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Shear Strength Parameters of Sand Fly Ash Cement Mixtures

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SHEAR STRENGTH PARAMETERS OF SAND FLY ASH CEMENT MIXTURES

by

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ABSTRACT

According to a 2012 American Coal Ash Association Coal production Survey Report, US coal fired power plants produced more than 109 million tons of waste that year. Approximately half of this waste is the valuable by-product fly ash. There are three classes of fly ash: cementitious class C and non-cementitious classes F and N. Over half of the fly ash produced is used in the geotechnical/construction industries. Most geotechnical soil stabilization studies using fly ash are focused on controlling shrink-swell potential of clays. This study utilized the less desirable class F fly ash to assess the improvement of shear strength parameters of granular soils. Two mix designs were developed and tested using consolidated undrained, unconfined compression, and triaxial testing. Mix designs consisted of 15% fly ash with 0.5 or 1% cement, and poorly graded Ottawa sand compacted using a standard effort at 10 percent moisture content. Consolidated undrained testing on Mix 1, which included flushing and saturating the specimens, produced higher shear strength parameters than for the sand alone. However, the results were inconsistent with respect to the increase in shear strength parameters with time. Unconfined compression testing was then conducted on both Mix 1 and Mix 2 to assess strength gain with time. Results showed both mixes gained appreciable strength with time but doubling the cement did not double the unconfined compressive strength. Triaxial testing was then conducted on Mix 1 using specimens that were not flushed or saturated. This testing was used to determine if flushing destroyed the specimen soil fabric. The shear strength parameters from the triaxial testing were very similar to those determined from consolidated undrained testing. This demonstrated that flushing did not affect the shear strength parameters. Inconsistent triaxial test results from fly ash-cement-sand mixes have been previously reported in the literature.

CHAPTER 1: INTRODUCTION

One of the major environmental concerns of energy production from coal burning is disposing of the industrial solid hazardous waste material. One of the solid waste materials which requires special handling is fly ash. The worldwide annual production of fly ash is approximately 500 million tons. The present utilization of fly ash on a worldwide basis widely varies from 3% to 57% with an average of 16 %. This leaves a substantial amount of ash to be disposed of in landfills and lagoons at a significant cost to utility companies, consumers, and the environment (Ahmurazzaman, 2010). Fly ash is commonly used as an additive in Portland cement and grouts and also has additional uses in construction using soil materials (ACCA, 2012). There are three different classes of fly ash, Class C, Class F and Class N, and the class depends on the chemical composition (ASTM C 618).

The purpose of this study is to assess the improvement in shear strength parameters and unconfined compressive strength of granular soils mixed with class F fly ash and cement. Two different sand-fly ash-cement mixes were developed and tested. The mixes were purposely developed to limit the amount of Portland cement and to use the fly ash as an additive to improve the engineering properties of the soil. The specimens were tested under both triaxial and unconfined conditions and tested at different times to assess the temporal property changes.

Mix 1 consisted of 84.5% sand, 15% fly ash, and 0.5% cement compacted at a 10% moisture content. Mix 2 consisted of 84.0% sand, 15% fly ash, and 1.0% cement compacted at a 10% moisture content. The curing times for the specimens ranged from one to twenty eight days, depending on the type of the test to be performed. Mix 1 specimens were tested using three different test configurations: consolidated undrained triaxial testing (CU), unconfined compression testing (UCS) and triaxial compression testing (TX). Mix 2 specimens were tested using only unconfined compression testing (UCS).

The thesis is divided into five chapters. Chapter 2 presents a background information on fly ash including how fly ash is formed during the coal burning process, classes of fly ash, how fly ash is used and the benefits of using fly ash. Also included in the literature review is how fly ash is used to improve soil properties. This discussion focuses on the types of tests and improvements in various soil properties. A special section is devoted to the improvement of granular soils with fly ash. The final section of the literature review is the motivation of this thesis.

Chapter 3 presents the descriptions and properties of the three materials (sand, fly ash, and cement) used in this study. Also included in this chapter are the development of the mix designs, the two mix designs used in this study, the specimen preparation technique, specimen curing times, and basic testing procedures.

Chapter 4 presents the test results for the two mix designs. This chapter also discusses the reasoning behind the use of multiple testing techniques to characterize the two mix designs.

Chapter 5 presents the conclusions of this study. Also included are recommendations for future studies incorporating similar materials.

CHAPTER 2: LITERATURE REVIEW

2.1 Coal Burning and the Production of Fly Ash

Coal ash is one of the waste materials produced from the burning of coal in thermal power stations. More than 100 million tons of coal ash in produced annually in the United States. The coal ash includes fly ash, bottom ash, boiler slag, flue gas desulfurization (FGD) gypsum, FGD wet and dry scrubbers, FGD others, and fluidized bed combustion (FBC) ash (ACAA, 2012). The four countries that produce the most coal ash, China, India, Poland, and United States, produce more than 270 million tons of fly ash every year (Sumesh et al., 2010). In 2012, the United States produced over 52 million tons of fly ash (ACAA, 2012).

Selving and Gibson (1956) and Abernethy et al. (1969) investigated more than 600 ash samples from commercial coal burning facilities in the United States. They found that the fly ash contains silica, alumina, and different oxides and alkalis, and can be considered a pozzolanic or self-cementing material depending on the amount of CaO. When exposed to water, class C fly ash hydrates and forms cementitious products similar to those produced during the hydration of Portland cement (Ferguson, 1993).

The most common chemical compounds in fly ash include SiO_2, TiO_2, Al_2O_3, Fe_2O_3, MnO, MgO, CaO, Na_2O, K_2O, P_2O_5, SO_3 and organic carbons (Kim et al., 2005). Fly ash is considered a threat to the environment because it contains harmful chemical compound such as silicon dioxide (SiO_2), heavy metals such as arsenic (As), chromium (Cr), and lead (Pb) (Maher et al., 1993, Snigdha and Vidya, 2006, and Sushil and Batra, 2006). In addition to the potentially harmful chemical compounds and heavy metals, the disposal of coal ash is an economic concern. The coal ash can be mixed with water and stored in containment ponds, processed to a dry state and stored in containment ponds, or processed to a dry state and landfilled (Clean Water Fund, 2014).

2.2 Classes of Fly Ash

According to ASTM C 618, there are three classes of fly ash: Class C, Class F, and Class N. This classification is based on chemical composition. Class C is produced from the combustion of western (subbituminous) coal. This fly ash has self-cementing characteristics and can be used in a wide range of construction applications. Typically this class of fly ash contains 20-35% calcium oxide (CaO) (DeGioia et al., 1986) and most of the calcium is combined as calcium aluminates, calcium silicates, and calcium sulfate (ASTM D 5239). Class C fly ash also contains significant amounts of free lime. However, it must be noted that fly ash properties are highly variable and depend on the chemical composition of the coal and the combustion technology used (ASTM D 5239).

Class F fly ash is produced from the eastern (bituminous) coals and many lignite coals. This fly ash contains minor amount of calcium (DeGioia et al., 1986). Class F fly ash contains a low percentage of calcium and magnesium ions, which means it does not exhibit self-cementing characteristics (ASTM D 5239).

Class N fly ash contains the same amount of silicon dioxide, aluminum oxide and iron oxide as class F fly ash, smaller amounts of sulfur trioxide than both class C and F fly ash, but has the highest amount of loss on ignition (LOI). This means it contains an abundance of an unburnt fuel (ASTM C 618). Table 2.1 provides a detailed chemical descriptions of the fly ash classes according to the ASTM C 618 standard.

Table 2.1 Chemical components for fly ash classes C, F, and N (ASTM C 618)

Chemical Components	Class C	Class F	Class N
Silicon dioxide (SiO_2) plus aluminum oxide (Al_2O_3) plus iron oxide (Fe_2O_3) (minimum %)	50.0	70.0	70.0
Sulfur trioxide (SO_3) (maximum %)	5.0	5.0	4.0
Moisture content (maximum %)	3.0	3.0	3.0
Loss on Ignition (maximum %)	6.0	6.0	10.0

The physical requirements for all classes of fly ash is the same. It includes items such as fineness, uniformity, and density. One of the primary physical requirements is the small grain size of fly ash. The percent retained when wet-sieved on 45 µm (No. 325) sieve is a maximum of 34% (ASTM C 618).

2.3 Benefits and Uses of Fly Ash

Fly ash exhibits cementing characteristics that can be adapted to a wide range of construction and soil stabilization applications. When exposed to water, class C fly ash hydrates and forms cementitious products similar to those produced during the hydration of Portland cement (Ferguson, 1993).

According to the American Coal Ash Association (ACAA, 2012), of the 52 million tons of fly ash produced in the United States 23 million tons were used in different industries. The highest use of fly ash is in the cement industry. Fly ash is used as an additive to the more expensive Portland cement. For construction/geotechnical applications, most of the fly ash is used as structural fills, stabilizing road bases, and soil stabilization (ACAA, 2012). The quantities of fly ash used in 2012 for cement and construction/geotechnical applications is shown in Table 2.2.

Table 2.2 Fly ash construction-related applications (ACAA, 2012)

Application	Quantity Used Million Tons
Cement production and/or concrete products	11.8
Structural fills or embankments	3.1
Stabilization of waste materials	2.2
Road base or subbase materials	0.2
Flowable fill and grouting mixes	0.15
Soil modification/stabilization	0.3

2.4 Soil Improvement by the Addition of Fly Ash

Fly ash has been used since the mid-1950s to improve the physical and engineering properties of soils (Selvig and Gibson, 1956). One of the first geotechnical uses of self-cementing fly ash was as a soil drying agent (Ferguson, 1993). Based on a literature review conducted using the ProQuest data base, there have been over 1100 articles published on the use of fly ash for geotechnical applications since 1960. A similar search using the Compendex data based yielded approximately 900 articles. Given the large number of studies conducted on fly ash use in geotechnical applications, it would be impossible to provide a comprehensive literature review. Instead, this section provides an overview of the types of soil stabilized, the amount and classes of fly ash used, curing times investigated, and the changes in engineering properties of soils by mixing with fly ash.

2.4.1 Types of Soils Stabilized with Fly Ash

Studies have used all types of soils mixed with fly ash to improve their soil properties. Fly ash treatment is most commonly used to reduce shrink-swell potential of clay soils. Fly ash is mixed with the soil and water is added so that short and long term chemical reactions form insoluble cementitious compounds. Such compounds are capable of producing strong permanent matrices and the soil mixtures are transformed into a new material that exhibits significant permanent strength (Amadi, 2010). Clay soils can also be treated with lime or Portland cement however the material cost for ash treatment is generally less than lime treatment and does not require the mellowing period prior to compaction (Abduljauwad, 1993). Beyond clay soils, other types of soils that have been improved or stabilized with fly ash include: silts (for example Lo and Wardani, 2002), sandy soils (for example Bhosale et al., 2011), and granular soils (for example Ferguson, 1993).

2.4.2 Amount and Classes of Fly Ash Used

Studies used between 5 percent (Amadi, 2010) and 90 percent (Sumesh at el., 2010) fly ash added to soils. For the low percentages of fly ash used, the fly ash can be considered an additive to the soils. As the percentage of fly ash increases, the fly ash can no longer be considered an additive but a replacement of the soil.

The vast majority of the studies use class C fly ash because of its self-cementing qualities. However a small percentage of studies have used the less desirable class F fly ash. Class F fly ash may be self-cementing or it may require an activator to initiate the hydration reactions. The most common activators are lime and Portland cement (Saeid et al., 2012). No research studies could be found that used class N fly ash.

2.4.3 Curing Times

Since fly ash is self-cementing (class C) or can be self-cementing with an activator (class F) curing time is an important aspect to investigate. It takes time for the hydration reactions to occur and bond the soil together. Studies tested soil mixtures at various time frames ranging from zero days (Bhosale et al., 2011) to 90 days (Ferguson, 1993). The small time frame studies were interested in detecting the mellowing time. This is a period of time, prior to compaction, to allowing the chemical reactions to occur in soils (McCarthy et al., 2009). The large time frame studies were interested in the strength gain as a function of curing time.

2.4.4 Changes in Engineering Properties

Soil-fly ash mixtures have been prepared and tested to assess a number of different engineering properties of the treated soils. The soil mixtures have consisted of different types of soil (plastic through granular), fly ash, water, and occasionally with cement or lime. Other more exotic substances, such as fibers (Sharma, 2012), shredded tires (Wiechert, 2011), and rice husks (Lu, 2014), have also been incorporated into mixtures. Since these exotic additives are not used in this study, they will not be listed below.

Fly ash treatment is used extensively to reduce shrink-swell potential and decrease the plastic limit of clay soils. This property is assessed through changes in the Atterberg Limits. Both the liquid limit and plasticity index decrease as fly ash content increases (Abduljauwad, 1993). EPRI (2012) noted in that fly ash cannot be effectively rolled to the required diameter to obtain a plastic limit, thus it is non-plastic.

Improvement of compaction characteristics of soils is important for construction. The optimum moisture content for fly ash alone has been reported to be between 19% and 44% (Sharma, 2012; Sahoo, 2010; Kim et al., 2005; Prabakar et al., 2004). Sahoo et al. (2010) conducted standard proctor tests and showed the optimum moisture content (OMC) of a treated plastic soil increased from 14.5% to 18.7%, and the maximum dry density (MDD) gradually decreased from 1.63 g/cm^3 to 1.82 g/cm^3. Amiralian et al. (2012) conducted standard proctor tests and showed the optimum moisture content of the treated granular soil increased and the maximum dry density also increased. These tests were conducted with sand mixed with 1% and 2% lime and 5% and 10% fly ash.

The strength and stiffness properties of road base and subgrade materials in marginal soils is important. The California Bearing Ratio (CBR) test is used to determine properties of these materials. Stabilization of clay soils for pavement subgrades can increase the California Bearing Ratio from 2 or 3 for the untreated soil to 25 to 35 for the fly ash stabilized materials (Ferguson and Zey, 1990).

Hydraulic conductivity is an important consideration when assessing soils to act as barriers to fluid flow. For fly ash alone, hydraulic conductivities range between 10^{-6} to 10^{-8} m/s (Goh and Tay, 1993 and Kim et al., 2005). Kumar and Sharma (2004) reported hydraulic conductivities for plastic soils changed from 9.7×10^{-7} cm/s for untreated soils to 3.95×10^{-7} cm/s for the same soil treated with 20% fly ash.

Perhaps the most important properties of soils mixed with fly ash are the increases in various measures of strength and stiffness. Fly ash, when used in stabilization, also increases the shear strength and subgrade support capacity of soils (Saeid et al., 2012). Fly ash stabilization can also be used for construction of embankments and backfill against retaining walls. The increased shear strength achieved through fly ash stabilization allows construction of embankments with steeper slopes and results in lower lateral earth pressures on retaining walls (Ferguson, 1993).

One common measure of strength is the unconfined compression test. Sahoo et al. (2010) reported the unconfined compressive strength in a silty soil increased from 101 kPa for untreated soil to 183 kPa for soil containing 15% class C fly ash. The unconfined compressive strength decreased for specimens containing 20% and 25% fly ash. Jadhao and Nagarnaik (2008) used silty soils mixed with 50% class F fly ash and reported the unconfined compressive strength increased by approximately 40% over the untreated soil.

Triaxial testing is conducted to determine the shear strength parameters (cohesion, c, and angle of internal friction, ϕ) of soils. Sahoo et al. (2010) conducted consolidated undrained (CU) tests on a silty soil and discovered that cohesion and angle of internal friction increases from 60.7 kPa to 65.5 kPa and 13 degrees to 15.2 degrees respectively with increase in the amount of fly ash from 5% to 15%. With increasing amounts of fly ash, the shear strength parameters decreased. They reported there is only marginal improvement in shear strength parameters with addition of fly ash or fly ash and lime. Prabakar et al. (2004) determined that increasing fly ash percentages increased the cohesion for a clay soil. However, the angel of internal friction increased for fly ash percentages up to 28.5% and then decreased at higher fly ash percentages. For silty soils increasing fly ash percentages decreased the cohesion but increased the angel of internal friction.

Stiffness is another important parameter for geotechnical design. Sahoo et al. (2010) conducted consolidated undrained (CU) tests on a silty soil and showed an increase in stiffness with soils treated with 15% fly ash over untreated soils. Jadhao and Nagarnaik (2008) used silty soils mixed with 50% class F fly ash and the stress-strain curves presented in their study do not show any change in modulus between treated and untreated soils. Yang et al. (2014) tested flowable fill with a class C fly ash content 14% at 1, 3, 7, 14, and 28 days. The stiffness increased with increasing curing times.

The research presented in this thesis is focused on the compaction parameters (for mix design), unconfined compression tests, and the shear strength parameters of sand-fly ash-cement mixtures. There are very few studies that focus on improving the properties of granular materials with fly ash. Table 2.3 contains a summary of recent studies that have focused on the improvement of sandy soils with fly ash, which is the focus of this thesis.

The recent studies that are the closest to the work performed in this thesis provide some interesting results. In terms of compaction, 10% fly ash provided the maximum dry density for standard compaction efforts (Sumesh et al., 2010 and Amiralian et al., 2012) whereas 5% fly ash provided the maximum dry density for the modified compaction effort (Prasad et al., 2013). Unconfined compression testing showed increased unconfined compressive strength with time due to additional cementitious bonds forming within the specimens (Sumesh et al., 2010). For triaxial testing, based on the work of Bhosale et al. (2010) the shear strength parameters of the soil mixes did not show the expected increase with curing time. Only one mix, which contained 35% fly ash and 3% cement, showed an increase in angle of internal friction with time. Mixes containing 0%, 1%, 2%, and 4% fly ash showed a decrease in angle of internal friction with time.

Table 2.3 Recent studies focusing on properties of granular soil fly ash mixtures

Author	Mixtures	Tests	Results and Comments
Bhosale et al., 2011	Fly Ash: 35% class F Cement: 1-4% Soil: sand (SP)	Triaxial compression tests (confining pressures of 1, 2, 3, and 4 kg/cm²) at 0, 7, and 28 days.	1. Based on presented stress-strain curves there is no significant change in stiffness 2. Peak strength increases with time (0 day versus 28 day curing) 3. At 7 days the angle of internal friction (ϕ) ranges between 26.5 and 32 degrees; there was no clear relationship between amount of cement and angle of internal friction 4. At 28 days the angle of internal friction (ϕ) ranges between 24 and 36 degrees; there was no clear relationship between amount of cement and angle of internal friction 5. After 28 days of curing, only sand mixed with 35% fly ash and 3% cement shows significant improvement shear strength parameters with time. Other mixes show shear strength parameters do not consistently increase with time
Sumesh et al., 2010	Fly ash: 0 to 90% class F Cement: 1 and 2% Soil: sand (SP)	Standard Compaction Unconfined compression tests at 0, 3, 7, 14, and 28 days	1. Maximum dry density peaks at 10% fly ash and decreases with increasing fly ash due to low specific gravity of fly ash 2. Unconfined compressive strength increases drastically with fly ash contents above 20% due to addition of self-cementing materials 3. Unconfined compressive strength increases with curing time due to formation of cementitious reaction products
Prasad et al., 2013	Fly ash: 5, 10, 15, 20 and 25%. Soil: gravely sand	Modified Compaction	1. 5% fly ash has a higher dry density compared to all other proportions of fly ash 2. Optimum moisture content remains approximately the same with increasing fly ash percentages amounts
Amiralian et al., 2012	Fly ash: 5 and 10% class C Soil: concrete sand	Standard Compaction	1. OMC content increased over untreated for 5% fly ash. 2. OMC decreased for 10% fly ash over 5% fly ash. 3. Untreated soil had lowest dry density and 10% fly ash had highest dry density.

2.5 Motivation for the Research.

The purpose of this thesis is to use the waste product from coal burning as a soil additive to improve shear strength parameters. The thesis will focus on:

- using class F fly ash, which is which less desirable than class C fly ash, to improve granular soil properties,
- using little or no cement to maximize potential cost savings for future field applications,
- limiting the percentage of fly ash in the mixtures to a maximum of 30% because the goal is to enhance the soil properties by using fly ash as an additive and not a soil replacement, and
- measuring the shear strength parameters because of the lack of triaxial testing on granular soil fly ash mixes.

CHAPTER 3: MATERIALS, MIX DESIGN, SPECIMEN PREPARATION AND TESTING METHODS

3.1 Materials

In this thesis, three materials were used: sand, fly ash, and Portland cement. This section described the three materials.

3.1.1 Sand

The sand used in this study was Ottawa sand. It is medium sized silica sand that is poorly graded (well sorted). The sand passes the No. 20 sieve and is retained on the No. 30 sieve. The specific gravity for the sand is 2.65. A standard proctor compaction test (ASTM D 698) was performed on the sand. The results of the compaction test are shown in Figure 3.1. The maximum dry density from the test was 1.77 g/cm^3. The optimum moisture content was 11.5%.

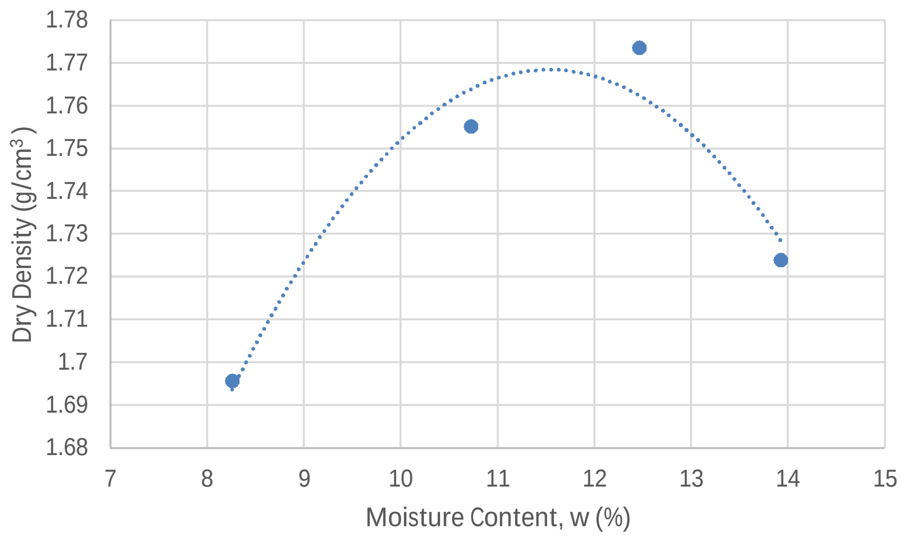

Figure 3.1 Results of the standard compaction test for sand

3.1.2 Fly Ash

The fly ash used in this study was from a power plant in Kentucky. The fly ash is gray to dark brown in color and has a burnt odor. The material safety data sheet (MSDS) lists the chemical components in the fly ash, which are listed in Table 3.1.

Table 3.1 Chemical compounds of the fly ash used in this thesis

Name	Chemical Formula	Percent
Silica, (crystalline)	SiO_2	53%
Aluminum Oxide	Al_2O_3	26%
Iron Oxide	FeO	11%
Potassium Hydroxide	KOH	3%
Calcium Oxide	CaO	4%
Titanium Dioxide	TiO_2	10%

According to ASTM C 618, which contains the classifications of fly ash, the fly ash is classified as Class F due to the low amount of calcium oxide (4%). The common name for this material is coal fly ash or bottom ash.

3.1.3 Portland Cement

Type 1 Portland cement was used in this thesis. Type 1 cement is a general purpose cement with fairly high C_3S (tricalcium silicate) content which is good for early strength development. The constituents of Portland cement, Class F fly ash, and the fly ash used in this study are shown in Table 3.2. As noted in Table 3.2, the fly ash used in this thesis is diminutive in calcium oxide which is the key component for cementitious reactions. Although the fly ash contains only a small percentage of CaO, it was hoped it was cementitious enough to act as a binder.

Table 3.2 Comparison of chemical characteristics of Portland cement, class F fly ash and fly ash used in this thesis (Silica Fume Association's User Manual, 2005)

Property	Portland Cement	Class F Fly Ash	Fly Ash This Thesis
SiO_2 content (%)	21	52	53
Al_2O_3 content (%)	5	23	26
Fe_2O_3 content (%)	3	11	11
CaO content (%)	62	5	4
Specific gravity	3.15	2.38	Not available

3.2 Mix Design

The goals of the mix design component of this thesis were to develop workable mixes that used a reasonable amount of fly ash while using little or no cement. Workability, within this context, refers to a mix that is easily compacted into a mold and a complete (whole) specimen can easily be extracted from the specimen mold. As discussed previously, the goal of the study is not to replace the soil with fly ash but to use fly ash to enhance the properties of the soil.

3.2.1 Sand-Fly Ash Mixes

Mix design is an iterative process. Based on the literature review, it was decided to use a minimum of 5% and a maximum of 30% fly ash in the initial mixes. The proportions of fly ash were 5, 10, 20, and 30%. In order to determine the moisture content of the sand-fly ash specimens, a series of standard proctor compaction tests were performed on trial mix designs. The results of the compaction tests are shown in Figure 3.2 and values are presented in Table 3.3.

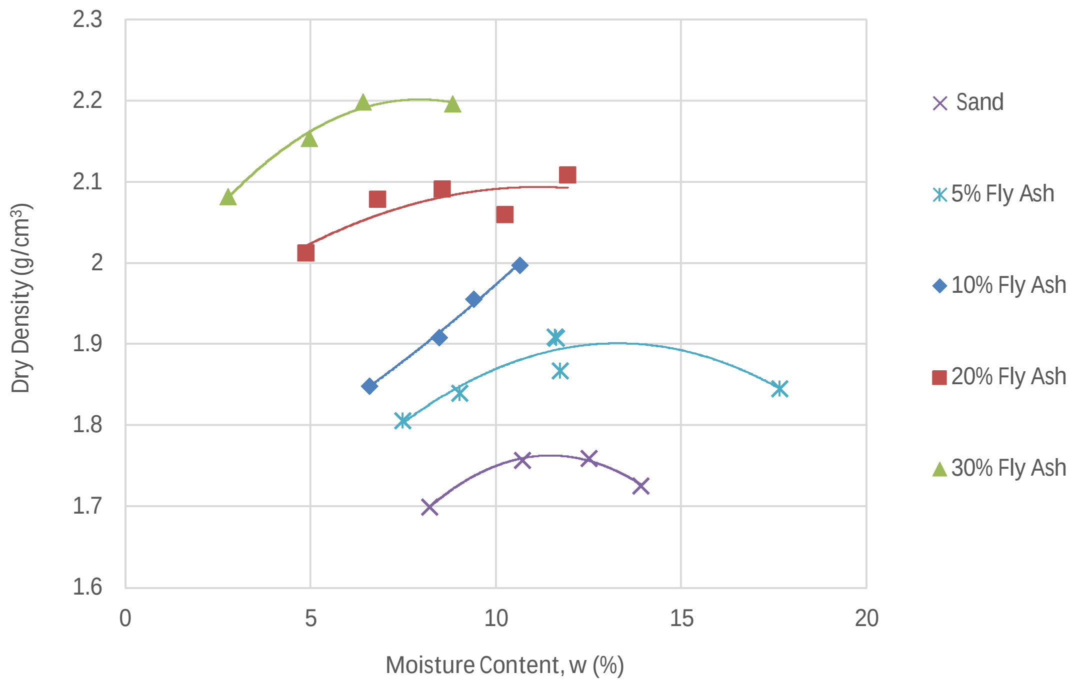

Figure 3.2. Results of the compaction test for sand and sand-fly ash Mixtures with 5, 10, 20 and 30% ash

Table 3.3 Results of the standard compaction testing (optimum moisture content and maximum dry density) for sand and the sand-fly ash mixtures

Trial Mix Design Designation	Material Percentages	Optimum Moisture Content (%)	Maximum Dry Density (g/cm^3)
	Sand	11.5	1.77
T1	Sand with 5% fly ash	11	1.90
T2	Sand with 10% fly ash	9	1.95
T3	Sand with 20% fly ash	8	2.06
T4	Sand with 30% fly ash	6.5	2.20

As the amount of ash increases in the mixture, the maximum dry density (MDD) increases (linearly) and the optimum moisture content decreases (linearly). These trends are shown in Figures 3.3 and 3.4

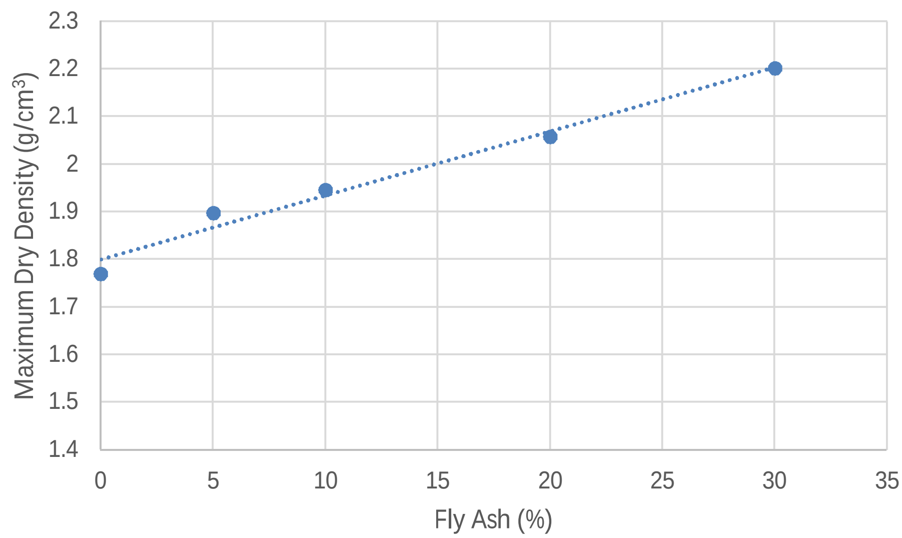

Figure 3.3 Optimum moisture content in trial mixes with different percentage of ash

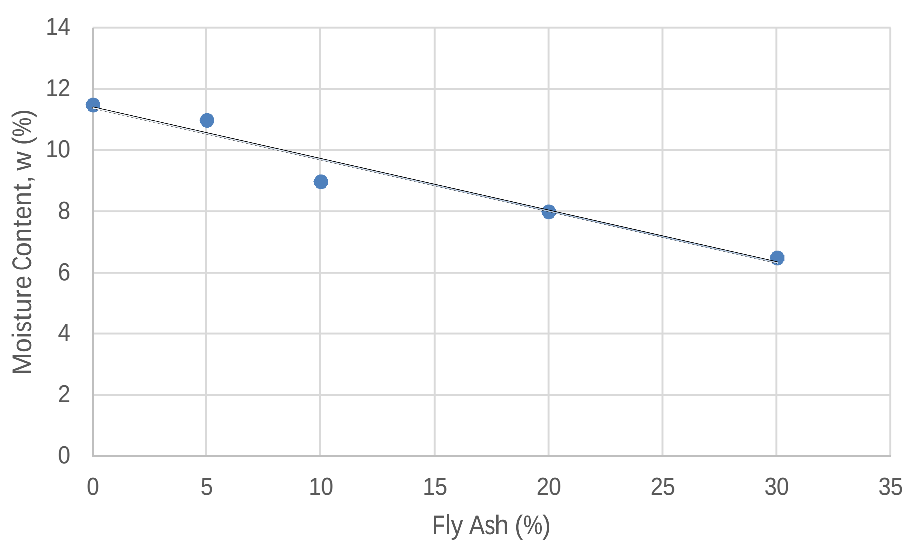

Figure 3.4 Dry unit weight in trial mixes with different percentage of ash

An increase in fly ash by 10 percent decreases the optimum moisture content by approximately 1 percent. An increase in fly ash by 10 percent increases the maximum dry density by an average of 0.13 g/cm^3.

After conducting the compaction test of the four trial mix designs and observing the workability of the mixes, a decision was made to use a moisture content of 10% for the final mix design. Using a 10% moisture content meant that 5% and 10% fly ash specimens would be dry of optimum, 20% fly ash specimens would be at approximately optimum moisture content, and 30% fly ash specimens would be wet of optimum.

3.2.2. Specimen Preparation

Once the moisture content for preparing the specimens was determined, a specimen preparation technique was developed. Dry sand and dry fly ash were mixed in their proper proportions in a stainless steel bowl. The materials were mixed by hand using a spoon until the mixture was a uniform dark gray color. Water was added to the dry components and was again mixed by hand until an even consistency was achieved.

Next thin walled aluminum specimen tubes (inside diameter of 7.0 cm, wall thickness of 0.32 cm and a height of 16.5 cm) were placed inside a 10.2 cm diameter compaction mold. The moist sand and fly ash were then divided into three equal portions. The first portion was placed in a tube and using a standard proctor hammer (2.5 kg weight with a 30.5 cm drop) was compacted 25 times. The same compaction effort was applied to the other two portions.

The specimens were then cured at a constant temperature (room temperature) at a constant humidity of approximately 100% by keeping specimens in the sealed container with an open container of water at the bottom and wet paper towel draped across the thin walled specimen tubes. Specimens were cured for 7, 14, 21, and 28 days. After the required curing time, specimens were ejected using a hand operated hydraulic specimen ejector.

During ejection of the specimens from the specimen tubes, each of the trial mix designs behaved differently. With lower amounts of fly ash (5% and 10%), the mixtures were observed to be drier and were more difficult to eject from the specimen tube. The specimens with higher amounts of fly ash (20% and 30%), were easier to eject from the specimen tube. The specimens did not hold together; specimens crumbled during ejection from specimen tube.

The specimens with longer curing times were behaved slightly differently than those with shorter curing times. The longer the curing time the more difficult it was to eject the specimens. It was initially thought the longer curing times meant the fly ash was cementing the particles together, yet none of the specimens held together after being ejected. The mix designs were not workable and needed to be revisited.

In order for the compacted sand-fly ash specimens to be bound together an activator must be added (Kanirah, et al., 1999 and Consoli et al., 1998). Therefore a decision was made to add a small percentage of Portland cement, between 1% and 2%, to the mix. The amount of Portland cement was limited because the purpose of this thesis was to use class F fly ash as the binder and not Portland cement.

3.2.3 Sand-Fly Ash-Cement Mixes

The mix design iterations continued using 1% Portland cement with three percentages of fly ash (10, 20 and 30%, named Mix T5, T6, and T7 respectively). The three sets of trial mixes were compacted in the specimen tubes and cured for 7, 14 and 28 days. After 7 days, there was a noticeable difference between the behaviors of the specimens during ejection. It was impossible to eject Mix T7 (highest fly ash content) from the specimen tube, but Mixes T6 and T5 could be ejected. Mix T5 was easier to eject than Mix T6.

Based on the extrusions from the seven-day curing, it was decided to hold the fly ash content at 15% and use two different percentages of cement. Mix T8 used 1% cement and Mix T9 used 2% cement. Specimens were cured for 7, 14 and 28 days. After 7, 14 and 28 days mix T8 could be extracted. After 7 days, Mix T9 could not be ejected and an electric drill had to be used to remove the material from the specimen tube. A summary of the trial mix designs (Mix T1 through Mix T9) is presented in Table 3.4.

Table 3.4 Results of trial mixes to obtain a workable mix for producing specimens

Commentary and Mix		Constituents (Sand + ...)	OMC (%)	MDD (g/cm^3)	Observations
Sand	Sand		11.5	1.76	N/A
Sand and Fly Ash	Mix T1	FA: 5%	11	1.90	No significant cementation; specimens could be ejected but would crumble
	Mix T2	FA: 10%	9	1.95	
	Mix T3	FA: 20%	8	2.06	
	Mix T4	FA: 30%	6.5	2.20	
Since mix was not workable, decided to add small percentage of cement and compacted all trial mixes at 10% moisture content					
Sand-Fly Ash-Cement Cured for 7 day to assess workability	Mix T5	FA: 10%, PC: 1%	w = 10%	N/A	Easy to eject from tube
	Mix T6	FA: 20%, PC: 1%	w = 10%	N/A	Difficult to eject from tube
	Mix T7	FA: 30%, PC: 1%	w = 10%	N/A	Could not eject from tube
Use only 15% fly ash. Determine amount of cement to use					
Sand-Fly Ash-Cement Cured for 7, 14, 28 days	Mix T8	FA: 15%, PC: 1%	w = 10%	N/A	Could be ejected from tube and held together
Sand-Fly Ash-Cement Cured for 7 days	Mix T9	FA: 15%, PC: 2%	w = 10%	N/A	Could not be ejected from tube

3.2.4 Final Mix Design

Based on Mix T9, 2% Portland cement was not useful. Therefore it was decided to reduce the amount of the cement to 0.5%. The final two mix designs were:

- Mix 1 – 84.5% sand, 15% fly ash, 0.5% cement compacted at 10% moisture content
- Mix 2 – 84.0% sand, 15% fly ash, 1.0% cement compacted at 10% moisture content

3.3 Specimens

A total of 38 specimens were tested as part of this thesis. The specimens had diameters of 7.0 cm, heights ranging from 12.19 cm to 15.24 cm, post-test moisture contents ranged between 5.57% and 11% (average of 8.45%), and bulk densities ranged between 2.19 g/cm^3 and 2.34 g/cm^3 (average of 2.23 g/cm^3). The individual specimens, test type, moisture content, and bulk densities are listed in Appendix A. The naming convention is as follows; "Mix#" "D#" "A, B, or C" "CU, UCS, or TX". Mix#, either 1 or 2, designates which mixed was used. D# indicates the number of day of curing. "A, B, and C" represents the confining pressures used for testing. "CU, UCS, or TX" represents the test that was conducted. CU is the consolidated undrained (specimen saturated) triaxial test; UCS is the unconfined compression test, and TX is triaxial testing without saturating the specimen.

Twenty four Mix 1 specimens were tested under consolidated undrained conditions, unconfined compression, and triaxial conditions. Fourteen Mix 2 specimens were tested under unconfined compression and conditions.

3.4 Test Methods

Testing was conducted based on ASTM 4767 "Standard Test Method for Consolidated Undrained Triaxial Compression Test for Cohesive Soils". Consolidated undrained and the triaxial testing was conducted to determine friction angle and cohesion. Unconfined compression testing was conducted to determine unconfined compressive strength.

The typical pre-test procedure is as follows. After the specimen was compacted in the specimen tube, cured, and ejected from the specimen tube, trimmed (to ensure the specimen was a right cylinder), weighed, and measured. Specimen heights were measured at four different locations (90 degrees apart) to obtain an average height. Specimen diameters were measured twice (approximately 90 degrees apart) at two specimen heights (for a total of four diameter measurements) to obtain an average diameter.

The specimens were then gently placed in a vertical position and placed on a porous stone on the bottom pedestal located on the base of the triaxial cell. Porous stones were placed on the top of the specimen followed by the top loading cap. A rubber membrane was placed over the specimen and secured using O-rings to the bottom pedestal and the top loading cap. Figure 3.5 is a photograph of a specimen on the base of the triaxial cell with a rubber membrane and top loading cap. The rubber membrane isolates the specimen from the water which provides confining pressure.

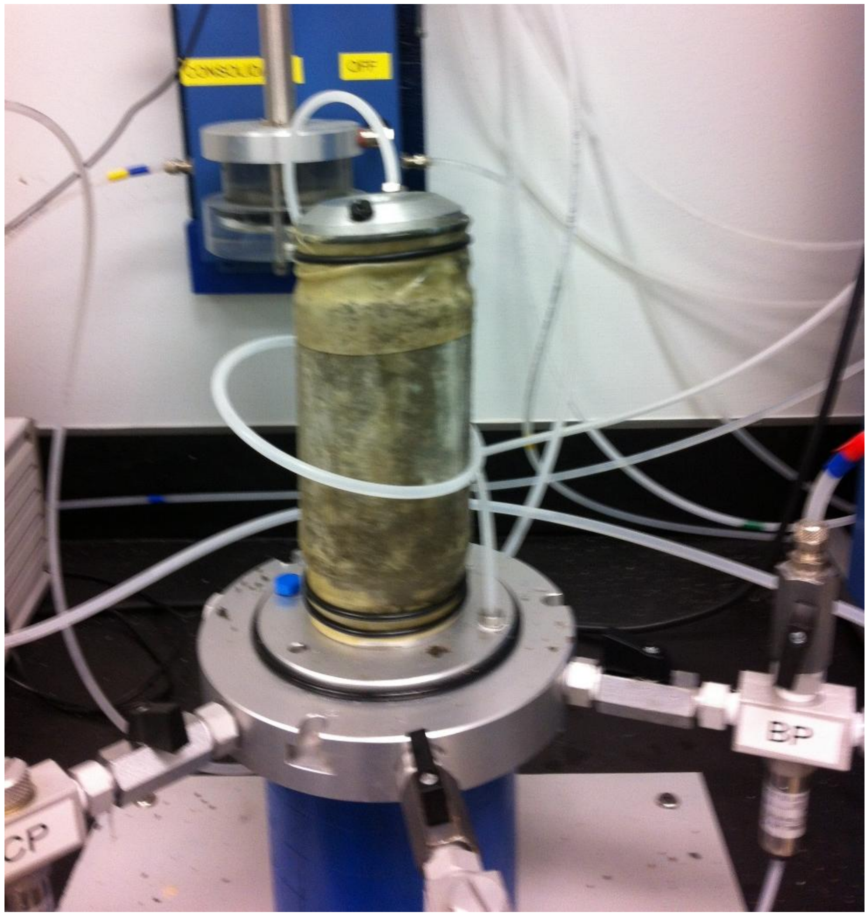

Figure 3.5. Specimen on base of triaxial cell. The rubber membrane is secured by O-rings to the bottom pedestal and loading cap

A Plexiglas chamber was then placed over the specimen and secured to the base using tie rods. The Plexiglas chamber acts as the triaxial cell in which water is added to induce confining pressures on the specimen. The assembly is then moved to a small load frame for testing. Figure 3.6 is a photograph of the assembly on the load frame. Finally the specimen is ready to be tested under consolidated undrained triaxial testing (CU), unconfined compression testing (UCS), or triaxial testing (TX) conditions.

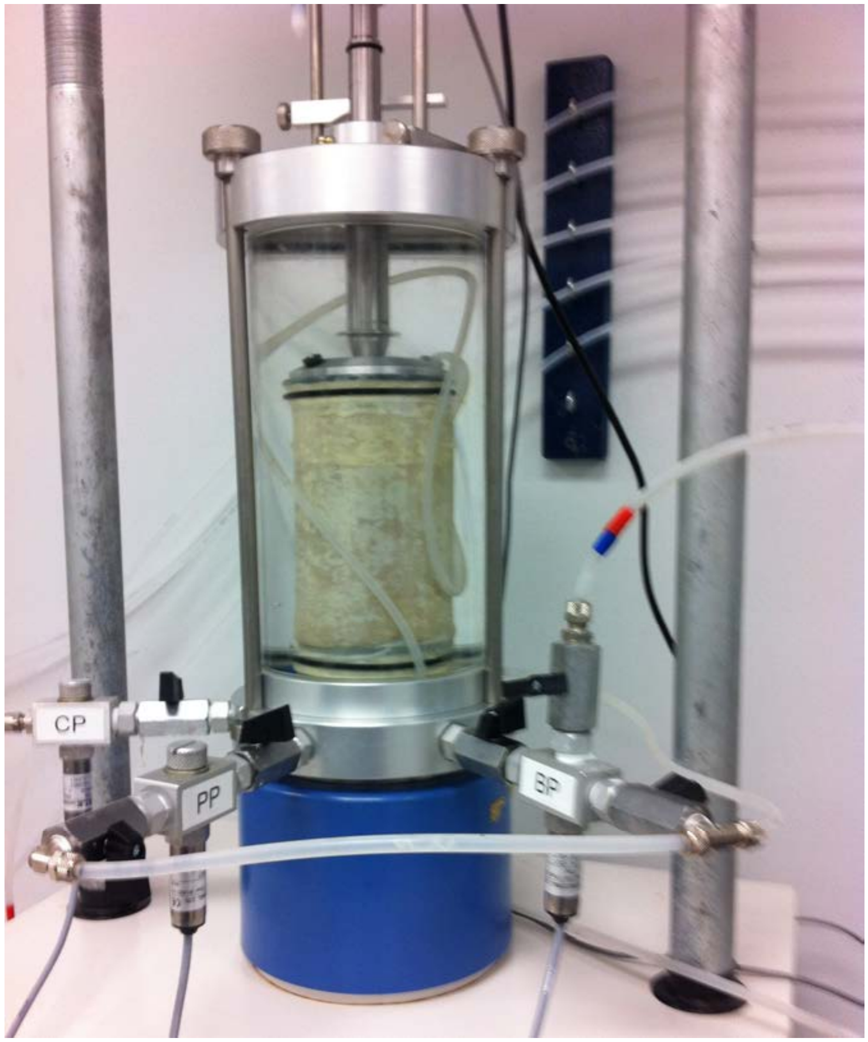

Figure 3.6. Triaxial cell placed on the load frame

3.4.1 Consolidated Undrained Triaxial Test (CU)

Consolidated undrained triaxial testing (CU) is one of the most common types of triaxial tests (Das, 2010). This test consists of saturation phase, consolidation phase, and shearing phase. Prior to saturation, the pore pressure transducer and drainage lines must be properly de-aired. After the de-airing procedure, water is passed through the specimen. Then the bottom drainage is closed and the specimen is saturated by filling the pore space within the specimen with the de-aired water. To insure that the specimen has reached complete saturation, a quick test conducted to determine Skempton's B-value. If a specimen is fully saturated, an increase in confining pressure will be the accompanied by the same increase in pore water pressure, and the B-value is 1. It is very difficult to fully saturate a specimen so a B-value greater than 0.95 is acceptable (ASTM D 4767). If the B-value is below 0.95, one method to reach a desired B-value is to apply a small increment back pressure to the specimen and check the B-value again. The backpressure will force any air in the specimen into solution. If the B-value is constant for two checks or its value is higher than 0.95, the specimen is fully saturated and the test can progress to the consolidation stage.

Consolidation is conducted by increasing the cell pressure while maintaining the constant back pressure and letting the pore pressure dissipate from the specimen. When the pore water pressure is zero the consolidation stage is complete and the shearing phase begins.

During shearing, an axial force is applied to the top of the specimen and the drainage lines are closed (the specimen is undrained). The axial force is applied at a certain rate and the force is continuously monitored and recorded. Since the drainage lines are closed, pore water pressure can be monitored and recorded.

3.4.2 Unconfined Compression Test (UCS)

Unconfined compression testing (UCS) is the simplest and fastest form of triaxial testing and is typically conducted on plastic or cemented soil specimens. This testing does not involve the application of confining pressure. The soil specimen is failed by applying axial force alone. During the UCS testing the drainage lines are open. This test provides only the compressive strength of the specimen and not the shear strength parameters.

3.4.3 Triaxial Test (TX)

Triaxial testing is similar to the consolidated undrained testing with the exception of the specimen saturation. The specimen is not saturated before consolidation and shearing. Triaxial testing provides shear strength parameters. Since the specimens are not saturated, pore water pressure measurements cannot be made and therefor the drainage lines are opened.

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CHAPTER 4: RESULTS AND DISCUSSION

4.1 Consolidated Undrained Test Results for Mix 1

This section presents the consolidated undrained (CU) test results for Mix 1. Three sets of three specimens (a total of nine specimens) were tested. Each set of three specimens were tested at different curing times, either 7, 14, or 28 days. Within each set of three specimens, each specimen was tested at a different confining pressure (nominally 48.3, 96.5 and 193.1 kPa). The specimens were tested to determine the effective shear strength parameters as a function of curing time.

4.1.1 Results for Mix 1 Seven Day Curing

For Mix 1, the seven day cured specimen confining pressures were 83.4, 117.9 and 210.3 kPa. (Table 4.1). With increasing confining stress the major principal effective stress is increasing linearly (Figure 4.1). Using the stress points, shear strength parameters values were determined to be ϕ'= 36.6° and c' = 0 kPa.

Table 4.1 Results for consolidated undrained Mix 1 seven day curing specimens

Curing time (days)	σ'_1 (kPa)	σ'_3 (kPa)	p' (kPa)	q (kPa)
7	315.1	83.4	199.3	115.8
7	438.5	117.9	277.9	160.6
7	850.8	210.3	530.2	320.6

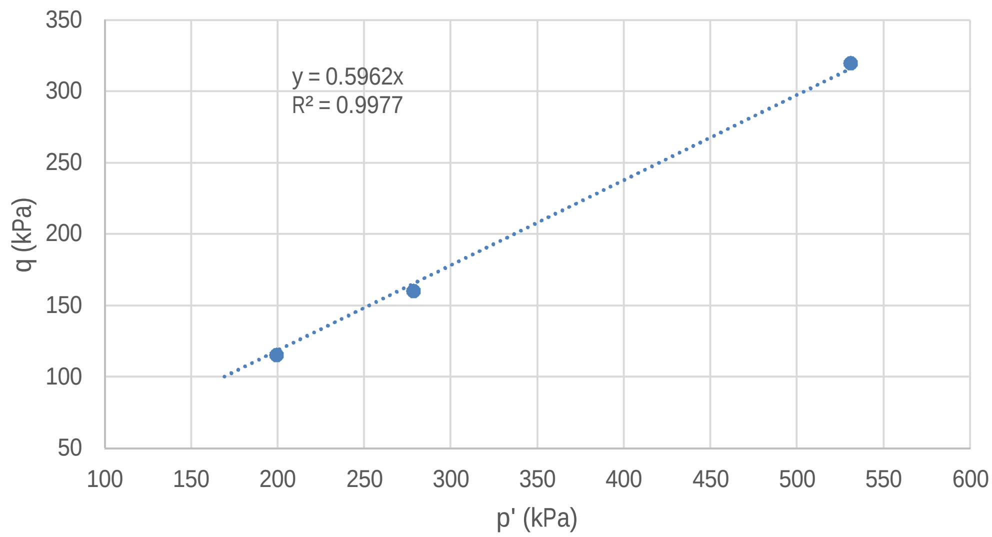

Figure 4.1 p'-q graph for consolidated undrained Mix 1 seven day curing specimens

The results show that Mix 1 specimens cured for 7 days have zero cohesion. This possibly occurred for two reasons: the specimens contained only a small amount of cement and the short curing time did not allow sufficient cementitious bonds to form or the saturation of the specimen modified the internal fabric of the specimens. The first possible reason is that only a small amount of cement was added (0.5%) and the short curing time did not allow the formation of significant cementation to yield any cohesion. The second possible reason is that during specimen saturation, the specimens were initially flushed with water to aid in saturation. During the flushing, clean and clear water entered the specimen and dark cloudy water exited the specimen. The flushing water removed cement and/or ash particles from the pore space of the specimens which may have altered the fabric of the specimens.

4.1.2 Results for Mix 1 Fourteen Day Curing

For Mix 1, the 14 day cured specimen confining pressures were 74.5, 124.1 and 248.9 kPa. (Table 4.2). With increasing confining stress the major principal effective stress increased linearly (Figure 4.2). Using the stress points, shear strength parameters values were determined to be ϕ' = 33.9° and c' = 0.2 kPa.

Table 4.2. Results for consolidated undrained Mix 1 fourteen day curing specimens

Curing time (days)	σ'_1 (kPa)	σ'_3 (kPa)	p' (kPa)	q (kPa)
14 days	404.0	74.5	241.3	164.8
14 days	506.8	124.1	315.1	191.7
14 days	886.7	248.9	552.3	315.8

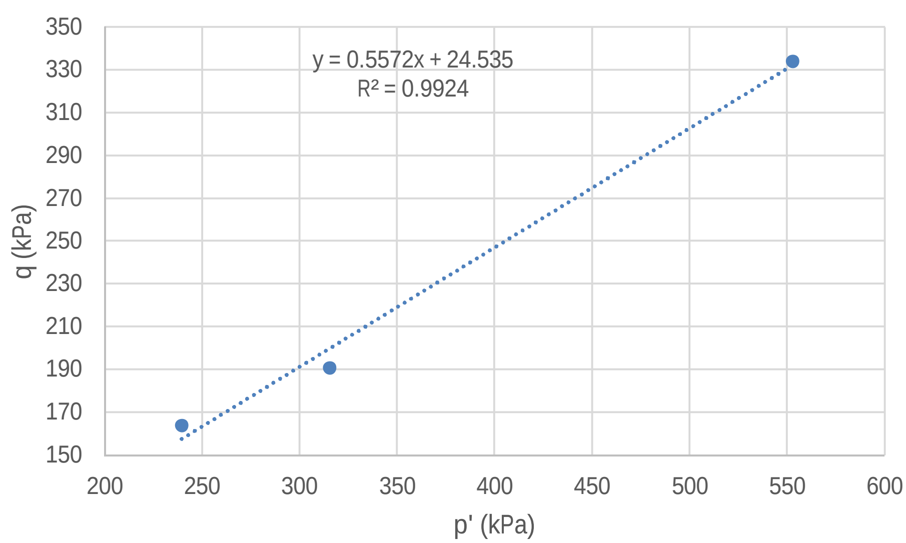

Figure 4.2 p'-q graph for consolidated undrained Mix 1 fourteen day cured specimens

The results show that the Mix 1 specimens cured for 14 days had an effective cohesion value of 0.2 kPa and an effective angle of internal friction of 33.9°. The presence of cohesion can be attributed to the longer curing time (14 days as compared with 7 days) and therefore cementitious bonds were formed to yield appreciable cohesion. Even though the specimens were flushed and the water that exited the specimen was discolored, the specimens still had some cohesion. However, the effective angle of internal friction for the 14 day cured specimens is less than the effective angle of internal friction for the 7 day cured specimens. A similar results was shown by Bhosale et al., (2011).

4.1.3 Results for Mix 1 Twenty Eight Day Curing

For Mix 1, the 28 day cured specimens were tested with confining pressures of 53.1, 66.9 and 174.4 kPa (Table 4.3). With increasing confining stress the major principal effective stress increased linearly (Figure 4.3). Using the stress points, shear strength parameters values were determined to be ϕ' = 37.7° and c' = 0.1 kPa.

Table 4.3 Results for consolidated undrained Mix 1 twenty eight day curing specimens

Curing time (days)	**σ'_1** (kPa)	**σ'_3** (kPa)	p' (kPa)	q (kPa)
28 days	287.5	53.1	170.3	117.2
28 days	364.0	66.9	215.8	148.9
28 days	796.3	174.4	485.4	311.0

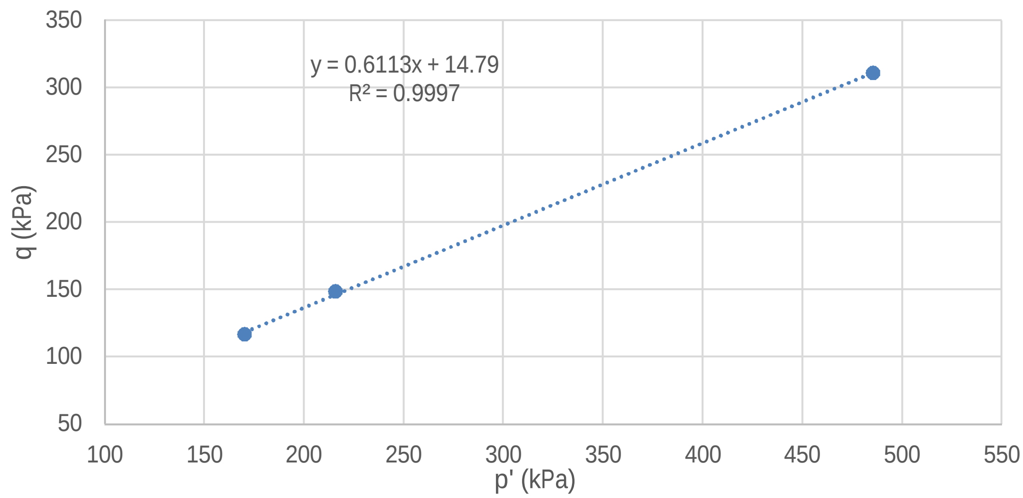

Figure 4.3 p'-q graph for consolidated undrained Mix 1 twenty eight day curing

The results show that the Mix 1 specimens cured for 28 days had cohesion value of 0.1 kPa and the friction angle of 37.7°. The presence of cohesion can be attributed to the longer curing time, (28 days as compared with 7 days) and therefore cementitious bonds were formed to yield appreciable cohesion. Even though the specimens were flushed and the water that exited the specimen were discolored, the specimens still showed some cohesion. As expected, the effective angle of internal friction for the twenty eight day specimens is greater than both the seven and fourteen day specimens.

4.1.4 Summary of the Consolidated Undrained Test Results for Mix 1

The consolidated undrained test results for Mix 1 (15% fly ash, 0.5% cement, and 84.5% sand) were discussed above. Three sets of three specimens (a total of nine specimens) were tested. Each set of three specimens were tested at different curing times, either 7, 14, or 28 days. Within each set of three specimens, each specimen was tested at a different confining pressure. The specimens were tested to determine the effective shear strength parameters as a function of curing time. The summary of the consolidated undrained tests for Mix 1 are presented in (Table 4.4). Figure 4.4 presents stress points for Mix 1, at 7, 14 and 28 days curing times.

Table 4.4 Test results for consolidated undrained test on Mix 1

Curing Time (days)	Major and Minor Effective Principal Stresses (kPa)		Effective Angle of Internal Friction (ϕ', degrees)	Effective Cohesion (c', kPa)
7 days	315.1	83.4	36.6	0
	438.5	117.9		
	850.8	210.3		
14 days	404.0	74.5	33.9	0.2
	506.1	123.4		
	886.7	217.9		
28 days	287.2	53.1	37.7	0.1
	364.0	66.9		
	796.3	174.3		

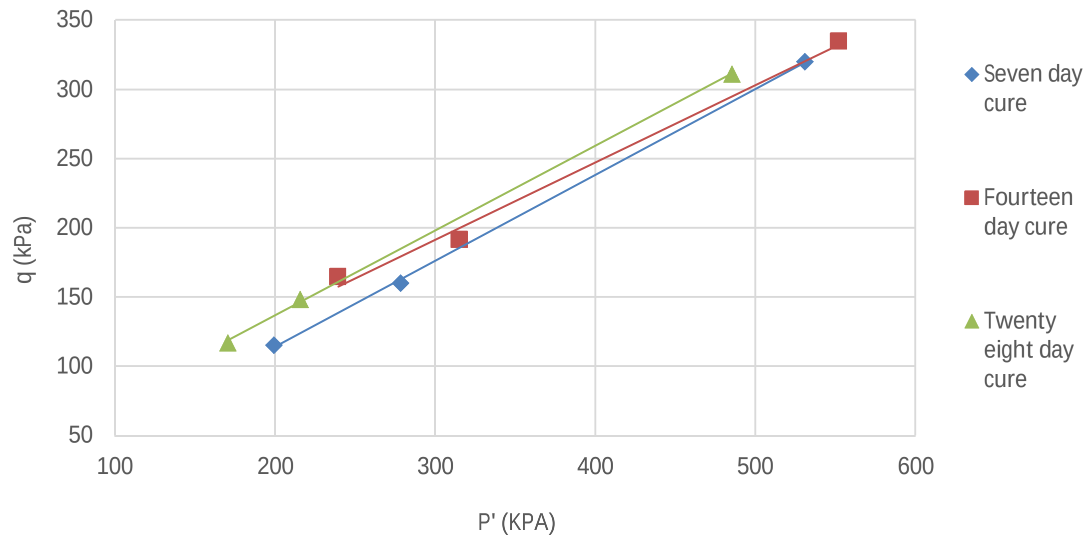

Figure 4.4 p'-q graph for consolidated undrained Mix 1 for seven, fourteen and twenty eight day cured specimens

It was expected that both the effective angle of internal friction and effective cohesion would increase with increased curing time. The results show the values of effective angle of internal friction are approximately the same; they vary by less than 10 percent. Similar results were found by Bhosale et al. (2011) where there was no relationship between curing time and percentage of fly ash (class F) and cement in the specimen. Specifically, their results for 35% fly ash and 4% cement show a 20 percent decrease in the angle of internal friction between seven and twenty eight days

Effective cohesion for Mix 1 as a function of time varies less than 7% (not including the zero cohesion at seven days curing). Cohesion went from zero (7 day) to 4.3 (14 day) to 2.7 (28 days); there was an increase but not what was expected. Although the Bhosale et al. (2011) study did not present cohesion values, it is apparent from their p'-q plots that their cohesion was also highly variable.

These results are somewhat surprising. It was expected that curing as curing time increased there would be an increase in the shear strength parameters of the specimens. However the results clearly show the change in shear strength parameters is not as expected. The seven day tests indicate zero effective cohesion and an intermediate value of effective angle of internal friction. After fourteen days curing, there is some measure of effective cohesion but the effective angle of internal friction has decreased. Finally, the twenty eight day curing yields a lower effective cohesion but the highest effective angle of internal friction. To asses if flushing of the specimen during the saturation stage of the consolidated undrained test had any effect on the shear strength parameters, it was decided to conduct unconfined compression strength tests.

4.2 Unconfined Compression Testing (UCS) Results for Mix 1 and Mix 2.

As noted, flushing the specimens may have affected the CU test results because the specimens with the different curing times did not show increases in shear strength parameters as expected. In order to determine if flushing destroyed and/or had any effects on the soil fabric, unconfined compression tests were conducted. Results from a total of 10 specimen results are discussed: five samples for Mix 1 cured at 1, 10, 10, 23 and 28 days (two specimens results for 10 day curing), and five specimens for Mix 2 cured at 1, 5, 10, 23 and 28 days. The specimens were tested to determine the unconfined compressive strength as a function of curing time with no confining stress and without flushing the specimens.

4.2.1 Results for Unconfined Compression Testing Mix 1

Results from five Mix 1 specimens will be discussed in this section; one of each at tested at 1, 10 (2 specimens), 23 and 28 days curing. The specimens were tested with no confining pressure and no flushing or saturation with water. This method eliminates the possible disturbance of the soil fabric. The number of curing days and unconfined compressive strength of the specimens are shown in Table 4.5 and Figure 4.5.

Table 4.5 Results for unconfined compression testing (UCS) for Mix 1

Curing time (days)	Unconfined Compressive Strength (kPa)
1 day	21.4
10 days	51.7
10 days	48.1
23 days	92.4
28 days	95.1

As expected, the unconfined compressive strength increased with increased curing time. From one day curing to 10 day curing the unconfined compressive strength increased by 142%. From 10 day curing to 23 day curing the unconfined compressive strength increased by 92%. From 23 day curing to 28 day curing the unconfined compressive strength increased by 3%. Unconfined compressive strength increases rapidly, however after 23 day curing the increase in unconfined compressive strength is insignificant. There is no drop in compressive strength around the fourteen day time period.

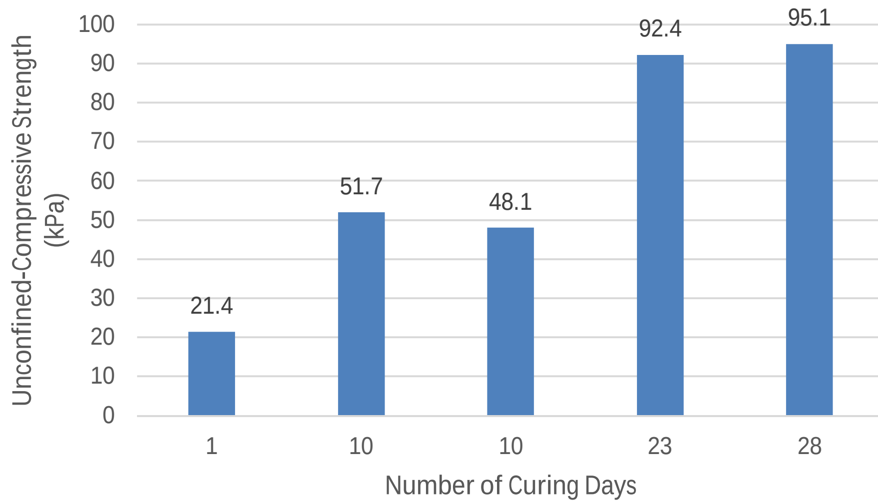

Figure 4.5 Results for unconfined compression testing Mix 1

4.2.2 Results for Unconfined Compression Testing Mix 2

The specimens made with Mix 2 had double the cement than the specimens made with Mix 1. Results from five Mix 2 specimens will be discussed in this section; one of each at tested at 1, 5, 10, 23 and 28 days curing. The specimens were tested with no confining pressure and no flushing or saturation with water. This method eliminates the possible disturbance of the soil fabric. The number of curing days and unconfined compressive strength of the specimens are shown in Table 4.6 and Figure 4.6.

Table 4.6 Results for unconfined compression testing (UCS) for Mix 2

Curing time (days)	Unconfined Compressive Strength (kPa)
1 day	26.9
5 days	84.8
10 days	103.4
23 days	89.6
28 days	128.4

For Mix 2 specimens, the unconfined compressive strength increased with increased curing time. From one day curing to 5 day curing, the unconfined compressive strength increased by 215%. From 5 day curing to 10 day curing the unconfined compressive strength increased by 22%. From 10 day curing to 28 day curing the unconfined compressive strength increased by 24%, and from 23 day curing to 28 day curing the unconfined compressive strength increased by 43%. The results are shown in Figure 4.6. There is a small drop in compressive strength from ten to twenty three days.

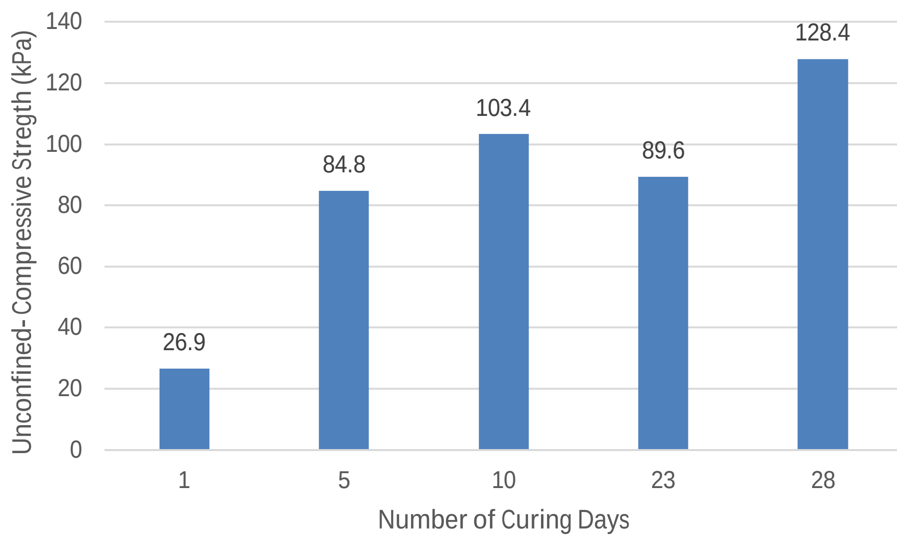

Figure 4.6 Results for unconfined compression testing Mix 2

4.2.3 Summary of the Results for Unconfined Compression Testing Mix 1 and Mix 2

The results shown were as expected; an increase in curing time is accompanied by an increase in unconfined compressive strength. The effect of 0.5% additional cement is noticeable; the unconfined compressive strengths are higher in Mix 2 than in Mix 1 in all cases except for the 10 days curing. The summarized results for Mix 1 and Mix 2 are listed in the Table 4.7.

Table 4.7 Results for unconfined compression testing (UCS) for Mix 1 and Mix 2

Curing time (days)	Unconfined Compressive Strength (kPa)	
	Mix 1	Mix 2
1 day	21.4	26.9
5 days	No Test	84.8
10 days	48.3 / 51.7	103.4
23 days	92.4	89.6
28 days	95.1	128.4

As expected, doubling the amount of cement (0.5% to 1%) increased the unconfined compressive strength but does not mean the unconfined compressive strength is doubled. The amount of cement which is added does not have a linear relationship between the unconfined compressive strength. The increase in unconfined compressive strength with time was also noted by Sumesh et al. (2010).

The unconfined compressive strength test does not provide shear strength parameters. In order to obtain the shear strength parameters, triaxial testing must be performed. In order to not change the soil fabric of the specimens, triaxial testing was conducted without flushing and saturating the specimens. This type of triaxial testing is denoted by TX.

4.3 Triaxial Testing (TX)

This section presents the triaxial testing results for Mix 1. Three sets of three specimens (a total of nine specimens) were tested. Each set of three specimens were tested at different curing times, either 7, 14, or 28 days (nominally 48.3, 96.5 and 193.1 kPa). Within each set of three specimens, each specimen was tested at a different confining pressure. The specimens were tested to determine the effective shear strength parameters as a function of curing time. To determine if the water used during the saturation or flushing in the specimen affected the shear strength parameters of the specimens, the specimens were not flushed or saturated like they were during the consolidated undrained testing.

4.3.1 Results for Mix 1 Seven Day Curing

For Mix 1, seven day curing the confining pressures were 53.8, 101.4 and 195.1 kPa (Table 4.8). With increasing confining stress the major principal effective stress is increases linearly (Figure 4.7). Using the stress points, shear strength parameters values were determined to be $\phi' = 34.1°$ and $c' = 0.19$ kPa.

Table 4.8 Results for triaxial testing Mix 1 seven day curing specimens

Curing time (days)	σ'_1 (kPa)	σ'_3 (kPa)	p' (kPa)	q (kPa)
7 days	272.3	53.8	163.4	108.9
7 days	501.9	101.4	302.0	199.9
7 days	779.1	195.1	486.8	292.3

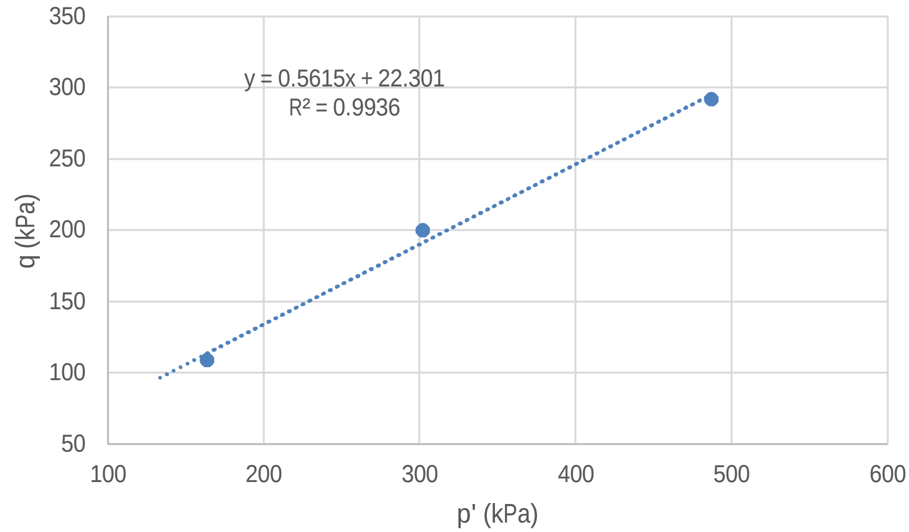

Figure 4.7 p'-q graph for triaxial testing Mix 1 seven day curing specimens

The results show that the Mix 1 specimens cured for 7 days had an effective cohesion value of 0.19 kPa and an effective angle of internal friction of 34.1°. The presence of cohesion may be attributed to not flushing the specimens prior to testing, the flushing water did not move the soil particles. Even though the specimens have only 0.5% cement and were cured for a short time (7 days), the specimens still showed some cohesion.

4.3.2 Results for Mix 1 Fourteen Day Curing

The Mix 1 fourteen day cured specimens were tested with confining pressures of 55.2, 95.8 and 191.0 kPa. (Table 4.9). With increasing confining stress the major principal effective stress increases linearly (Figure 4.8). Using the stress points, shear strength parameters values were determined to be ϕ' = 33.9° and c' = 0.21 kPa.

Table 4.9 Results for triaxial testing Mix 1 fourteen day curing specimens

Curing time (days)	σ'$_1$ (kPa)	σ'$_3$ (kPa)	p' (kPa)	q (kPa)
14 days	284.8	55.2	167.5	117.2
14 days	480.6	95.8	287.5	192.4
14 days	476.0	191.0	486.8	277.2

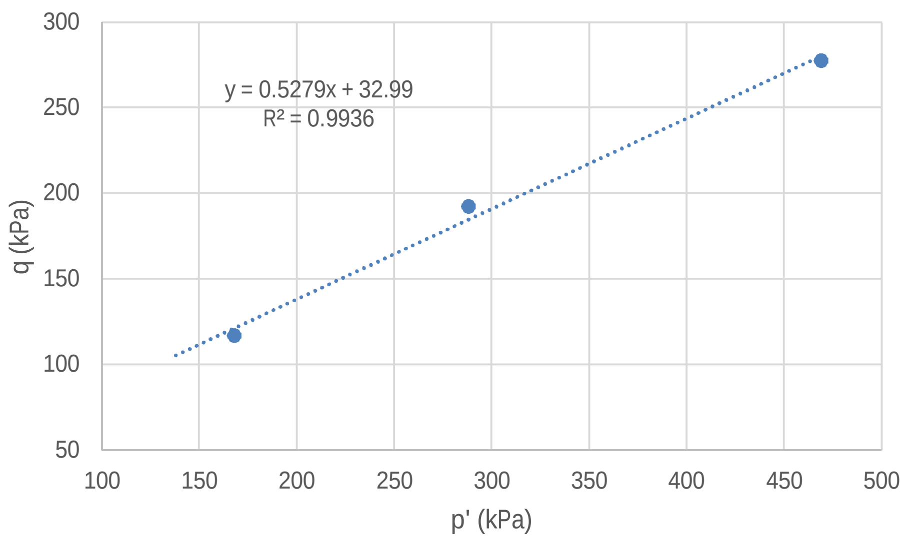

Figure 4.8 p'-q graph for triaxial testing Mix 1 fourteen day cured specimens

The results show the Mix 1 specimens cured for 14 days, had an effective cohesion value of 0.21 kPa, and an effective angle of internal friction value of 31.9°. The presence of a higher cohesion from 7 day curing (44% increase) can be attributed to the longer curing time (14 days as compared with 7 days).

4.3.3 Results for Mix 1 Twenty Eight Day Curing

The Mix 1 twenty eight day cured specimens were tested with confining pressures of 55.0, 110.5 and 136.6 kPa. (Table 4.10). With increasing confining stress the major principal effective stress is increases linearly (Figure 4.9). Using the stress points, shear strength parameters values were determined to be $\phi' = 40.81°$ and $c' = 0$ kPa.

Table 4.10 Results for triaxial testing Mix 1 twenty eight day curing specimens

Curing time (days)	σ'_1 (kPa)	σ'_3 (kPa)	p' (kPa)	q (kPa)
28 days	256.8	55.0	156.0	100.9
28 days	534.5	110.5	322.5	212.0
28 days	641.6	136.6	388.9	252.5

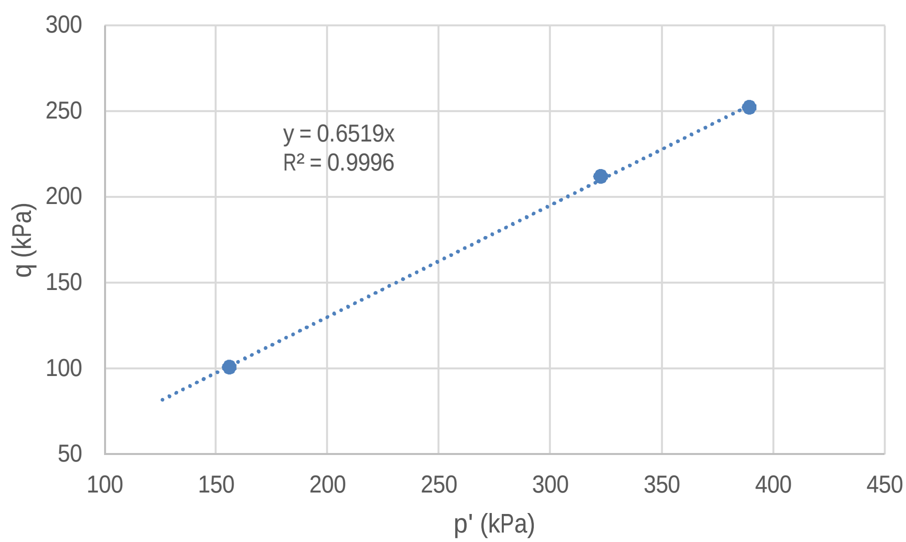

Figure 4.9 p'-q graph for triaxial testing Mix 1 twenty eight day curing specimens

The results show the Mix 1 specimens cured for 28 days, had a cohesion value of zero, and an angle of internal friction value of 40.8°. Surprisingly, there was no cohesion even though there a longer curing time and the seven day and fourteen day specimens had cohesion. However, the twenty eight day specimens had the highest angle of internal friction.

4.3.4 Summary of Triaxial (TX) Testing

The triaxial testing results for Mix 1 (15% fly ash, 0.5% cement, and 84.5% sand) were discussed above. Three sets of three specimens (a total of nine specimens) were tested. Each set of three specimens was tested at different curing times, either 7, 14, or 28 days. Within each set of three specimens, each specimen was tested at a different confining pressure (nominally 48.3, 96.5, and 193.1 kPa). The specimens were tested to determine the effective shear strength parameters as a function of curing time. The summery of the results for triaxial testing Mix 1 are represented in (Table 4.11).

Table 4.11 Total results for triaxial testing Mix 1 seven, fourteen, twenty eight day curing

Curing Time (days)	Major and Minor Effective Principal Stresses (kPa)		Effective Angle of Internal Friction (ϕ', degrees)	Effective Cohesion (c', kPa.)
7 days	272.3	53.8	34.1	0.19
	501.9	101.4		
	779.1	195.1		
14 days	284.8	55.2	31.9	0.21
	480.6	95.8		
	476.0	191.0		
28 days	256.8	55.0	40.8	0.0
	534.5	110.5		
	641.6	136.6		

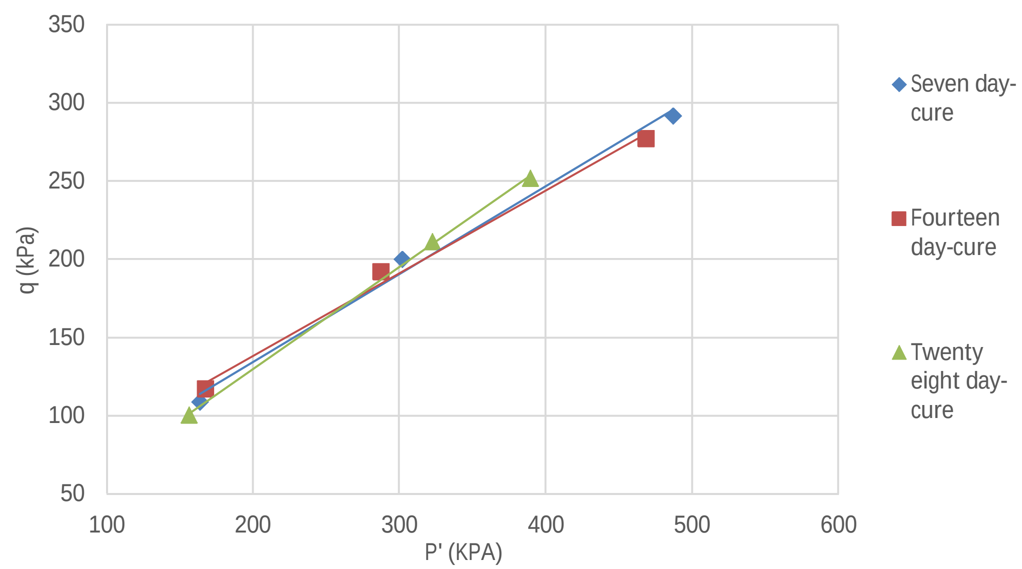

Figure 4.10 p'-q graph for triaxial testing Mix 1 specimens at seven, fourteen and twenty eight day curing

It was expected that both the effective angle of internal friction and effective cohesion would increase with increasing curing time. However, the effective angle of internal friction decreases from 7 days to 14 days and then increases at 28 days. The effective cohesion increased from 7 days to 14 days but then decreased to zero at 28 days (Figure 4.10).

4.4 Comparison of Consolidated Undrained Test Results and Triaxial Testing Results

This section presents the comparison of consolidated undrained test results and triaxial testing results for Mix 1. Each test (consolidated undrained and triaxial testing) were conducted on three sets of three specimens (a total of nine specimens per test) were tested. Each set of three specimens were tested at different curing times, either 7, 14, or 28 days. Within each set of three specimens, each specimen was tested at a different confining pressure (nominally 48.3, 96.5, and 193.1 kPa). The specimens were tested to determine the effective shear strength parameters as a function of curing time. The summery of the results for consolidated undrained test Mix 1 and the triaxial testing Mix 1 are represents in Table (4.12).

Table 4.12 Comparison of effective angle of internal friction and effective cohesion for consolidated undrained test and triaxial testing for Mix 1

Curing Time (days)	Effective Angle of Internal Friction (ϕ', degrees)		Effective Cohesion (c', kPa)	
	Consolidated Undrained	Triaxial	Consolidated Undrained	Triaxial
7 days	36.6	34.1	0.0	0.19
14 days	33.9	31.9	0.21	0.27
28 days	37.7	40.8	0.13	0

With respect to the effective angle of internal friction the same relationship with time is noted for both test methods. The consolidated undrained (CU) and triaxial (TX) testing the effective angle of internal friction is relatively high at seven days, decreases at 14 days, than increases at 28 days. Comparing CU and TX test results, the CU results are higher than the TX results. Interestingly, they both decrease by approximately three degrees. The TX test has the highest twenty eight day effective angle of internal friction.

With respect to the effective cohesion, the results are rather inconclusive. The highest cohesion value is at 14 days for both test methods. The cohesion values are so low that they would not be considered for geotechnical design and the soil-fly ash-cement mixtures would be considered granular soils.

With respect to the inconsistent results of shear strength parameters not increasing with time, this phenomena was observed by Bhosale et al. (2011). There results show decreasing shear strength parameters with time for several mixes.

With respect of flushing of the specimens during saturation of the CU test, the results show that flushing did not cause a change in soil shear strength parameters. During the flushing it appeared that enough material was removed from the specimen to influence the shear strength parameters, but the data shows that this is not the case.

4.5 Testing Results Summary

The unconfined compression test clearly shows an increase in strength as a function of curing time. This relationship has been demonstrated by other researchers using similar materials. Doubling the amount of cement did not double the unconfined compressive strength.

Results from the triaxial testing were somewhat inconclusive. The effective angle of internal friction increased over that of sand alone however the effect of curing time was inconclusive. The seven day effective angle of internal friction was relatively high, the fourteen day effective angle of internal friction was lower, and the twenty eight day effective angle of internal friction was higher than the seven day effective angle of internal friction. This relationship was consistent between consolidated undrained testing where specimens were flushed and saturated and triaxial testing where the specimens were not flushed or saturated. This inconclusive behavior has been noted by other researchers using similar materials.

The effective cohesion had a similar inconclusive nature. The fourteen day effective cohesion was highest for both consolidated undrained and triaxial testing. Again, this inconclusive behavior has been noted by other researchers using similar materials.

CHAPTER 5: CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

The main goal of this thesis was to use a waste product from coal burning as a soil improvement additive. The work was focused on using class F fly ash, which is which less desirable than class C fly ash, to improve granular soil properties with no or minimal cement to maximize potential cost savings for future field applications. The percentage of fly ash in the soil mixture was limited because the goal is to enhance the soil properties by using fly ash as an additive and not as a soil replacement and to focus on shear strength parameters because of the lack of triaxial testing on granular soil fly ash mixes.

Unconfined compression tests were conducted on Mix 1 and Mix 2 to assess the strength gain over time without confining pressure or saturating the specimens. A total of 10 specimen were tested: five specimens for Mix 1 cured at 1, 10, 10, 23 and 28 days (two specimens results for 10 day cure), and five specimens for Mix 2 cured at 1, 5, 10, 23 and 28 days. As expected, the specimens show increase in unconfined compressive strength with time. Doubling the amount of cement did not double the unconfined compressive strength.

Triaxial testing on unsaturated Mix 1 specimens was conducted to determine if flushing specimens during saturation associated with consolidated undrained testing affected the shear strength parameters The effective angle of internal friction were calculated to be 34.1 degrees (7 day), 31.9 degrees (14 day), and 40.8 degrees (28 day). The effective cohesion was calculated to be 0.19 kPa (7 day), 0.27 kPa (14 day), and 0.0

kPa (28 day). It was expected shear strength parameters would increase with time but these results were inconclusive. Based on the results from triaxial testing, flushing of the specimens during consolidated undrained testing did not affect the shear strength parameters. Other researchers using similar materials have shown the same inconclusive shear strength parameter increase with time results.

5.2 Recommendations

Moving forward with this research, I would recommend to:

- Investigate the phenomena of the fourteen day effective angle of internal friction decreasing from that of the seven day effective angle of internal friction. It was expected that the effective angle of internal friction would increase with time. I would suggest performing additional tests at all time frames (7, 14, 28 days) and include tests at other time frames such as 10 days and 18 days. This could help verify if this is a true aspect of material behavior.
- Extend the study so as not to use a controlled sand as the material to be improved but to use an unacceptable construction material such as dredged material with high percentage of clay. A good candidate for testing would be dredged material from the St. Johns River.
- Use a split mold rather than a solid aluminum specimen tube. Ejecting the specimen with the specimen ejector may have damaged the specimen.

- Use a staged triaxial test rather than testing three different specimen to obtain the shear strength parameters. This will reduce specimen variability and provide higher quality results.

VITA

Oksana Nikolayevna Spears was born . She graduated with Bachelor of Science in Civil Engineering from University of North Florida in May, 2012. As a graduate student she worked with Dr. Hudyma on research involving determining the shear strength parameters of sand-fly ash-cement mixtures. This thesis is the result of the research. Ms. Spears should defend her thesis in Fall 2014 and will graduate at the Fall 2014 graduation. She is currently a staff engineer at Terracon, Inc. in Jacksonville, FL.

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APPENDIX A

Specimen name, moisture content, height, and bulk density

Specimen	Moisture Content (%)	Specimen Height (cm)	Bulk Unit Weight (g/cm^3)
Mix 1 D7 A CU	10.99	13.5	2.19
Mix 1 D7 B CU	11	14.5	2.22
Mix 1 D7 C CU	10.93	13.5	2.21
Mix 1 D14 A CU	8.7	13.2	2.18
Mix 1 D14 B CU	7.69	14.7	2.29
Mix 1 D14 C CU	8.33	14.2	2.22
Mix 1 D28 A CU	11	14.2	2.22
Mix 1 D28 B CU	8.18	14.1	2.25
Mix 1 D28 C CU	8.46	15.0	2.23
Mix 2 D7 A CU	9.07	14.2	2.23
Mix 2 D7 B CU	8.69	14.2	2.25
Mix 2 D7 C CU	8.81	14.0	2.25
Mix 2 D14 A CU	7.16	13.9	2.23
Mix 2 D14 B CU	9.48	14.6	2.27
Mix 2 D14 C CU	8.33	13.4	2.25
Mix 2 D28 A CU	9.12	14.2	2.24
Mix 2 D28 B CU	10.31	14.1	2.29
Mix 2 D28 C CU	9.25	14.1	2.22
Mix 1 D1 UCS	9.22	13.2	2.34
Mix 1 D5 UCS	8.2	14.2	2.20
Mix 1 D10A UCS	9.96	14.6	2.27
Mix 1 D10BUCS	7.49	15.5	2.19
Mix 1 D23UCS	6.62	14.4	2.20
Mix 1D 28UCS	5.76	14.2	2.20
Mix 2 D1UCS	8.7	13.5	2.20
Mix 2 D5 UCS	6.8	14.2	2.22
Mix 2 D10 UCS	5.57	14.0	2.19
Mix 2 D23UCS	5.88	13.2	2.19
Mix 2 D28UCS	7.99	13.7	2.20
Mix1 D7 A TX	8.16	16.0	2.21
Mix 1 D7 B TX	7.83	12.2	2.21
Mix 1 D7 C TX	8.88	15.0	2.23
Mix1 D14 A TX	7.26	14.9	2.24
Mix 1 D14 B TX	8.01	14.6	2.23
Mix 1 D14 C TX	7.69	15.1	2.22
Mix1 D28 A TX	8.74	14.5	2.25
Mix 1 D28 B TX	8.57	13.4	2.25
Mix 1 D28 C TX	8.19	15.5	2.22