Evaluation of CFBC fly ash for Improvement of Soft Clays

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ABSTRACT

Soft soil improvement or stabilization has been practiced for quite some time by mixing admixtures to the soil, such as cement and lime, to increase its strength and stiffness. In recent years ground improvement using fly ash class F or C has also been reported. In contrast very little has been studied about the applicability of CFBC fly ash which is a byproduct obtained from power plants that burn their coal using circulating fluidized bed combustion. CFBC fly ash often has a unique composition which justifies the need for research to study the feasibility of using this fly ash type for ground improvement applications. This paper presents results from a comprehensive laboratory study carried out to investigate the feasibility of using CFBC fly ash for improvement of engineering properties (strength and stiffness) of soft clays. The CFBC fly ash was obtained from the AES power plant located in Guayama, Puerto Rico. This study is part of a larger initiative currently being carried out by AES to investigate possible recycling or reutilization alternatives for their carbon combustion products.

INTRODUCTION

Electric utility companies in many parts of the world generate electricity by burning coal which generate voluminous amounts of fly and bottom ash. Fly ash generated by coal combustion based power plants typically fall within the ASTM fly ash classes C and F. However, many coal-based power plants have fly ash that does not fall into these two common categories. This is particularly true for plants using circulating fluidized bed combustion (CFBC) which is being used as a very effective technology for burning high-sulfur fuels with low SO_2 emissions[1]. In CFBC plants the SO_2 is captured by limestone added during the process and the resulting ashes do not typically fall within the typical ASTM fly ash classes.

Like in mainland United States, electric utility companies in Puerto Rico are facing the serious challenge to find effective and environmentally safe ways to dispose, recycle or re-use their coal combustion products (CCP's). However, for Puerto Rico this problem is further exacerbated due to its relatively small size and island environment. AES

Puerto Rico, LLC, the only coal combustion electric plant in Puerto Rico, recently sponsored a study[2] to identify different recycling alternatives for their CCP's. This paper presents a summary of a research project investigating one of the identified reutilization alternatives of this study. Specifically the paper presents results of a laboratory investigation of the stabilization characteristics of clayey soils blended with CFBC fly ash from the AES Puerto Rico power plant located in Guayama, Puerto Rico. To date, most of the literature related to soil stabilization using fly ash has involved use of fly ash classes C or F. This paper hopes to contribute to fill this gap of information regarding ground improvement studies involving use of CFBC fly ash as a soil admixture.

BACKGROUND

Civil engineering projects located in areas with soft or weak soils have traditionally considered improving soil properties by using cement[3,4], and lime[5,6]. More recently projects involving soil mixed with Class C or Class F fly ash have been reported[7,8, 9,10,11]. Use of fly ash as a ground improvement soil admixture, when found technically viable, constitutes a cost effective and environmentally beneficial alternative with considerably less capital investment. For the particular case of CBFC fly ash no literature was found reporting ground improvement applications.

EXPERIMENTAL PROGRAM

The feasibility of using CFBC fly ash from the AES Power plant in Guayama Puerto Rico was investigated through a comprehensive laboratory experimental program. The program primarily involved assessing the stabilization characteristics of a clay soil from an actual construction site when blended with CFBC fly ash. For comparison purposes the stabilization characteristics (strength and stiffness) were also measured for the same base soil blended with class C fly ash and lime. The stabilization characteristics were measured in terms of strength and stiffness gain, failure strain, and on swelling potential. The stabilization characteristics were evaluated with respect to a) curing time (0, 7, 14, 28, 40, and approximately 100 days), and b) amount of fly ash (or lime) (5,10,15 and 20% by dry weight).

The following subsections describe the materials used (i.e., base clay soil, CFBC fly ash, Class C fly ash, and lime), and experimental procedures (i.e., sample preparation, curing procedures, and test procedures).

MATERIALS

Four materials were used for the laboratory experimental program carried out in this research: clay base soil (i.e., soil to be treated), CFBC fly ash, Class C fly ash, and lime. These materials are described below.

Clay base soil

The clayey soil used for this study was obtained from a highway interchange project located in Hormigueros, Puerto Rico. This project was selected do to presence of large volumes of soft compressible soils. Several 5-gallon pales of the clayey soil were retrieved from the base of an excavation approximately 4.27 m deep. The sampled soil was a dark grey, high plastic clay with traces of sand. A summary of the main properties of the base clay used for this research is presented in Table 1. A grain size distribution analyses was carried out following ASTM Standard D 422 indicating the Hormigueros clay had 20% sands, 22% silt sizes, and 58% clay sizes. According to the AASHTO Classification System this soil classifies as a A-7-5, which has a general subgrade rating of fair to poor. According to the Unified Classification system this soil classifies as a CH which corresponds to a high plasticity clay.

Table 1. Index properties and compaction characteristics of the Hormigueros clay

Property	Value	ASTM standard
Natural water content (in-situ when sampled)	59-64	D 2216
Liquid Limit	80-90	D 3418
Plastic Limit	35-37	D 3418
Plasticity Index	45-53	D 3418
Specific gravity, Gs	2.68	D 854
Moist unit weight, γ_{wet} (kN/m^3)	16.2-16.6	-
pH	7.4-7.6	D 1293
In-situ unconfined compressive strength, q_u (kN/m^2)	28-36	D 2166
Organic matter content (% by weight)	1.2-2.2	-
Maximum dry density (Standard Proctor) (kN/m^3)	12.1	D 698
Optimum water content (Standard Proctor) (%)	31	D 698

CFBC fly ash

The CFBC fly ash used in this study was retrieved from the AES Power Plant in Guayama, Puerto Rico. A 454 MW electric plant using a CFBC boiler. This plant generates about 15% of the electricity consumed in Puerto Rico. The chemical composition of this CFBC fly ash material is summarized in Table 2. Most values shown in this table for the CBFC fly ash comply with the chemical requirements for class C fly ash as specified by ASTM C618. However the main difference with class C fly ash is that the CFBC fly ash exceeds the upper limit of sulfur trioxide (SO_3) content by about 7.57%.

The CFBC fly ash was sampled from the AES plant on july 2006. This fly ash is gray (in dry state) and has the physical properties shown in Table 3. The results of the particle size distribution analysis carried out using hydrometer tests are shown in Figure 1. This figure indicates a fairly uniform particle size distribution with particle sizes mainly within the silts sizes.

Self-cementing properties of the CFBC fly ash were assessed by means of compressive strength tests following ASTM C109 and ASTM D5239-04. For a water/fly ash ratio of 0.46, an average unconfined compressive strength of 4754 kPa was measured after a 7 day curing period, which corresponds to a very self cementing fly ash according to ASTM C109.

Table 2. Chemical composition of the two fly ashes used

Chemical component	CFBC fly ash (% Wt)[a]	Class C fly ash (% Wt)[b]
Silica, SiO_2	39.41	31.17
Alumina, Al_2O_3	12.59	18.76
Ferric Oxide, Fe_2O_3	4.35	5.30
$SiO_2 + Al_2O_3 + Fe_2O_3$	56.35	55.77
Titania, TiO_2	0.51	-
Lime, CaO	27.02	27.90
Magnesia, MgO	1.27	7.41
Potassium Oxide, K_2O	1.17	2.37
Sodium Oxide, Na_2O	0.44	2.12
Sulfur Trioxide, SO_3	12.57	0.36
Alkalis as Na_2O	-	2.36
Phosphorus Pentoxide, P_2O_5	0.28	-
Strontium Oxide, SrO	0.14	-
Barium Oxide, BaO	0.23	-
Manganese Oxide, Mn_3O_4	0.02	-
Undetermined	0.0	-
Total	100%	100%

Notes: [a]: From AES power plant, in Guayama, Puerto Rico.
[b]: From Pawnee Power Plant in Brush, Colorado.

Class C fly ash
The Class C fly ash used in this study came from the Pawnee Power Plant in Brush, Colorado. It is a 500 MW pulverized coal station burning Powder River Basin Coal from the Eagle Butte Mine. The chemical and physical properties are summarized in Tables 2 and 3, respectively. This fly ash is yellow in color (in dry state) and very fine. The particle size distribution of the Class C fly ash is presented in Figure 1.

Table 3. Physical Properties of the two fly ashes used

Physical property	CBFC fly ash[a]	Class C fly ash[b]
As received moisture content (%)	0.11	0.03
Specific gravity, Gs	2.55	2.72
Loss on Ignition (LOI) (%)	2.6	0.34
pH	12.55-12.62	n.a.
Compressive strength at 7 days (kN/m^2)	4,754[c]	n.a.

Notes: [a]: From AES power plant, in Guayama, Puerto Rico.
[b]: From Pawnee Power Plant in Brush, Colorado.
[c]: Based on water/fly ash ratio of 0.46.
n.a.: value not available.

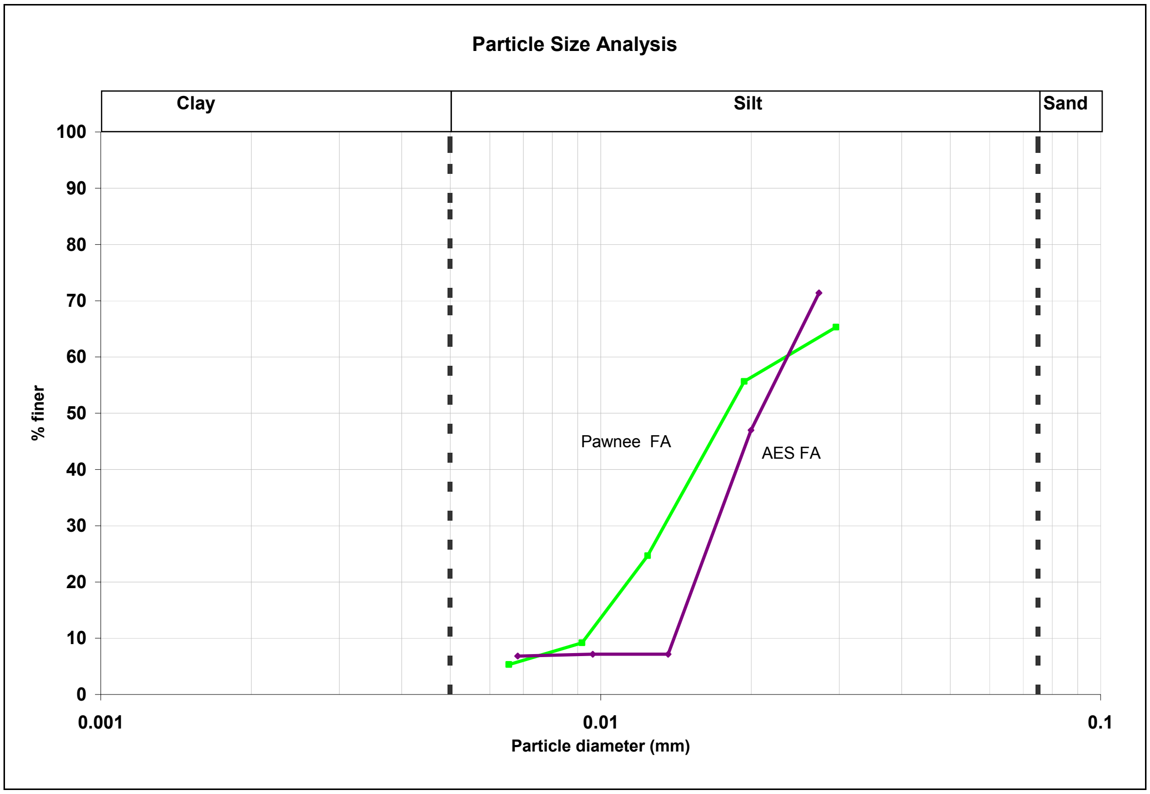


Figure 1. Particle size distributions for fly ashes used

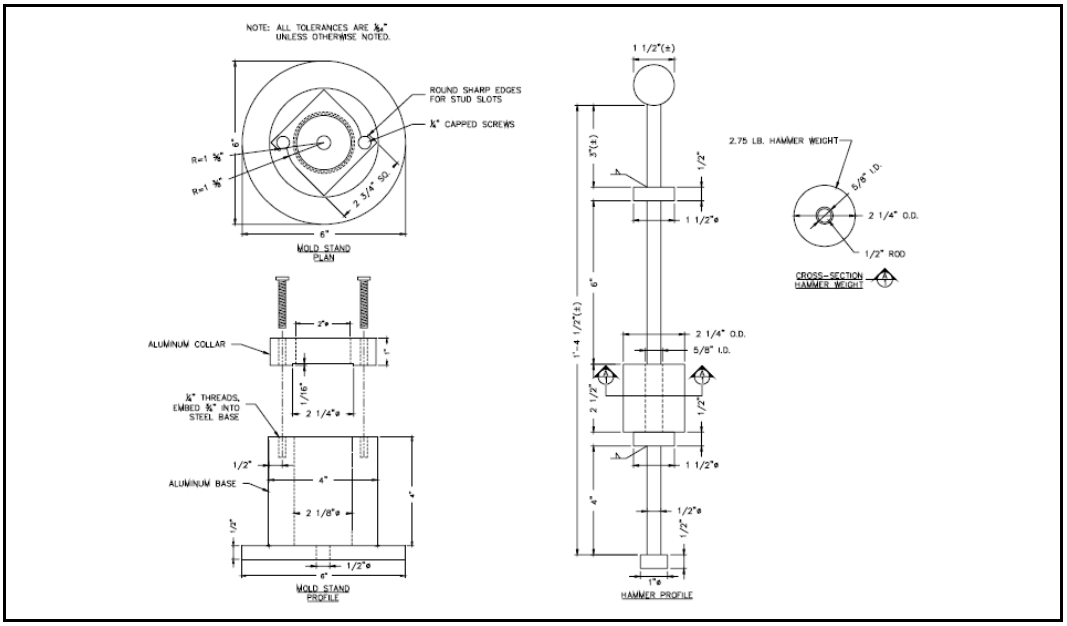
Lime
The lime used for comparison purposes was a commercially available lime typically used for construction purposes. It is a type S or hydrated lime according to ASTM C 206 produced by Cemex Company in Puerto Rico.

EXPERIMENTAL PROCEDURES

Prior to soil treatment, the base clay soil from Hormigueros was air dried for two weeks and then processed using a crushing equipment. The maximum particle size of the base soil was restricted to 4.75 mm which corresponds to the opening of a standard Sieve No. 4. A Standard Proctor compaction test (ASTM 698) carried out on the base clay soil yielded an optimum moisture content of 31 % and maximum dry unit weight of 12.1 kN/m^3 (see Table 1).

Compacted samples of treated soil, i.e. clay soil blended with either fly ash or lime, were all prepared to the same target moisture content of 31% (i.e., the optimum moisture content of the untreated soil). Soil samples treated with fly ash were prepared with four amounts of fly ash (5, 10, 15, and 20% of fly ash by weight), while soil treated with lime were only prepared at two amounts (5 and 10% of lime by weight). The proportions selected for the fly ash treated soil mixes were based on previous studies[9, 10, 11]. The proportions selected for lime were selected based on values commonly used in practice[5,12].

Before compaction of the samples, the initial moisture content of the air dried clay was measured to ensure the correct amount of water was added to obtain the target moisture content of 31%. The pre-moisten soil was kept in sealed bags for 24 hours prior to adding the corresponding amount of admixture. To ensure homogeneous blends of soil and admixture the specific quantities of admixture and pre-moisten soil were mixed for 3 minutes using an electrical mixing machine at about 138 rpm. According to Barbu[13], maximum stabilization effects are obtained when fly ash-treated soils are mixed quickly and immediately compacted. Based on this, all the samples were immediately compacted after mixing. This procedure minimized effects related to the early hydration reaction associated when using fly ash or lime. The soil-admixture (fly ash or lime) samples were compacted inside plastic molds with a 2-inch diameter and a 4-inch height. The plastic molds were placed inside the compaction device shown in Figure 3, prior to soil filling and compaction. This compaction device was built at the University of Puerto Rico based on the design by Geiman et al.[12]. The soil-admixture blends were compacted by placing the mixtures in 6 equal layers and applying 13 blows to each layer using the hammer rod shown in Figure 3. This compaction procedure corresponds to the same compaction energy of a Proctor Standard test (ASTM D 698). Immediately after compaction, the molds of the samples were sealed with a plastic cap and stored in a curing chamber with controlled conditions of temperature and humidity. Prior to unconfined compressive testing, samples were cured for 7, 14, 28, 40 and a maximum time of about 103 days. Unconfined compressive tests were also carried out on uncured samples which were tested immediately after compaction, i.e., corresponding to an age of 0 days. To consider inherent sample and test result variability, at least three samples were tested at each admixture proportion level and curing time. A total of 184 specimens were prepared and tested using this procedure.



(After Geiman et al. 2005)

Figure 2. Miniature compaction equipment

RESULTS

The cured samples were tested for unconfined compressive strength following a test procedure in general accordance with ASTM Standard D 2166. The tests were carried out using a GeoComp Load Trac II frame at a strain rate of 1%/minute. For each unconfined compressive test, the stress-strain relationships were recorded along with their moisture contents at the end of curing. This allowed measuring three parameters: unconfined compressive strength, stiffness, and strain at failure. For the sake of brevity, this paper only presents strength results.

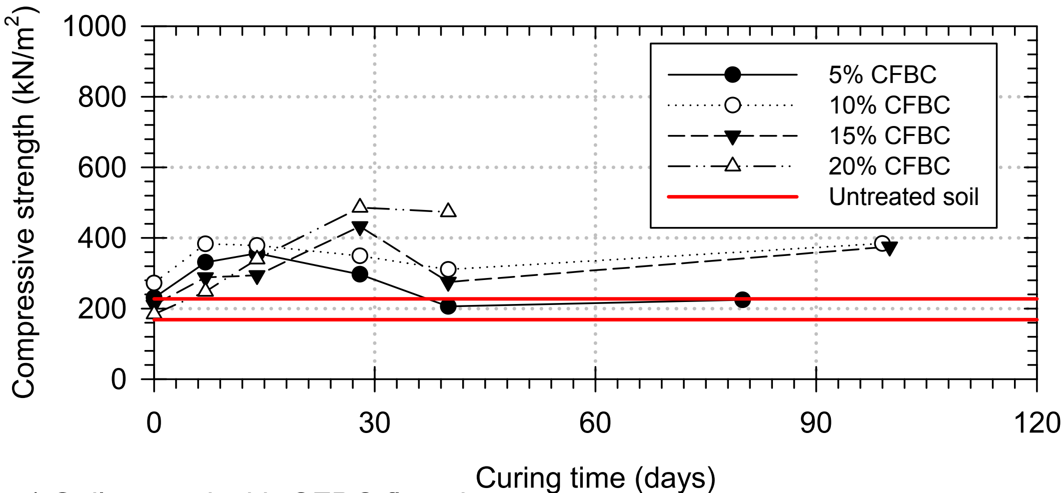
Effect of curing time on strength gain

Figure 3 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.

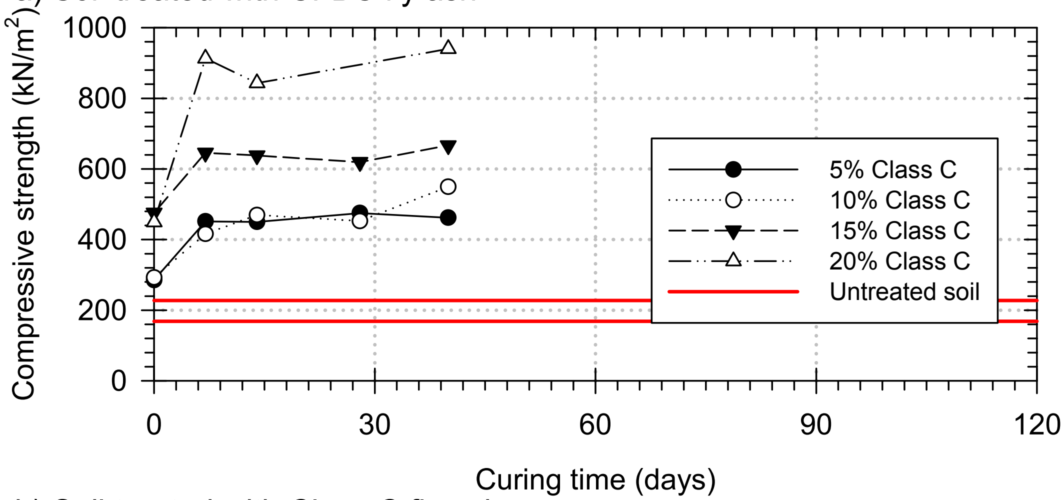
In general, compressive strength values shown in Figure 3 indicate that all admixture treatment types resulted in strength gains and that most of the gain occurred within the first seven days of curing. This is consistent with other published results[11]. This fast strength gain is believed to be related to the initial rapid hydration that takes place with these admixtures. The unconfined compressive strength values for the clay treated with class C fly ash had the highest levels of strength gain and these seem to stabilize after 14 days of curing time. Lime treated had the second highest level of strength gains and values started to stabilize only after 30 days of curing. However a slight strength increase was still observed in the lime-treated samples. CFBC treated samples exhibited strength gains for samples treated with at least 10% of CFBC. CFBC treated samples (for 5%, 10% and 15% admixture) showed a marked strength drop at a curing times between 14 and 40 days. The reason for this strength drop is not certain, but could be related to sample degradation during curing. Interestingly, CFBC samples treated with 10% and 15% admixture showed a tendency to regain their lost strength beyond 40 days curing. A similar behavior was reported by Misra and co-workers[11] for clays treated with class C fly ash. It is important to note that samples treated with only 5% CFBC did not regain the strength lost and in fact showed strength values similar to those of untreated soil.

To investigate the observed strength loss, Scanning Electron Microscope (SEM) images were obtained from several samples at different curing times and treatment levels. SEM images of samples treated with 10% CFBC fly ash at curing times of 7 and 35 days are shown in Figures 4a and 4b, respectively. Figure 4b, shows the formation of an unidentified crystal on the sample with 35 days of curing time. Further tests are underway to help identify these crystals. The presence of these crystals could be partly responsible for the observed decrease in the soil strength. This crystal growth could be related to the high sulfur content (>10%) of this CFBC fly ash, however more tests are necessary to confirm this statement.

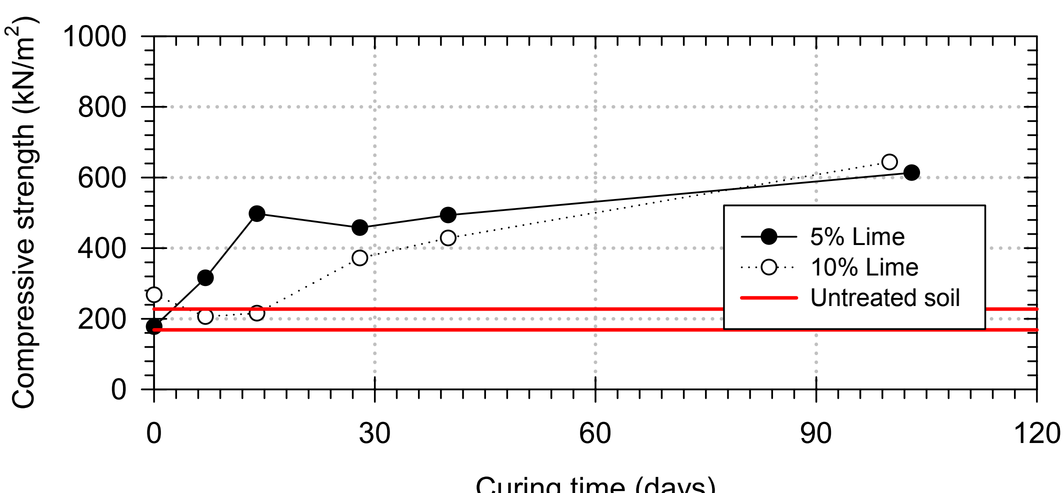
Strength values shown in Figure 3 indicate that in general all soil treatments were effective in increasing the strength of the samples with respect to the untreated soil. Strength improvement levels were observed to be highest for class C fly ash treated soils where most improvement was achieved with 20%. The soils treated with 5% and 10% lime showed similar strength values for curing timed beyond 30 days, however for short term curing periods (i.e., less than 30 days) the samples treated with 5% lime showed higher strengths than samples treated with 10% lime. Soils treated with CFBC fly ash showed the general trend of increasing strength with increasing admixture amount. Accordingly, the highest strength values were recorded for 20% CFBC fly ash.



a) Soil treated with CFBC fly ash

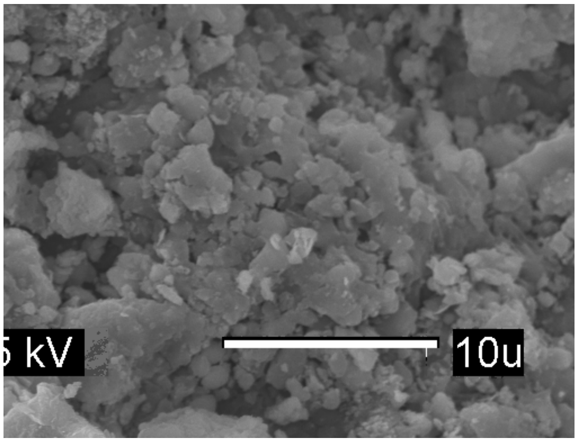


b) Soil treated with Class C fly ash



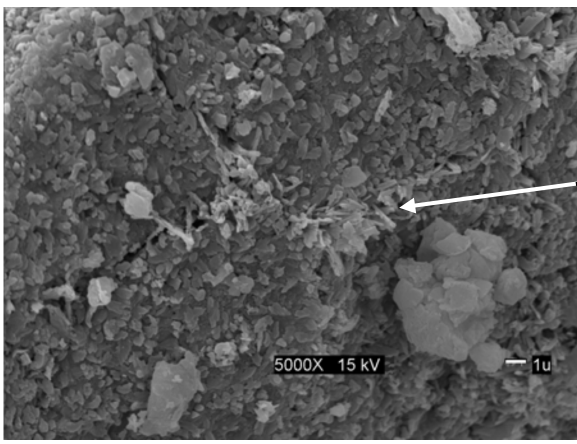
c) Soil treated with lime

Figure 3. Unconfined compressive strength development for stabilized Hormiguero clay



Note: line equals 10 micrometers

a) Image of sample treated with 10 % CFBC fly ash and 7 day curing



Formation of crystals

Note: line equals 1 micrometer

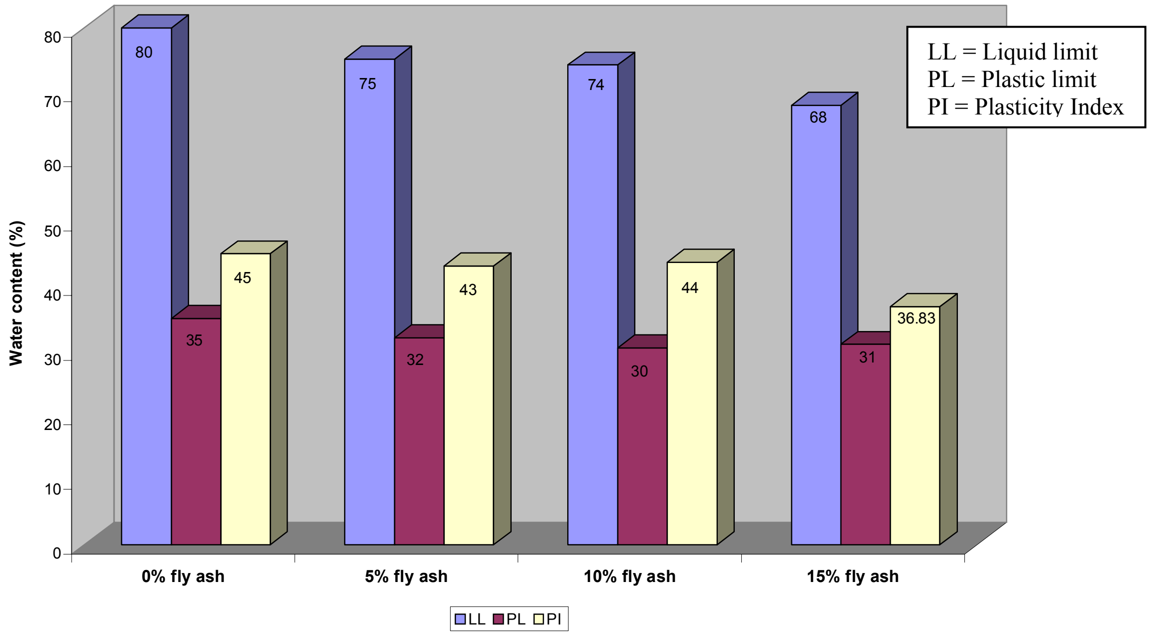
b) Image of sample treated with 10 % CFBC fly ash and 35 day curing

Figure 4. SEM image on a 10% AES fly ash with 7 days curing time

Effect of curing time on plasticity properties

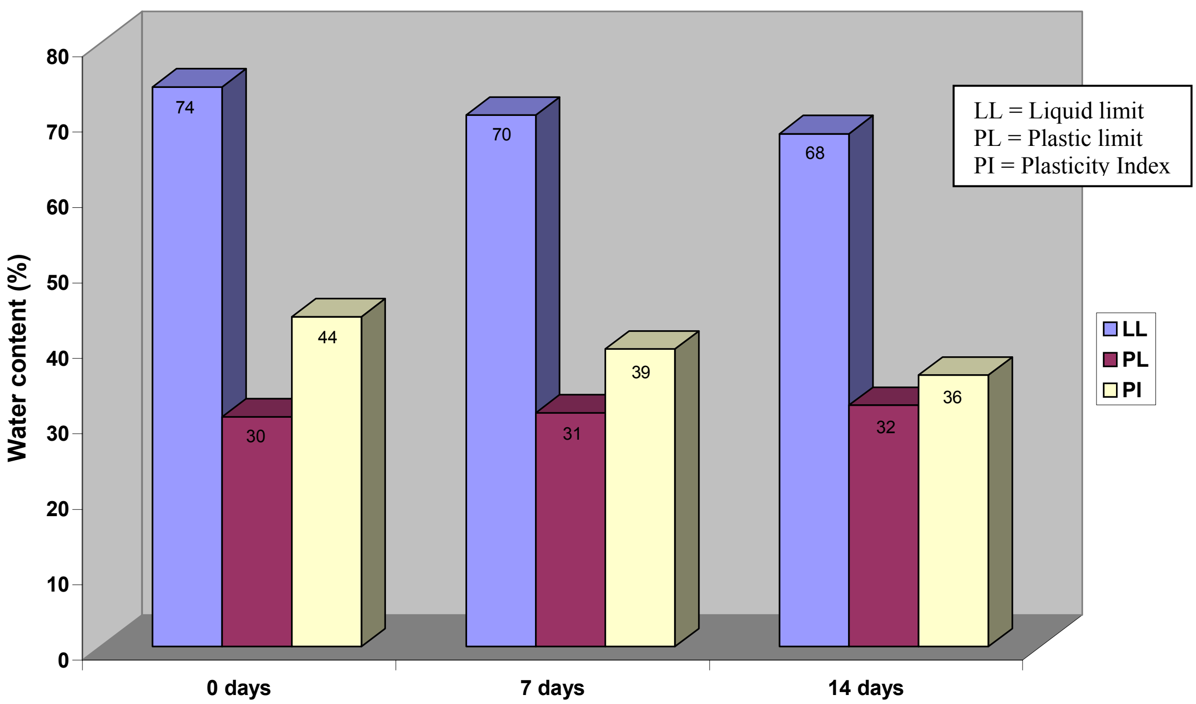
Possible changes in plasticity of the treated soils were investigated by measuring Atterberg limits of samples with different treatment levels and curing ages for CFBC fly ash. Figure 5 shows the Atterberg limits measured on soil samples treated with 5, 10 and 15 percent of CFBC fly ash.

Figure 5 indicates that the amount of CFBC fly ash used to treat the Hormigueros clay can have a significant impact on the plasticity of the treated soil. For example, an addition of 15 percent of CFBC fly ash resulted in decreases of the Liquid limit, Plastic limit, and Plasticity Index of 12, 4, and 9 percentage points, respectively. These results correspond to samples tested immediately after compaction, i.e., with no curing time. The effect of curing time on the plasticity of the samples was also investigated and the results are summarized in Figure 6.



Note: All tests carried out on samples with no curing time

Figure 5. Effect of level of CFBC fly ash treatment on treated soil plasticity



Note: All tests carried out on samples with 10% CFBC

Figure 6. Effect of curing time on plasticity of samples treated with CFBC fly ash

Figure 6 shows the Atterberg limits obtained from clay samples treated with 10% CFBC fly ash and curing periods of 0, 7, and 14 days. Increasing curing time seems to result in a decrease of the Liquid limit and an increase of the Plastic limit. For the clay treated with 10% CFBC fly ash a 14 day curing period resulted in a decrease of the Liquid limit of 6 percentage points and an increase of the Plastic limit of 2 percentage points. This translates into a net reduction of the Plasticity Index of 8 percentage points. The reduction of plasticity with curing time is probably related to the hydration process which is most active in the first 14 days of curing.

CONCLUSIONS

This paper 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 indicate that clayey soils treated with CFBC fly ash result in adequate 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. In general, 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 (except samples with 5% CFBC) a temporary drop of strength was observed between curing ages of 14 and 40 days. SEM microscopy on CFBC treated soils at 40 days of curing revealed growth of an unidentified crystal that could possibly be responsible for this temporary strength loss. The influence that the high sulfur content (12.57%) of this CFBC ash could have on the observed strength loss is being investigated. Strength values on CFBC treated samples with curing periods beyond 40 days showed a strength gains to similar levels as observed within the initial 14 day curing period.

Plasticity of soil samples was found to decrease with CFBC treatment. The level of plasticity decrease was more noticeable as the amount of CFBC increased and with increasing curing time.

The results obtained from this laboratory program seem to suggest that CFBC may effectively improve soft clays. However due to the scarcity of published data or well-documented case histories it is recommended that actual field implementation be based on a similar laboratory test program using the site specific soil and proper engineering judgment.

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