash reutilization has increased from less than 10 million metric tons in 1981 to about 25 million metric tons in 2004. This increase is a positive trend but still less than 50% of the annual production is being reutilized hence constituting a waste. Stimulation of CCPs recycling and reutilization is being promoted through utilization programs such as the one promoted by the American Coal Ash Association (ACAA).

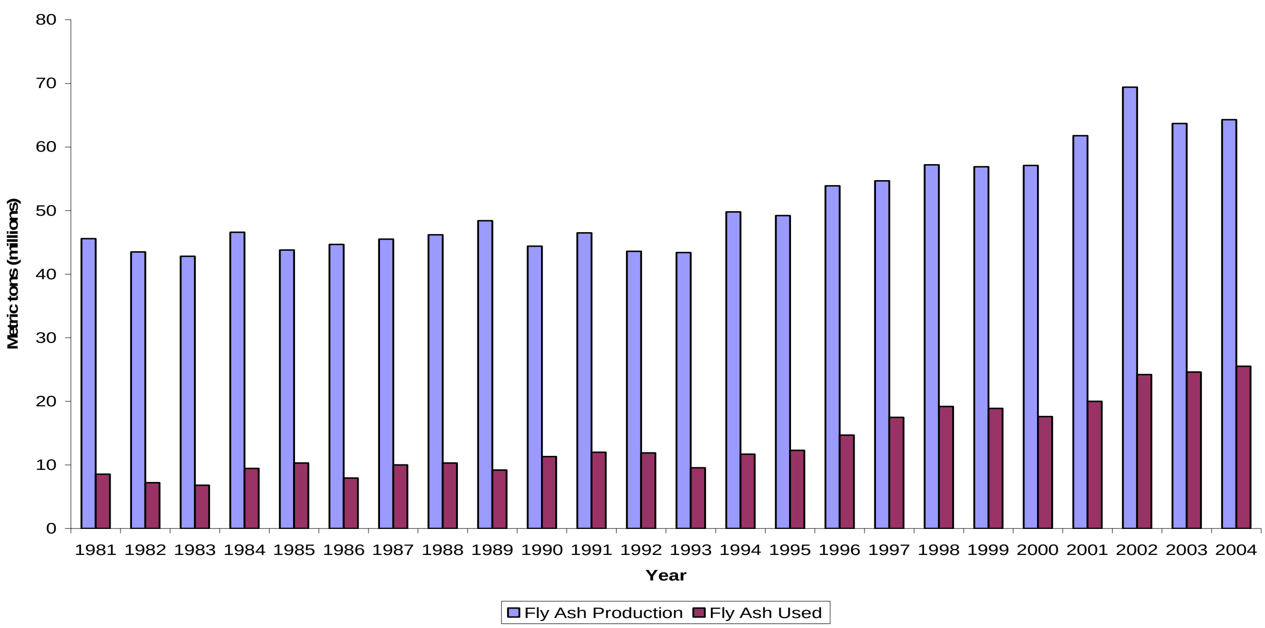


Figure 2.1 Fly ash production and re-utilization statistics for the US (adapted from Kelly and Matos, 2005)

2.2.1 General definition of fly ash

ASTM C593-95 defines fly ash as the finely divided residue that results from the combustion of ground or powdered coal and is transported from the boiler by flue gases. The physical and chemical characteristics of fly ash vary greatly and mainly depend on the combustion method, coal properties, and particle shape of the fly ash.

According to the literature, coals from different sources produce different burning characteristics and these differences will influence the effectiveness of fly ash as a soil stabilizer. These different sources can categorize the coal as lignite coal, sub-bituminous coal, bituminous coal and anthracite coal. Each of them has different properties based in the carbon content, hardness and geological age among others.

This subsection provides background information related to fly ash composition which will help illustrate the range of property values that this material can have.

Two main coal-based power generation technologies are: Pulverized Coal (PC), and Fluidized Bed Combustion (FBC). PC technology is the most popular method and it refers to any combustion process that uses very finely ground (pulverized) coal in the process. In this type of system, the coal is processed by grinding it to a very fine consistency for combustion and the ash is formed in the combustion chamber while the coal combusts (Undeerc, 2007). Figure 2.2 presents a schematic drawing of the pulverized coal combustion process. This process results in 65 to 85% fly ash while the remaining material is bottom ash and boiler slag.

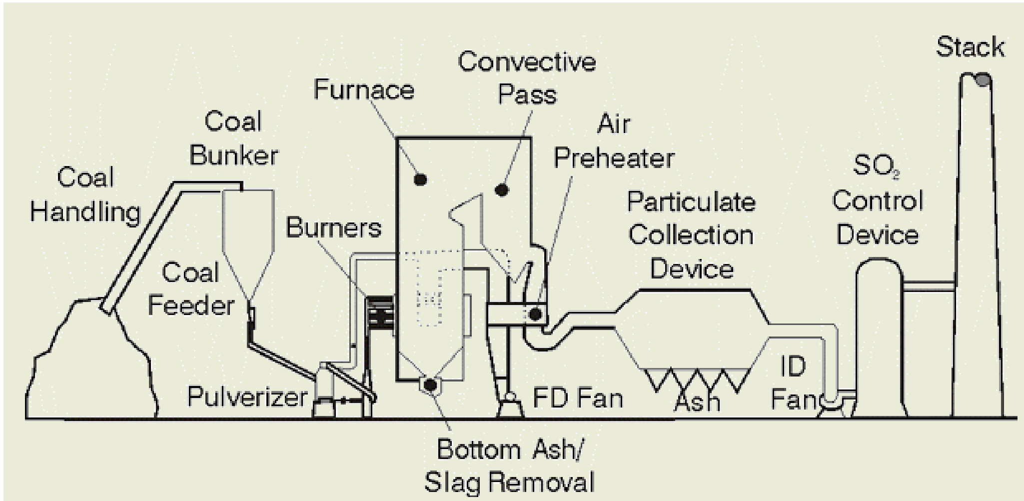


Figure 2.2 Pulverized Coal Process (from Undeerc, 2007)

FBC is a technology that uses a coal boiler which accomplishes coal combustion by mixing the coal with a sorbent such as limestone ($CaCO_3$), dolomite or other bed material (Figure 2.3). The fuel and bed material mixture is fluidized during the combustion process to allow complete combustion and removal of sulfur gases. In this process the sulfur in the coal comes off as sulfur dioxide (SO_2) and is converted to calcium sulfate ($CaSO_4$). The following equations show the chemical reaction in the process described above (Anthony et al., 2003):

$$CaCO_3 \rightarrow CaO + CO_2 \quad (2.1)$$

$$CaO + SO_2 + 1/2\ O_2 \rightarrow CaSO_4 \quad (2.2)$$

FBC is a low cost combustion method for obtaining energy particularly from high sulfur coal in an environmentally acceptable manner. Table 2.1 shows a comparison between the PCC and FBC combustion technologies. This table highlights important differences in the resulting ashes such as coal particle size, pH, and porosity.

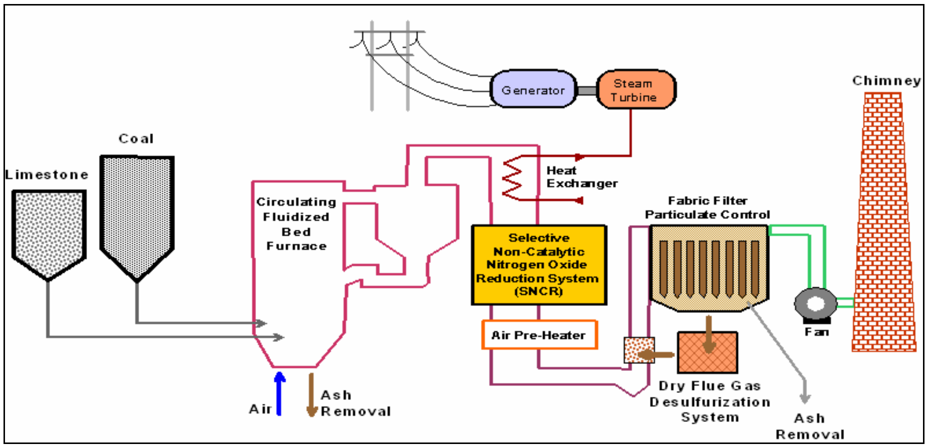


Figure 2.3. CFBC process (from www.dom.com)

Table 2.1. Comparison between PCC and FBC processes (Adapted from Botha 2001)

Parameter	PCC	FBC
CaO in Boiler	No	Yes
Coal Particle Size	< 75mm	1-3 mm
Combustion temperature (°C)	1300-1700	800-900
Ash porosity	low	high
Ash pH	neutral-acidic	alkaline
SO2 emissions (lbs/mm BTU)	1.2	0.1
Nox emissions (lbs/mm BTU)	0.6	0.15
Nox origin	thermal, fuel	Fuel

2.2.2 Fly ash classification

According to ASTM C618, fly ash can be classified into two main types, class C fly ash and class F fly ash. This classification depends mainly on the percentages of silica (SiO_2), alumina (Al_2O_3), and ferric oxide (Fe_2O_3). The typical chemical requirements of both fly ash classes are shown in Table 2.2. Fly ash class C is normally produced from the combustion of lignite or subbituminous coal. This type of fly ash has cementitious and pozzolanic properties. The term cementitious means that the material will harden in presence of water. The term pozzolanic means that in presence of water, fly ash will react with calcium hydroxide at ordinary temperatures to also produce cementitious compounds (Fly Ash Facts for Highway Engineers). Class F fly ash on the other hand is produced from burning anthracite or bituminous coal and is considered to have only pozzolanic properties.

Table 2.2 Chemical Requirements for Fly Ash according to ASTM C 618

Chemical Composition		Class	
		F	C
$SiO_2 + Al_2O_3 + Fe_2O_3$	min %	70	50
SO_3	Max%	5	5
Moisture Content	Max%	3	3
Loss on Ignition	Max%	6	6

The above two fly ash classes (C and F) are considered the most common fly ash types. However, as mentioned before fly ash materials have a wide range of properties and characteristics which depend on factors such as coal type, combustion process, additives, etc. Many fly ashes may not fall within these two categories. As discussed later, this is the case of the CFBC fly ash used in this study.

2.2.3 Hydration of fly ash

Hydration is the process where free lime (CaO) reacts with alumina (Al_2O_3), silica (SiO_2) and ferric oxide (Fe_2O_3) in presence of water to produce a cementitious material. According to Anthony et al. (2003) the hydration process is dominated by direct hydration of the CaO component. In the case of fly ash class C, the high lime content react with the siliceous and aluminous materials known as pozzolans found in the ash itself. On the other hand, class F fly ash has low lime content and in order to achieve a similar hydration process with the pozzolans, addition of lime is necessary. The following equations represent the hydration process described above:

$$CaO + H_2O \rightarrow Ca(OH)_2 \quad (2.3)$$

$$Ca(OH)_2 \rightarrow Ca^{++} + 2[OH]^- \quad (2.4)$$

$$Ca^{++} + 2[OH]^- + SiO_2 \rightarrow CSH \quad (2.5)$$

$$Ca^{++} + 2[OH]^- + Al_2O_3 \rightarrow CAH \quad (2.6)$$

The rate of hydration is an important factor controlling the rate at which the materials will set. This is one of the reasons why delay in compaction of fly ash treated soils is observed and this may also result in lower strengths of the stabilized materials.

2.3 Lime

Lime for ground improvement applications is typically is used in the form of quicklime, CaO, or hydrated lime, $Ca(OH)_2$. Lime is also often used for agricultural purposes as ground limestone ($CaCO_3$). Quicklime (CaO) is manufactured by chemical processes transforming calcium carbonate (limestone – $CaCO_3$) into calcium oxide (CaO). When quicklime reacts with water it transforms into hydrated lime as follows:

$$CaO + H_2O \rightarrow Ca(OH)_2 + Heat \quad \textbf{(2.7)}$$

Hydrated lime ($Ca(OH)_2$) reacts with clay particles and transforms them into a strong material due to chemical reactions. The most used lime for soil treatment or stabilization is “high calcium” lime which contains less than 5 percent magnesium oxide or hydroxide. The soil stabilization with lime occurs through pozzolanic reaction causing a long-term strength gain. The calcium from the lime reacts with the aluminates and silicates from the clay producing stabilization along with hydration process. As a result, lime treatment can produce high and long-lasting strength gains. The stabilization degree will depend on the soil type, a good mix design, and reliable construction practice.

2.4 Soil stabilization

2.4.1 Techniques used for soil improvement

According to the FHWA (Elias et al. 2000) ground improvement technologies are geotechnical construction methods used to alter poor ground conditions to meet project requirements, where replacement or bypass of such condition is not feasible. A soil is stabilized by altering its engineering properties and thus improving its performance. Depending on the method used to stabilize a soil, there are several principal properties that are affected in a positive way. Characteristics such as plasticity, unit weight, water content, strength, and hydraulic conductivity are among them.

From the engineering point of view, the main functions of soil improvement techniques are to increase the bearing capacity, to reduce the liquefaction potential, to accelerate consolidation, increase density and to control deformations. Several commonly used ground improvement techniques are:

- Wick drains
- Preloading
- Lightweight fills
- Vibrocompaction and Dynamic Vibrocompaction
- Deep dynamic compaction
- Reinforced soil
- Chemical stabilization through soil admixtures
- Stone columns
- Grouting

The technique discussed in this study is the chemical stabilization through soil admixtures. Chemical stabilization refers to the increase in strength due to a chemical reaction between the soil and the admixture. There are different ways of mixing additives and it will depend on the application. A common way of preparing a surface to be stabilized is excavating and breaking up the soil, adding the stabilizer and water if necessary. After that, soil and additive are mixed thoroughly, compacted according specifications and finally cured. For the mixing stage are available different processes and equipments as the mix-in-place equipment. This technique is effective in the way that the soil and the additive can be mixed and compacted at the same time avoiding the delay that causes a decrease in the strength of the soil-mixture. The disadvantage of this is the difficulty to produce a homogeny soil-mixture. The mixing process in a stationary plant can yield better results but the cost of material transportation makes this a less cost-effective option.

2.4.2 Soil-fly ash stabilization

Many researchers have studied the mechanism that contributes to the stabilization process of soils treated with fly ash. According Acosta et al. (2003) there are three primary mechanisms contributing the stabilization. The first one is that strength of the soil increases as result of the cementation produced from hydration of tricalcium aluminate present in the fly ash. Other mechanism is that free lime (CaO) in the fly ash reacts with the clay minerals, causing compression of the absorbed layer and reduction in plasticity. Finally, the free lime that does not react with the clay minerals is available for additional cementation process through pozzolanic reaction with silica and alumina compounds.

Cocka (2001) explains that the stabilization of soils treated with fly ash is the result of cation exchange between the clay particles and aluminum (Al^{3+}), calcium (Ca^{2+}) and iron (Fe^{3+}) in the fly ash. He describes the stabilization process indicating that fly ash can provide an adequate array of divalent and trivalent cations which under ionized condition promote flocculation of dispersed clay particles.

According to White (2005), the initial cementitious reaction is due to the hydration of tricalcium aluminate, he also explains that the strength gain that occurs during curing time periods over 28 days can be attributed to the pozzolanic reactions between calcium oxide and the aluminous and siliceous materials in the fly ash.

All mechanisms of stabilization are related with a chemical change or process. Here is the significance of study and evaluate the properties of the fly ash as of the soil to be treated.

2.4.3 Soil-fly ash compaction characteristics

When fly ash is added to a soil, the compaction characteristics (density and optimum water content) of the soil change. The hydration process produced during the contact between the soil, the ash and the water causes bonding and cementation generating high density values. However adverse effect like density and strength decreasing can arise when a delay period between the addition of fly ash and compaction is allowed. An explanation for this is that the hydration process develops immediately after soil-water-fly ash contact and in order to densify the material, the bondings formed must be disrupted. According to Mackiewicz et al.(2005), a portion of the compactive effort is spent mainly to overcome the initial cementitious bonds and the remaining energy is used to compact the mixture. It has been found that compaction delays of 1 hour after incorporating the fly ash can cause decreases in densities up to 4 to 10 pcf depending the mineralogy of the ash. Mackiewicz et al. (2005) explain that the strength reduction is the result of the rupture of the cementitious bond that occurs during compaction and reduced number of intergranular contact. These authors suggest avoiding any time delays in the field while compacting fly ash treated soils.

3 LITERATURE REVIEW

3.1 Introduction

This chapter presents a review of the most relevant literature in the area of soil improvement using fly ash as admixture. Where possible emphasis has been given to references where CFBC type fly ash was used. It presents a synthesis of the lessons learned in terms of the different key variables that need to be considered when designing an experimental study such as one proposed for this study.

The literature review carried out for this thesis reveals that most of the existing studies related to ground improvement using fly ash have involved either Class C or Class F fly ash produced using combustion processes different than the CFBC process discussed in Chapter 2. Hence there is limited work published related to ground improvement studies involving use of fly ash from CFBC technology like the one produced by AES Puerto Rico. Furthermore, despite the existence of a few studies on CFBC fly ash even these may not be adequate given the differences in chemical and physical composition of the AES CFBC fly ash. As mentioned before, these differences are due to a large extent, to the particular type of coal and sorbent used. Another important consideration is the fact that the physical and chemical properties of the soil will also influence the results and levels of soil improvement.

3.2 Previous studies

Trzebiatowski et al. (2004) presented a case study involving stabilization of a road subgrade using fly ash class C from the Pleasant Priarie Electric Power plant in Wisconsin. The soft subgrade of the road was stabilized “insitu” by spreading fly ash over the weak soil using a laydown truck. The result of this work was a firm working platform which provided good conditions for road construction. The laboratory tests in this project confirmed the field results showing significant stiffness and strength gains where using subgrade improvement with fly ash stabilization.

Another study by Cokca (2001) involved an evaluation of expansive soil stabilizing using low calcium and high calcium class C fly ash mixtures from Turkey Power Plants. The study also included comparison with treatment using lime and cement. The results showed that a mixture with 20% fly ash had nearly the same stabilizing effect on the swelling potential as a soil treated with 8% lime. The author also found that the addition of the stabilizers changed the classification of the treated soil. This observed change was due to the additional silt size particles added from the fly ash and also is related to the chemical reaction that cause immediate flocculation of the clay particles. The author concluded that high-calcium class C fly ash can be an effective stabilizing agents for expansive clayey soils.

A similar study to investigate the effectiveness of class C fly ash as a stabilizer of expansive soil in Turkey was performed by Nalbantoglu (2004). This study showed reductions of the plasticity index of high plasticity soils. However little influence on the plasticity index was observed on already low plastic fine soils. The study found that fly ash was an effective way of reducing the swell potential for one of the tested soils; however the study showed adverse effects for other of the studied soils. This study helped highlight the importance of considering the chemical composition of base soil being treated and how this will affect the effectiveness of the improvement levels expected when using fly ash.

In Iowa State University, White (2005) prepared construction guideline for stabilization of non-uniform subgrade soils using self-cementing fly ash. This study evaluated five soil types and different fly ash sources. The study included evaluation of hydrated and conditioned fly ashes from six power plants in Iowa. The laboratory test program revealed that strength gains in the soil-fly ash mixtures depends greatly on curing time and temperature, compaction energy, and compaction delay. CBR test results showed that soils treated with 20% by weight of fly ash can have CBR values similar to those from compacted gravel.

Acosta et al. (2003) studied the effects of adding class C and unclassified fly ash to soft organic soils. The authors found that fly ash may not be practical or effective for treatment of organic soils due to hydration inhibition due to the presence of the organic matter. This study carried out CBR tests which showed that soils with 10% or more of organic matter inhibited pozzolanic reactions, resulting in smaller increases in CBR compared to those recorded from inorganic soils with similar levels of treatment with fly ash. For soils with low organic content, this study revealed that addition of 10% fly ash resulted in unconfined compression strengths increased by a factor of 3, and adding 18% fly ash yielded unconfined compressive strengths increased by a factor of 4. In relation to curing time, this study found that curing periods longer than 7 days produce only marginal increases in unconfined compressive strength with respect to the gains observed in the first week of curing.

Nalbantoglu et al. (2001) found that addition of lime or fly ash decreases swelling potential in expansive soils. The hydraulic conductivity of treated soils was also found to increase with increasing lime or fly ash and with increasing curing time.

In Finland, Kukko (2000) carried out an investigation focused on different binder alternatives based on industrial by-products. In this study the author included commercial stabilization binders which are mainly based on coal fly ash. Comparison of compressive strength results of clays stabilized with different byproducts binders showed that in general values for samples stabilized with byproducts were higher than results from samples stabilized with cement based products. Furthermore the rate of hardening of by-product binders was slower than the rate observed for cement-based binders. Tests were carried out using binder contents up to 20-30% by weight of the sample of dry clay.

Edil et al. (2002) conducted a field evaluation of construction alternatives for roadways over soft subgrade soils. The evaluation took place along a 1.4 km segment of State Highway 60 in Wisconsin. Different by products where evaluated such as fly ash, bottom ash, foundry slag, and foundry sand. Class C fly ash was used for a test section of 305 m. Unconfined compression tests showed that using a of 10% fly ash admixture (on the basis of dry weight) was sufficient to provide the necessary strength gain for roadway construction on the originally soft subgrade (Acosta et al. 2003). This study concluded that ground stabilization using class C fly ash was adequate and provides equal or better stiffness improvement levels as those recorded within the test sections constructed using the traditional method of excavating and replacement with rock aggregate.

Zachary (2002) studied the properties of soil-fly ash subgrade mixtures. The author found the real advantage to using fly ash is long-term strength gain for poor subgrade soils under pavements. The samples were cured in a 100% humid environment at 72°F. It was observed that soil mixed with atmospheric fluidized bed combustion (AFBC) ash showed considerable volume increase. The explanation to this is that AFBC ash contains high amounts of sulfur and when mixed with water, calcium, alumina, and silica forms long, needlelike crystals of ettringite which cause the volume expansion. In relation with delay on compaction Zachary (2002) indicates that when fly ash, soil, and water are mixed, the clay particles in the soil to flocculate and agglomerate. Agglomerated soil particles have less of a tendency to be compacted into a tight mass hence resulting in lower densities and reduced strength values. With this investigation he concludes that fly ash used for stabilization should be self-cementing and contain less than 5% sulfur to reduce the swelling potential, also recommends that soil-fly ash mixtures should be compacted as close to completion of mixing as possible to reduce flocculation and agglomeration effects. Finally, as result of adding 30% fly ash, the moisture content of wet soil were reduced by 9%; while the soil gains strength at the same time.

Misra et al. (2005) studied the physico-mechanical behavior of self cementing class C fly ash-clay mixtures. The study evaluated the short and long term strength and stiffness developed by the mixtures in terms of gain in compressive strength, failure strain and swelling potential. Samples were prepared adding montmorillonite (bentonite) quantities varying from 5, 10 and 20% to determine the effect of the clay mineralogy in the results. Results obtained from the analyses showed changes in the optimum water content due to the addition of fly ash to the prepared clay mixtures. Results from this study show that samples rapidly gained compressive strength and stiffness within 7 days curing period. After 28 days of curing, the samples became very brittle. Results also show reduced swelling potential with increasing amounts of class C fly ash.

The above studies are some of the most relevant publications found related to the subject of soil improvement using fly ash as a chemical admixture. These studies provide important evidence supporting the use of fly ash for ground stabilization projects. However all of these studies used non-CFBC fly ash for their evaluations. Further studies are needed to evaluate the suitability of using CFBC fly ash. An important point revealed from this literature review is that the success of the ground improvement process will depend to a large extent on the chemistry of the fly ash used as well as the properties of the soil being treated (i.e., organic content, mineralogy, etc). Hence project specific studies appear to be necessary, at least for large projects, in order to design the ground improvement scheme to be used.

3.3 Variables affecting the ground improvement levels of fly-ash treated soil

This section provides a summary of the key variables found to affect the soil improvement levels of fly ash treated soils. Table 3.1.1 summarizes the key variables found during the literature review carried out for this research. The following paragraphs explain the key variables in more details.

3.3.1 Quantity of stabilizer

As expected, and supported by findings from previous studies summarized in the previous section, the quantity of stabilizer (i.e., fly ash) plays a vital role on the final levels of improvement observed. However most studies determined that the increase is not unlimited and will be maximum at an optimum quantity of fly ash. Studies listed in Table 3.1 show that quantity values of admixtures go from 5 to 30% by dry weight. However, based on the experimental results reported in Table 3.1, the optimum amount of fly ash to be mixed with the soil can typically be expected between 10 and 25%.

3.3.2 Water content of soil-fly ash admixtures

The water content of soil-fly ash specimens is a variable which will greatly influence the strength and stiffness results obtained from unconfined compression tests. According to the studies presented in Table 3.1 there is no specific water content value at which the specimens should be prepared and tested. Common values used have been from the dry or wet side of the optimum moisture content of the compaction curve. Other water content values used have been the corresponding to the optimum moisture content value obtained from the soil compaction which is typically based on the Proctor Standard or Modified Proctor Standard.

3.3.3 Curing conditions

Studies listed in Table 3.1 seem to suggest that curing temperature has an important effect on the strength and stiffness gains observed. However, there is no definite recommended value for optimum curing temperature. Cokca (2001) and Nalbantoglu (2004) used a curing temperature of 22˚ C and a relative humidity of 70%. Edil et al. (2002) and Jacobson et al. (2002) do not provide the value of curing temperature but cured samples at 100% of humidity.

3.4 Summary

The literature review revealed several studies that showed use of class C or class F fly ash as a ground improvement chemical admixture is feasible and in many cases effective. It also showed that these types of fly ash are effective for reducing swelling potential of expansive clays. The literature review helped define the key variables affecting the ground improvement levels of fly-ash treated soils. The literature also seems to support the notion that ground improvement levels will highly depend on the composition of the soil to be treated. Actual projects should carry out site-specific studies to help design the ground improvement scheme to be used.

Table 3.1 Key variables affecting levels of ground improvement

Study	Stabilizer	Engineering Application	% of stabilizer (by dry weight)	Curing time (Days)	Curing temperature	Specimens water content
Acosta et al. (2003)	Class C fly ash	Soil stabilization	0, 10, 18, 30	14, 28	100% humidity	$\omega_{optimum}$ 18% wet of $\omega_{optimum}$
Edil et al. (2002)	Class C fly ash	Field evaluation Roadway over soft subgrade	10	7, 28	100% humidity	ω_n
Nalbantoglu (2002)	Class C fly ash	Expansive clay stabilization	0, 15, 25	0, 7, 30, 100	22˚C & 70% humidity	$\omega_{optimum}$
Cokca (2001)	Fly ash + lime+ cement	Expansive soil stabilization	0 & 25→F.A. 0 & 8→lime+cement	7, 28	22˚C & 70% humidity	n/s
Jacobson et al. (2002)	Lime-cement	Factors affecting lime-cement colums	0→100	7,14,28,56	5,10,20 & 40, 100% humidity	ω→LL
Phani et al. (2004)	Fly ash	Expansive soils	0, 5, 10, 15, 20	n/s	n/s	$\omega_{n + 20,25,30,35}$
Glazewski (2004)	Class C Fly ash	Clayey soils stabilization	0, 20, 40, 60, 80, 100	n/a	n/a	$\omega_{optimum}$
Kukko (2000)	Cement-lime, slag, desulfuration waste, binders based on fly ash	Clayey soils stabilization	10, 15, 20, 30	7, 28, 91, 180	8, 20 & 60˚C	n/s

n/a=not apply n/s=not specified

4 MATERIALS

4.1 Introduction

This chapter presents descriptions for the materials used for the experimental program of study. The materials used include: the soft clay (base soil), CFBC fly ash, class C fly ash and lime.

4.2 Soil description

The base soil to be treated (or improved) in this investigation was retrieved from a project located in Hormigueros, Puerto Rico, as shown in Figure 4.1. The project is related to the conversion of road PR2 to an expressway (PH-3). The geographic coordinates of the sampling site were N 33311.508 m and E 80898.749 m, this coordinates were obtained using a Total Station by the surveyor in charge of the project.

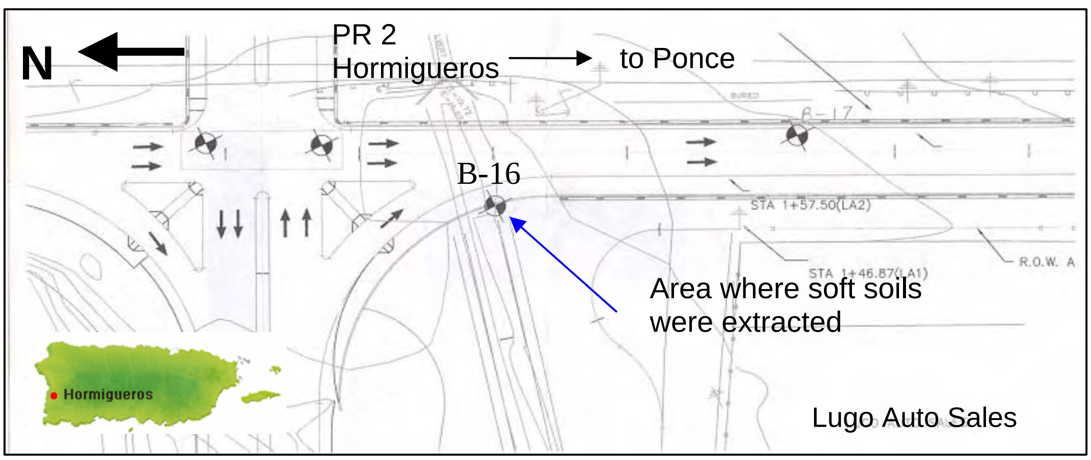


Figure 4.1 General location map showing base soil sampling site

This sampling location was chosen because the project involved large extents of soft soils and included use of several ground improvement techniques. Specific ground improvement techniques used at this project included vibrated cement columns (VCC) and preloading and wick drains. At the moment of the sample extraction, the site was in earth moving phase. This project was selected do to existence of compressible soft soils. The soil samples were retrieved from boring no.16 at an approximate depth of 14 ft from the road elevation with the aid of an excavator (see Figure 4.2). Figure 4.3 shows the borehole log for boring No. 16 which shows the general soil conditions of the sampling site. This figure also presents SPT and moisture content from borehole No. 16. The water level was found to a depth of 13 ft at the moment of the excavation. The soil was dark gray and occasionally olive green. Oxidation was visible in some soil pockets which presented a red-orange color. Traces of sand were also visible. The bottom of the excavation showed clay with a soft consistency and very high plasticity. Several 5 gallon pales were sampled and transported to the geotechnical laboratory of the University of Puerto Rico for further testing and evaluation. The sampling process also included retrieval of undisturbed Shelby tubes for evaluation of unit weight and strength.

Figure 4.2 Sampling excavation pit

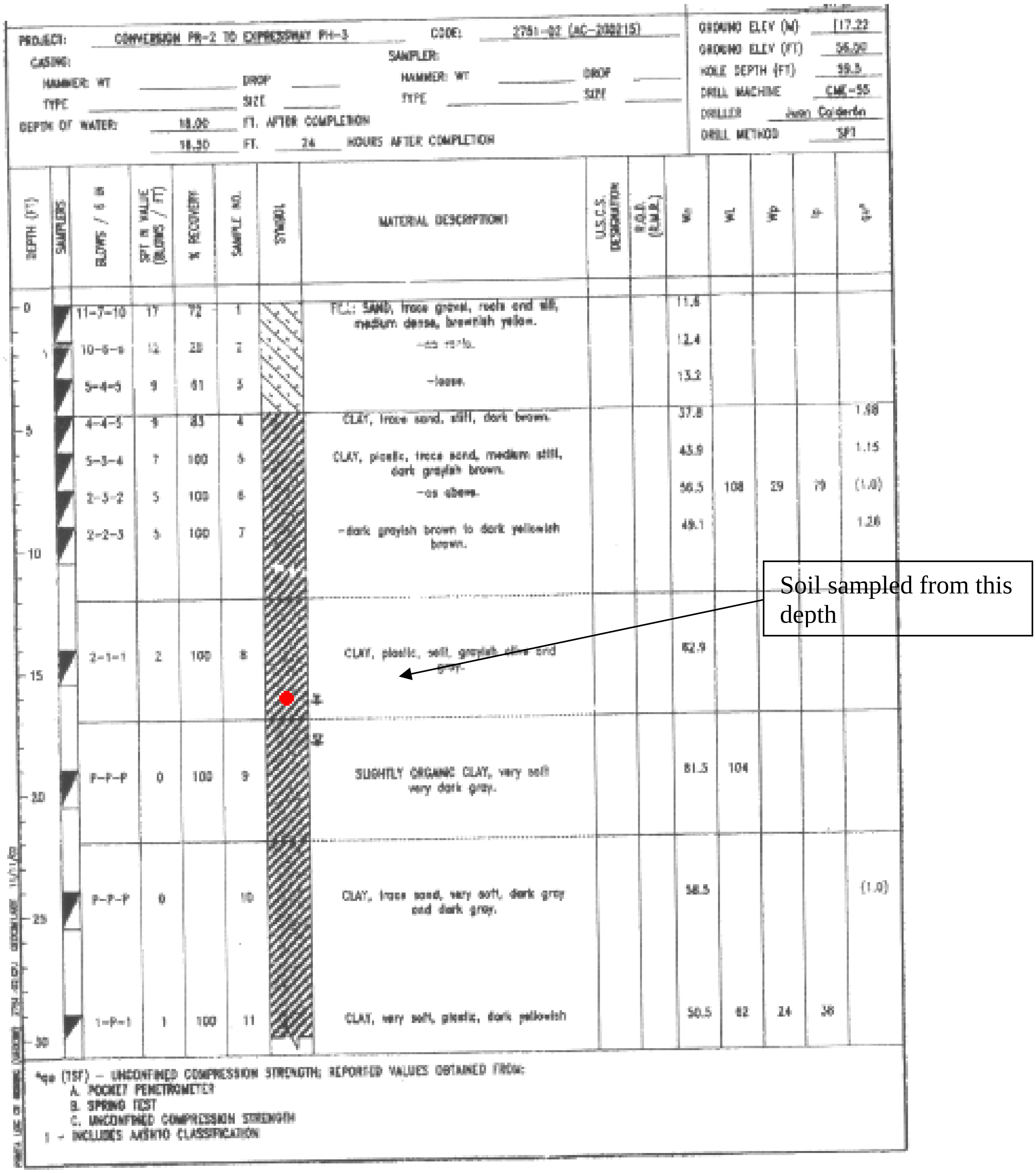


Figure 4.3 Soil profile of the sampling site

4.2.1 *Base soil classification*

4.2.1.1 *Particle size analysis*

Sieve and hydrometer analyses were conducted on a representative sample of the base soil in order to determine its particle size distribution. Figure 4.4 shows the particle size distribution curve for the base soil. According to the figure, approximately 20 percent of the base soil particles are sand sizes, 22% are silt sizes and 58% are clay sizes. The AASHTO Classification System classifies this soil as A-7-5. The general subgrade rating is fair to poor. A scanning electron microscopy (SEM) image of the clay portion of the base soil is shown in Figure 4.5.

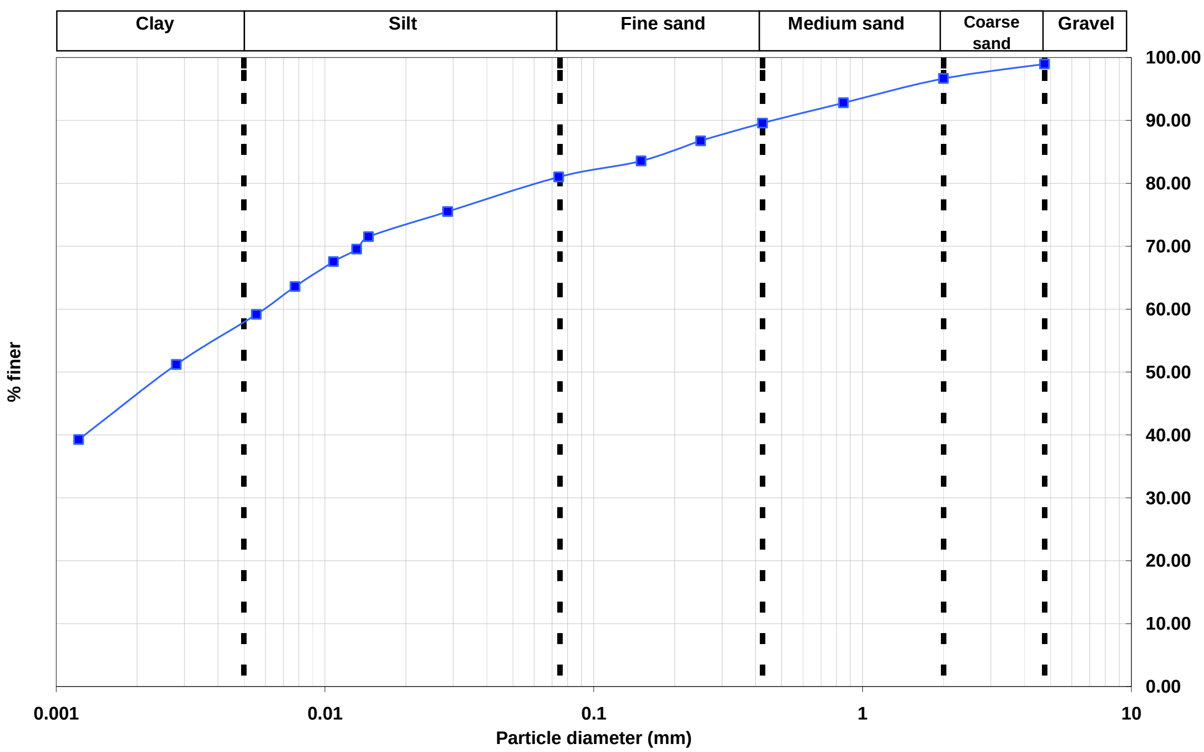


Figure 4.4 Particle size analysis of soil from Hormigueros

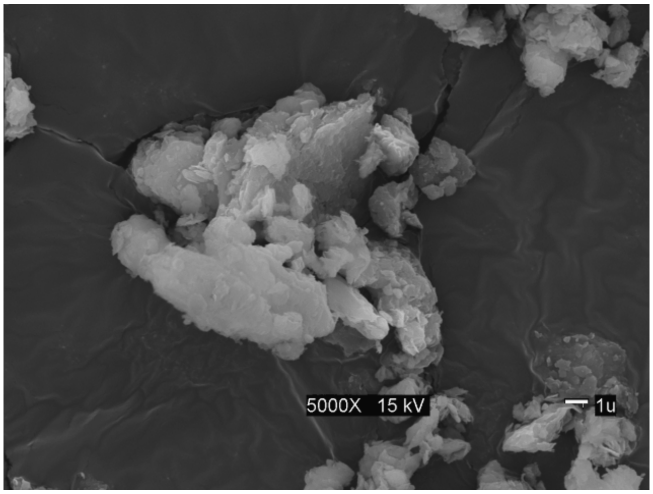


Figure 4.5 SEM image of clay portion

4.2.1.2 Atterberg limits

Atterberg limits for the base soil were determined following test procedures according to ASTM D3418. The Liquid limit was found to range between 80 and 90%, and the Plastic limit ranged between 35 and 37%. This corresponds to a Plastic index values between 45 and 53%. The obtained Atterberg limits correspond to high plasticity clay as shown in Figure 4.6. The solid dots represent the Atterberg limits for the base soil.

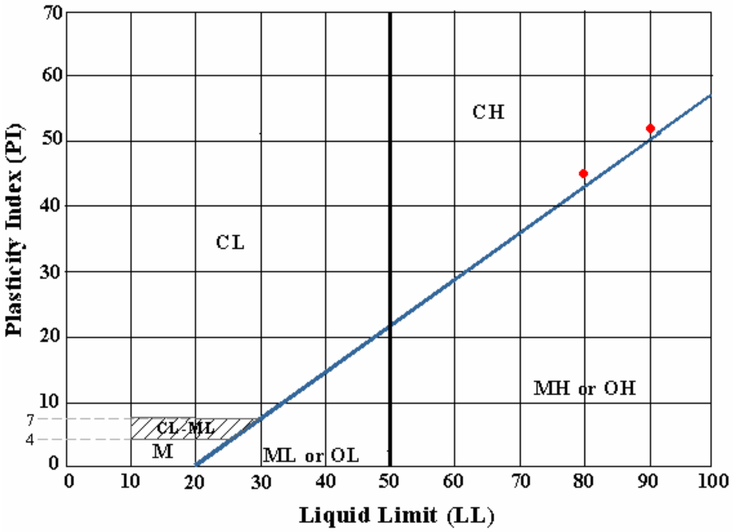


Figure 4.6 Unified soil classification plasticity chart
(Adapted from **http://www.crma.ac.th**)

4.2.1.3 Other index properties

As part of the characterization of the base soil the following additional index properties were assessed:

- Specific gravity (Gs): Obtained using procedure described in ASTM D854. The specific gravity of Hormigueros clay was found to be 2.68.
- Natural moisture content (ωn): Based on the different disturbed and undisturbed soil sample retrieved from the site the natural moisture content ranged between 59 to 64%.
- Moist unit weight (γmoist): Samples from the shelby tube yield values between 103 and 106 pcf.
- pH: Results indicated that pH for Hormigueros clay was in the range of 7.4 to 7.6.
- Specific surface: The specific surface area of Hormigueros clay was found to be 222.42 m^2/g which is a typical value of clays particles.

4.2.2 Organic matter of base soil

The organic matter content of the base soil sample was determined using the Walkley-Black method. This method quantifies the amount of oxidizable organic matter (OM) in presence of a known amount of potassium dichromate ($K_2Cr_2O_7$) and sulfuric acid (H_2SO_4). The calculation of OM assumes that 77% of the organic carbon is oxidized by the method and that soil organic matter contains 58% carbon. The equations to calculate the organic content (OC) and organic matter (OM) are as follows:

$$\% OC = \frac{((\text{ml potassium dichromate})*N - (\text{ml ammonic ferrous sulphate})*N)*0.003g/ml}{\text{Soil solid weight}} \quad (4.1)$$

$$\%OM = \%OC*(1/0.77)*(1/0.58) \quad (4.2)$$

During the procedure, 0.5 g of air dried soil is transferred to an Erlenmeyer flask with a capacity of 500ml. Ten milliliters of potassium dichromate 1N and 20 ml of sulfuric acid are added to the soil in the flask. The solution is left to rest for a 30 minutes period. After the resting period, 200ml of distilled water and 5 drops of ferroine are added and the solution is hand agitated. At this point start the process of titration with ferrous ammonium sulfate at 0.5N. The OC and OM are calculated with the results obtained from the titration process. For the Hormigueros clay, the organic matter values were found to range between 1.2 to 2.2%.

4.2.3 Mineralogy of base soil (XRD)

The mineralogical composition of the base soil was evaluated using X Ray Diffraction analysis on the clay fraction. The XRD tests required first dissolving the carbonates and organic matter using sodium acetate. This process took approximately 3 hours. The clay fraction was separated from the sand and silt fractions by mean of centrifugation using a velocity of 700 rpm. The soil sample was centrifuged until the entire clay fraction was decanted. The clay fraction was dried using liofilization process. This method prevents the loss of structural water which is important in minerals like halloysite.

A qualitative XRD scan analysis was carried out using a Siemens XRD diffractometer D 5000 at 40 mA and 45kV. The step size used was 0.02 and the start and stop angles were 4 and 70 degrees. The minerals found in the clay fraction were kaolinite, halloysite and quartz which are considered to have low expansive potential. Figure 4.7 shows the results of the analysis. The presence of quartz could be the result of some sand or silt particles that dropped into the clay sample during the decanting process from the centrifuge machine. Therefore the main clay minerals of the Hormigueros clay (base soil) are kaolinite and halloysite.

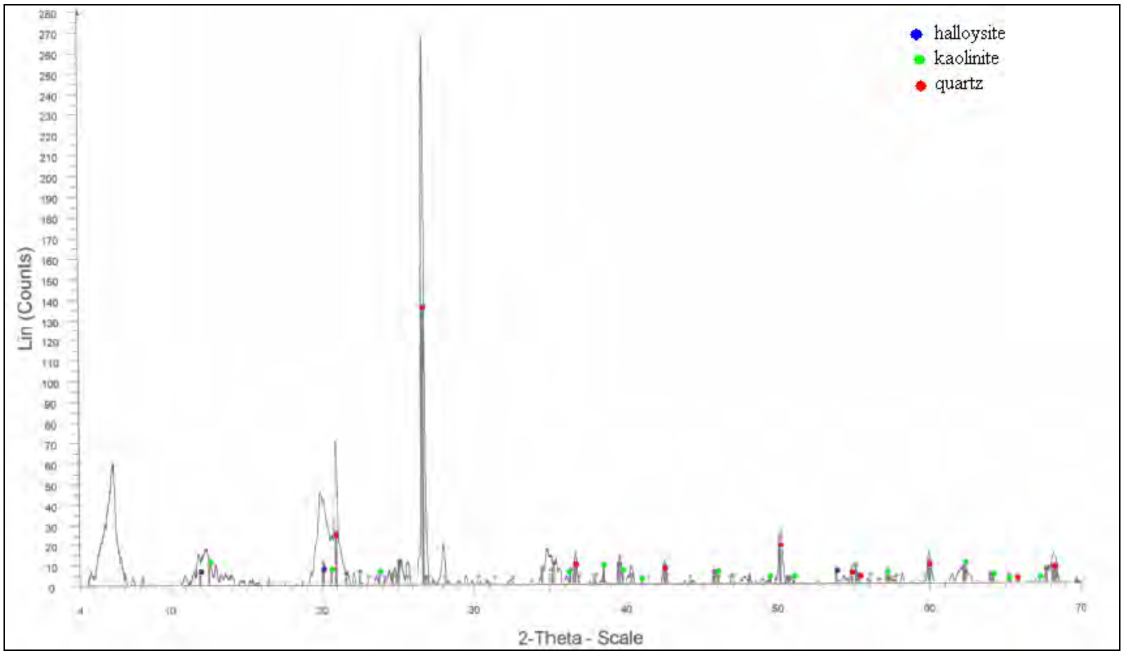


Figure 4.7 XRD for clay fraction of base soil

4.2.4 Base soil Standard Proctor test

The optimum water content and the maximum dry density of the base were obtained using the Proctor standard compaction test carried out according to ASTM D698. As mentioned before, the soil natural water content ranged between 59% and 64%. To obtain the water contents necessaries to develop the compaction curve, values near the plastic limit were selected as a starting point. Figure 4.8 shows the compaction curve obtained and shows an optimum water content close to 31% and a maximum dry density of about 77 pcf.

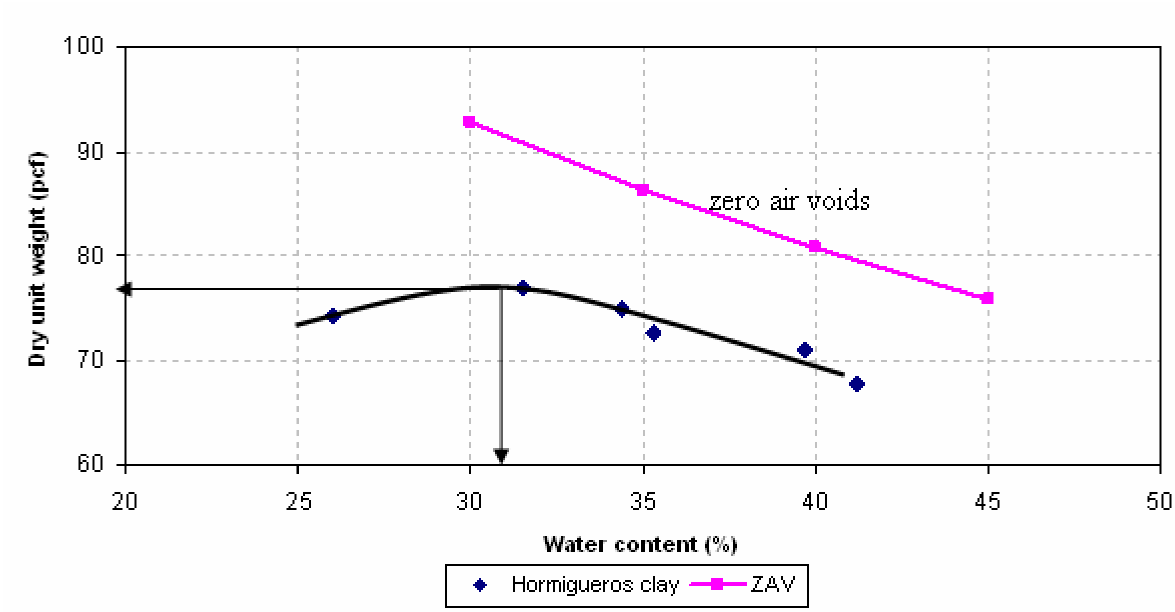


Figure 4.8 Standard Proctor compaction curve for the base soil

4.2.5 Unconfined compressive test of insitu base soil

The insitu strength of the base soil was evaluated with the unconfined compression test according to ASTM D2166. Two samples of undisturbed soil were obtained from the site at the location of boring 16 at a depth of 14ft below the ground level. Both samples were moved to the laboratory in sealed containers. The natural water content of the carefully sealed and transported samples was between 52 and 60%. The unconfined compression test results are presented in Figure 4.9. Photos of the failed samples are shown in Figure 4.10. The sample with an initial water content of 60% showed a maximum deviator stress value of 4.1 psi. The sample with 52% of water content failed at 5.2 psi. These unconfined compression strength values (4.1 and 5.2) correspond to a soil of soft consistency.

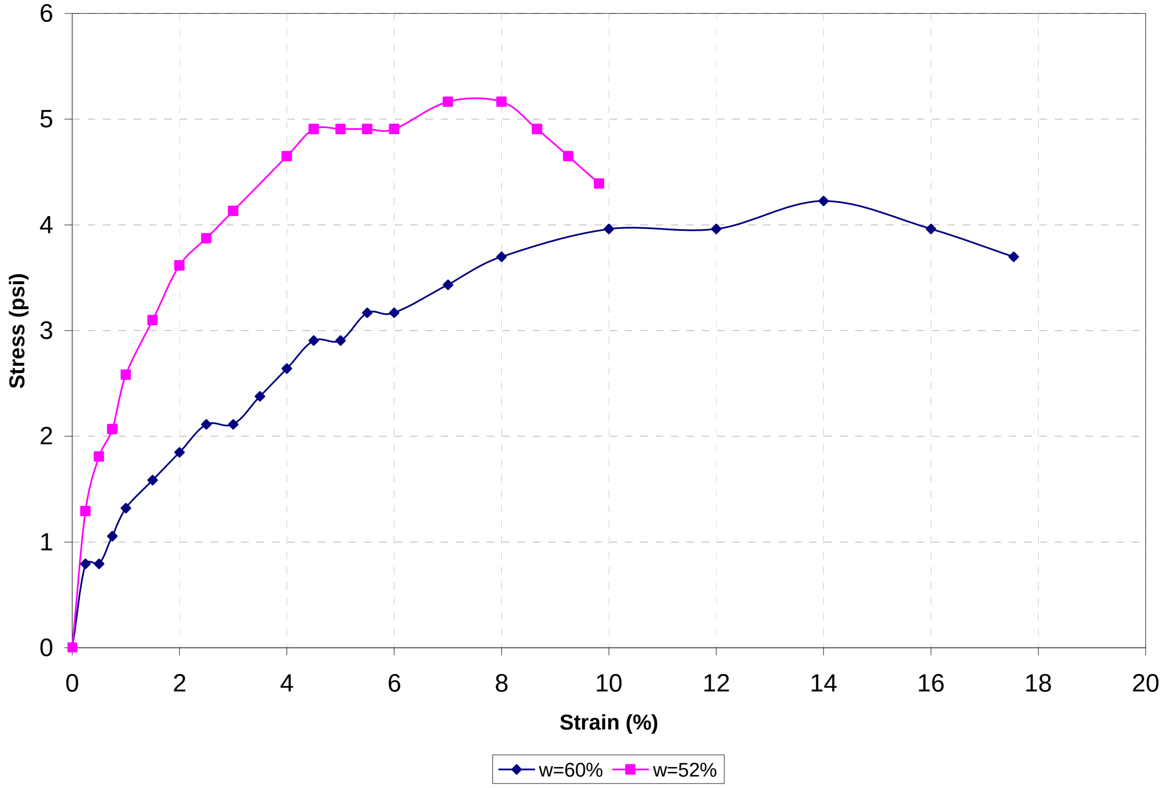


Figure 4.9 Unconfined compression test results for insitu base soil

Figure 4.10 Failed samples of insitu base soil subjected to unconfined compression test.

4.2.6 Summary of base soil testing

The base soil retrieved from a Project site in Hormigueros, P.R. was subjected to several tests for characterization and classification. Table 4.1 summarizes the main results obtained.

Table 4.1 Physical and engineering properties of Hormigueros clay

Property	**Value**
Natural water content	59-64
Liquid Limit	80-90
Plastic Limit	35-37
Plasticity Index	45-53
Gs	2.68
γ_{wet} (pcf)	103-106
pH	7.4-7.6
qu (psi)	4.1-5.2
Organic matter	1.2-2.2
Specific surface (m^2/g)	222.42

Based on there results, the base soil classifies as a soft high plasticity clay (CH) according to the Unified Classification System. The classification according to the AASHTO system is A-7-5. The base soil has predominately clay particles with mineralogy test indicating primarily kaolinite and halloysite.

4.3 CFBC Fly Ash

The main ground improvement admixture used in this thesis was a CFBC fly ash supplied by the AES Power Plant located in Guayama, Puerto Rico. The following subsection summarizes the main properties of this fly ash.

4.3.1 Chemical composition

The chemical composition of AES CFBC fly ash is presented on Table 4.2 and was provided by the Power Plant. This information is based on a chemical analysis performed by the laboratory SGS North America Inc. on January 19, 2005 from a sample obtained on December 16, 2004. The requirements for fly ash classification according ASTM C618 are presented in (Table 4.3). This table shows that AES fly ash complies with most of the chemical requirements for a Class C fly ash but exceeds the content of sulfur trioxide (SO_3) of 5% . Based on this, the AES fly ash cannot be classified as Class C nor F. As discussed before, it will be referred herein as CFBC fly ash based on the coal combustion process used for its production.

Table 4.2. Chemical composition of AES fly ash by SGS Laboratory

Composition	**% Wt**
Silica, SiO_2	39.41
Alumina, Al_2O_3	12.59
Ferric Oxide, Fe_2O_3	4.35
$SiO_2 + Al_2O_3 + Fe_2O_3$	***56.35***
Titania, TiO_2	0.51
Lime, CaO	27.02
Magnesia, MgO	1.27
Potassium Oxide, K_2O	1.17
Sodium Oxide, Na_2O	0.44
Sulfur Trioxide, SO_3	12.57
Phosphorus Pentoxide, P_2O_5	0.28
Strontium Oxide, SrO	0.14
Barium Oxide, BaO	0.23
Manganese Oxide, Mn_3O_4	0.02
Alks. As Na_2O, Dry Coal Basis	1.12
Base : Acid Ratio	0.65
T250 Temperature	2224

Table 4.3 Chemical Requirements for fly ash according to ASTM C 618

Chemical Composition	%by Wt	F	C	AES Fly Ash
$SiO_2 + Al_2O_3 + Fe_2O_3$	min %	70	50	56.35
SO_3	max%	5	5	12.57
Moisture Content	max%	3	3	0.11
Loss on Ignition	max%	6	6	2.6

4.3.1.1 XRD

An XRD analysis was carried out on a CFBC fly ash sample. XRD results indicate that the minerals present in a dry sample of fly ash were: Quartz (SiO_2), Calcite ($CaCO_3$), Anhydrite ($CaSO_4$), Lime (CaO), Portlandite ($Ca(OH)_2$), Hematite (Fe_2O_3), Hydrophilite ($CaCl_2$) and amorphous material. Figure 4.11 shows an image with some of the resulting minerals.

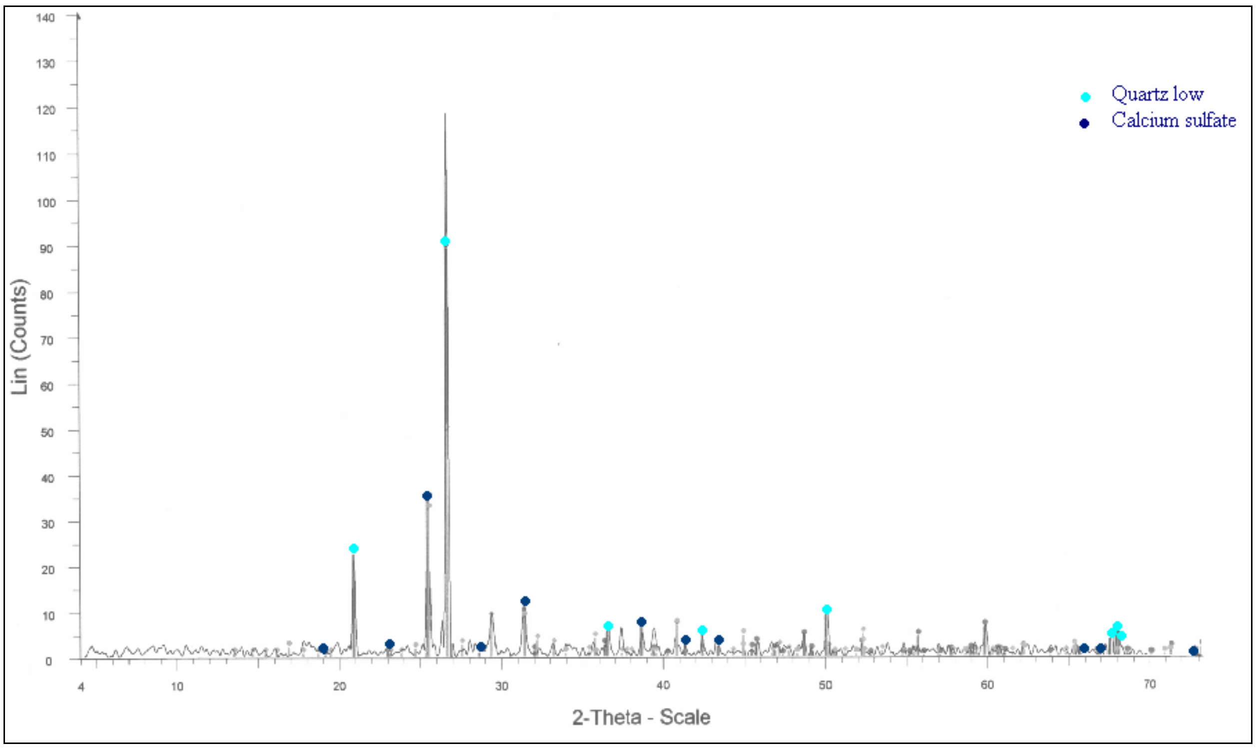


Figure 4.11 XRD image showing some of the minerals founded in CFBC fly ash

4.3.2 Physical properties

The CFBC fly ash is produced from a lignite or soft coal ash. The color of the CFBC fly ash was gray as presented in Figure 4.12 The water content of the as-received fly ash varied between 0.08% and 0.11% indicating the material was practically dry. The specific gravity was measured to be 2.55 reported by the author. The value was calculated as of the solid density using the ASTM C188 where kerosene was used instead of water to avoid any chemical reaction. Figure 4.13 shows an SEM image of the CFBC fly ash. This figure illustrates the general spherical shape of the CFBC fly ash illustrating the general spherical shape of the CFBC ash particles.

Figure 4.12 AES fly ash sample

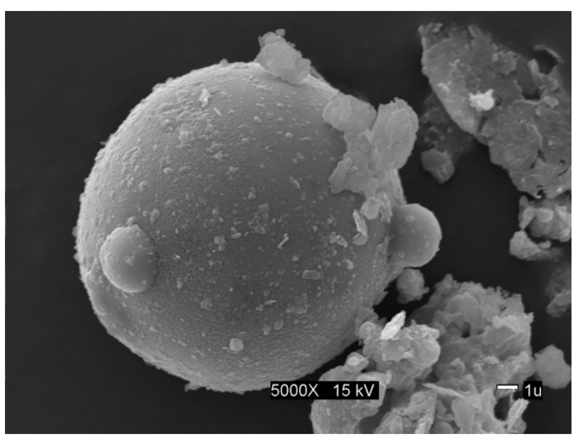


Figure 4.13 SEM image of CFBC fly ash

4.3.2.1 *Particle size analysis*

A particle size analysis was performed on the CFBC fly ash according to ASTM D422. The sample was tested as received from the power plant on June 2006. Results are shown in Figure 4.14. This figure shows that the CFBC AES fly ash has particles ranging from medium sand to clay size. The effective diameter for the 50% finer (D50) is approximately 0.023 mm which corresponds to silt sizes. The particle size distribution curve indicates about 86% of the particles sizes of the CFBC fly ash are within the silt sizes.

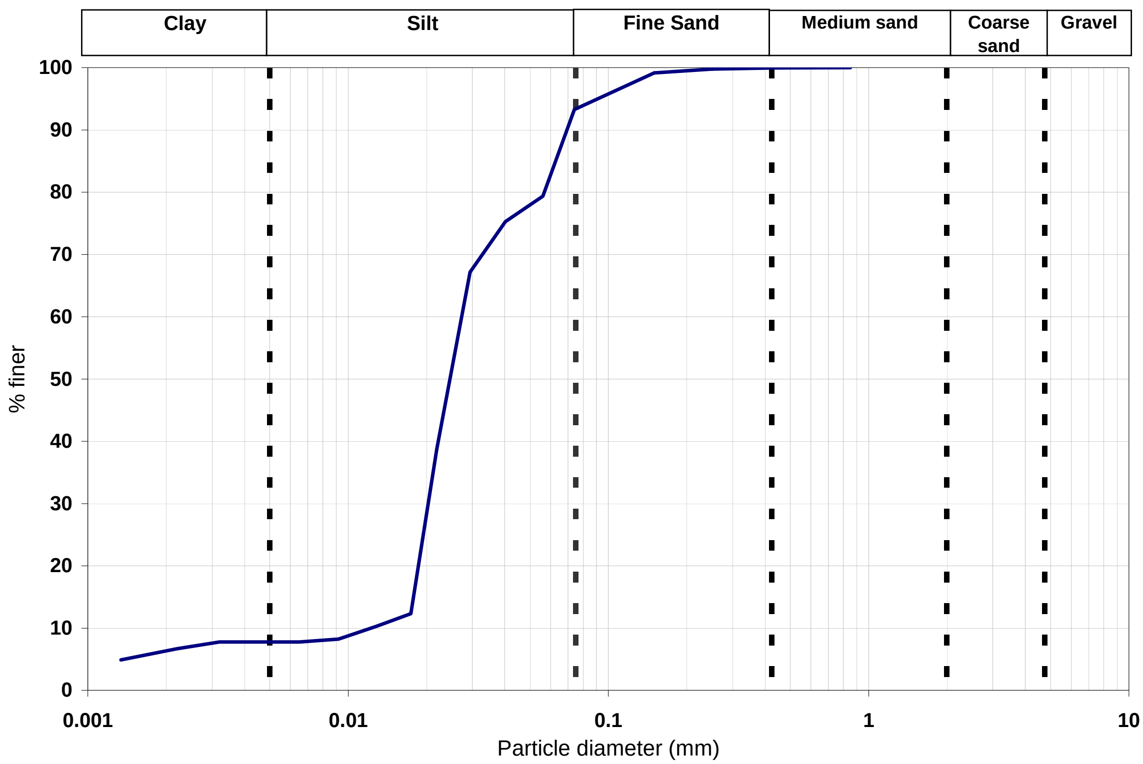


Figure 4.14. Particle size distribution curve of AES CFBC fly ash

4.3.2.2 *Setting time CFBC fly ash*

A setting time test of CFBC fly ash was conducted according to ASTM C191. The setting time test gives an indication of the rate at which the hydration processes are occurring and therefore helps estimate the development of strength with time. The curve of penetration versus time is shown in Figure 4.15. The setting time value at a penetration of 25 mm was about 108 minutes. This value represents the initial setting time of fly ash and it can be used as a guide to predict the maximum delay time that could be allowed between mixing in the fly ash and the sample compaction stage.

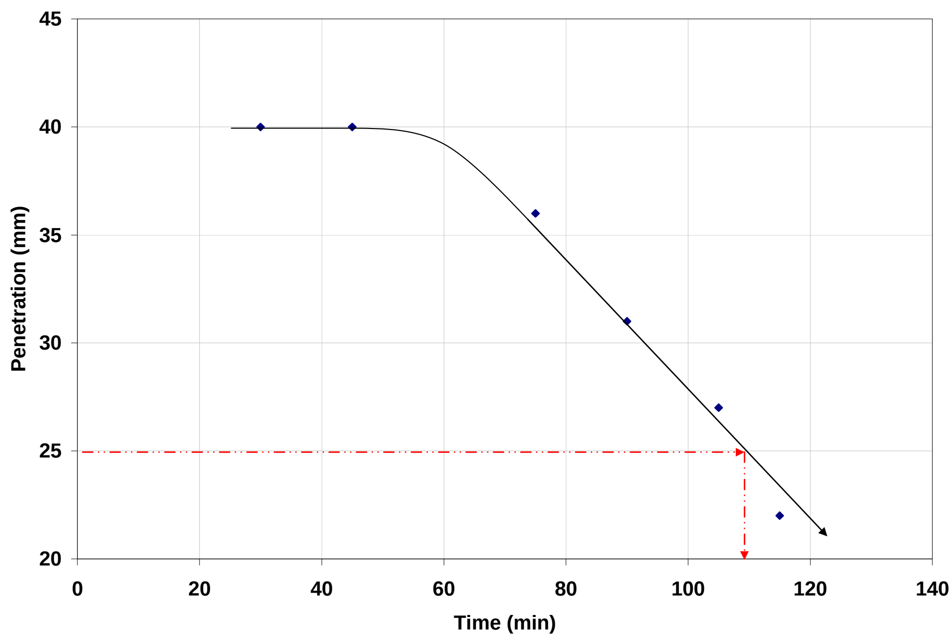


Figure 4.15. Setting time of CFBC AES fly ash

4.3.2.3 Self cementing properties

The self cementing properties of the CFBC fly ash was estimated from compressive strength test performed according to ASTM C109. This standard was prepared for hydraulic cement, but can be adapted for fly ash by making the changes suggested by ASTM D5239. According to the ASTM standard, the water to fly ash ratio (w/fa) to be used is 0.35 while Portland cement uses a w/c ratio of 0.48. The mixing paste should be prepared according to ASTM C305. For this study during the mixing phase of fly ash and water it was noticed that the w/fa ratio of 0.35 was impractical given that the consistency of the sample was too dry which caused difficulties to compact the samples. For this reason, the w/fa ratio was adjusted to 0.48. A total of 8 samples were prepared and compacted in square metal molds. Samples were cured in the molds during 24 hours at an approximate temperature 89°F (28 ˚C). Completed the 24 hour curing period, the cubes were carefully removed from the metal molds. Four samples were submerged in water as specified by the ASTM C109, but after 5 minutes of submersion the cubes were disintegrated in approximately 50% of their volume. These samples were disposed. The other four samples continued to cure at 89°F for another 6 days without being submerged in water. The compressive strength was determined at 7 days curing and the results are presented in Table 4.4. The average compressive strength was 690 psi which corresponds to a very self cementing classification according to ASTM D5239, as shown in Table 4.5.

Table 4.4. Compressive strength of AES fly ash at 7 days

Cube #	**Compressive Strength (psi)**
1	842
2	767
3	575
4	577

Table 4.5. Classification of fly ash according to the compressive strength

Classification	**Compressive strength @ 7 days (psi)**
Non Self –Cementing	100
Moderately Self Cementing	100 – 500
Very Self Cementing	> 500

The very self cementing classification of the CFBC fly ash implies that it will not need addition of an activator like lime or Portland cement. Figure 4.16 presents the failure modes of the fly ash cubes during the compression test, the walls of the cubes became detached at the end of the test.

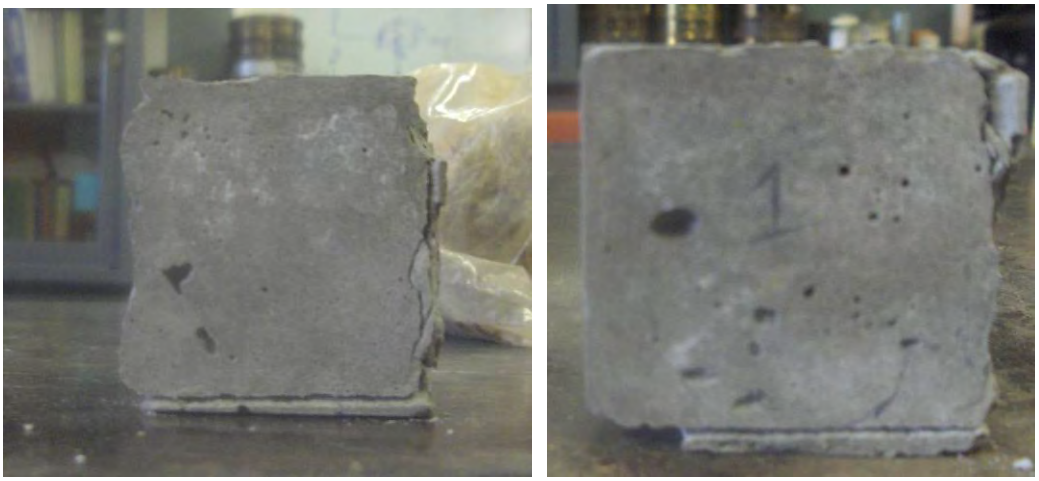


Figure 4.16. Failure mode of fly ash cubes during compression test.

4.4 Class C Fly Ash

For comparison purposes this thesis also involved tests using a class C fly ash. The class C fly ash came from the Pawnee Power Plant in Brush, Colorado. This power plant generates 500 MW using pulverized coal station burning low sulfur Powder River Basin Coal from the Eagle Butte Mine. Pawnee fly ash is classified as class C according ASTM C618.

4.4.1 Chemical composition

The chemical composition of the class C fly ash from the Pawnee power plant is shown in Table 4.6. Comparison with the ASTM C618 requirements is shown in Table 4.7. As mentioned after, fly ash is mainly composed of silica, alumina and ferric oxide which are pozzolans and, calcium oxide.

Table 4.6 Chemical composition Pawnee fly ash

Composition	% Wt
Silica, SiO_2	31.17
Alumina, Al_2O_3	18.76
Ferric Oxide, Fe_2O_3	5.30
$SiO_2 + Al_2O_3 + Fe_2O_3$	***55.77***
Lime, CaO	27.90
Magnesia, MgO	7.41
Potassium Oxide, K_2O	2.37
Sodium Oxide, Na_2O	2.12
Sulfur Trioxide, SO_3	0.36
Alks. As Na_2O	2.36

Table 4.7 Chemical Requirements for fly ash according to ASTM C 618

Chemical Composition	%by Wt	F	C	Pawnee Fly Ash
$SiO_2 + Al_2O_3 + Fe_2O_3$	min %	70	50	55.77
SO_3	Max%	5	5	0.36
Moisture Content	Max%	3	3	0.03
Loss on Ignition	Max%	6	6	0.34

4.4.2 Physical properties

Pawnee fly ash is yellow ash with a small quantity of black particles. Microscopically this fly ash is composed by particles with perfect spheres shape (see Figure 4.17). The physical properties of this class C fly ash are presented in Table 4.8. Data were provided by Boral Material Technologies from a sample tested on January 18, 2007. The water content recorded by the author was 0.03%. The specific gravity and LOI values are 2.72 and 0.34% respectively.

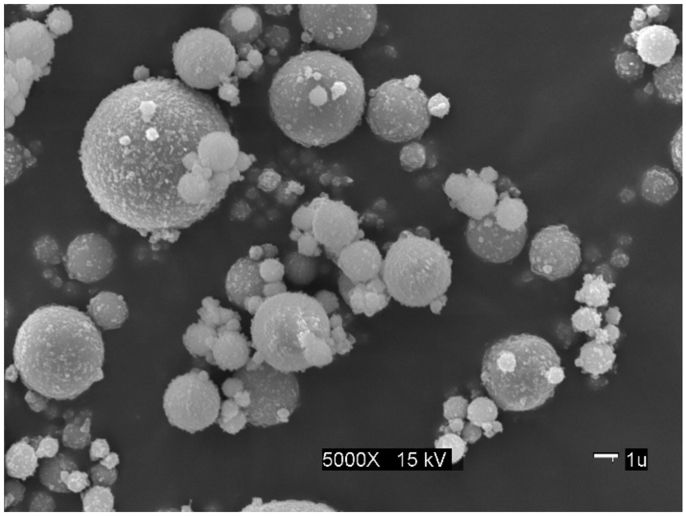


Figure 4.17 SEM image of class C fly ash

Table 4.8 Physical properties of Pawnee fly ash

Property	**% Wt**
Moisture content	0.03
LOI	0.34
Amount Retained on No.325 Sieve	14.09
Specific Gravity	2.72
Autoclave Soundness	0.10
SAI, with Portland Cement at 7 days (% of control)	93.30
SAI, with Portland Cement at 28 days (% of control)	100.80
Water Required, (% of control)	93.4

4.4.2.1 Particle size analysis

To determine the particle size distribution, sieve and hydrometer analysis were performed on a dry sample. The resulting curve is presented in Figure 4.18. According it 90% of the sample passed sieve #200 (0.075mm). Seventy percent of the sample has particle of silt size. The effective diameters for the 50 and 10% finer (D_{50} and $D_{10)}$ values are 0.0218 and 0.0042 mm respectively.

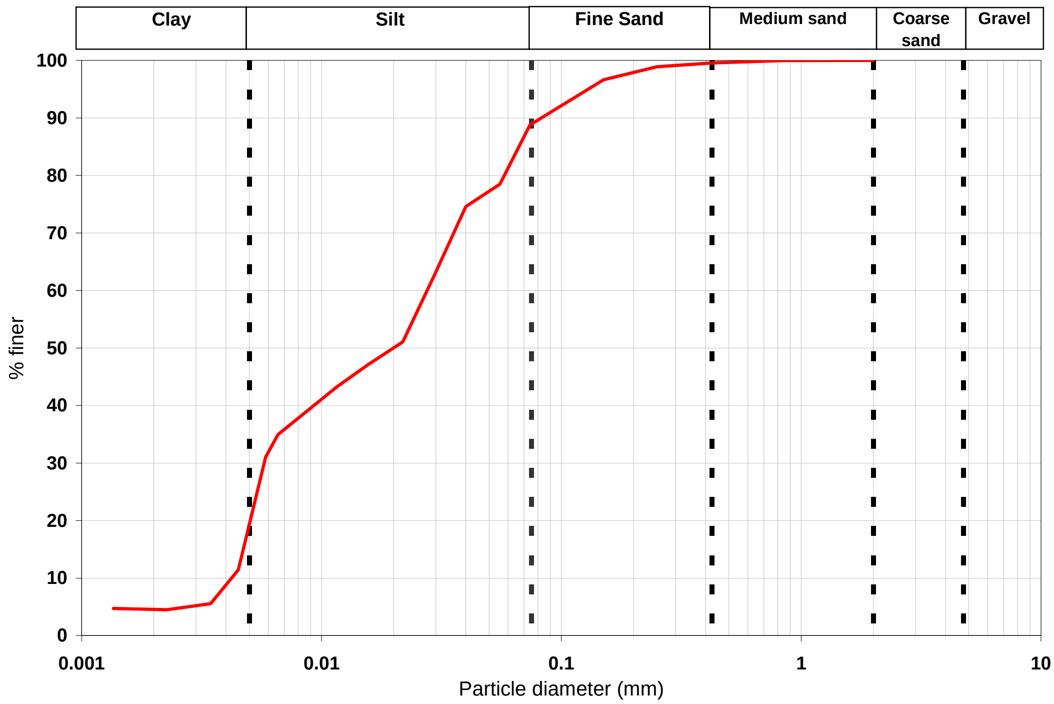


Figure 4.18 Particle size distribution curve of Pawnee class C fly ash

4.4.2.2 Self cementing properties

Compressive strength of Pawnee fly ash was determined using the test procedure described in section 4.3.2.3. The resulting average strength value was 557 psi. According this value, Table 4.5 classifies this fly ash as very self cementing. The failure mode of the tested cubes is presented in Figure 4.19.

Table 4.9 Compressive strength of Pawnee fly ash at 7 days

Cube #	**Compressive Strength (psi)**
1	564
2	550
3	558

Figure 4.19 Failure modes of fly ash cubes during compression test

4.5 Lime (Hydrated lime)

The lime used for comparison purposes was a commercially available lime used for construction. It is a type S or hydrated lime according to ASTM C 206 produced by Cemex Company in Ponce Puerto Rico. The chemical and physical characteristics are presented in Table 4.10 and Table 4.11 respectively. These tests were done in a sample of lime in February 8, 2007 by Ponce Cemex Company.

4.5.1 Chemical composition

Ponce Hydrated lime basically consists of calcium oxide (CaO), and magnesium oxide (MgO). These compounds form the 98.78% of the dry weight

Table 4.10 Chemical composition of Ponce Lime

Property	(%by dry weigth)		(%by dry weigth)	**ASTM Type S Requirements**
Combined Water	21.95	Carbon Dioxide	3.3	5max POM or 7 max AOP
Insoluble Residue	0.32	Mechanical Water	0.31	
Calcium Oxide	73.24	Unhydrated Oxides	0.88	8 max.
Magnesium Oxide	0.45	Loss on Ignition	25.54	
Sulfur Trioxide	0.23	CaO + MgO Non volatile Basis	98.78	95 min.

4.5.2 Physical properties

Ponce lime is a white fine material with a specific gravity of 2.2. Table 4.11 shows the properties selected to characterize the material. The particle size distribution curve is presented in Figure 4.20. According the size curve, 13% was sand size particles and 85% was silt size particles. Values D_{50} and D_{10} are 0.018 and 0.010 mm respectively. An image of the lime particles is presented on Figure 4.21 showing not a specific shape.

Table 4.11 Physical properties of Ponce Lime

Property		**ASTM Type S Requirements**
Air Content (%)	3.8	7 max
Residue Retained #30 Sieve (%)	0	0.5 max.
Residue Retained #200 Sieve (%)	4.6	15 max.
Plasticity [30 min. soak]	345	200 min.
Water Retention(%)	93	85 min.

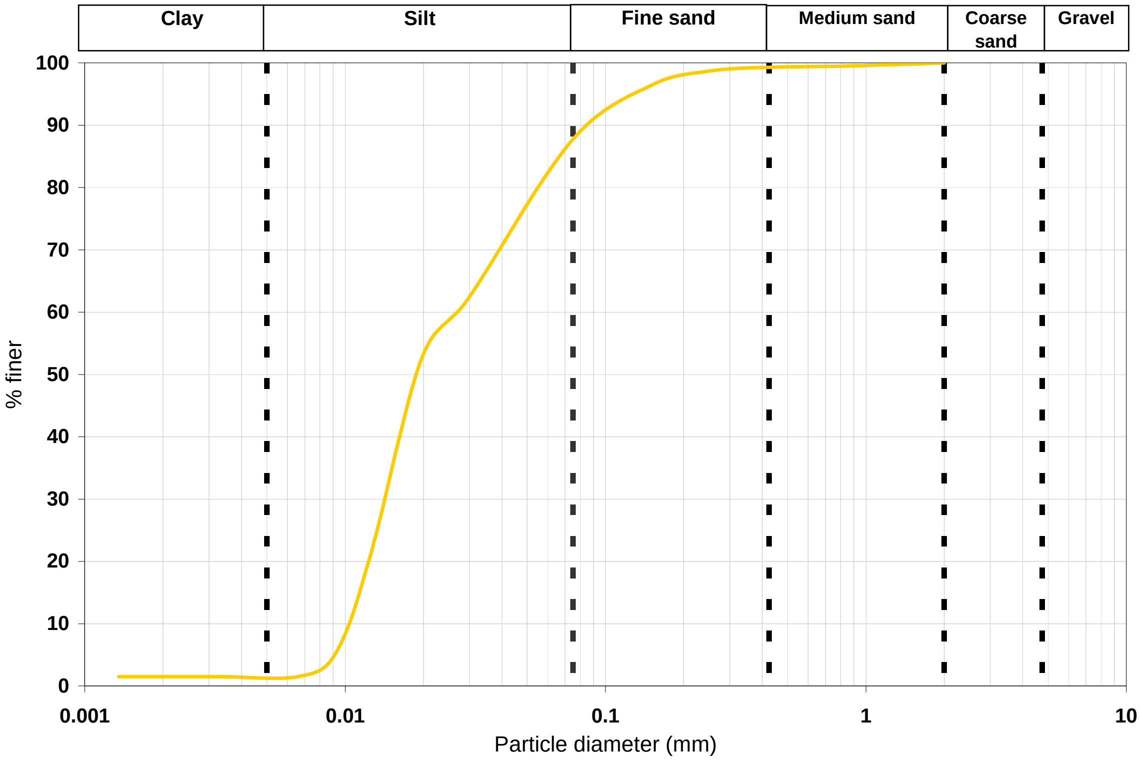


Figure 4.20 Particle size distribution curve of lime

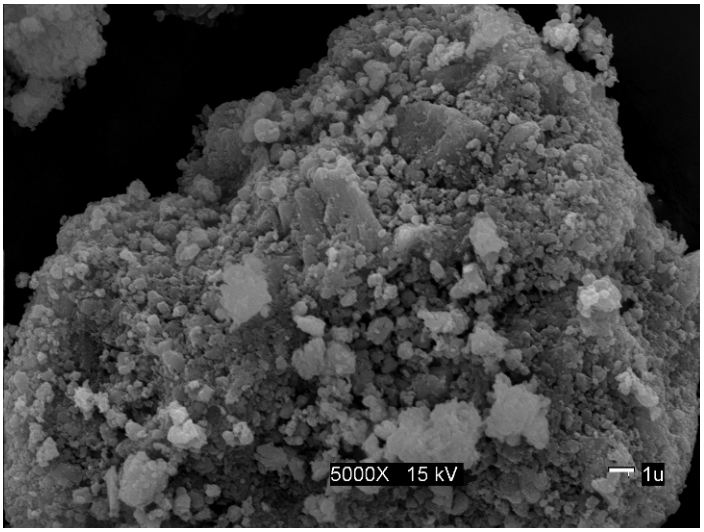


Figure 4.21 SEM image of lime

4.6 Comparison between AES CFBC fly ash and Pawnee class C fly ash

This section will provide a comparison of the chemical and physical properties of AES and Pawnee fly ash.

4.6.1 Chemical properties

A comparison between AES and Pawnee fly ash chemical properties is presented in Figure 4.22. According to this bar chart, both fly ashes have similar properties with exception of the sulfur trioxide content (SO_3). CFBC has a higher value due to the combustion process as explained in section 2. This factor influences the possible expansion in the treated soil samples. Fly ash posses practically the same composition than typical cement, the difference is in the proportions of the composition.

A chemical comparison between fly ash and cement is presented in Table 4.12. Cement has a much higher value of free lime (CaO) and lower values of silicon dioxide (SiO_2), aluminum oxide (Al_2O_3) and ferric oxide (Fe_2O_3).

4.6.2 Physical properties

Table 4.13 shows some of the physical properties of CFBC and class C fly ash. As discussed in previous sections, the difference in the fly ash color is due to difference in the LOI percentage. CFBC is gray and class C is a yellow fly ash. Class C fly ash posses a higher value of specific gravity than CFBC. Class C particles are smaller than CFBC, this can be noticed in the D_{10} values. Finally, both fly ashes have similar self-cementing properties even when CFBC ash has a higher value of compressive strength. They both classify as very self-cementing ashes.

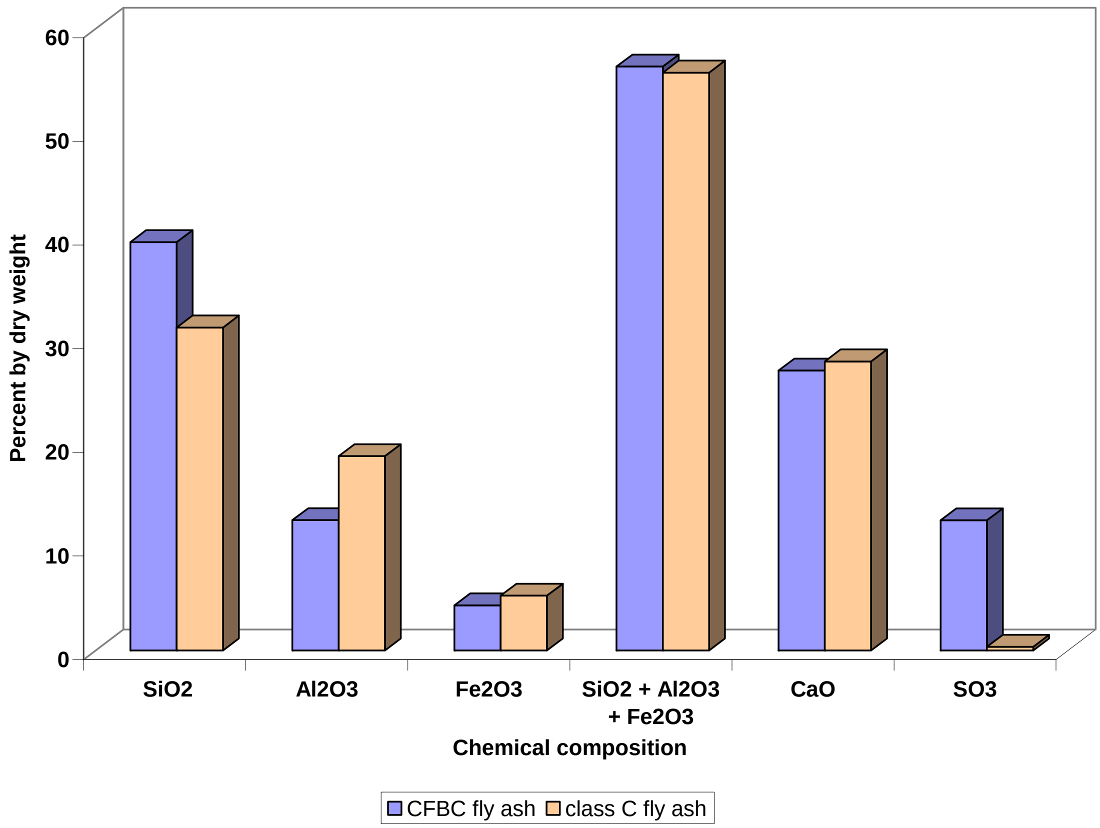


Figure 4.22 Chemical comparison between AES and Pawnee fly ash

Table 4.12 Chemical comparison between fly ash and Portland cement.
(Adapted from Fly Ash Facts for the Highway Engineers. FHNA-SA-44-081)

Chemical Species	Typical Class C	Typical Class F	Typical P. Cement	AES CFBC	Pawnee class C
CaO	24.3	8.7	64.4	27.02	27.9
SiO_2	39.9	54.9	22.6	39.41	31.17
Al_2O_3	16.7	25.8	4.3	12.59	18.76
Fe_2O_3	5.8	6.9	2.4	4.35	5.3
MgO	4.6	1.8	2.1	1.27	7.41
SO_3	3.3	0.6	2.3	12.57	0.36

Table 4.13 Comparison of physical properties of CFBC and clas C fly ash

Property	AES CFBC	Pawnee class C
Color	Gray	Yellow
Moisture content (%)	0.08-0.11	0.03
LOI (%)	2.6	0.34
Gs	2.55	2.72
D50 (mm)	0.023	0.0218
D10 (mm)	0.0128	0.0042
Ave. compressive strength (psi)	690	557

5 LABORATORY TESTING AND RESULTS

5.1 Introduction

This chapter presents a description of the laboratory experimental program carried out for this research as well the results obtained. The main focus of the experimental program was to evaluate the impact that CFBC fly ash had on the engineering soil properties of the Hormigueros clay. However the chapter also presents test results obtained from sample treated with lime and class C fly ash.

5.2 Test Program

The experimental work of this thesis consisted of a detailed program involving test samples prepared with one base soil and three admixtures. All test samples were prepared following the procedures described in the following subsection.

5.2.1 Base soil preparation

As mentioned in Chapter 4, the base soil for this research was obtained from a highway project in Hormigueros P.R. The main properties of this soil were presented in Chapter 4. This section describes how the base soil was treated and prepared before adding and mixing the admixtures.

As mentioned earlier, the soil was retrieved from the base of a 14 ft deep excavation and its natural moisture content ranged from 59 to 64%. The soil was in the form of large lumps which made it difficult to use for mixing. Before admixture mixing, the soil had to be crushed and dried. The target moisture content was the optimum water content obtained from the Standard Proctor Test presented in Chapter 4 which was found to be 31%. This represents substantial drying which was achieved by placing the soil in large trays subjected to air drying for 2 weeks. After these 2 weeks the average moisture content was 11% which represents a loss of approximately 50 percentage points. At this low moisture content the Hormigueros clay was very hard and difficult to handle. The next step in preparing the soil was to grind it so the hard lumps were crushed and broken down as shown in Figure 5.1. At the end of this step the soil was free of any roots and stones and the maximum size of the crushed particles was 4.75mm (corresponding to a standard Sieve No. 4).

Figure 5.1 Soil crushing procedure

The next step in the preparation process was to add water to achieve the optimum water content corresponding to the Standard Proctor test. This stage was carried out in general accordance with the procedure outlined in ASTM Standard D698. This standard suggests using a minimum standing time of 16 hours to allow moisture equalization between the addition of water and the compaction stage. For purposes of this investigation a 24 hours period was used. The crushed soil from the previous step was mixed with the predetermined amount of water using an electric mixer at 138 rpm during 2 minutes. The moisten soil was then placed inside plastic bags and stored for 24 hours. After placing the soil in the bags, vacuum was applied.

The amount of water required to achieve the Standard Proctor optimum moisture content (w_{opt}) was calculated using the following procedure.

The following variables are defined:

- Weight of air-dried soil, $W_{.ads}$
- Moisture content of air-dried soil, w_{ads}
- Target moisture content, w_{opt}
- Weight of soil solids, W_{solid}
- Weight of water to be added, W_{H2O}

The weight of solids of the air-dried soil sample is computed as follows:

$$W_{solid} = \frac{W_{ads}}{w_{ads}} \qquad (5.1)$$

The amount of water present in the air-dried soil sample is:

$$W_{winitial} = W_{solid} \times w_{ads} \qquad (5.2)$$

The final amount of water that the prepared soil sample should have at the target moisture content of the Standard proctor optimum moisture content is the following:

$$W_{wfinal} = W_{solid} \times w_{opt} \qquad (5.3)$$

The amount of water that should be added to the air-dried soil sample can be obtained by subtracting Equation 5.2 from Equation 5.3, as follows:

$$W_{H2O} = W_{w\,final} - W_{w\,initial}$$

$$W_{H2O} = W_{solid} \times (w_{opt} - w_{ads}) \qquad (5.4)$$

Table 5.1 presents an example calculation for a 5 pound sample at an initial air-dried moisture content of 11%.

Table 5.1 Example calculation of water required to achieve optimum moisture content

Quantity	**Value**	**Comment**
Air-dried soil ($W_{.ads}$)	5 lbs	Known
Initial moisture content (w_{ads})	11%	Known
Target moisture content (w_{opt})	31%	From Standard Proctor Test
Weight of soil solids (W_{solid})	4.5 lbs	From Eq. 5.1
Initial water weight ($W_{w\ initial}$)	0.49 lbs	From Eq. 5.2
Final water weight ($W_{w\ final}$)	1.39 lbs	From Eq. 5.3
Water to be added (W_{H2O})	0.9 lbs	From Eq. 5.4

5.2.2 Procedure for mixing soil with admixture

As mentioned before, three admixture types were selected for this research project: CFBC fly ash, class C fly ash, and lime. The amounts of admixture in terms of percentage by dry weight of soil are summarized in

Table 5.2, 6.3 and 6.4, respectively. These tables also present the number of samples prepared and the curing times for each test sample. The selected proportions of fly ash were based on the literature review presented in Chapter 3. Key references for defining the proportions were Cokca (2001), Nalbantoglu (2004), and Phani et al. (2004). The proportions of lime shown in Table 5.4 were mainly based on the work by Little (1987).

The soil preconditioned, as described in the previous subsection, was mixed with the admixture in a quick fashion to obtain best stabilization effects as suggested by (Barbu 2004). The preconditioned soil was taken out from the sealed plastic bags and mixed with the corresponding proportion of admixture. The mixing was carried out for 3 minutes at a 138 rpm. The soil-admixture blend was immediately compacted to avoid any delay. Therefore a maximum of 4 cylindrical samples were mixed in each batch and compacted. The total number of specimens prepared in this fashion was 184. The following subsection describes the compaction procedure.

Table 5.2 Proportions of AES CFBC fly ash

		Percent of F.A. by dry weight				
		0%	**5%**	**10%**	**15%**	**20%**
	0	2	2	2	2	2
Curing Time (Days)	**7**	3	4	4	4	4
	14	3	4	4	4	4
	28	3	4	4	4	4
	40	3	4	4	4	4
	infinite	2	3	3	3	3

Table 5.3 Proportions of Pawnee class C fly ash

		Percent of F.A. class C by dry weight			
		5%	**10%**	**15%**	**20%**
	0	2	2	2	2
Curing Time (Days)	**7**	2	2	2	2
	14	2	2	2	2
	28	2	2	2	2
	40	2	2	2	2
	infinite	2	2	2	2

Table 5.4 Proportions of lime

		Percent of lime	
		5%	**10%**
	0	3	3
Curing Time (Days)	**7**	3	3
	14	3	3
	28	3	3
	40	3	3
	infinite	3	3

5.2.3 Compaction procedure

Test samples were compacted at compaction energy comparable to the Standard Proctor compaction test (ASTM D698). This test specifies a compaction energy of 12,400ft-lb/ft^3. Given the amount of test soil limitation and the requirement of having cylindrical test specimens with a height to diameter ratio of two, it was decided to compact samples in plastic molds of 2-inch diameter and 4-inch height. A typical plastic mold is shown in Figure 5.2.

Figure 5.2 Plastic mold with lids

The compaction of samples in these molds was done using the device shown in Figure 5.3 and Figure 5.4. The compaction device was fabricated in the machine shop of the Department of Mechanical Engineering of the University of Puerto Rico at Mayagüez. The original design was made by Geiman et al. (2005) for a study at the University of Virginia Tech. involving stabilization of soft subgrades using quicklime, cement, synthetic polymers and other admixtures. This device involves using a drop hammer of 2.315 pounds and a drop height of 0.5 ft. The test specimens were compacted using 6 layers and applying 13 blows per layer. For the volume of the test mold the specific compaction energy applied is as follows:

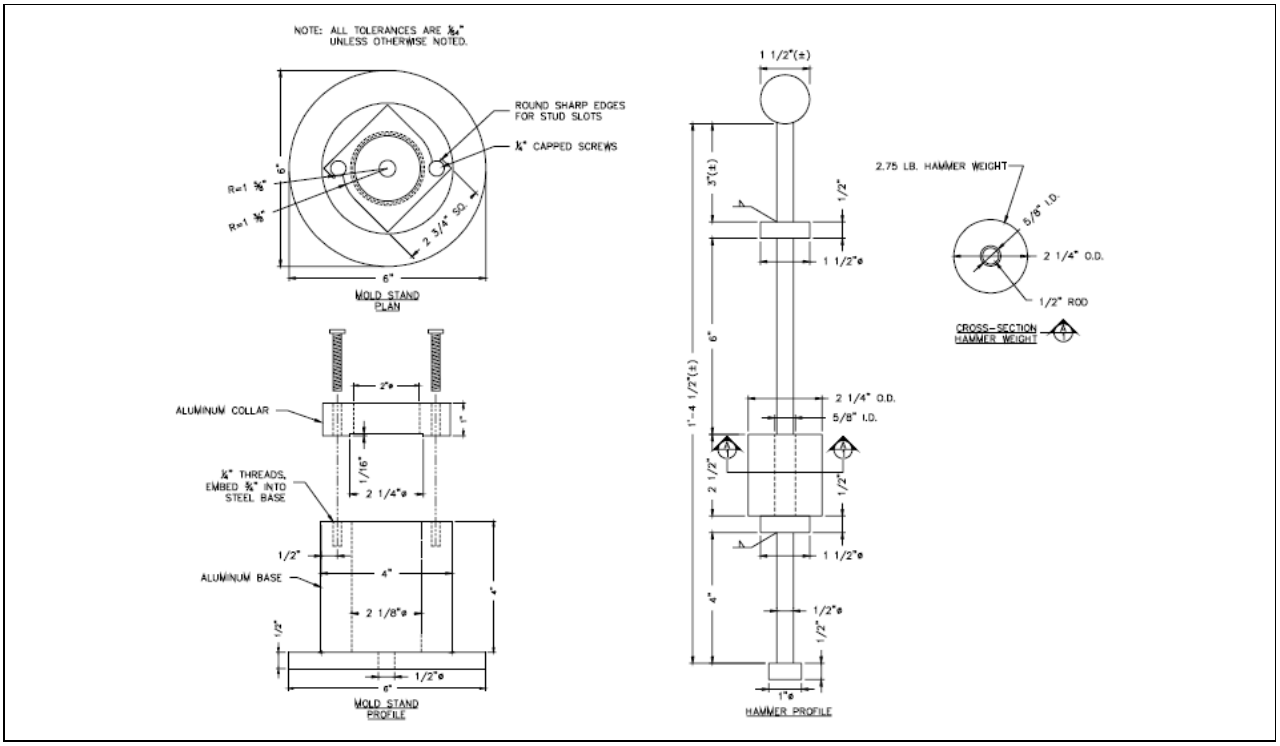


Figure 5.3 Compaction equipment drawing (Geiman et al 2005)

Figure 5.4 Compaction equipment

$$E = \frac{(no.blows.per.layer) \times (no.of.layers) \times (weight.of.hammer) \times (height.of.drop.of.hammer)}{volume.of.mold}$$

$$E = \frac{(13 \times 6 \times 2.315 lb \times 0.5\, ft)}{0.00726\, ft^3} = 12435.95 \frac{\text{lb.ft}}{\text{ft}^3}$$

This compaction energy is comparable to that produced with the Proctor Standard equipment which provides approximately 12,400 ft-lb/ft^3 of energy.

5.2.4 Curing process

The compacted samples were stored in plastic cylinders with their respective lids to avoid moisture loss. A room with controlled temperature (84°F) and relative humidity of 74% was used for keep the samples until reaching the proposed curing time (Figure 5.5).

Figure 5.5 Curing room

5.2.5 Unconfined compressive testing

The quantification of soil improvement was carried out by means of unconfined compressive testing on samples treated with different admixtures, proportions and curing times.

This subsection describes the test procedure used for unconfined compressive testing.

After sample curing was completed, samples were carefully removed from the molds and taken to the geotechnical laboratory for unconfined compressive testing. The samples were placed on a pedestal and loading cap was placed on top. The load was applied using a GeoComp Load Trac II frame as shown in Figure 5.6. The tests were carried out in general accordance with ASTM Standard D2166. The tests were strain controlled with a constant strain rate of 1%/min. The load was measured using a calibrated load cell and the displacement was measured using a calibrated LVDT. The GeoComp Load Trac II device has a data acquisition system which recorded load and displacement at a specified frequency.

Prior to testing, samples were carefully weighed and measured. After specimen testing the mode of failure was recorded and the final water content was measured. A summary of the unconfined compression test are presented in the following section, however Appendix C presents complete details of the test results.

Figure 5.6 Equipment for unconfined compression test

5.2.6 *Potential volume change*

A potential volume change test (PVC) was done to evaluate the possible swelling conditions of fly ash treated Hormigueros clay. This test is usually used by the Federal Housing Administration (FHA) to evaluate potentially dangerous swelling or shrinking conditions existing in some clay soils used in residential and commercial developments (http://eleusa.com). The equipment used for this test was a soil volume change meter model C-260 as shown in Figure 5.7. This device produces values of the maximum possible volume change that a soil could experience when subjected to changes in moisture conditions. The test was done following the procedure presented by ELE International.

Figure 5.7 Soil volume change meter

5.3 Results

This section presents the test results of the experimental program carried out for this thesis. The following properties are discussed in this section.

- Plasticity
- Compaction
- Unconfined compression
- Potential volume change

5.3.1 Influence of CFBC fly ash on soil plasticity

Changes in soil plasticity were evaluated by measuring the Atterberg limits on treated samples of Hormigueros clay. Three levels of treatment were evaluated: 5, 10, and 15 percent of CFBC fly ash by weight. Liquid limit (LL), plastic limit (PL) and plasticity index (PI) values were calculated at three curing times: 0, 7, and 14 days. Figure 5.8 presents Atterberg limits for 0, 5, 10, and 15% CFBC fly ash at zero curing time. This figure shows a reduction in the plasticity of the soil with increasing fly ash. The change is more evident in the liquid limit with a decrease of 12% points when 15% of fly ash is added to the soil. The plasticity index decreased 8% points, from 45% to 37%, when adding 15% CFBC fly ash.

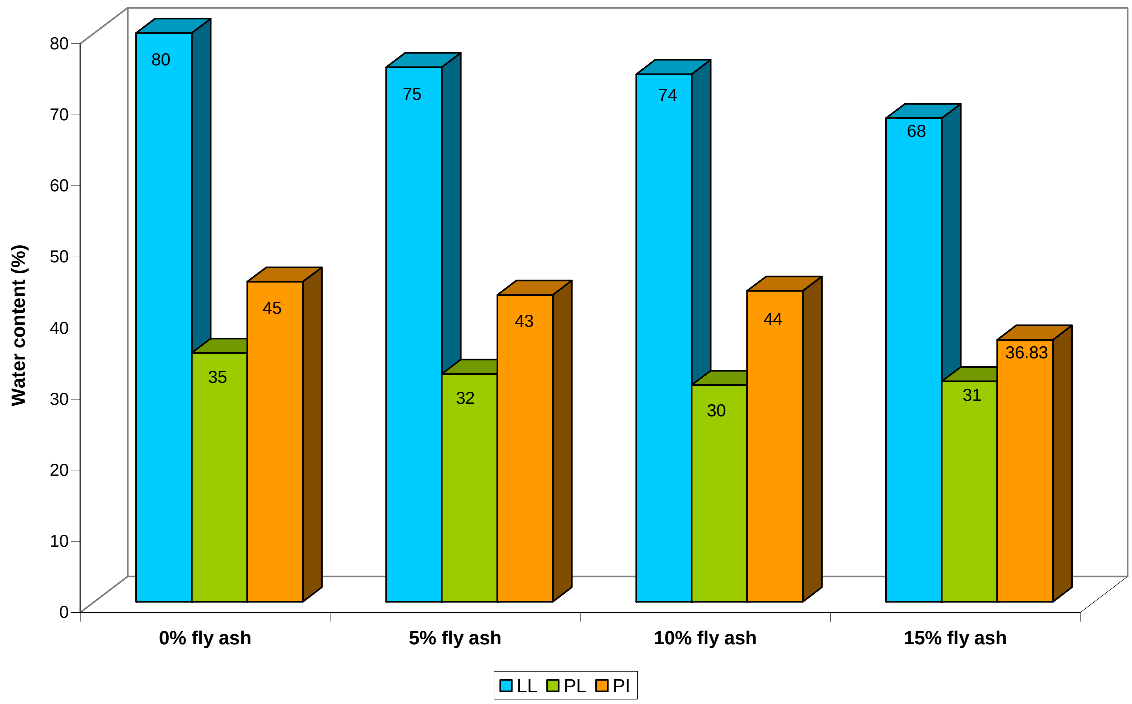


Figure 5.8 Variation in soil-admixture Atterberg Limits at zero curing time

The effect of curing time was evaluated for samples treated with 10% CFBC fly ash. Curing times of 0, 7, and 14 days were considered and results are shown in Figure 5.9. This figure shows the liquid limit and the plasticity index decreasing with curing time. For example, the Liquid limit decreased 6% points, from 74% to 68% after 14 days of curing time. The Plasticity Index decreased 8% points in the same period.

As observed in Figure 5.8, there is an instantaneous effect in the plasticity of soil when CFBC fly ash is added to soil. This effect continues as function of curing time. The location of the treated soil in the plasticity chart is shown in Figure 5.10. This figure shows 3 points: the untreated Hormigueros soil (point A), the treated soil with 10% CFBC fly ash at 0 curing time (point B), and the treated soil with 10% CFBC fly ash after 14 days of curing time (point C).

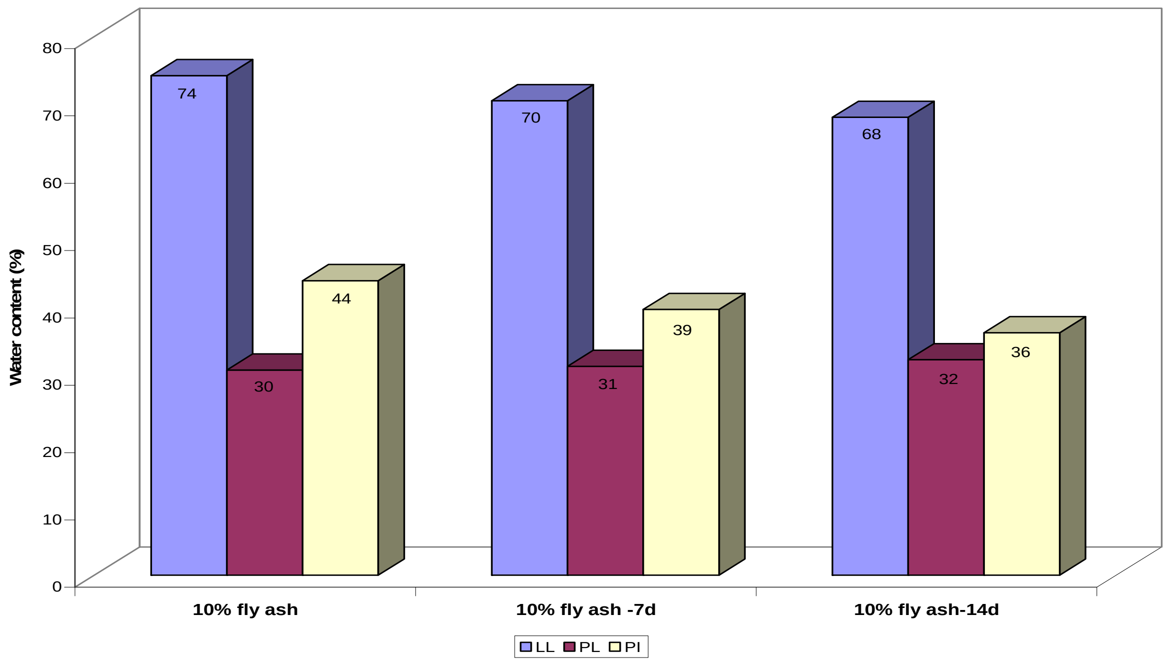


Figure 5.9 Atterberg limits versus curing time

As shown in Figure 5.10 the Hormigueros clay at these 3 states remains within the CH region of the plasticity chart. However this observation may not be applicable to other base soils or levels of treatment.

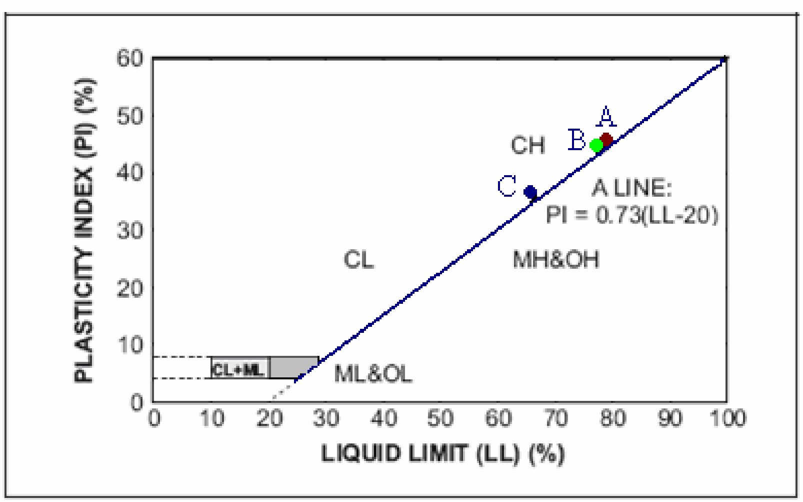


Figure 5.10 Change in plasticity properties of Hormigueros clay treated with 10% fly ash and 14 days curing time.

5.3.2 Influence of CFBC fly ash on compaction characteristics

The effect of addition of CFBC fly ash in the compaction properties (Standard Proctor optimum water content and maximum dry unit weight) of base soil treated with 10% fly ash was investigated as part of this study. The Standard Proctor curves for the Hormigueros base soil and soil treated with 10% CFBC fly ash at zero curing time are shown in Figure 5.11. As shown in the figure, optimum water content of the soil changed from 31% to 28% and the maximum dry unit weight increased from 77 pcf to 90 pcf representing and increase of 17%. The shift of the compaction curve to the left and upwards is considered an indication of an improvement in the compaction characteristics of the treated soil with respect to the untreated soil.

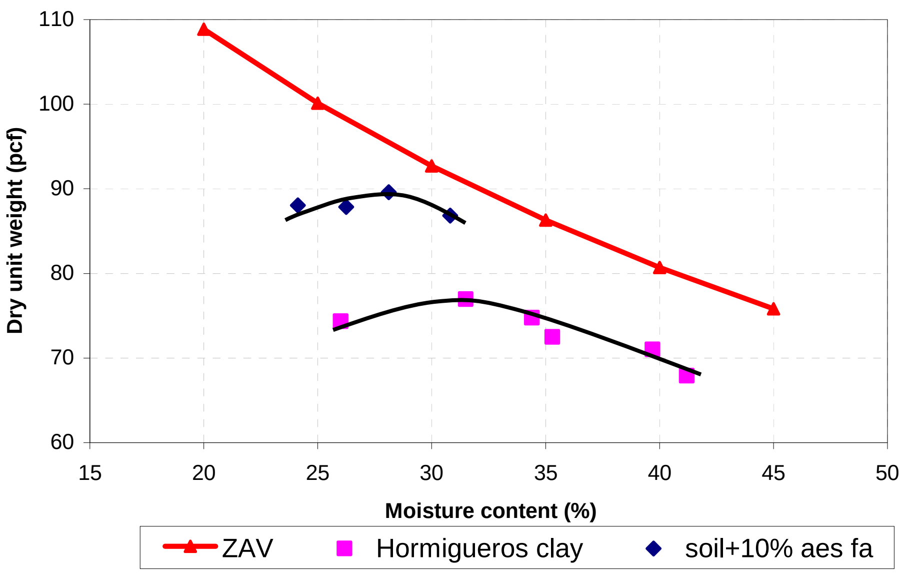


Figure 5.11 Influence on compaction characteristics on CFBC treated soils

Other proportions of CFBC fly ash and the effect of curing time should be investigated. This was outside the scope of this study.

5.3.3 *Unconfined compression test results*

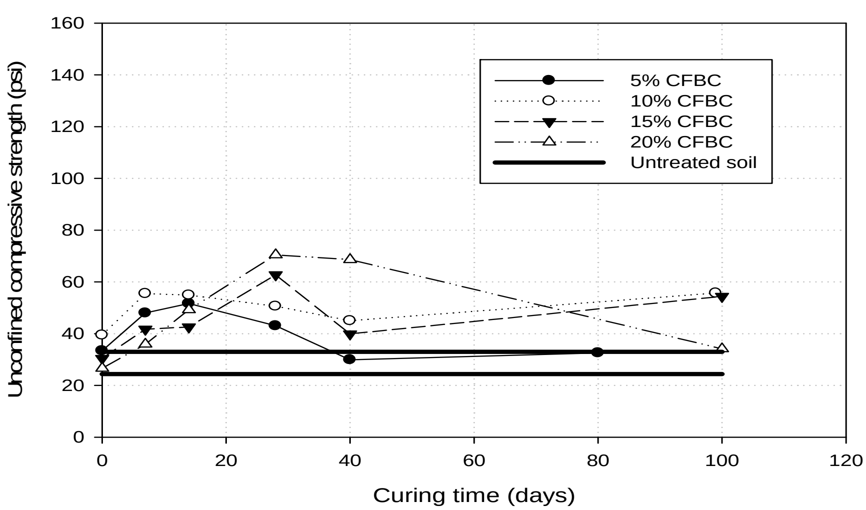
This section will provide the results of strength, stiffness and strain at failure on untreated and treated soil with the three admixtures: CFBC, class C fly ash and lime.

5.3.3.1 Strength

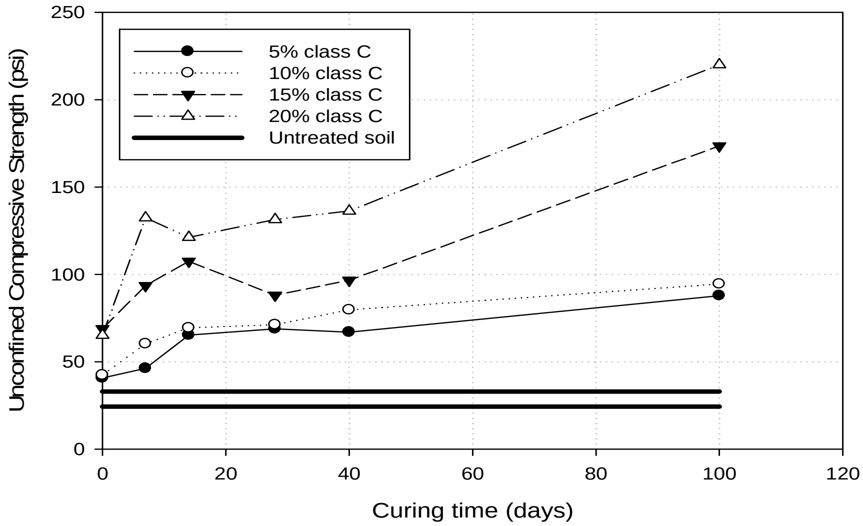
The samples with different curing times and admixtures percentages were tested for unconfined compressive strength following the test procedure in general accordance with ASTM Standard D 2166. For each unconfined compressive test, the stress-strain relationships were recorded along with their moisture contents at the end of the curing period. This allowed measuring three parameters: unconfined compressive strength, stiffness, and strain at failure. All results are presented graphically.

Figure 5.12 shows the gain in unconfined compressive strength with respect to curing time for the three admixtures investigated and the different proportions. For comparison purposes this figure also shows the range of unconfined compressive strength values measured on untreated clay samples compacted using the same procedure as the one used for treated samples.

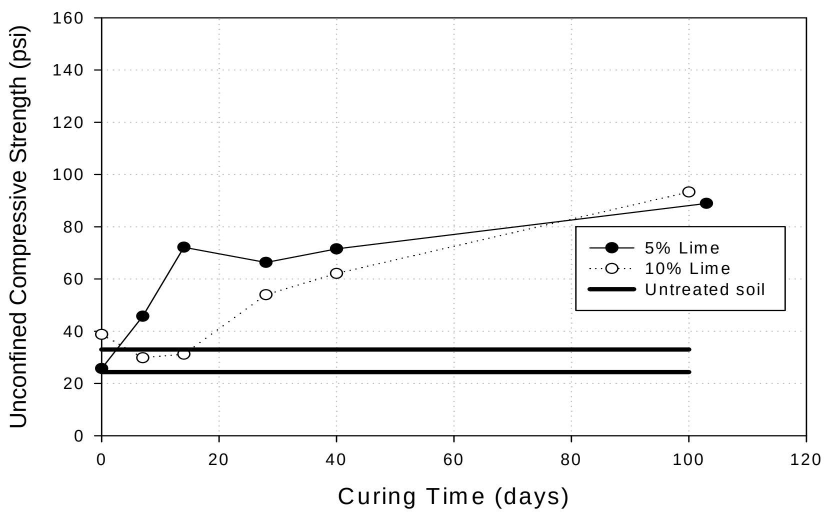
In general, compressive strength values shown in Figure 5.12 indicate that all types of treated samples gained most of their strength within fourteen days of curing. The unconfined compressive strength values for the clay treated with class C fly ash continued to increase at a higher rate up to a curing age of about 100 days. On the other hand, samples treated with CFBC fly ash strengths beyond 14 days had a tendency to decrease strength probably due to degradation during curing. However, beyond 40 days of curing the strength development resumes and reaches similar strength values to those measured in 14 day old samples except for 5 and 20% CFBC fly ash where the strength after 40 days reached values similar to that of 0 day curing time. To investigate this further, Scanning Electron Microscope (SEM) images were obtained from several samples at different curing times and treated level. SEM images of samples treated with 10% CFBC fly ash and curing times of 7 and 35 days are shown in Figure 5.13, Figure 5.14, and Figure 5.15. Figure 5.14 shows the formation of a crystal on the sample with 35 days of curing time. Figure 5.15 is a closer view of the 35 days cured sample showing the separation in the mass due to the crystal formation. At a curing time of 100 days, a sample with this percentage shows the growth of crystals all around (see Apendix A). An XRD analysis was carried out on the sample with 7 days of curing (Figure 5.16) and other in the sample which presented the crystals formation (Figure 5.17). This last one showed that the crystals formation are minerals composed of sulfates like Alunogen ($Al_2(SO4)_3$*$16H_2O$). It also shows minerals like quartz low (SiO_2), and saponite (½$Ca(Mg,Fe^{+2})_3(Si,Al)_4O_{10}(OH)_2{\cdot}4H_2O$) which is a member of the montmorillonite group.



a) CFBC fly ash



b) class C fly ash



c) Lime

Figure 5.12 Unconfined compressive strength development for stabilized Hormigueros clay

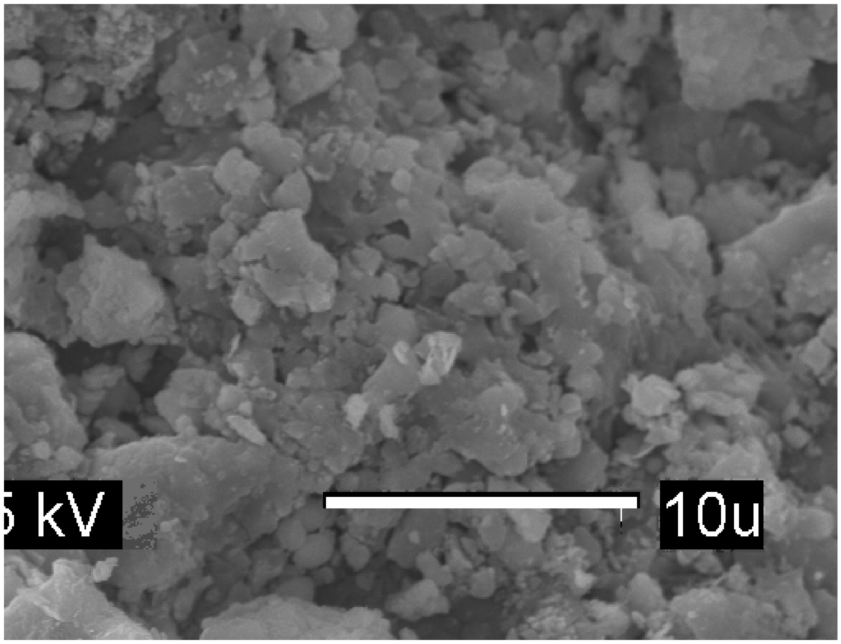


Figure 5.13 Sample treated with 10% CFBC fly ash at 7 days curing time

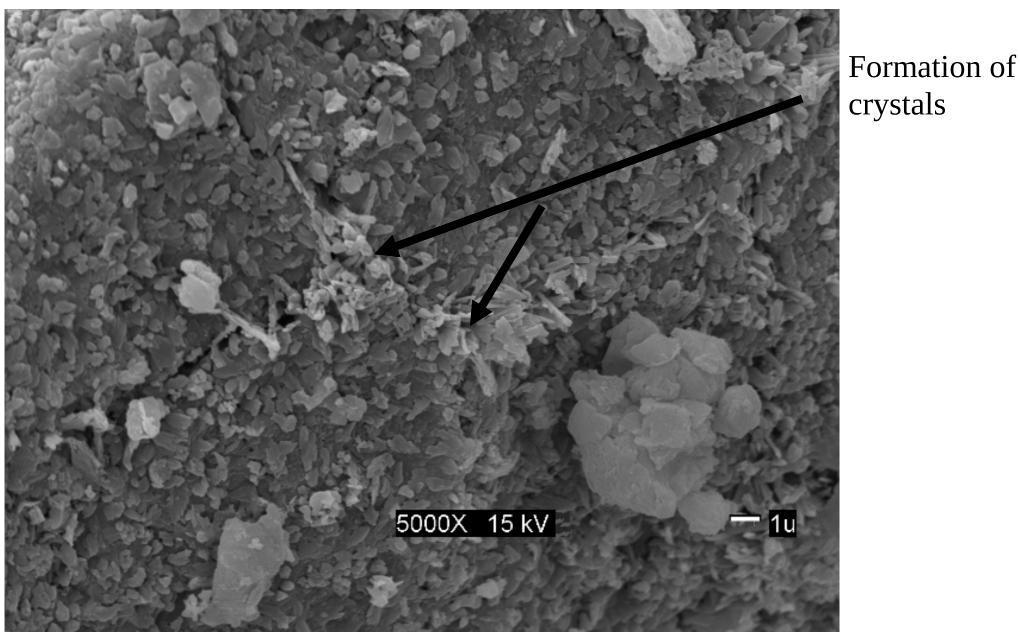


Figure 5.14 Sample treated with 10% CFBC fly ash at 35 days curing time

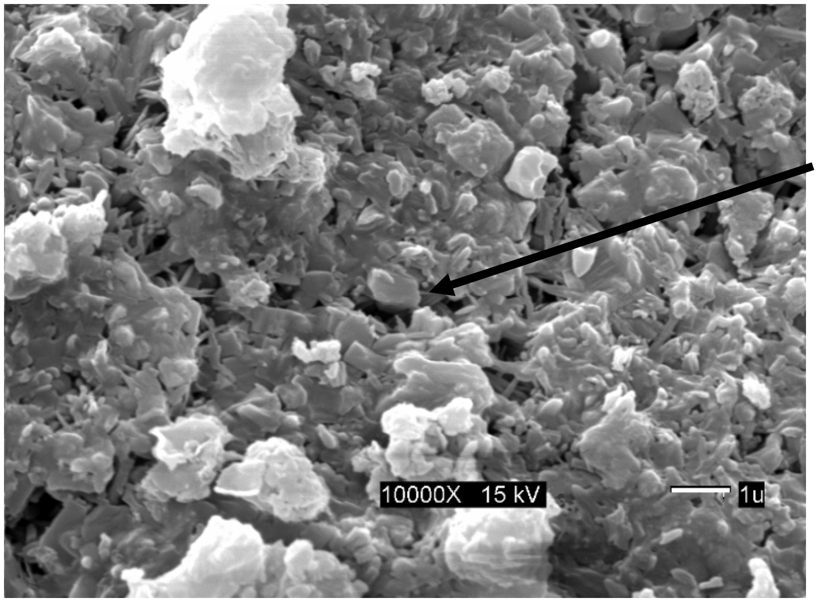


Figure 5.15 Sample treated with 10% CFBC fly ash at 35 days curing time

Figure 5.12 also shows that in general all soil treatments were effective in increasing the strength of the samples with respect to the untreated soil with exception of 20% CFBC. Samples treated with 20% CFBC fly ash showed high values of strength but after a curing period of 14 days for 5 and 10% of CFBC fly ash and 28 for 15 and 20% CFBC fly ash, the strength values decreased until reach values similar to those of untreated soil. Strength improvement levels were observed to be highest for class C fly ash treated soils where the optimum admixture content seems to be 20%. The soils treated with lime have an optimum admixture percentage of 5% and for those treated with CFBC fly ash is 10 %. In this particular case at 10% fly ash, the initial strength gain is higher than in the case of 20% fly ash but between a curing time of 18 and 28 days the strength values for a 20% admixture are higher than for the other case. After 28 days of curing time, the strength values for 20% CFBC fly ash decreased considerably.

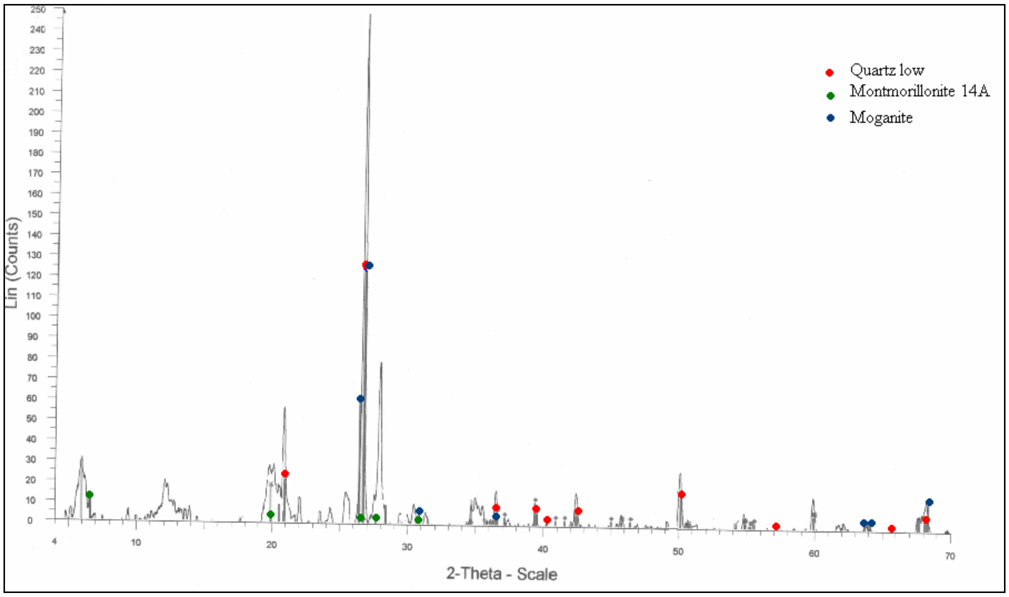


Figure 5.16 XRD soil treated with CFBC fly ash at 7 days curing time

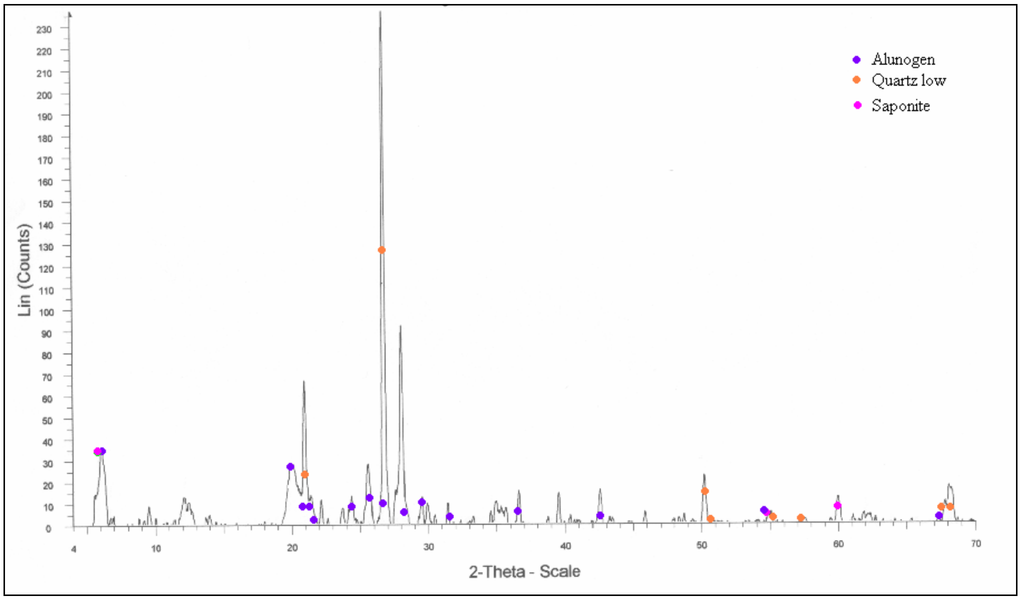


Figure 5.17 XRD soil treated with CFBC fly ash at 35 days curing time

5.3.3.2 Soil-admixture stiffness (E_t)

The effect of CFBC fly ash, class C fly ash, and lime on soil stiffness was measured by means of the Initial tangent modulus (E_t). This is the slope of the initial linear portion of the stress- strain curve. It was obtained as the average value of each specimen group with same curing time and additive proportion. Stress-strain curves with initial irregular behavior due to poor initial contact between sample and caps were corrected. Figure 5.18 shows an example of correction for the axes. The average E_t of the treated and untreated samples are presented in Figure 5.19. For soil treated with CFBC fly ash, the values increase with increasing curing time until reach stabilization after 40 days. In the case of lime, E_t continues increasing with curing time without becoming constant.

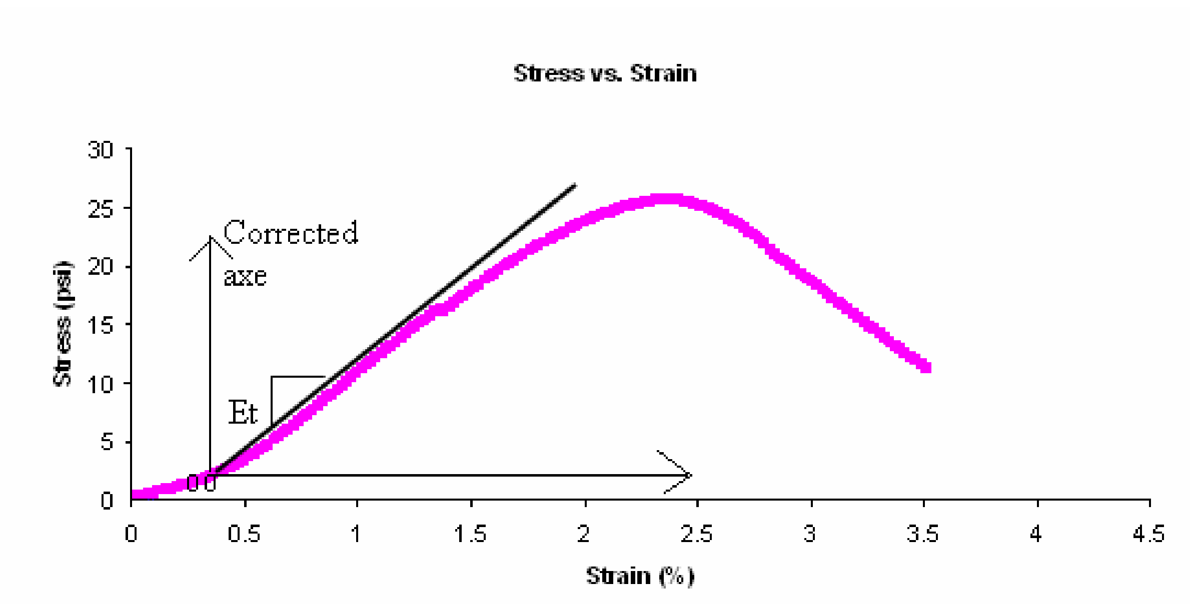


Figure 5.18 Correction for stress-strain curves

Soil treated with 10% class C fly ash shows a maximum value of E_t equals to 10.3 ksi at a curing time of 28 days. This represents an increase of approximate 307% when compared with the maximum value for untreated soil which is 2.56 ksi. The maximum value reported for lime was 9.9 ksi at a curing time of 103 days. This was obtained for soil treated with 5% lime. CFBC treated soil yielded the lower values for E_t reporting a maximum value of 4.5 ksi at 14 days curing time for samples stabilized with 10% CFBC. This value represents an increase of 76%.

According to the values presented in Figure 5.19 there is no a direct relationship between the percentages of stabilizer and the results of $E_{t.}$ The higher values of E_t were not related with the higher percentages of the additives. In the case of CFBC and class C treated soil, the maximum values were found at 10% of additive.

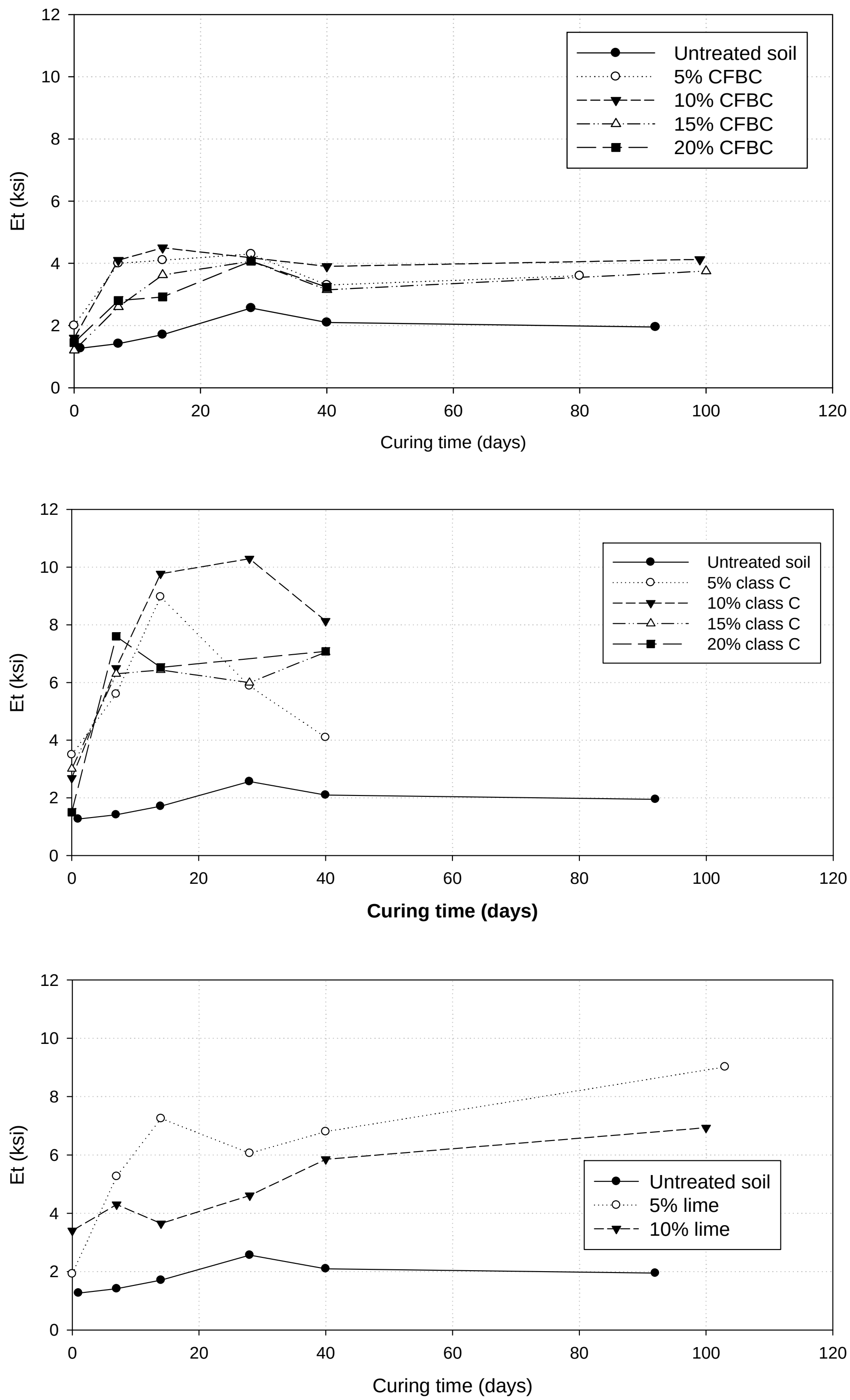


Figure 5.19 Initial tangent modulus for stabilizes soil

5.3.3.3 *Effect of admixture percentage on failure strain*

Strain at failure was recorded on each tested sample. The soil samples with 0% fly ash exhibited a ductile behavior (in comparison with those treated) with an average failure strain value of 5.4%. During the addition of the different admixtures percentages, the samples become brittle. The behavior of CFBC and class C samples was similar reaching values of strains at failure between 3.4 and 1.2%. The reduction in strain at failure is approximately from 37 to 78%. In the case of Ponce lime, the samples behaved more brittle than the other two admixtures. The measured strain values were between 1.9 and 0.79%. This represents a reduction of 65% to 583%.

The graphs in Figure 5.20 illustrate that during the first seven days of curing time there is a linear reduction in the strain at failure that becomes stable when increasing the period of curing. These curves also present the higher the percentage of chemical, the lower the strain at failure with exception on the samples with class C fly ash where this tendency was not obtained.

5.3.4 *Effect of soil-fly ash compaction delay on unconfined compressive tests*

The effects of compaction delay were evaluated on samples treated with 9, 10 and 20% of CFBC and class C fly ash. Compaction delay refers to the time between the addition of the admixture to the soil and the compaction stage. The selected delay times were 40 and 60 minutes. The results are presented in Figure 5.21. It is evident that delay in compaction has negative effect on the strength of soil mixtures. The values on strength can decreases from 14 psi to 38 psi. The effect is more critical in class C fly ash than in CFBC.

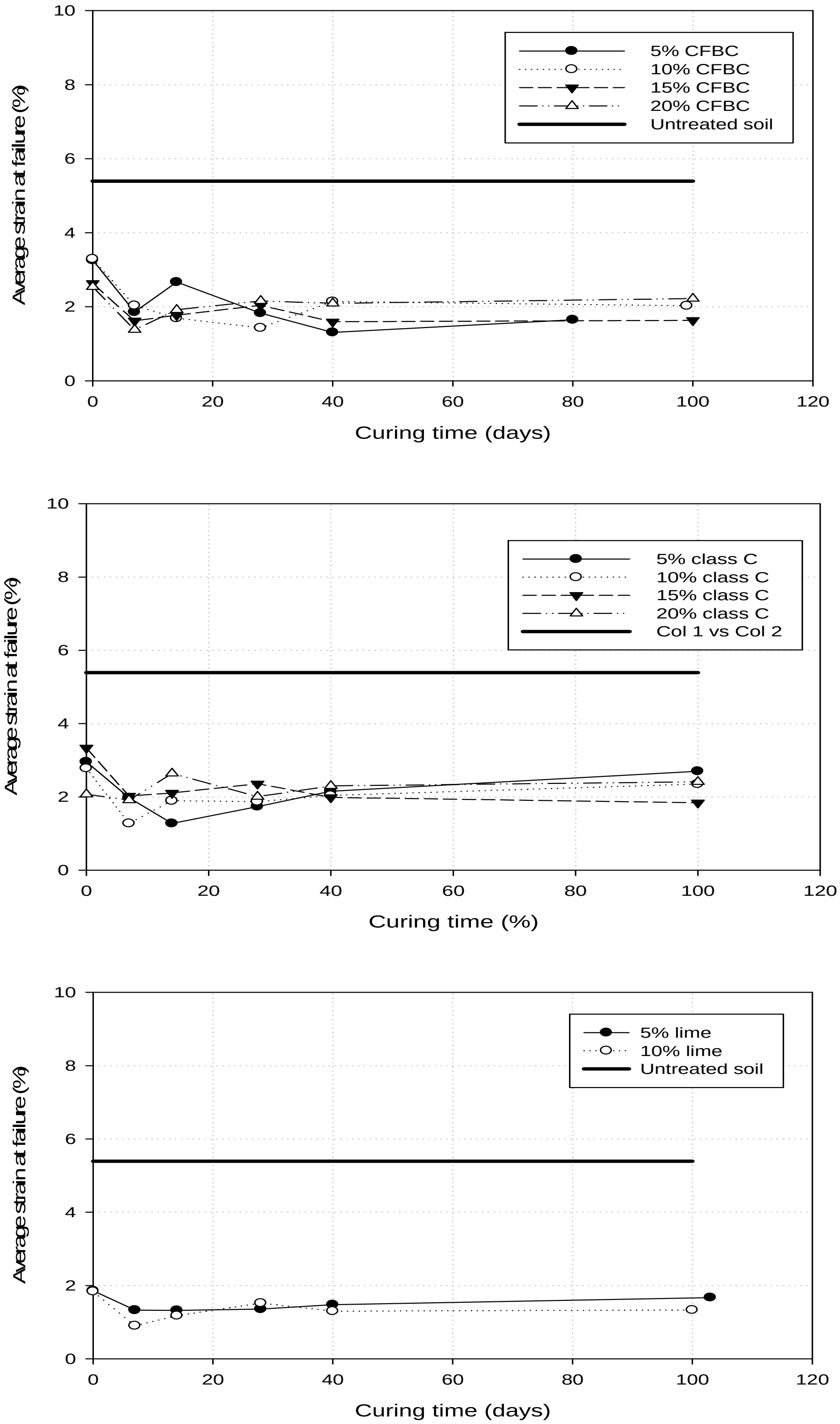


Figure 5.20 Strains at failure for stabilized Hormigueros clay

The sample with 9% CFBC fly ash presented a reduction in strength of 29% at 60 minutes of compaction delay while the sample mixed with 10% class C fly ash presented a reduction near 48% at 40 minutes of delay. When evaluating the dry density, there is a reduction for samples compacted with delay period. Samples with a delay period of 60 minutes between the addition of fly ash and the compaction showed a reduction in dry density 7.74 pcf, this represents 8%. This value is within the range presented by Mackiewicz et al.(2005). Due to this situation, it is recommended in the field work a maximum delay period of 30 minutes.

Table 5.5 Compaction delay effect on soil-fly ash samples

% Fly ash	curing time (days)	time delayed (minutes)	delayed samples		no delay		γdry % Difference	Qu %Difference
			qu (psi)	γdry (pcf)	qu (psi)	γdry (pcf)		
9 (CFBC)	7	60	36.16	88.05	51	95.8	8	29
10 (Class C)	40	40	41.62	81.23	79.65	85	4.4	48
20 (CFBC)	40	40	36.14	83	68.6	84.2	1.5	47

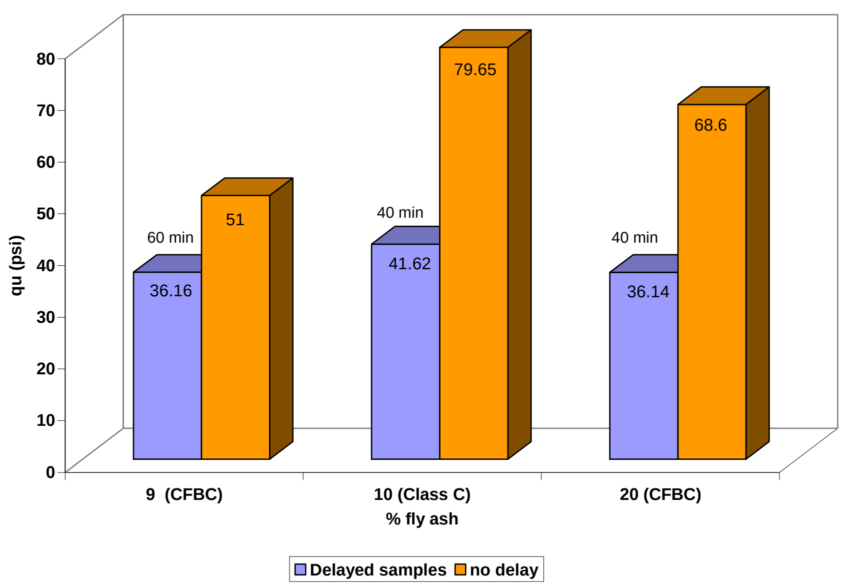


Figure 5.21 Effect of delay in compaction of soil-fly ash admixtures

5.3.5 Potential Volume Change (PVC)

The possible influence on the volume change of samples treated with CFBC fly ash was investigated using the PVC test. The same test was done on samples treated with class C fly ash for comparison purposes. Samples were compacted using different percentages of fly ash and using an initial water content of 22%. Figure 5.22 shows the swell pressure values at 2 hours of fly ash addition which was the time when the soil-fly ash stabilized. Swell pressure refers to the force per unit area the soil exerts when water is added to a compacted soil sample. The graph shows the behavior of soil volume change when subjected to different moisture conditions. Swell pressure values for CFBC fly ash treated soil fall above the line representing the soil indicating expansion. In the other hand, class C fly ash treated soil shows a reduction in the swell pressure.

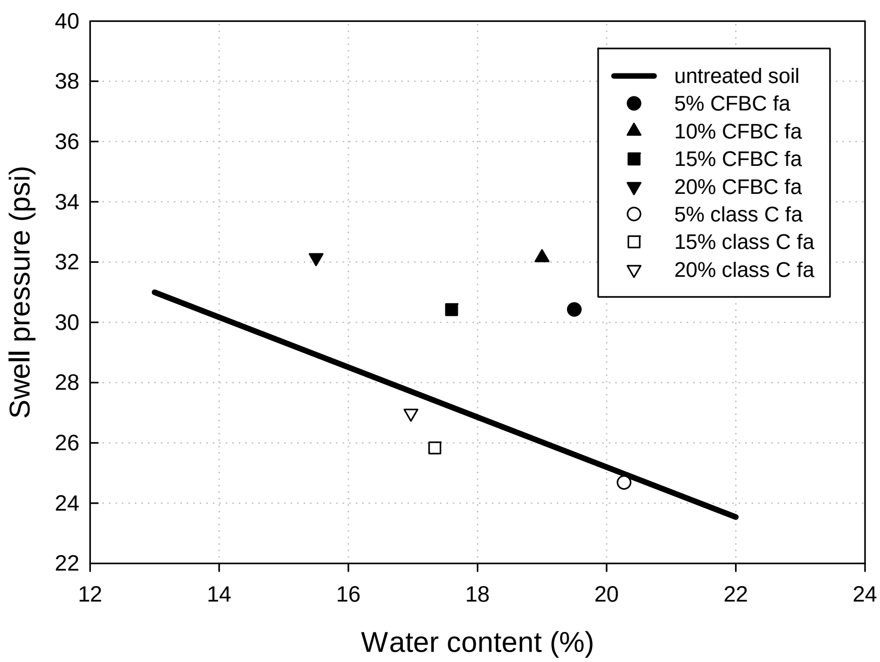


Figure 5.22 PVC for soil treated with CFBC and class C fly ash

5.4 Summary and Discussion

This chapter provided the results of the laboratory tests performed to evaluate the behavior of Hormigueros clay when treated with CFBC fly ash. Results obtained from class C fly ash and lime were used for comparison purposes.

The plasticity properties of Hormigueros clay was found to decrease with increasing CFBC fly ash content. Test results indicate that CFBC fly ash reduces the liquid and plastic limit values with increasing admixture amounts and curing time. A similar behavior was reported by Cokca (2001) where he found liquid limit values of the soil treated decreasing with increasing amount of stabilizer. The soil treated with CFBC fly ash in this study does not change its classification (remained as CH) but it moved along the A-line in the Plasticity chart. The change produced by the CFBC fly ash in the plasticity properties of the soil can be attributed to the addition of new particles with different sizes and the chemical reaction between the soil, fly ash, and water.

When evaluating the compaction properties of the CFBC fly ash treated soil it was found that additional CFBC fly ash increases the Standard Proctor maximum dry density and optimum water content of the Hormigueros clay. This increase in the maximum dry unit weight is believed to occur because the spherical fly ash particles act filling the voids in the soil. Zachary (2002) reported a similar behavior on soils treated with class C fly ash.

The unconfined compressive strength results indicate that unconfined compressive strength increase as increase the quantity of stabilizer with exception of lime. This behavior was also reported by Acosta et at. (2003). All types of treated samples gained most of their strength within the first fourteen days of curing. This is similar to other published results (Misra et al.

2005). This fast strength gain is believed to be related to the initial rapid hydration that takes place in with these admixtures. The similar trend exhibited by the soil samples treated with CFBC fly ash tend to indicate a similar initial rapid hydration process is taking place within the first few days. At 40 days of curing, the strength values for CFBC fly ash present a reduction. Beyond this period the strength development reaches similar strength values to those measured in 14 day old samples with exception of the samples treated with 20% CFBC fly ash where strength values never reached similar values to those measured during the first fourteen days. The reduction of strength is related with the crystals formation reported in the SEM images. This phenomena is associated to the high sulfur content (>10%) of this CFBC fly ash. For a given admixture type, test results indicate that higher the amount of additive the higher is the strength improvement level with respect to strength levels measured from untreated soils.

Initial tangent modulus increases in the way the cementation process takes place. Class C reported higher values than CFBC fly ash and lime.

CFBC, class C fly ash and lime affect the strain at failure of Hormigueros clay causing a decrease in the strain values. This phenomenon occurs due to the stiffness the soil-mixture experiment when hydration process starts between the fly ash particles and water. The initial strength gain reduces the strains and the soil turns into a brittle material.

Compaction delay causes a decrease in strength and unit dry weight of the treated soil. The cementation process occurs at the moment the fly ash is in contact with water and soil. The soil start to form lumps which have to be broke with the delayed compaction. These results are similar to those presented by Mackiewicz et al (2005). He explains that the strength reduction is the result of cementitious bonds that have been disrupted during compaction and reduced number of intergranular contact. The reduction in maximum density and strength depends on the time that hydration process takes place and also depends on the ash source, that is why CFBC and class C fly ash samples show different results.

6 CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

This investigation has discussed the results of a laboratory investigation involving use of CFBC fly ash for ground improvement of soft clays. For comparison purposes the laboratory investigation also involved tests on treated soils with lime and class C fly ash. In general test results indicated that clayey soils treated with CFBC fly ash result in ground improvement as evidenced from higher strengths and stiffnesses measured from unconfined compressive tests. However, the level of ground improvement was not as high compared to soils treated with lime or class C fly ash.

Compressive strength gains were observed primarily in the initial 14 days of curing and then had a tendency to stabilize showing little strength gain. For CFBC treated soils, a drop of strength was observed after 14 days of curing and SEM microscopy revealed growth of crystal minerals (alunogen) that could be responsible for this temporary strength loss. The mineral growth could be related to the high sulfur content (12.57%) in the CFBC ash. However tests on samples with curing periods beyond 40 days showed compressive strength was regained to similar levels observed in the initial 14 day curing period with exception of soil treated with 20% CFBC.

Plasticity evaluation indicated that CFBC fly ash changes the plasticity when increasing fly ash percentage and curing time. The tendency presented indicates that higher percentage of fly ash and longer curing times could change the classification of the soil into a better one such as low plasticity clay or silt.

The results obtained from this laboratory program seem to suggest that CFBC may effectively improve the strength and stiffness of Hormigueros clay but cause some expansion which is critical for roads and buildings. For this reason it is recommended to evaluate the expansion potential using similar loads to those the soil will be experimenting. Proper engineering judgment is recommended complemented with laboratory tests results carried out using the site specific soil and following a similar test program as the one presented in this investigation.

6.2 Recommendations for Future Work

Recommendations for further research into the behavior of engineering properties of clays treated with fly ash include:

- Study the *in-situ* strength gain of clay soils treated with fly ash and make correlations between field and laboratory results.

- Study the effective strength parameters as effective cohesion and effective friction angle by means of triaxial tests.

- Study the possible ettringite formation which is a mineral responsible for expansion in FBC fly ashes by monitoring samples at different curing times using the technology of SEM images.

- The evaluation of the pH changes in samples treated with different percentage of fly ash to obtain a correlation of the improvement degree.

- The evaluation of the saturation effect on particles integrity and strength gain.

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APPENDIX A: SEM IMAGES

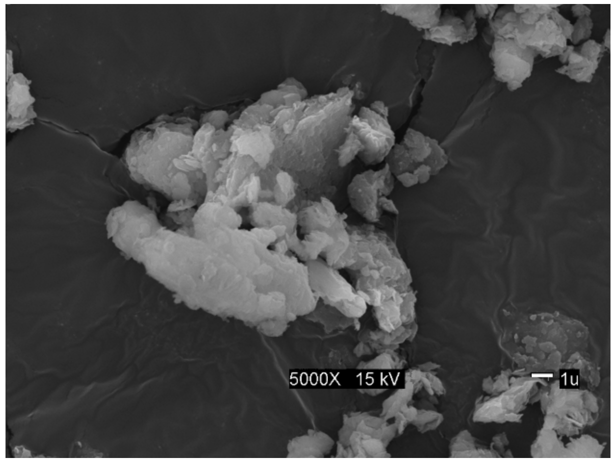


Figure 6.1. SEM Hormigueros clay

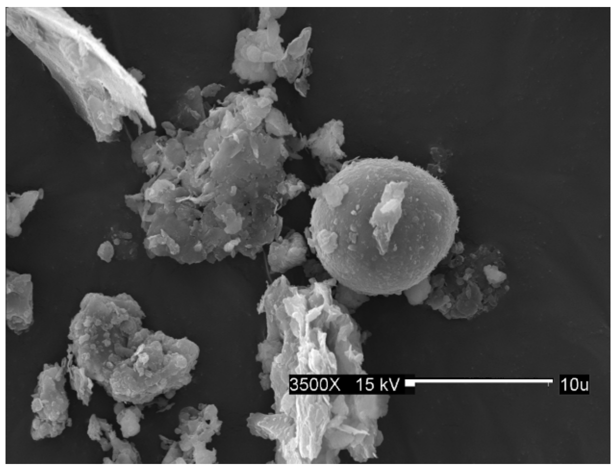


Figure 6.2. SEM CFBC fly ash

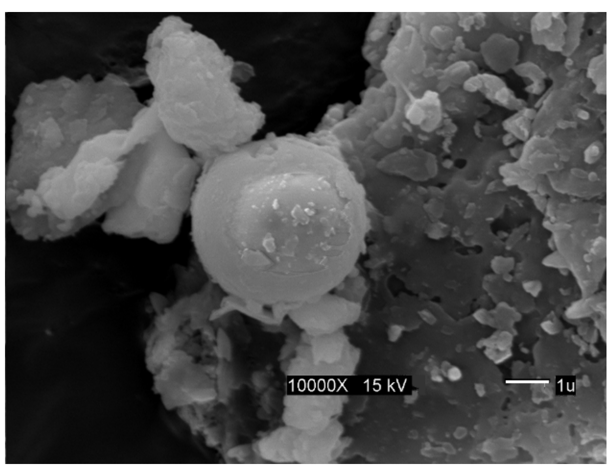


Figure 6.3. SEM 2 CFBC fly ash

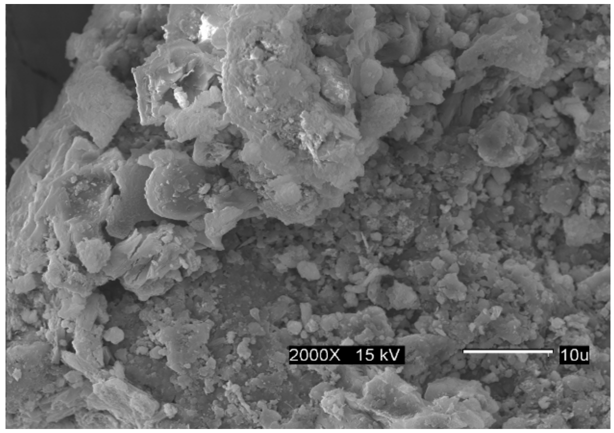


Figure 6.4. 10% CFBC fly ash + Hormigueros clay 7 days curing time

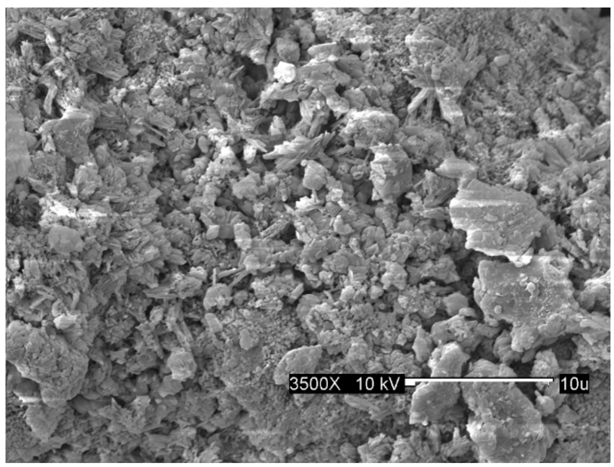


Figure 6.5. 10% CFBC fly ash + Hormigueros clay 35 days curing time

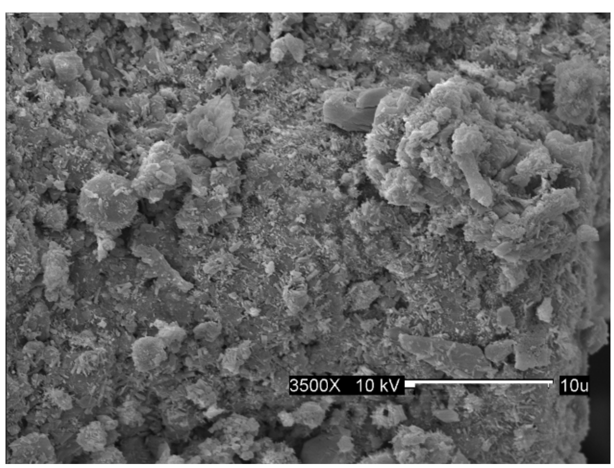


Figure 6.6. 15%CFBC fly ash + Hormigueros clay 100 days curing time (1)

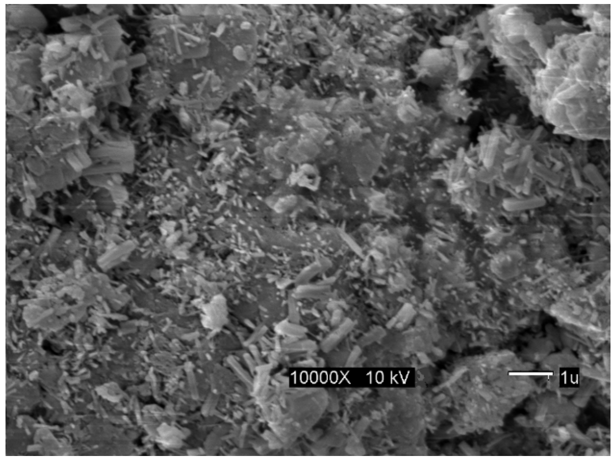


Figure 6.7. 15%CFBC fly ash + Hormigueros clay 100 days curing time (2)

APPENDIX B: FAILED SAMPLES PICTURES

Failed samples

Admixture: **none**
percentage: 0%   curing time: 7days

s1

s2

s3

percentage: 0%   curing time: 14days
No pictures

percentage: 0%   curing time: 28days

s1

s2

percentage: 0%   curing time: 40 days

s1

s2

s3

percentage: 0%   curing time: 92days

s1

s2

Admixture: **lime**

percentage: 5%   curing time: 0 days

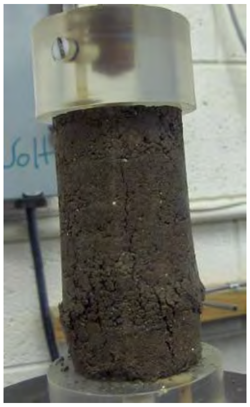
s1   s2

percentage: 5%   curing time: 7 days

s1   s2   s3

percentage: 5%   curing time: 14 days

s1   s2



percentage: 5%   curing time: 28 days

s1 

s2 

s3 

percentage: 5%   curing time: 40 days

s1 

s2 

s3 

percentage: 5%   curing time: 103 days

s1 

s2 

s3 

percentage: 10% curing time: 0 days

s1

percentage: 10% curing time: 7 days

s1 s2 s3



percentage: 10% curing time: 14 days

s1 s2 s3



Percentage: 10% curing time: 28 days

s1

s2

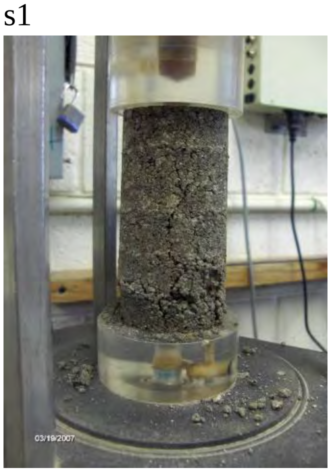
percentage: 10% curing time: 40 days

s1

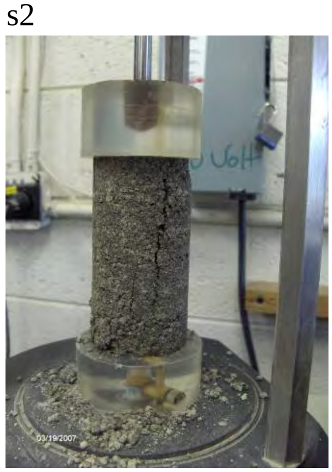
s2

Percentage: 10% curing time: 100 days

s1



s2



s3

Admixture: AES **fly ash**

percentage: 5%   curing time: 0 days

s1

s2

percentage: 5%   curing time: 7 days

s1

s2

s3

percentage: 5%   curing time: 14 days

s1

s2

percentage: 5%   curing time: 28 days

s1

s2

s3

percentage: 5%   curing time: 40 days

s1

s3

percentage: 5%   curing time: 80 days

s1

s2

s3

percentage: 10%   curing time: 0 days

s1

percentage: 10%   curing time: 7 days

s1

s2

s3

s4

percentage: 10%   curing time: 14 days

s1

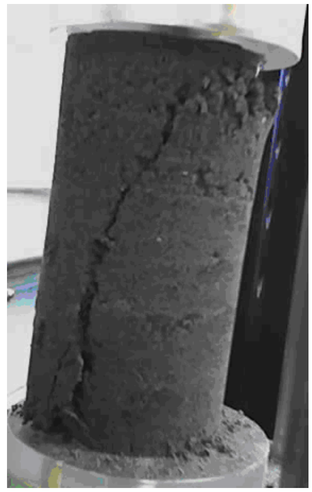
s2

s3

Percentage: 10% curing time: 28 days

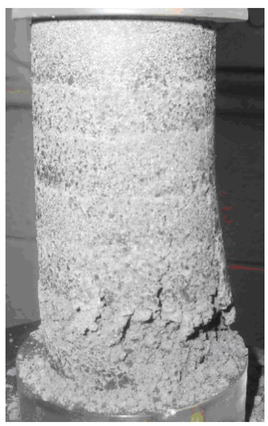
S1 s2 s3 s4






percentage: 10% curing time: 40 days

s1 s2

percentage: 10% curing time: 99 days

s1 s2


percentage: 15%   curing time: 0 days
no picture

percentage: 15%   curing time: 7 days

s1

s2

percentage: 15%   curing time: 14 days

s1

s2

s3

s4

percentage: 15%   curing time: 28 days

s1

s2

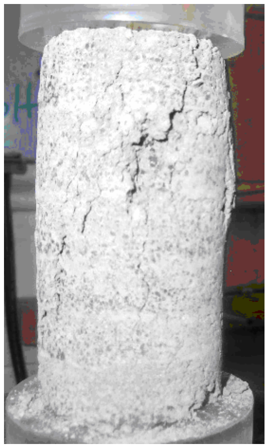
s3

s4

percentage: 15%   curing time: 40 days

s1

s2



s3

percentage: 15%   curing time: 100 days

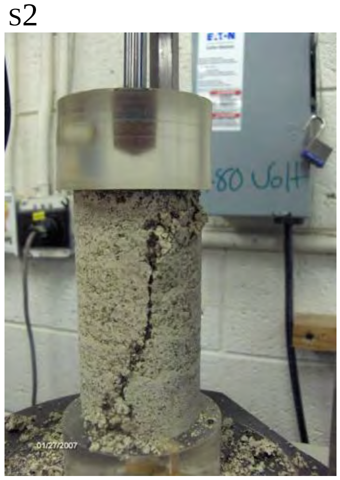
s1

s2

percentage: 20%   curing time: 7 days

s1

s2



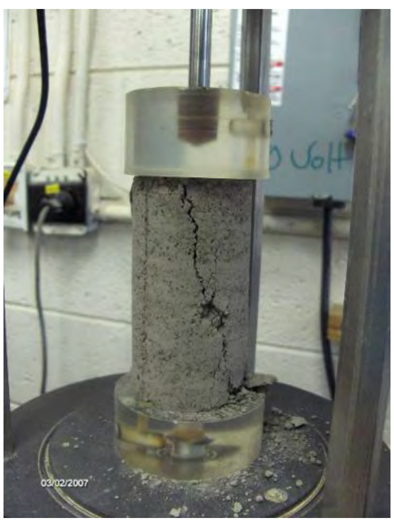
s3

percentage: 20%   curing time: 14days

s1 

s2 

percentage: 20%   curing time: 28 days

s1 

s2 

s3 

Admixture: **fly ash** Colorado

percentage: 5% curing time: 7 days

s1 s2


percentage: 5% curing time: 14 days

S1 s2

percentage: 5% curing time: 28 days

s1 s2


percentage: 10%   curing time: 7 days

s1 s2


percentage: 10%   curing time: 14 days

s1 s2


percentage: 10%   curing time: 28 days

s1 s2


percentage: 15%   curing time: 7 days

s1 s2

percentage: 15% curing time: 14 days

s1 s2

percentage: 15% curing time: 28 days

s1

percentage: 20%   curing time: 7 days

s1 

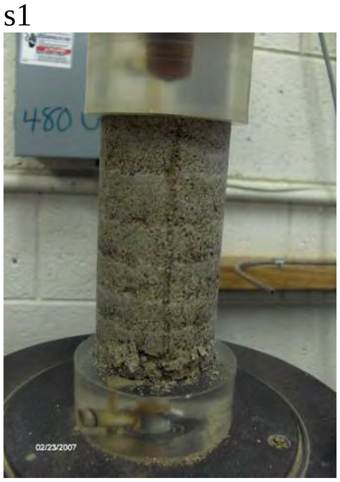
s2 

percentage: 20%   curing time: 14 days

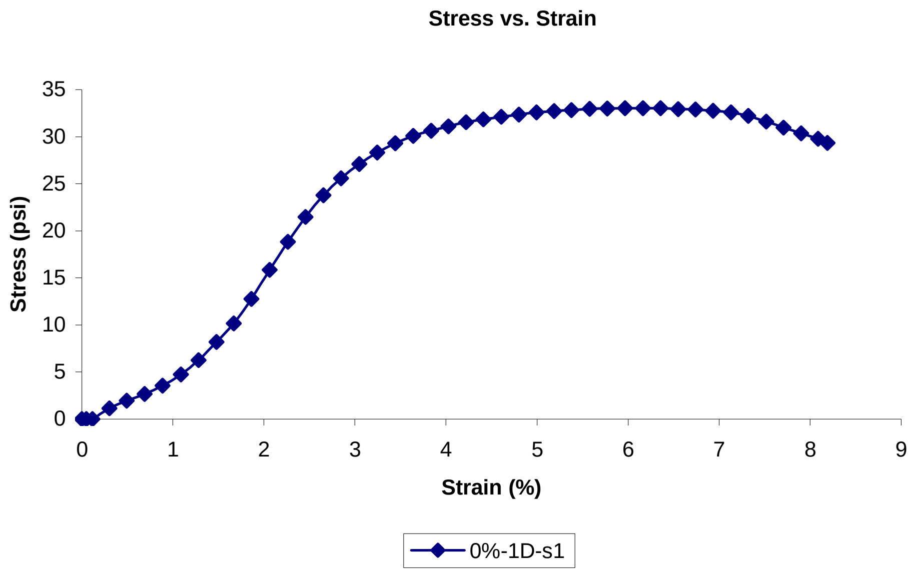
s1 

s2 

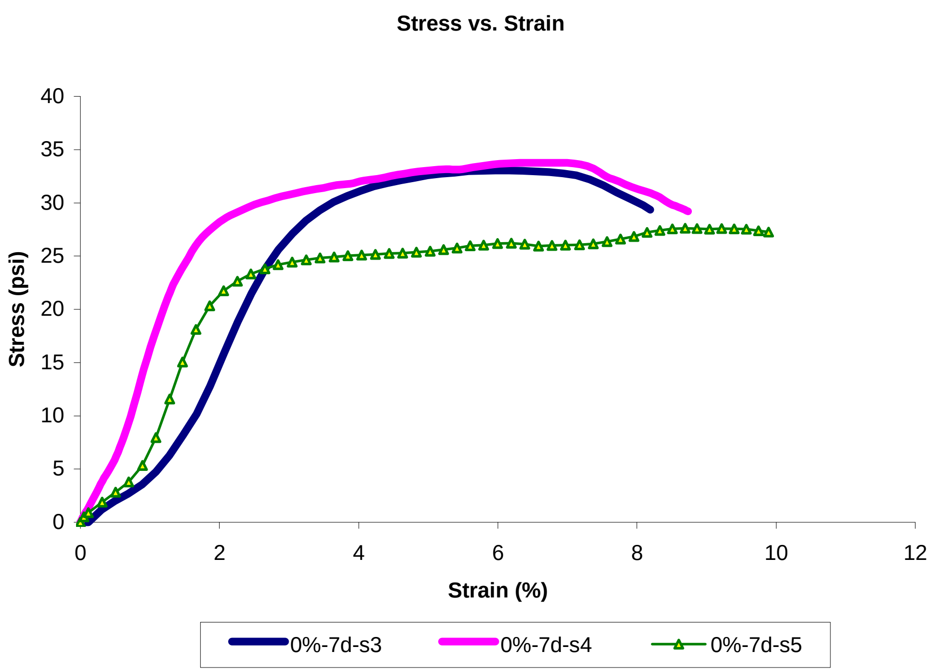
percentage: 20%   curing time: 28 days

s1 

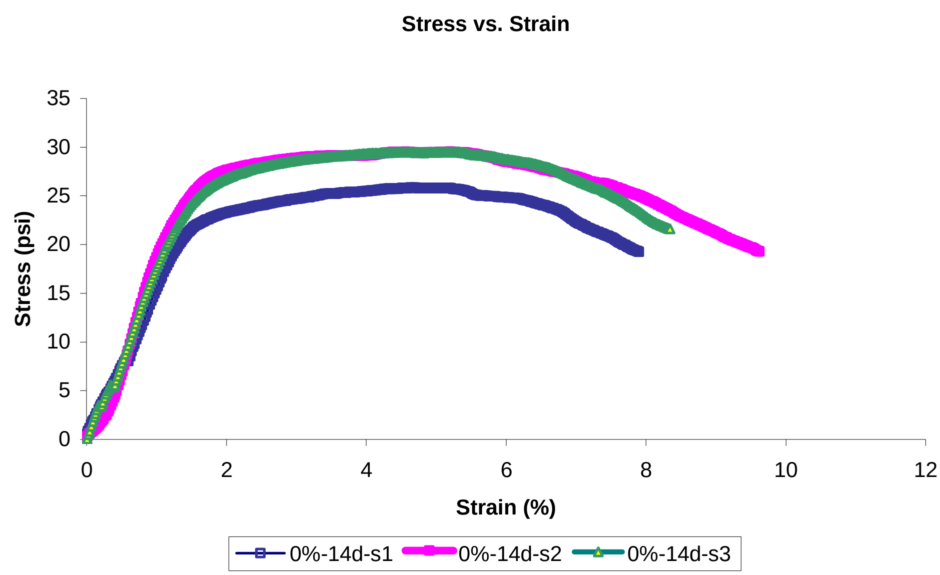
APPENDIX C: STRESS VS. STRAIN CURVES

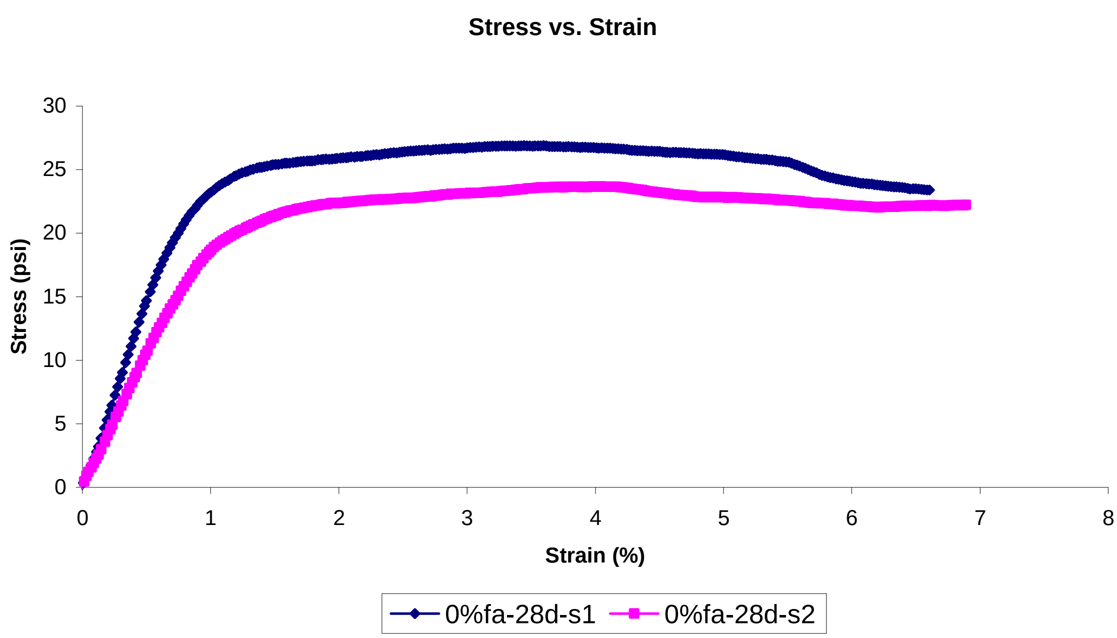


Stress vs. Strain
Stress (psi)
35
30
25
20
15
10
5
0
0
1
2
3
4
5
6
7
8
9
Strain (%)
0%-1D-s1

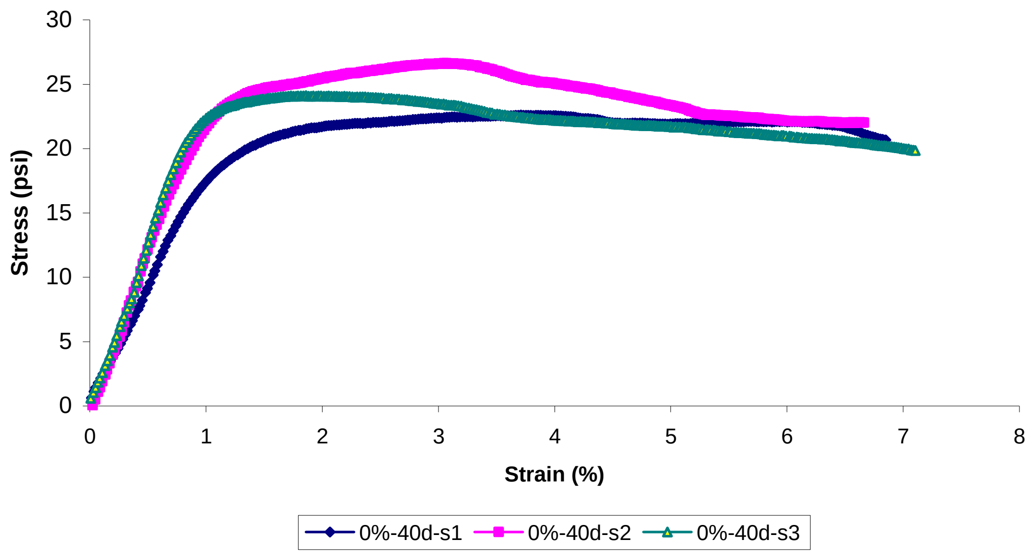


Stress vs. Strain
Stress (psi)
40
35
30
25
20
15
10
5
0
0
2
4
6
8
10
12
Strain (%)
0%-7d-s3
0%-7d-s4
0%-7d-s5

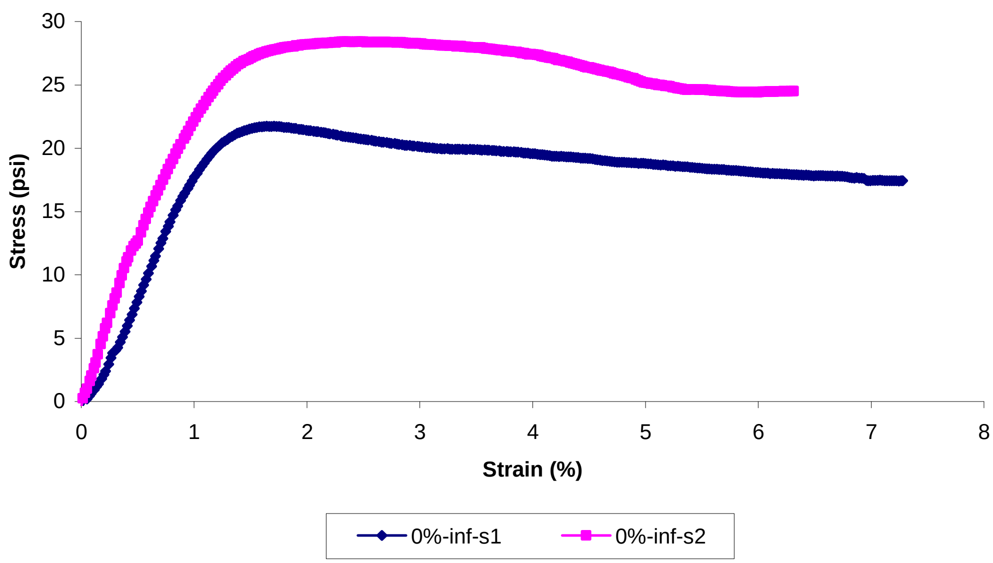

Stress vs. Strain
Stress (psi)
35
30
25
20
15
10
5
0
0
2
4
6
8
10
12
Strain (%)
0%-14d-s1
0%-14d-s2
0%-14d-s3


Stress vs. Strain
Stress (psi)
30
25
20
15
10
5
0
0
1
2
3
4
5
6
7
8
Strain (%)
0%fa-28d-s1
0%fa-28d-s2

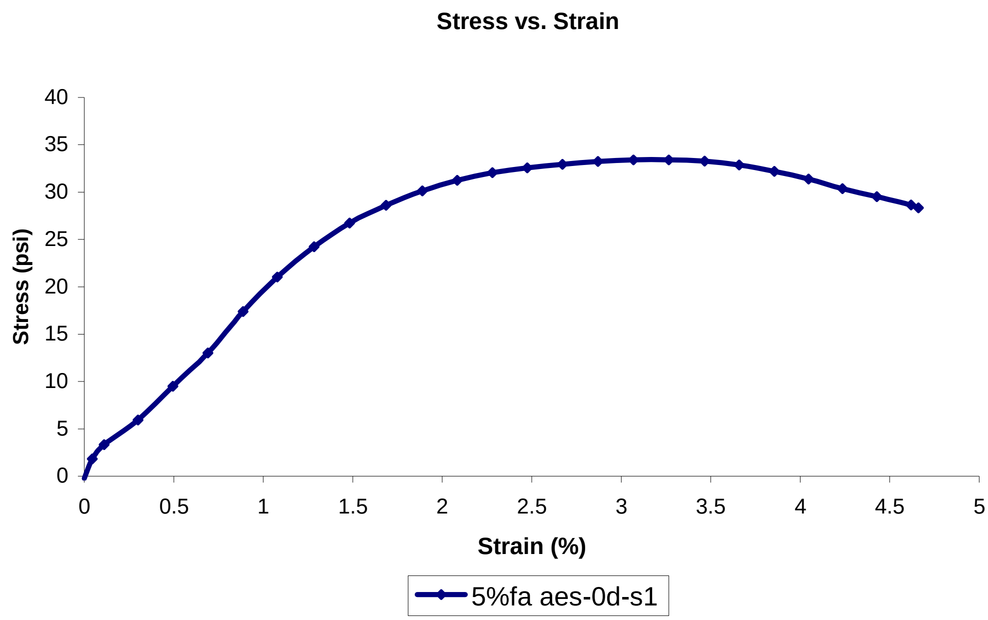
Stress vs. Strain

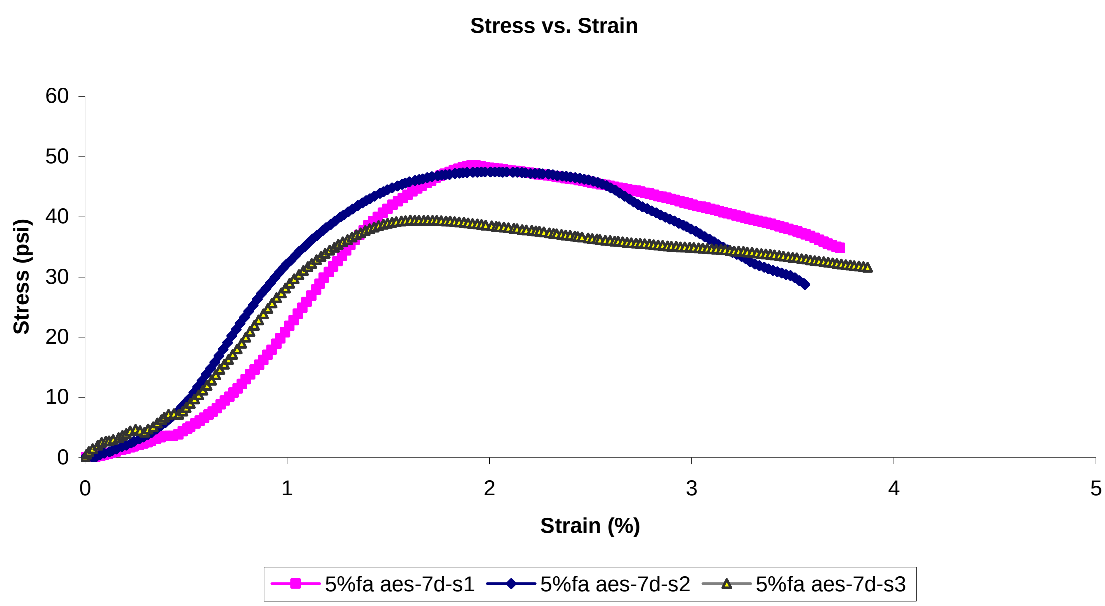


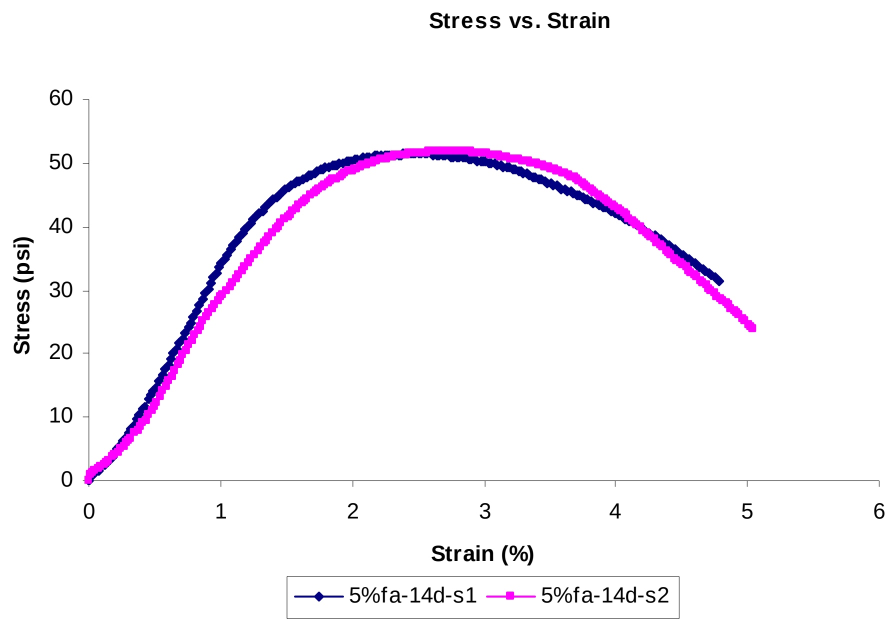
Stress vs Strain

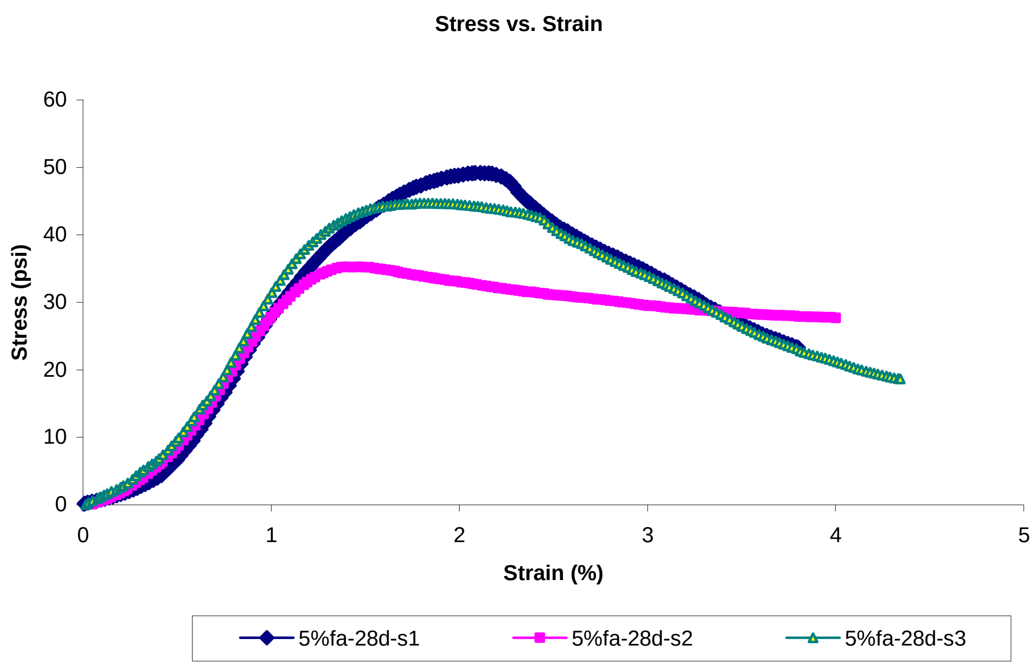


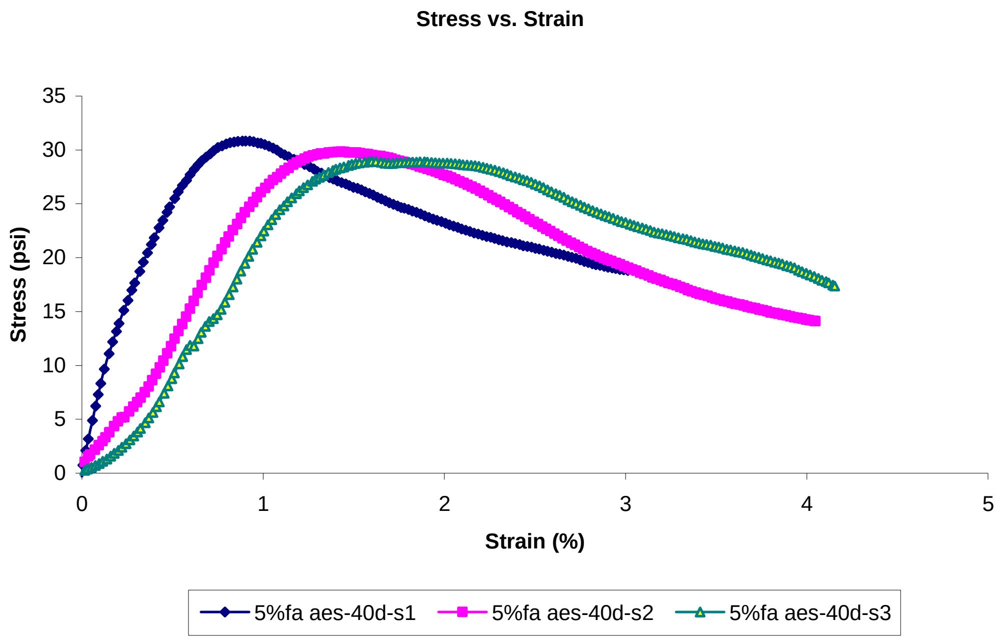
CFBC fly ash

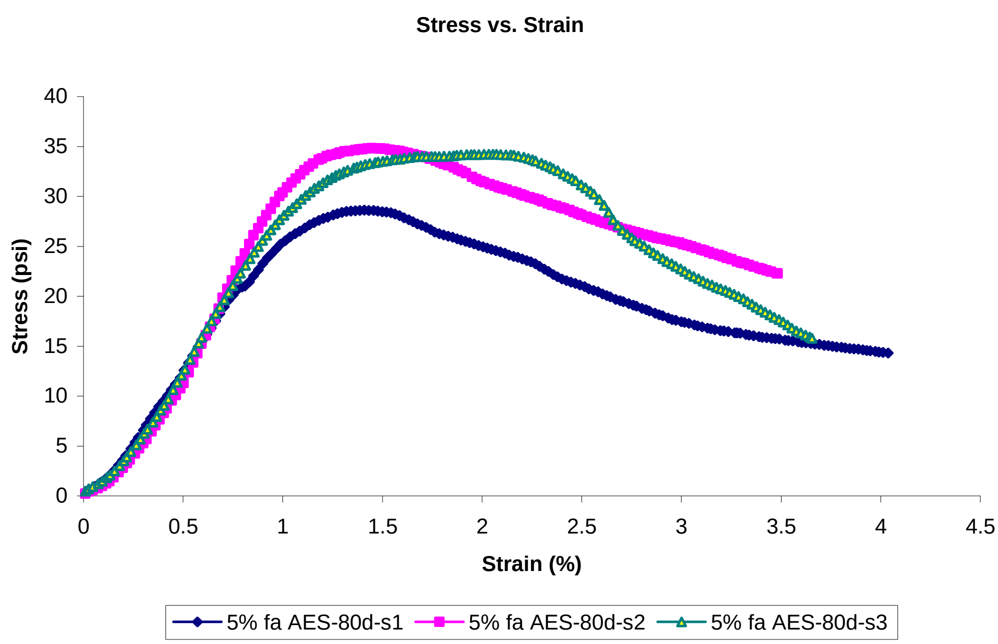

Stress vs. Strain
Stress (psi)
40
35
30
25
20
15
10
5
0
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
Strain (%)
5%fa aes-0d-s1

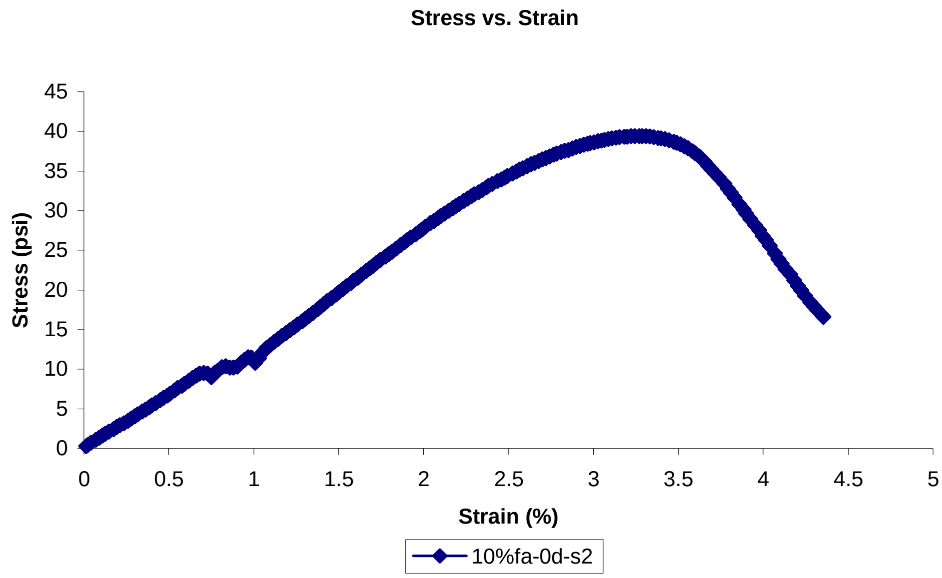

Stress vs. Strain
Stress (psi)
60
50
40
30
20
10
0
0
1
2
3
4
5
Strain (%)
5%fa aes-7d-s1
5%fa aes-7d-s2
5%fa aes-7d-s3

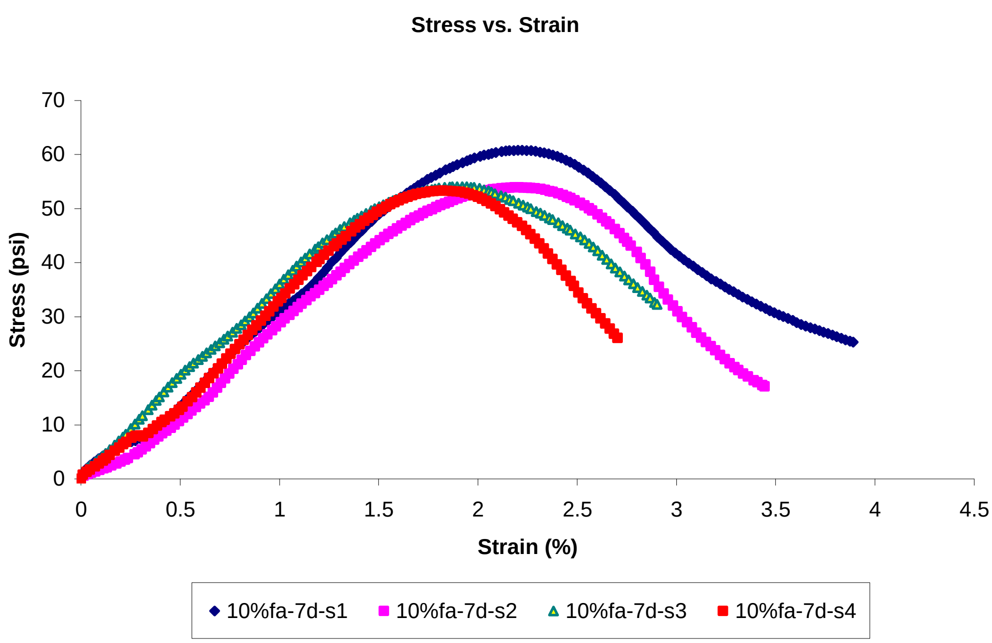

Stress vs. Strain
Stress (psi)
60
50
40
30
20
10
0
0
1
2
3
4
5
6
Strain (%)
5%fa-14d-s1
5%fa-14d-s2

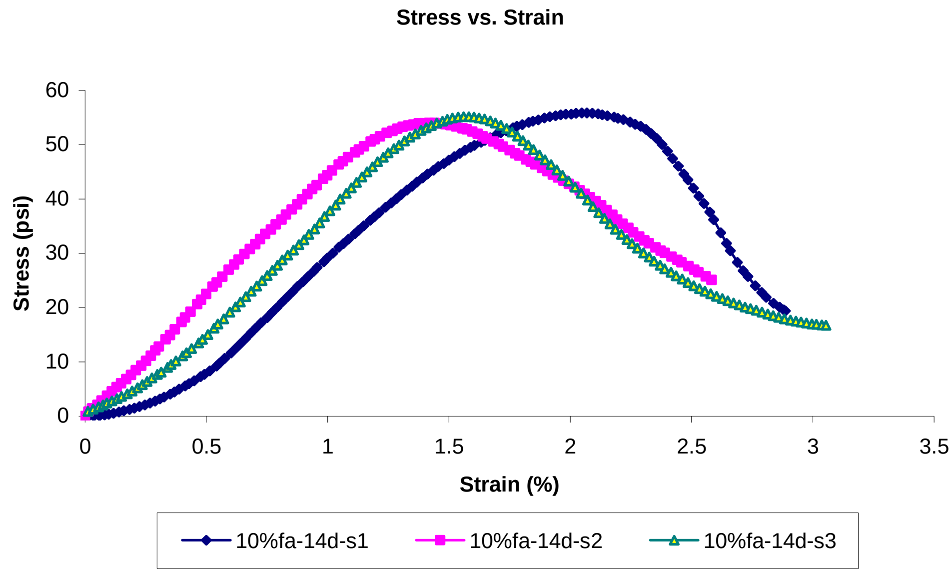

Stress vs. Strain
Stress (psi)
60
50
40
30
20
10
0
0
1
2
3
4
5
Strain (%)
5%fa-28d-s1
5%fa-28d-s2
5%fa-28d-s3

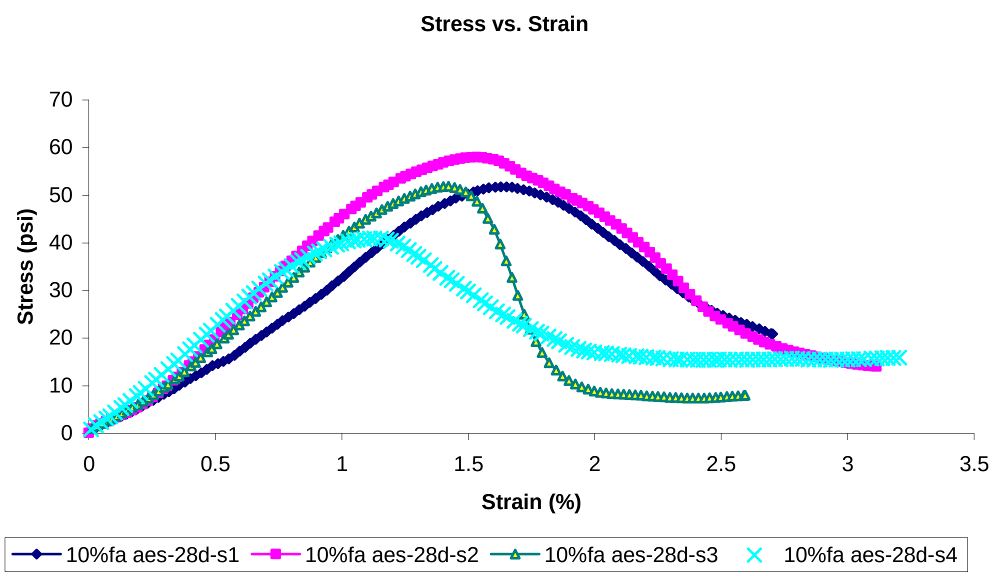

Stress vs. Strain
Stress (psi)
Strain (%)
5%fa aes-40d-s1
5%fa aes-40d-s2
5%fa aes-40d-s3

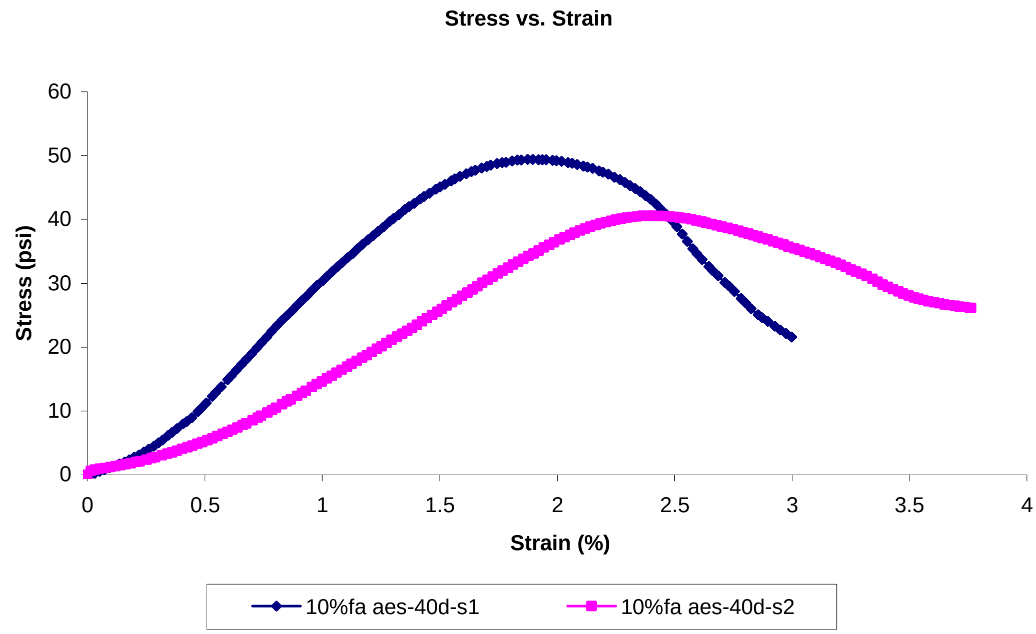

Stress vs. Strain
Stress (psi)
Strain (%)
5% fa AES-80d-s1
5% fa AES-80d-s2
5% fa AES-80d-s3


Stress vs. Strain
Stress (psi)
45
40
35
30
25
20
15
10
5
0
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
Strain (%)
10%fa-0d-s2

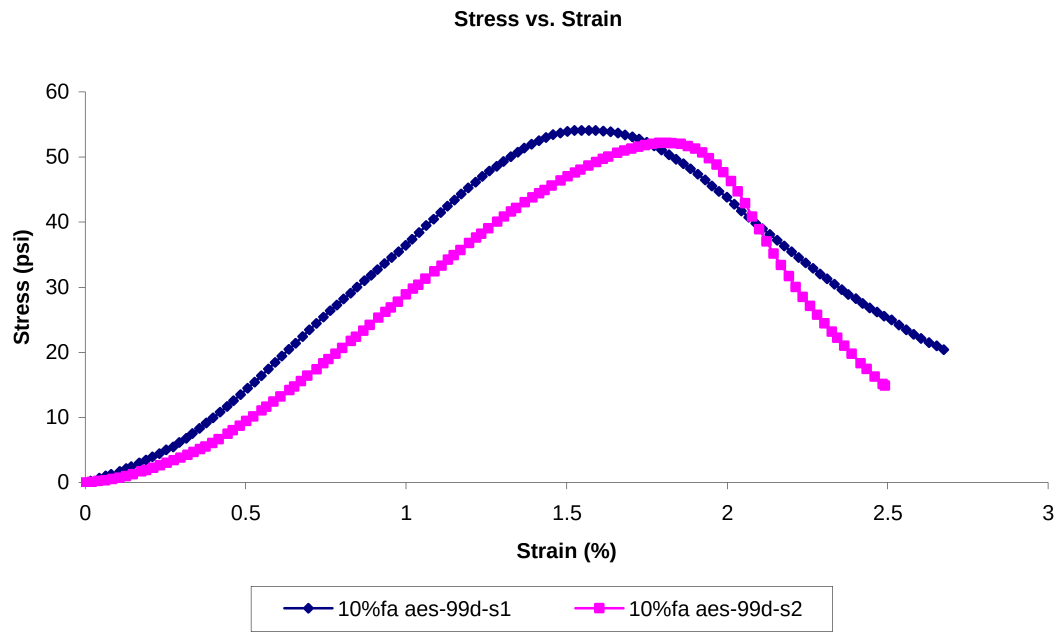

Stress vs. Strain
Stress (psi)
70
60
50
40
30
20
10
0
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
Strain (%)
10%fa-7d-s1
10%fa-7d-s2
10%fa-7d-s3
10%fa-7d-s4


Stress vs. Strain
Stress (psi)
60
50
40
30
20
10
0
0
0.5
1
1.5
2
2.5
3
3.5
Strain (%)
10%fa-14d-s1
10%fa-14d-s2
10%fa-14d-s3

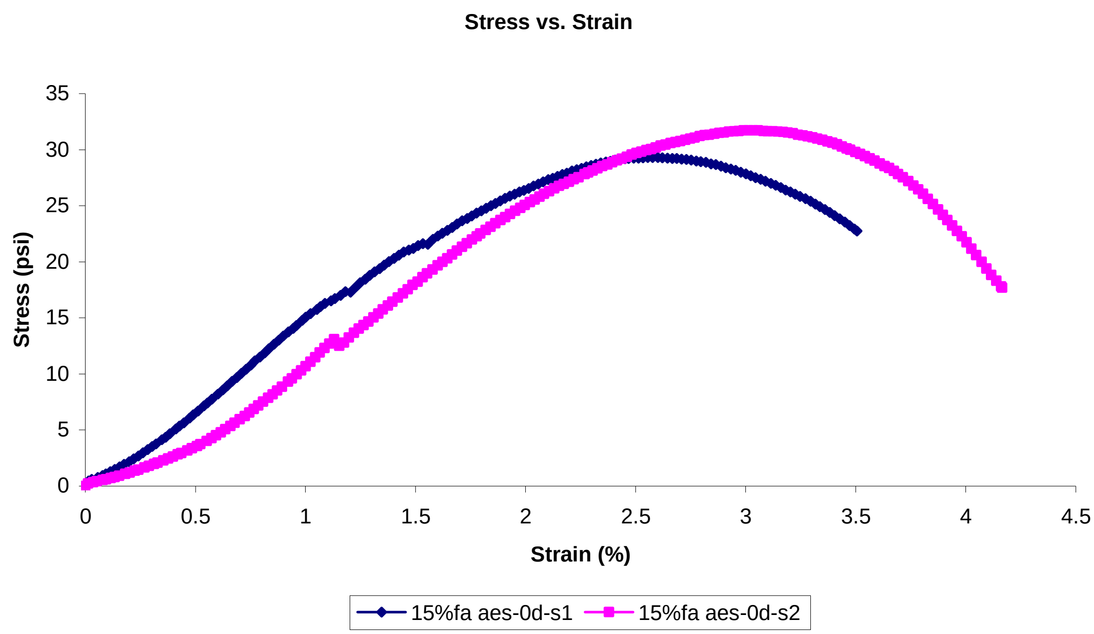

Stress vs. Strain
Stress (psi)
70
60
50
40
30
20
10
0
0
0.5
1
1.5
2
2.5
3
3.5
Strain (%)
10%fa aes-28d-s1
10%fa aes-28d-s2
10%fa aes-28d-s3
10%fa aes-28d-s4

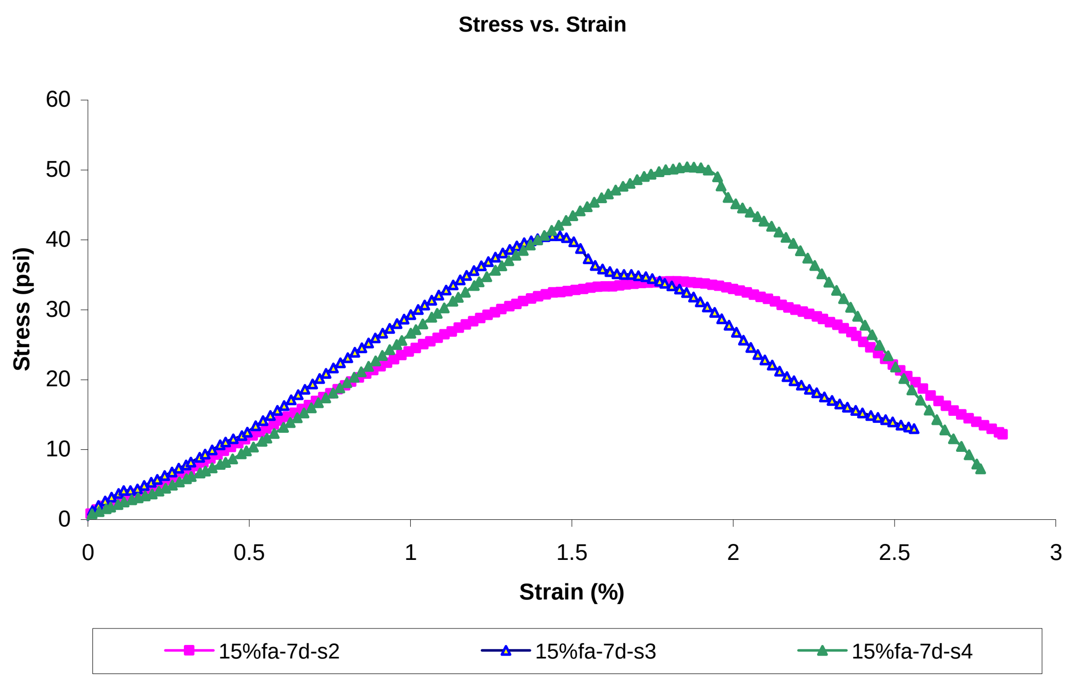


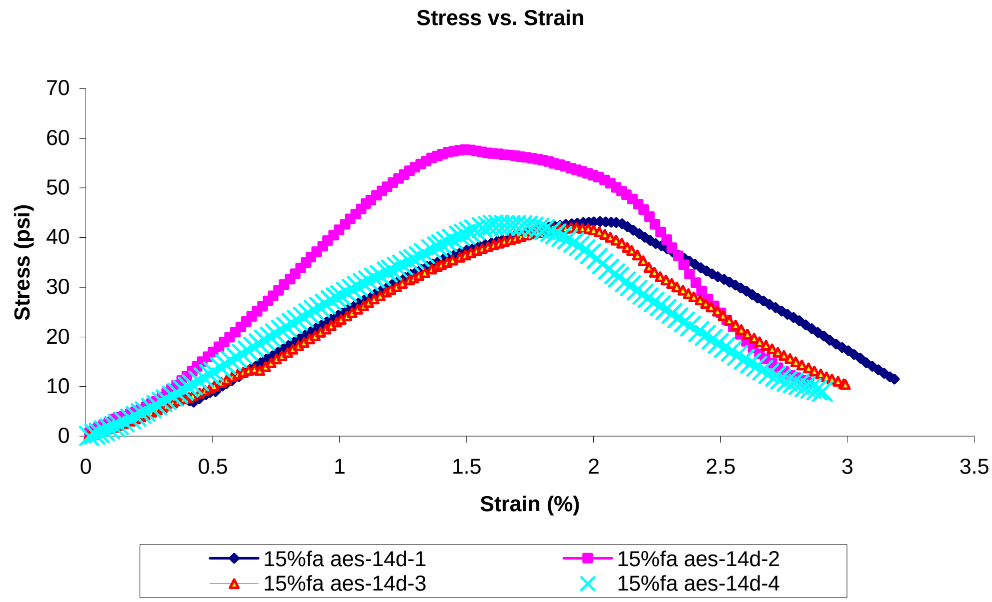
Stress vs. Strain
Stress (psi)
60
50
40
30
20
10
0
0
0.5
1
1.5
2
2.5
3
3.5
4
Strain (%)
10%fa aes-40d-s1
10%fa aes-40d-s2

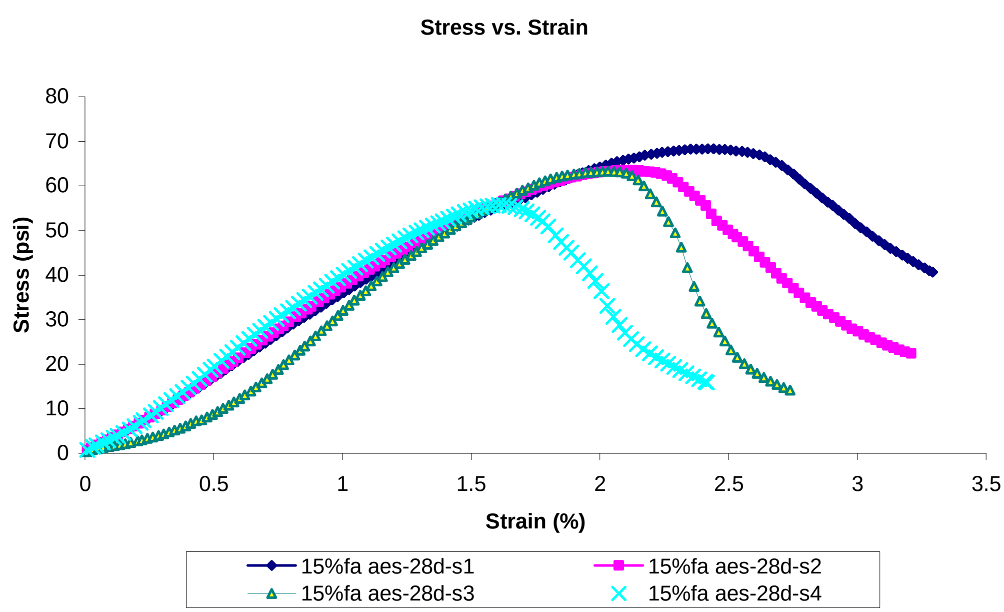


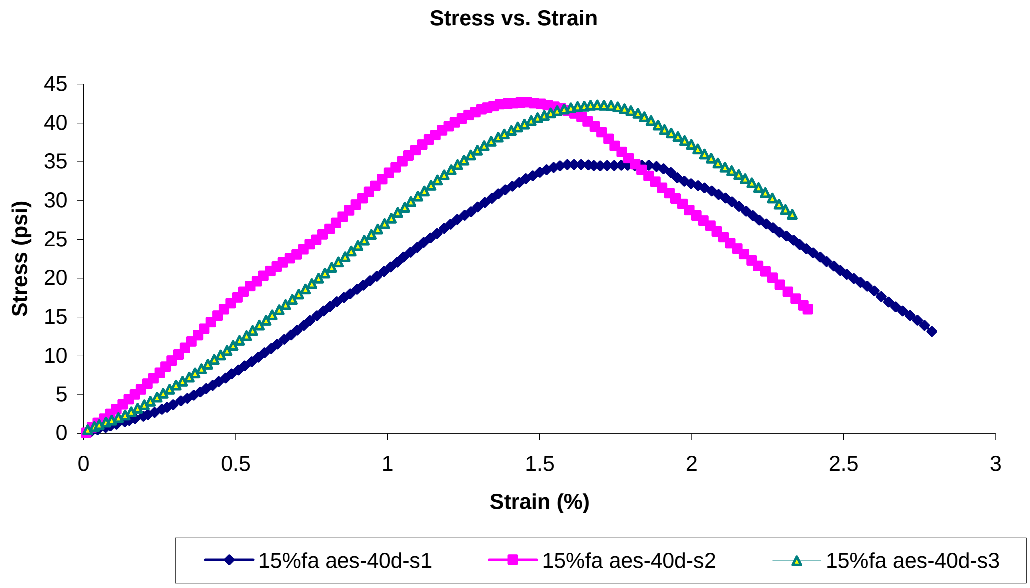
Stress vs. Strain
Stress (psi)
60
50
40
30
20
10
0
0
0.5
1
1.5
2
2.5
3
Strain (%)
10%fa aes-99d-s1
10%fa aes-99d-s2

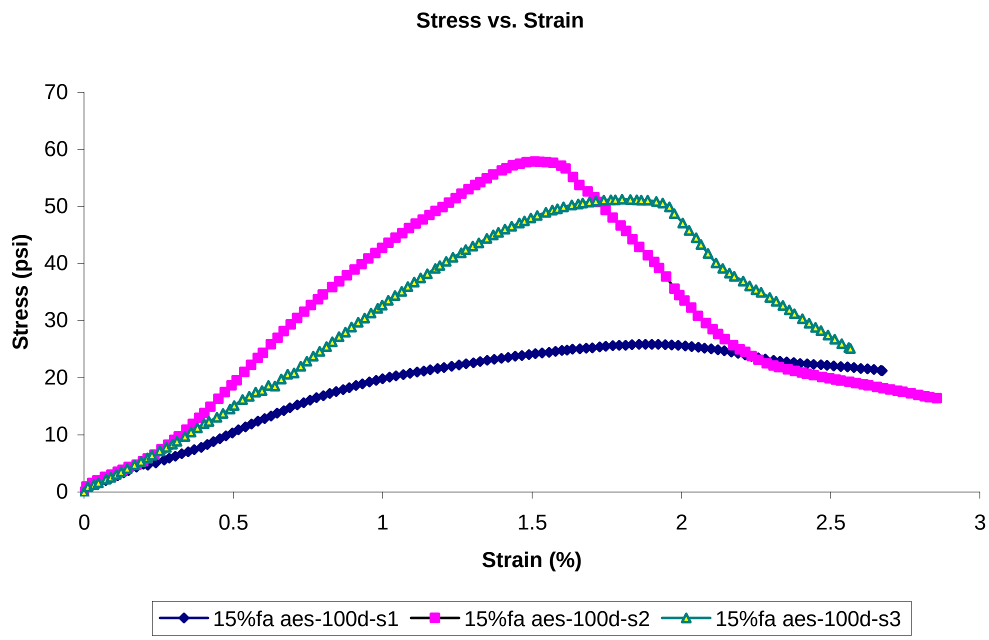

Stress vs. Strain
Stress (psi)
35
30
25
20
15
10
5
0
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
Strain (%)
15%fa aes-0d-s1
15%fa aes-0d-s2

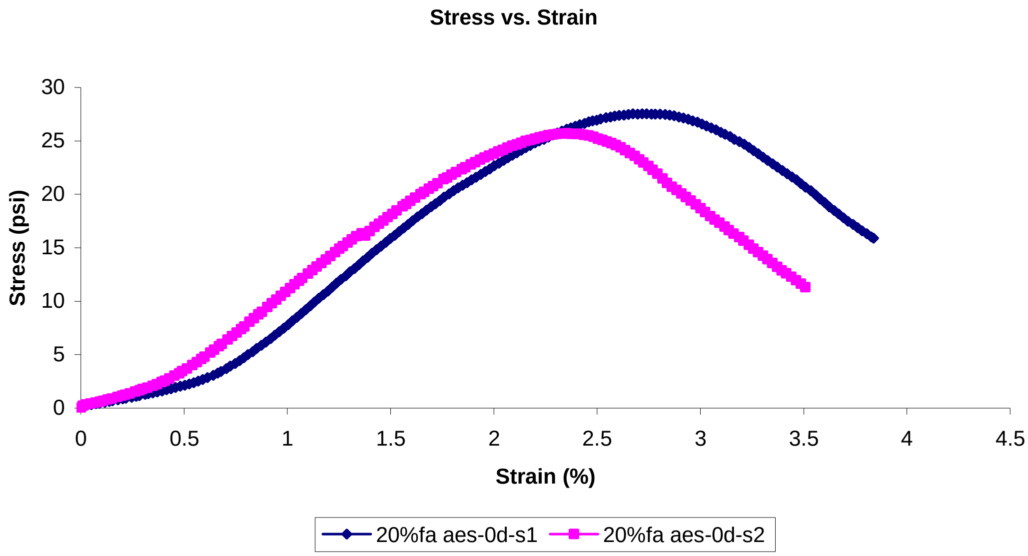

Stress vs. Strain
Stress (psi)
60
50
40
30
20
10
0
0
0.5
1
1.5
2
2.5
3
Strain (%)
15%fa-7d-s2
15%fa-7d-s3
15%fa-7d-s4

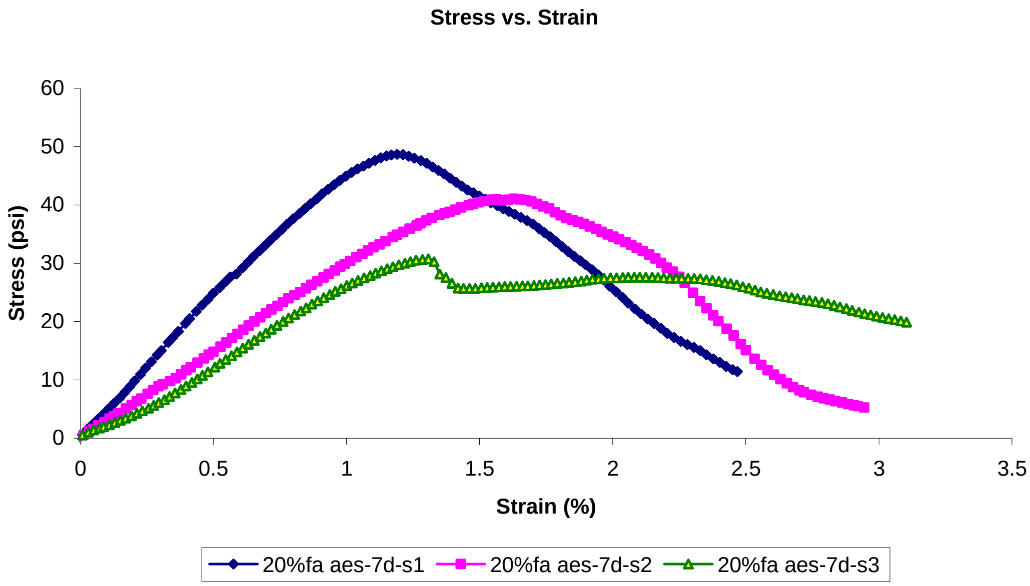

Stress vs. Strain
Stress (psi)
70
60
50
40
30
20
10
0
0
0.5
1
1.5
2
2.5
3
3.5
Strain (%)
15%fa aes-14d-1
15%fa aes-14d-2
15%fa aes-14d-3
15%fa aes-14d-4

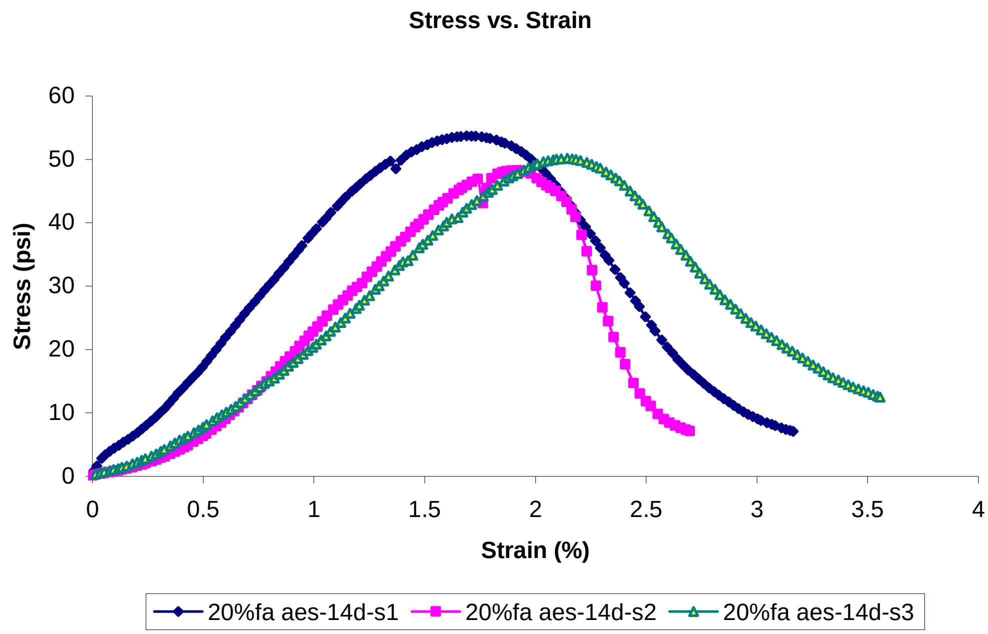

Stress vs. Strain
Stress (psi)
80
70
60
50
40
30
20
10
0
0
0.5
1
1.5
2
2.5
3
3.5
Strain (%)
15%fa aes-28d-s1
15%fa aes-28d-s2
15%fa aes-28d-s3
15%fa aes-28d-s4

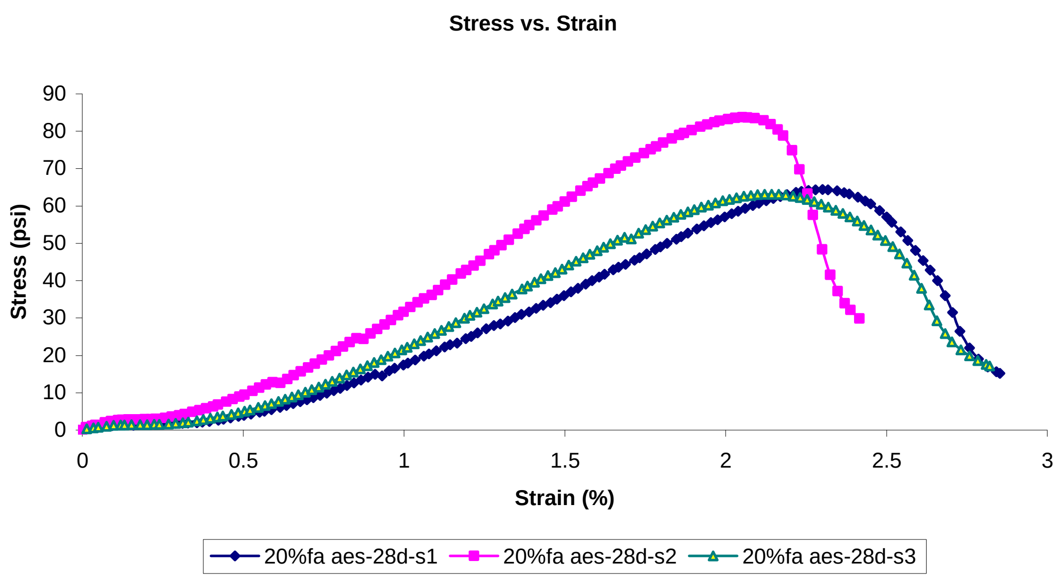

Stress vs. Strain
Stress (psi)
45
40
35
30
25
20
15
10
5
0
0
0.5
1
1.5
2
2.5
3
Strain (%)
15%fa aes-40d-s1
15%fa aes-40d-s2
15%fa aes-40d-s3

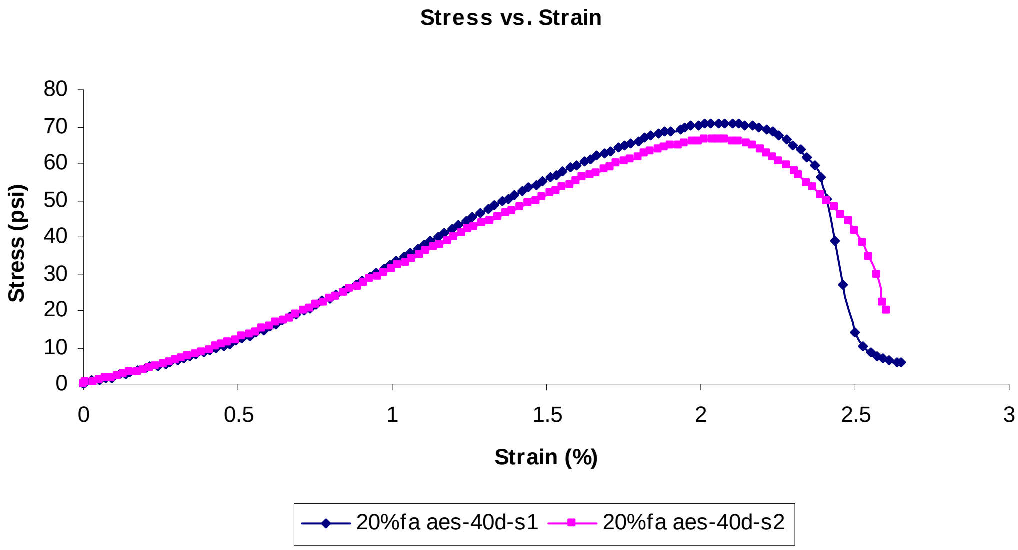

Stress vs. Strain
Stress (psi)
70
60
50
40
30
20
10
0
0
0.5
1
1.5
2
2.5
3
Strain (%)
15%fa aes-100d-s1
15%fa aes-100d-s2
15%fa aes-100d-s3


Stress vs. Strain
Stress (psi)
30
25
20
15
10
5
0
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
Strain (%)
20%fa aes-0d-s1
20%fa aes-0d-s2


Stress vs. Strain
Stress (psi)
60
50
40
30
20
10
0
0
0.5
1
1.5
2
2.5
3
3.5
Strain (%)
20%fa aes-7d-s1
20%fa aes-7d-s2
20%fa aes-7d-s3

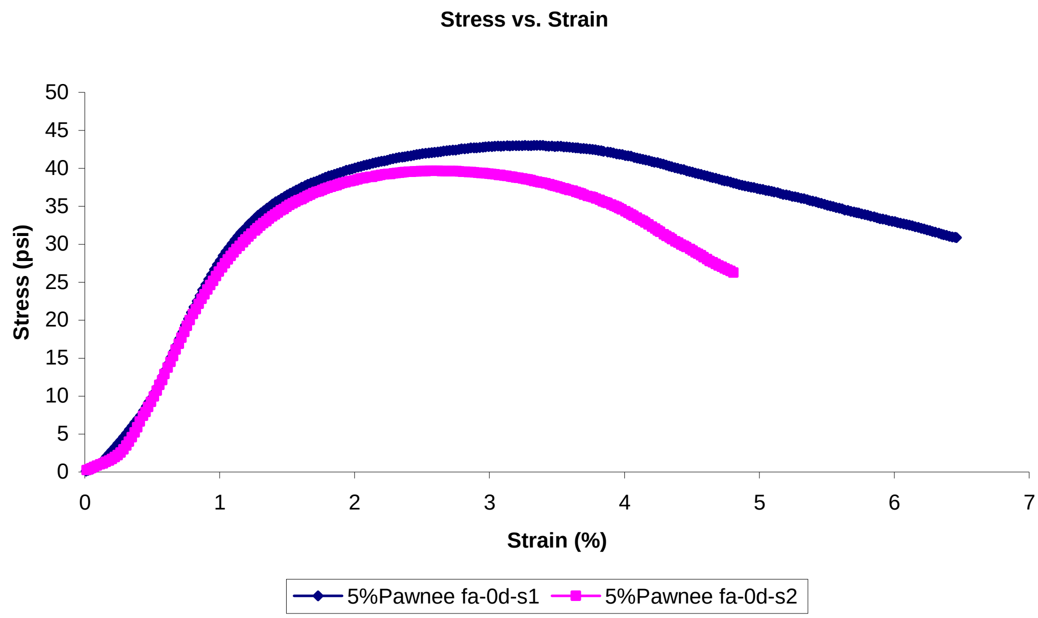

Stress vs. Strain
Stress (psi)
Strain (%)
20%fa aes-14d-s1
20%fa aes-14d-s2
20%fa aes-14d-s3

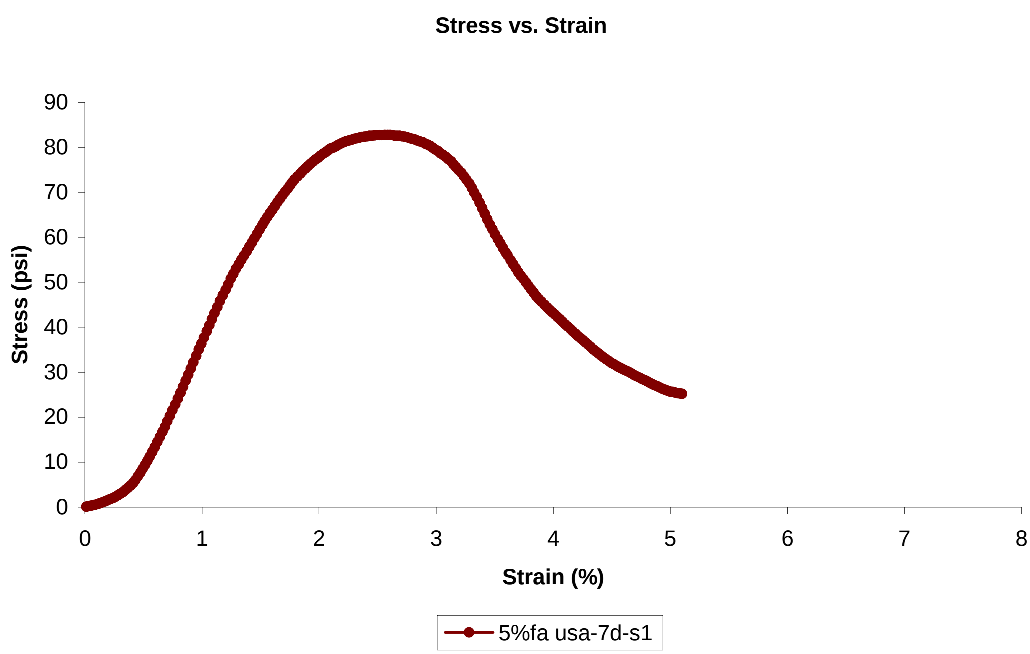

Stress vs. Strain
Stress (psi)
Strain (%)
20%fa aes-28d-s1
20%fa aes-28d-s2
20%fa aes-28d-s3

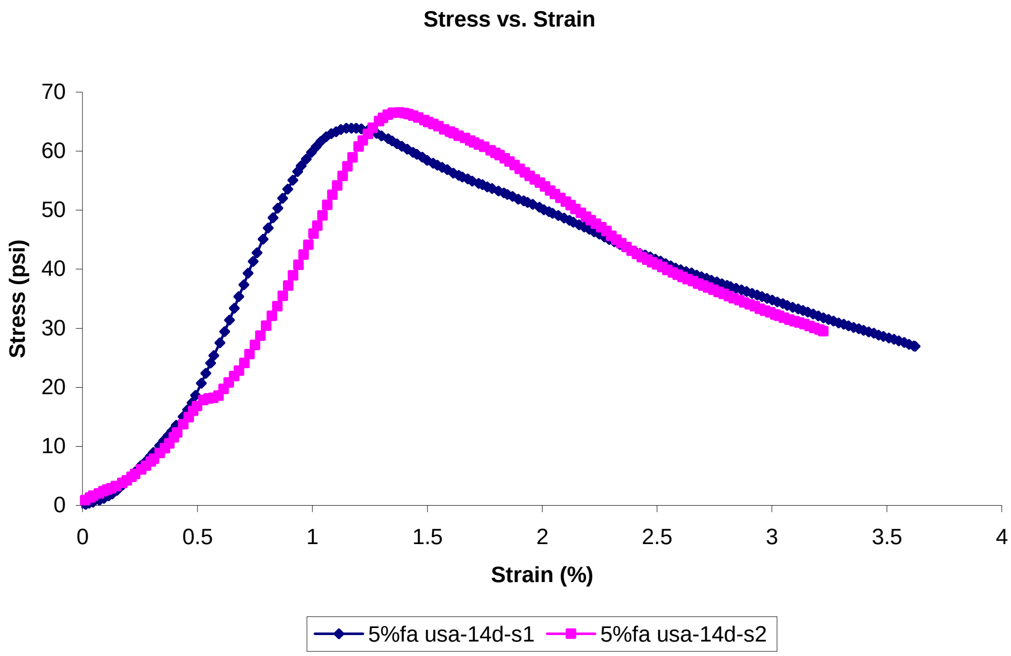


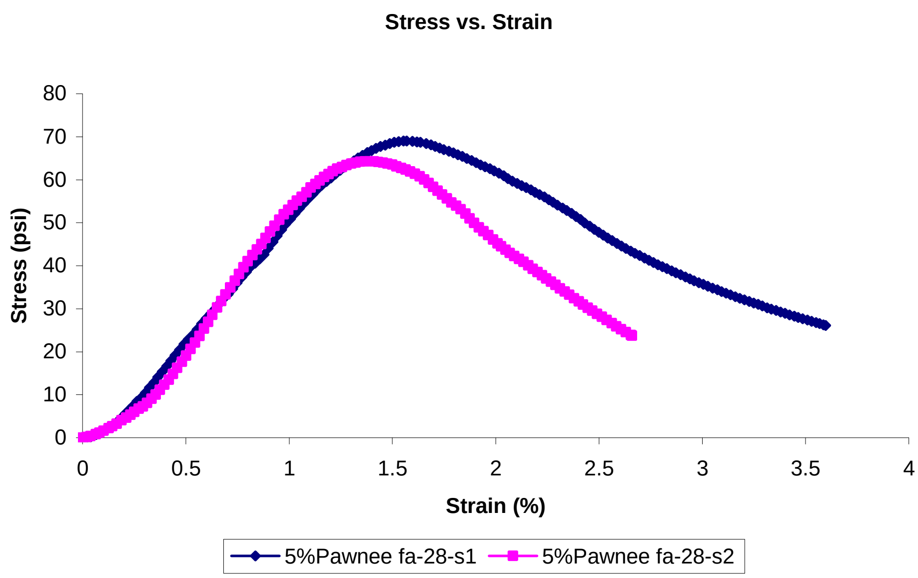
Stress vs. Strain
Stress (psi)
80
70
60
50
40
30
20
10
0
0
0.5
1
1.5
2
2.5
3
Strain (%)
20%fa aes-40d-s1
20%fa aes-40d-s2

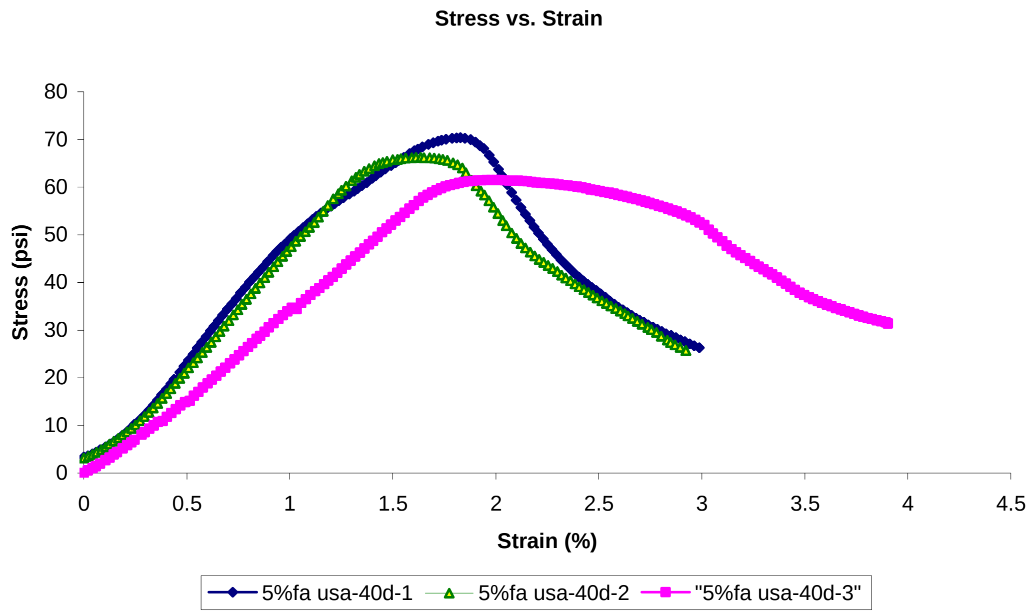
Class C fly ash

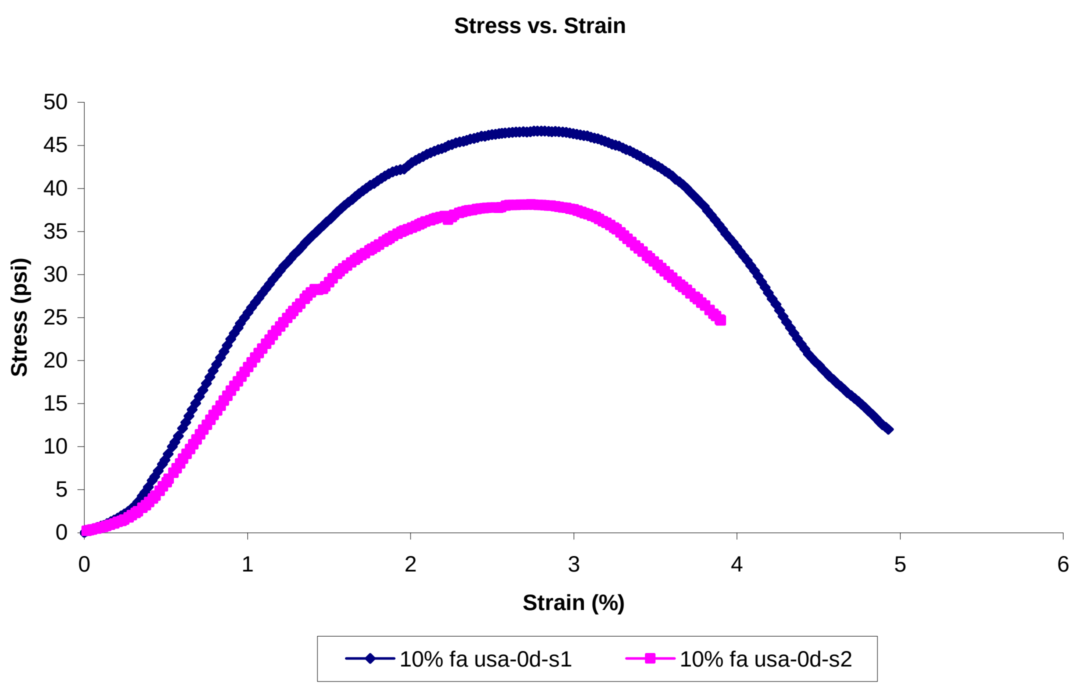


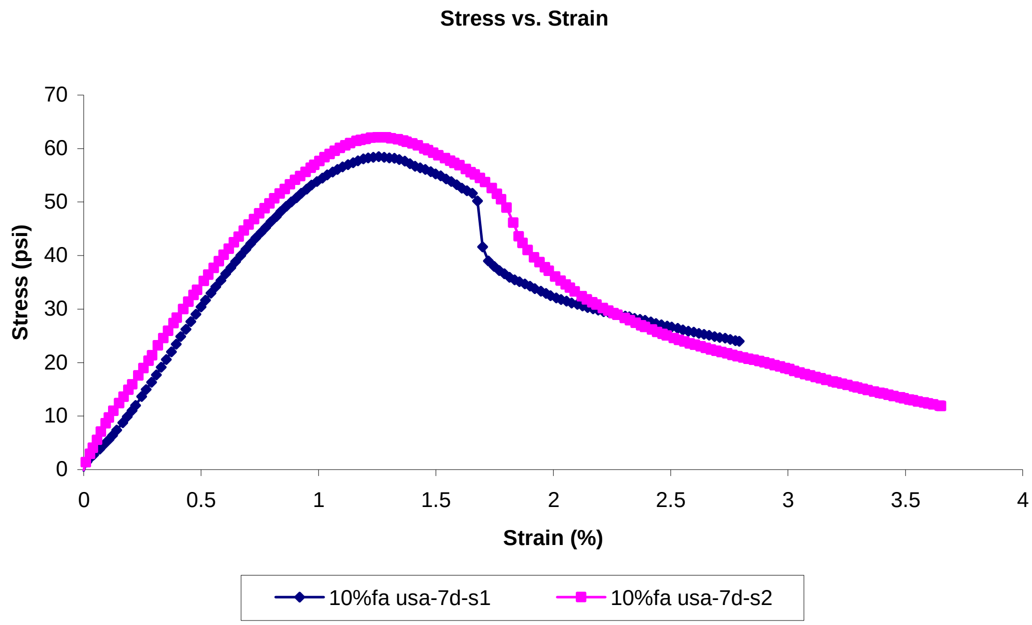


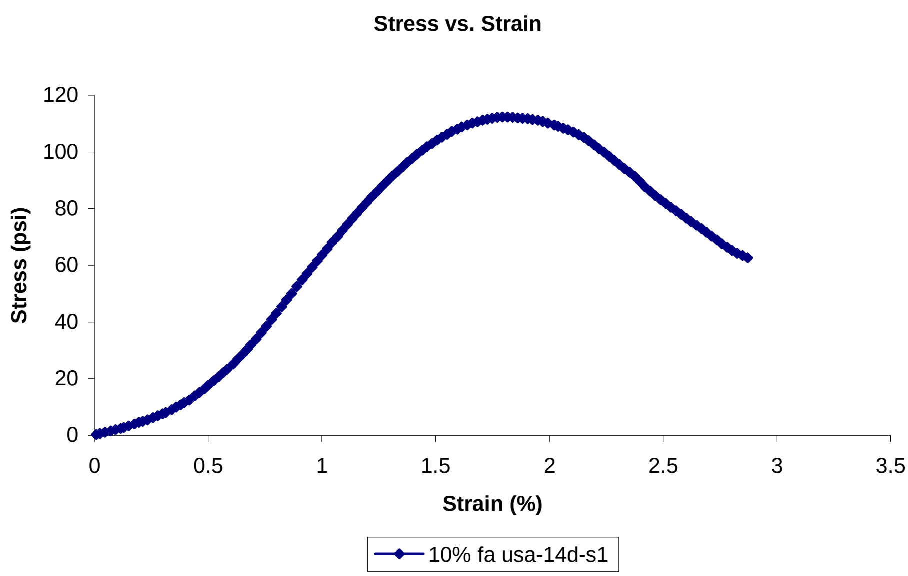

Stress vs. Strain
Stress (psi)
70
60
50
40
30
20
10
0
0
0.5
1
1.5
2
2.5
3
3.5
4
Strain (%)
5%fa usa-14d-s1
5%fa usa-14d-s2

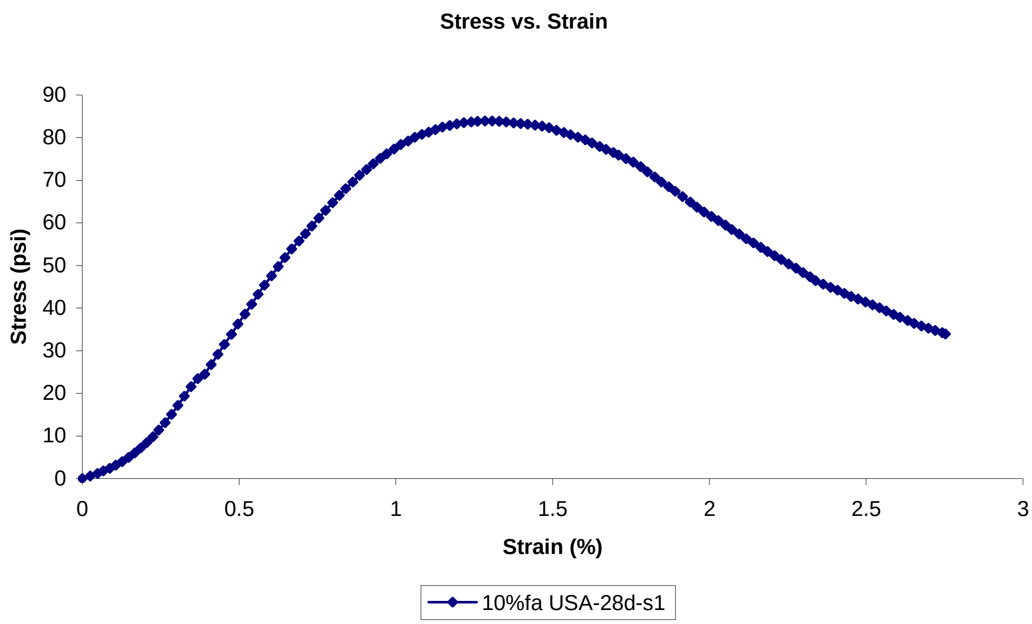

Stress vs. Strain
Stress (psi)
80
70
60
50
40
30
20
10
0
0
0.5
1
1.5
2
2.5
3
3.5
4
Strain (%)
5%Pawnee fa-28-s1
5%Pawnee fa-28-s2

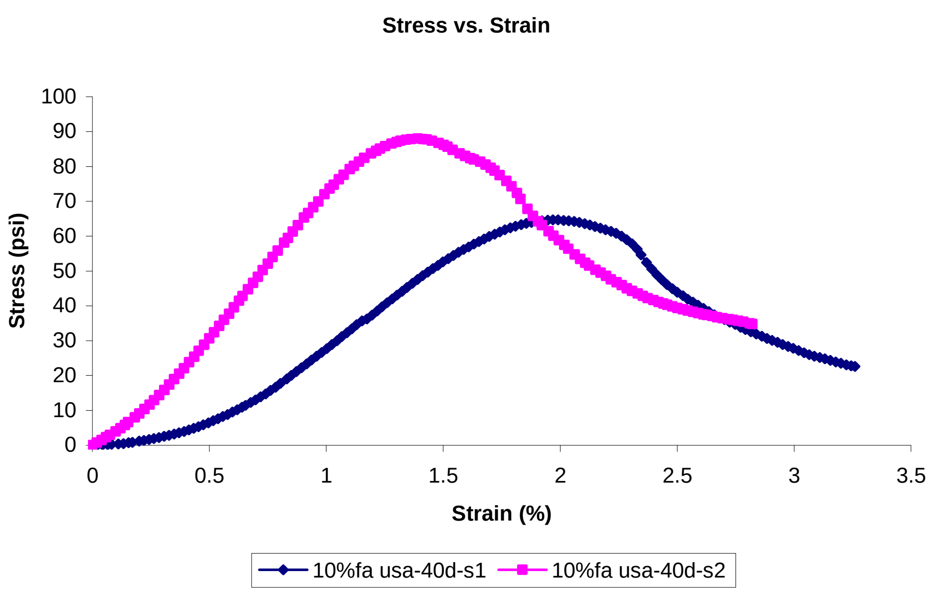

Stress vs. Strain
80
70
60
50
40
30
20
10
0
Stress (psi)
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
Strain (%)
5%fa usa-40d-1
5%fa usa-40d-2
"5%fa usa-40d-3"


Stress vs. Strain
50
45
40
35
30
25
20
15
10
5
0
Stress (psi)
0
1
2
3
4
5
6
Strain (%)
10% fa usa-0d-s1
10% fa usa-0d-s2

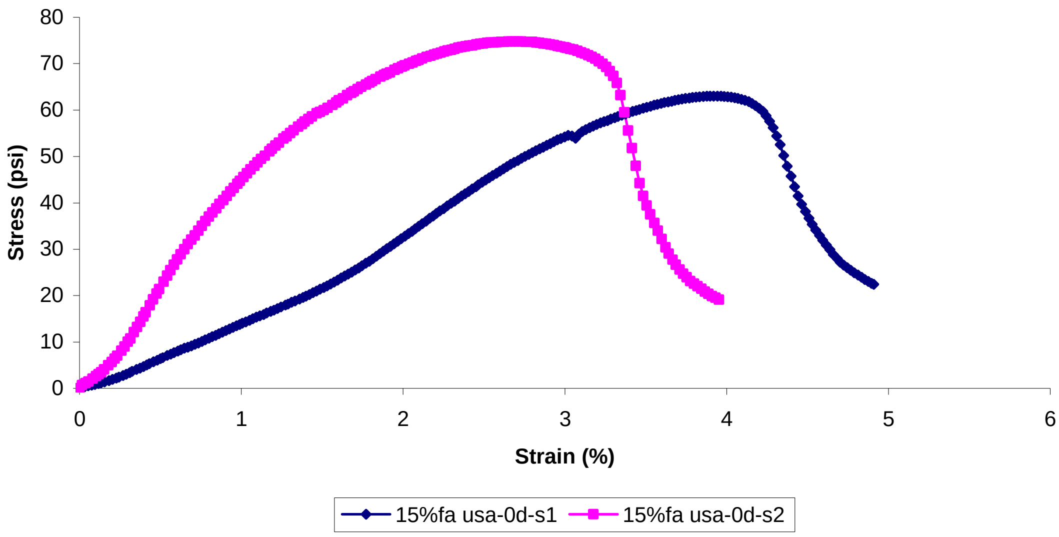

Stress vs. Strain
70
60
50
40
30
20
10
0
Stress (psi)
0
0.5
1
1.5
2
2.5
3
3.5
4
Strain (%)
10%fa usa-7d-s1
10%fa usa-7d-s2


Stress vs. Strain
120
100
80
60
40
20
0
Stress (psi)
0
0.5
1
1.5
2
2.5
3
3.5
Strain (%)
10% fa usa-14d-s1

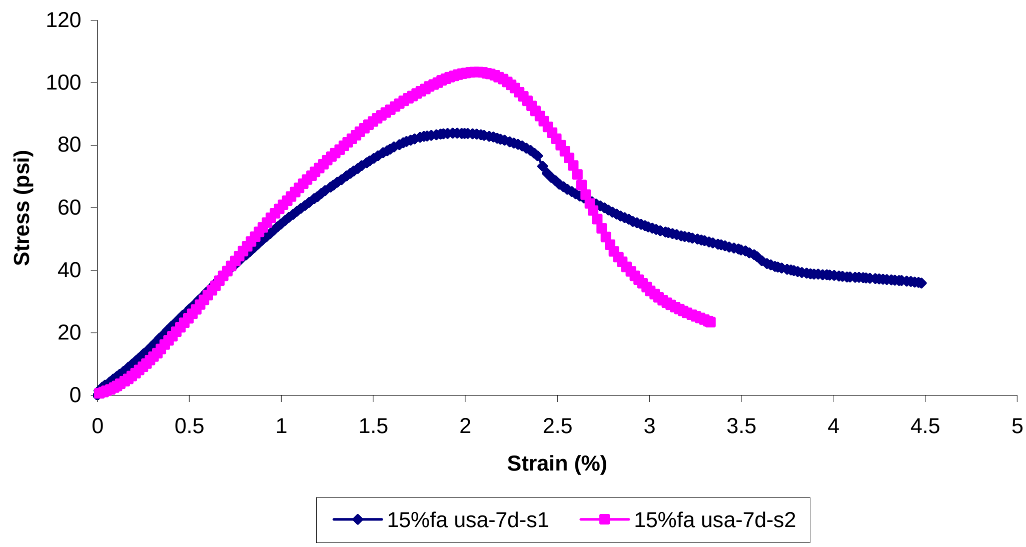

Stress vs. Strain
Stress (psi)
0
10
20
30
40
50
60
70
80
90
0
0.5
1
1.5
2
2.5
3
Strain (%)
10%fa USA-28d-s1

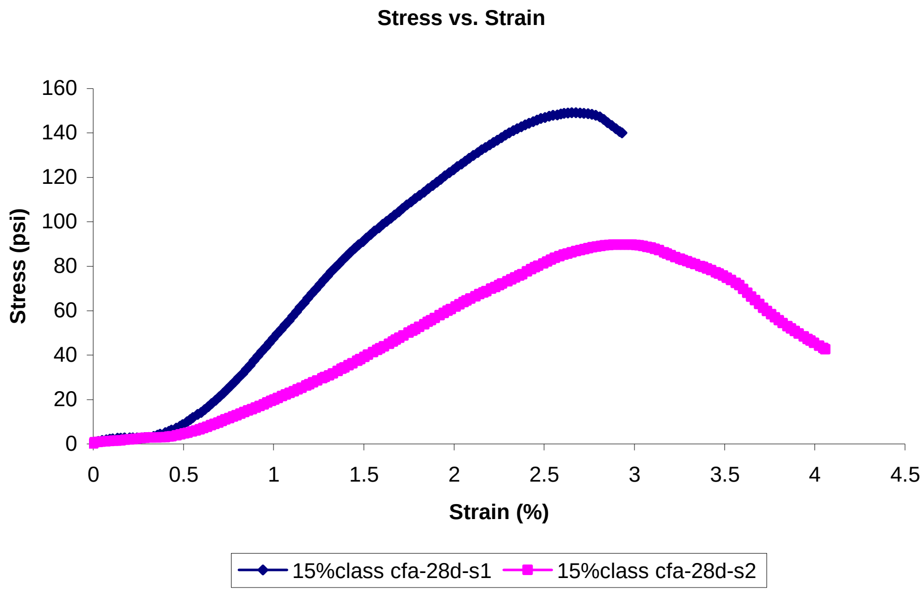

Stress vs. Strain
Stress (psi)
0
10
20
30
40
50
60
70
80
90
100
0
0.5
1
1.5
2
2.5
3
3.5
Strain (%)
10%fa usa-40d-s1
10%fa usa-40d-s2

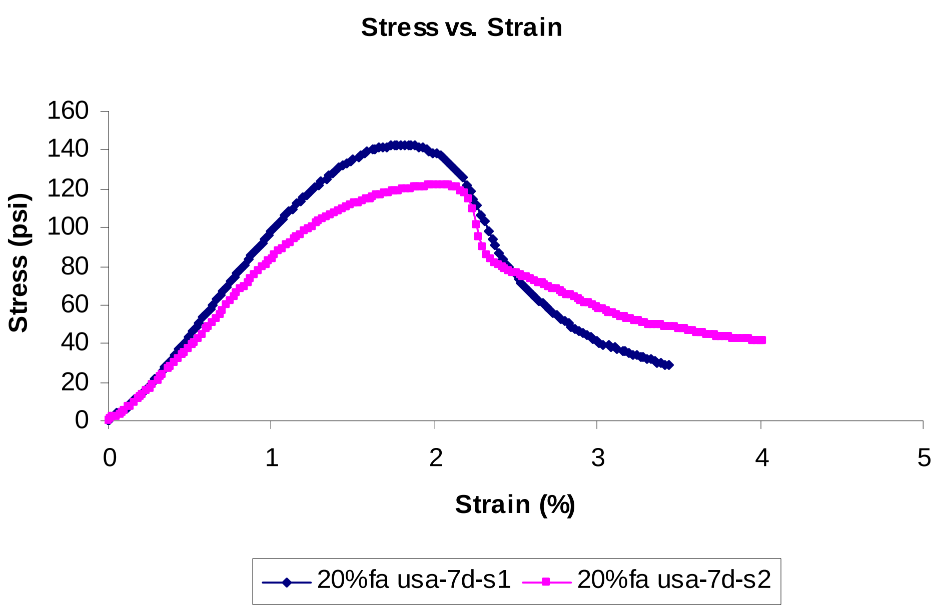
Stress vs. Strain



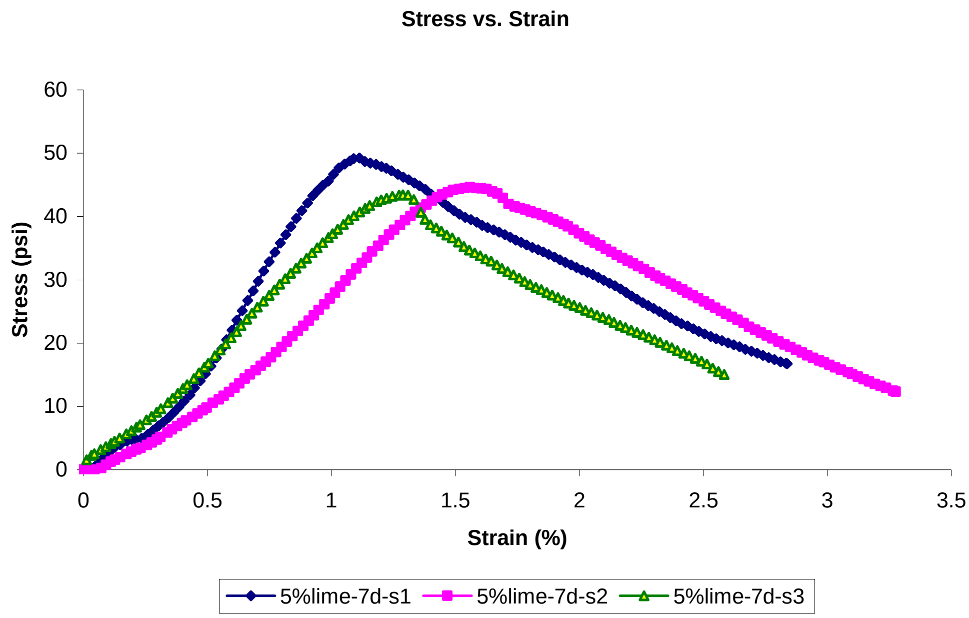
Stress vs. Strain

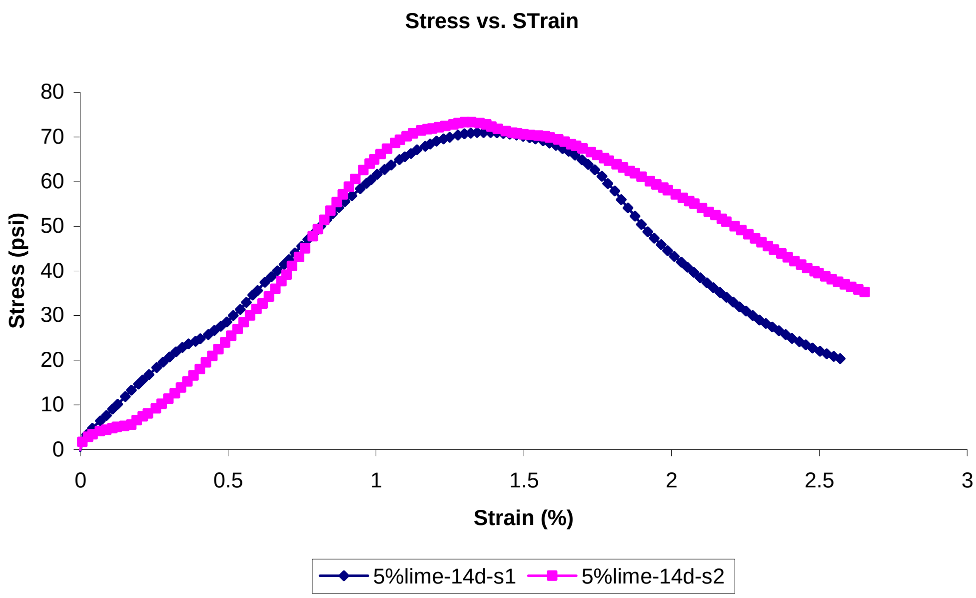


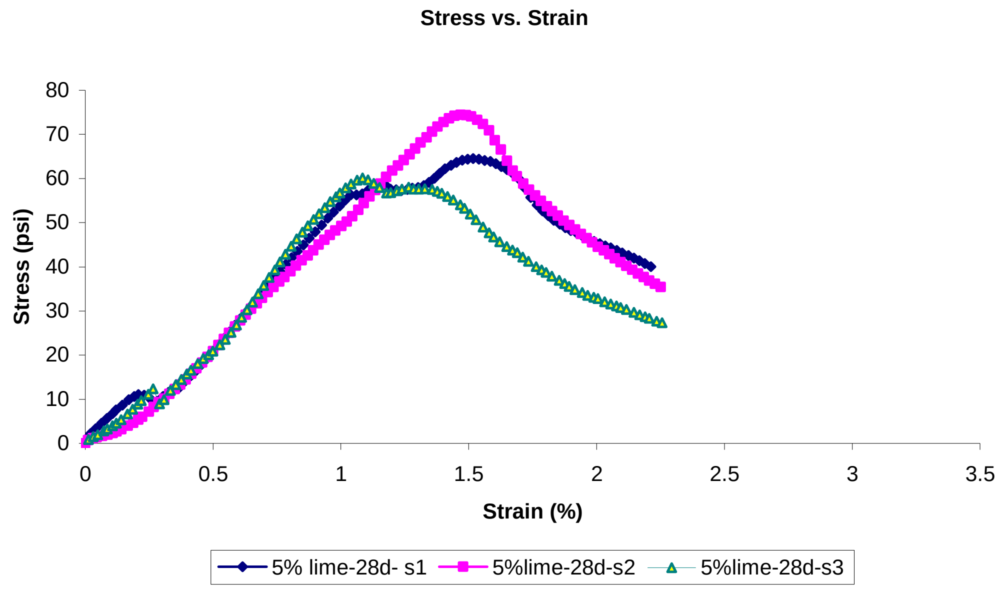

Stress vs. Strain
Stress (psi)
160
140
120
100
80
60
40
20
0
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
Strain (%)
15%class cfa-28d-s1
15%class cfa-28d-s2


Stress vs. Strain
Stress (psi)
160
140
120
100
80
60
40
20
0
0
1
2
3
4
5
Strain (%)
20%fa usa-7d-s1
20%fa usa-7d-s2

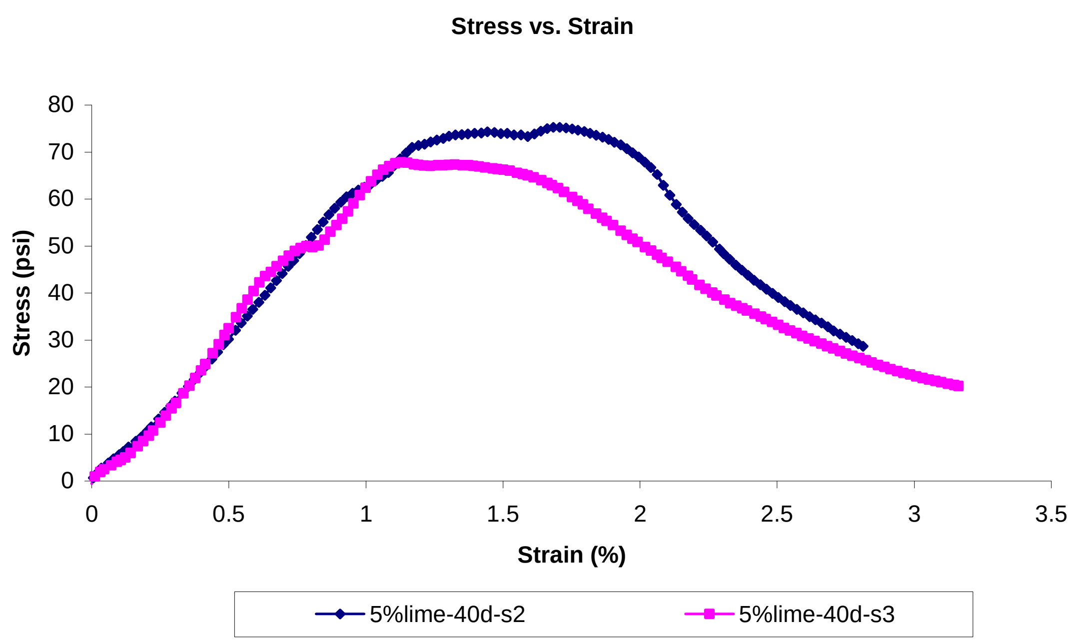
Lime


Stress vs. Strain
60
50
40
30
20
10
0
Stress (psi)
0
0.5
1
1.5
2
2.5
3
3.5
Strain (%)
5%lime-7d-s1
5%lime-7d-s2
5%lime-7d-s3

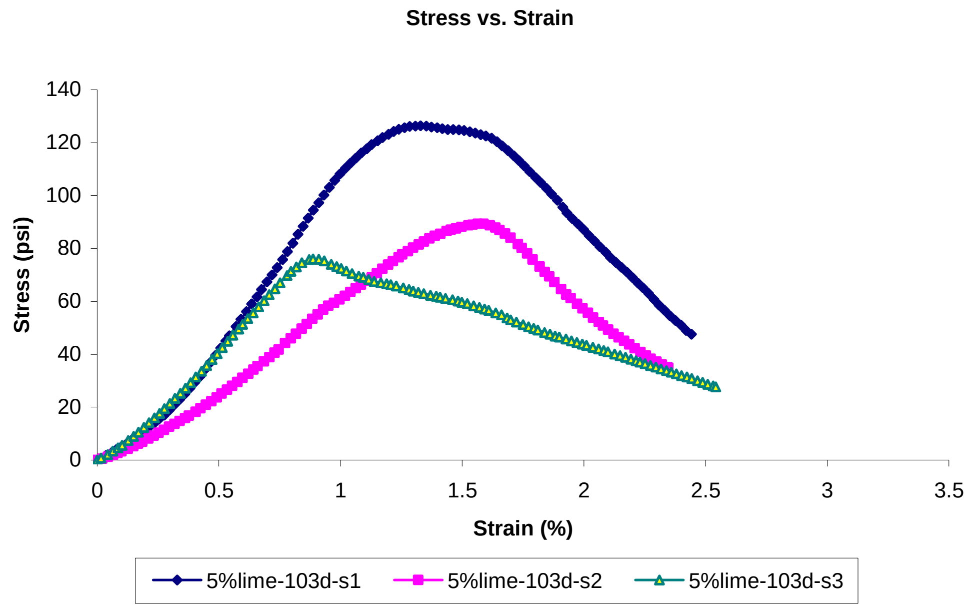

Stress vs. STrain
80
70
60
50
40
30
20
10
0
Stress (psi)
0
0.5
1
1.5
2
2.5
3
Strain (%)
5%lime-14d-s1
5%lime-14d-s2

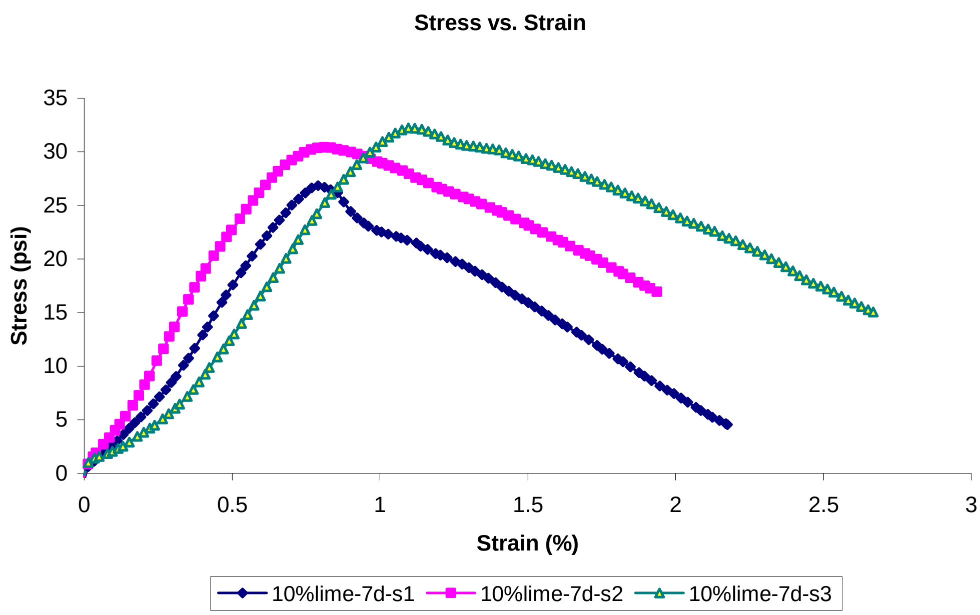


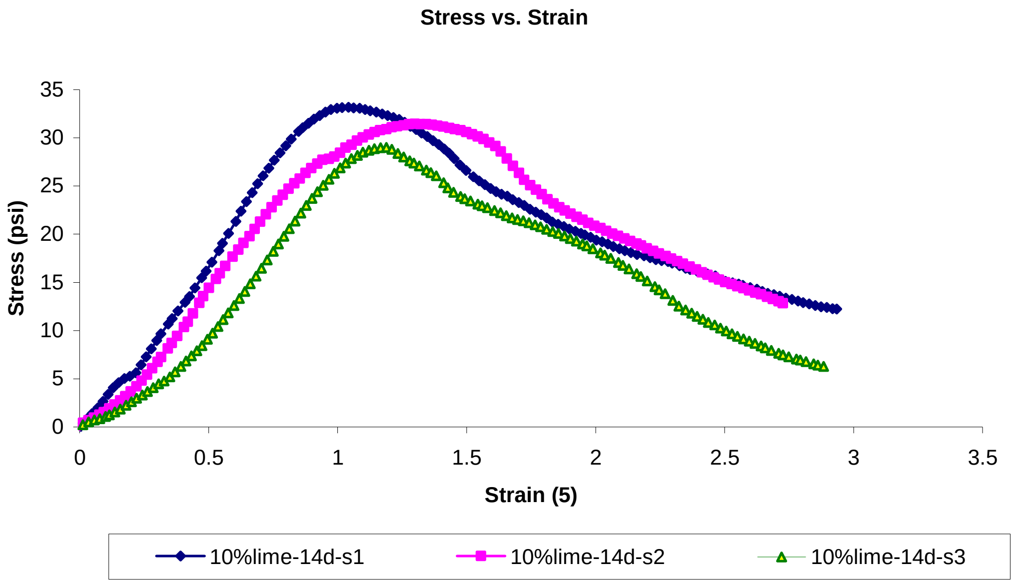
Stress vs. Strain
80
70
60
50
40
30
20
10
0
Stress (psi)
0
0.5
1
1.5
2
2.5
3
3.5
Strain (%)
5% lime-28d- s1
5%lime-28d-s2
5%lime-28d-s3

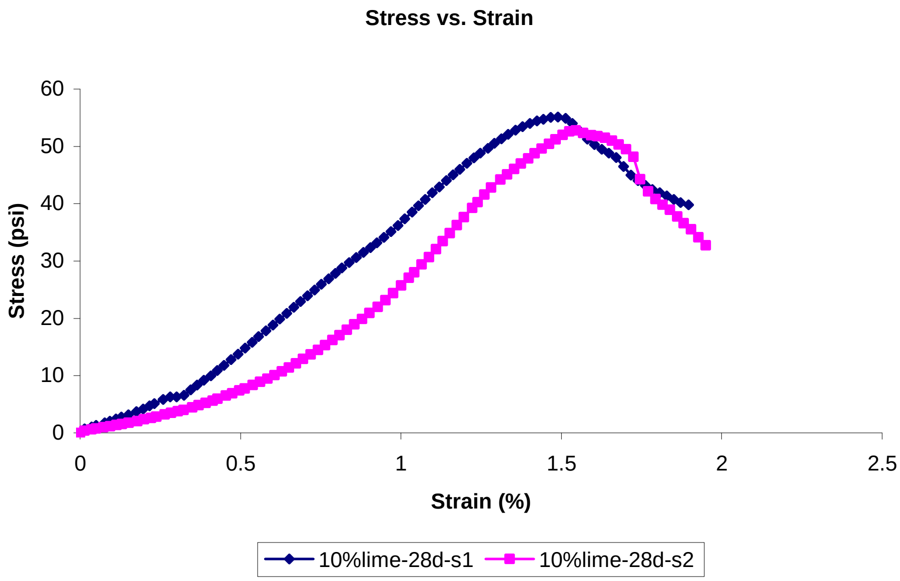


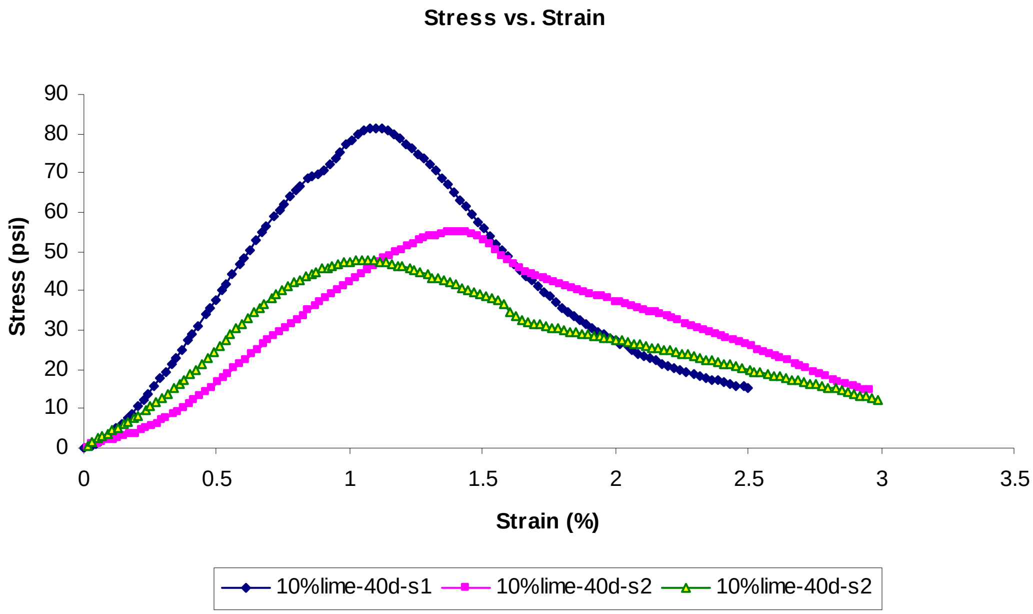
Stress vs. Strain
80
70
60
50
40
30
20
10
0
Stress (psi)
0
0.5
1
1.5
2
2.5
3
3.5
Strain (%)
5%lime-40d-s2
5%lime-40d-s3


Stress vs. Strain
140
120
100
80
60
40
20
0
Stress (psi)
0
0.5
1
1.5
2
2.5
3
3.5
Strain (%)
5%lime-103d-s1
5%lime-103d-s2
5%lime-103d-s3


Stress vs. Strain
35
30
25
20
15
10
5
0
Stress (psi)
0
0.5
1
1.5
2
2.5
3
Strain (%)
10%lime-7d-s1
10%lime-7d-s2
10%lime-7d-s3


Stress vs. Strain
Stress (psi)
35
30
25
20
15
10
5
0
0
0.5
1
1.5
2
2.5
3
3.5
Strain (5)
10%lime-14d-s1
10%lime-14d-s2
10%lime-14d-s3


Stress vs. Strain
Stress (psi)
60
50
40
30
20
10
0
0
0.5
1
1.5
2
2.5
Strain (%)
10%lime-28d-s1
10%lime-28d-s2


Stress vs. Strain
Stress (psi)
90
80
70
60
50
40
30
20
10
0
0
0.5
1
1.5
2
2.5
3
3.5
Strain (%)
10%lime-40d-s1
10%lime-40d-s2
10%lime-40d-s2