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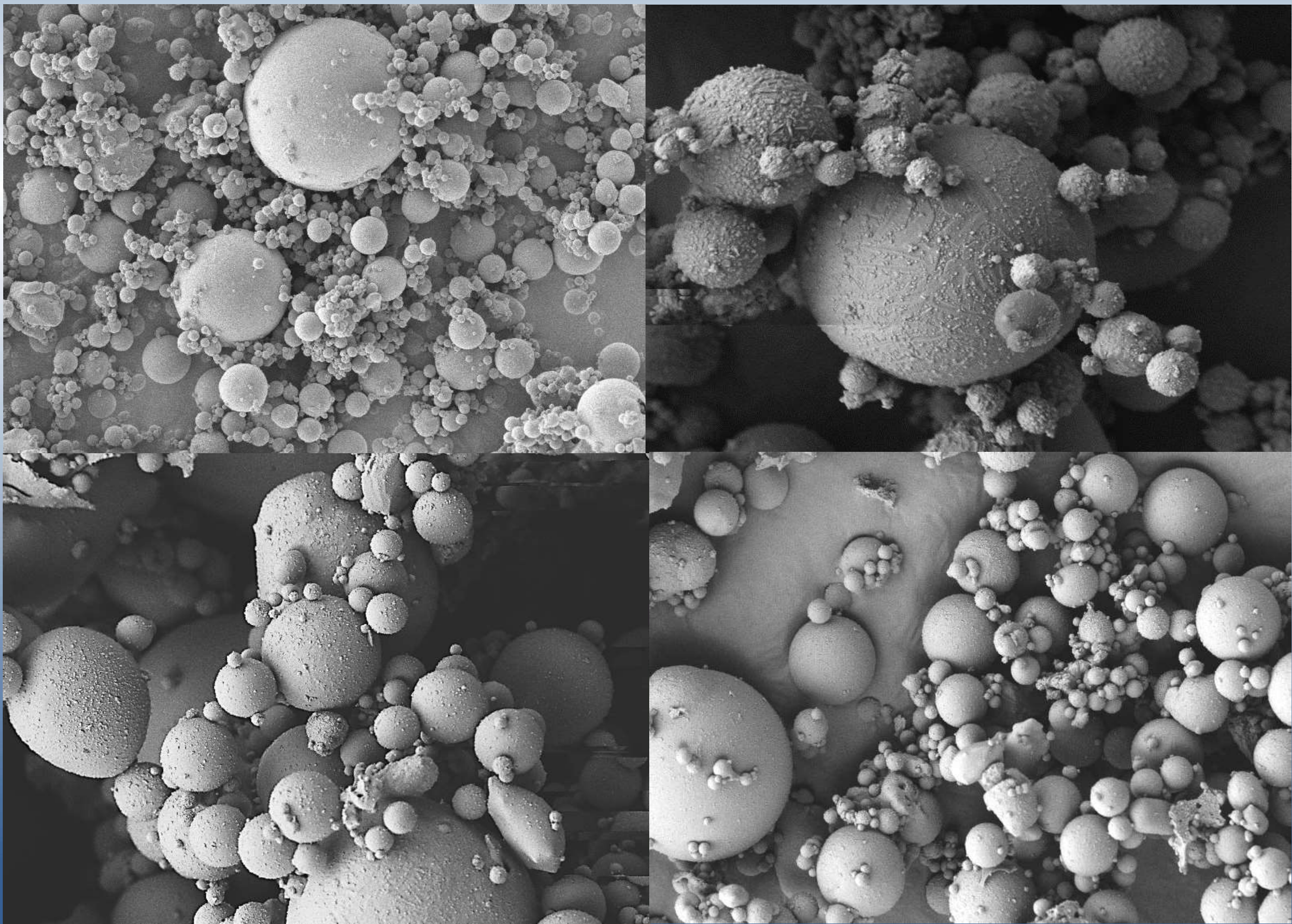

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MECHANICAL PROPERTIES OF CALCAREOUS FLY ASH STABILIZED SOIL

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ABSTRACT. Construction of any type of structure on clayey ground could be problematic due to the high swelling potential and/or low strength characteristics of the soil. This can lead to low stability or differential settlement of the ground. Many soil stabilization techniques have been proposed to prevent the uneven settlement and failure of the soil. Stabilization of soil with class C fly ash offers many advantages such as improving engineering characteristics, being cost-effective and being environmentally friendly. Class C fly ash chemically reacts with clay which results in a more durable and stronger soil. It has been shown by various researchers that fly ash-stabilized soil is typically stiff and strong even though there is no available standard or guidelines for the use of fly ash in construction industry. This paper presents the results from a program of experimental research on stabilization of a fine-grained soil with fly ash. Laboratory experiments, including Atterberg limits, compaction, uniaxial, and consolidation tests, were conducted on samples of a clay soil with different percentages of fly ash. The results show that adding fly ash decreased the plasticity index, increased compressive strength, and decreased the swelling and compressibility index. The maximum dry density increased and optimum moisture content decreased with addition of over 5 % fly ash by dry weight of the soil.

Keywords: Class C fly ash, Clay, Soil stabilization, Laboratory tests

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INTRODUCTION

Fine-grained soils are generally weak and their stability is low under heavy loading [1]. Traditionally, this type of soil is considered too incompetent for construction and in many cases is entirely replaced with soil with better properties. However, this solution is not only expensive and time-consuming but it is also a difficult task. Many soil stabilization techniques have been proposed to improve the characteristics of fine-grained soils. These techniques can be categorized into the 3 groups; mechanical stabilization, chemical stabilization, and geo-synthetic stabilization [2].

Several mechanical stabilization techniques have been proposed to improve the properties of fine-grained soils, especially problematic clayey soils. However, it has been found that there is also need to alter the physicochemical characteristics of clay to provide permanent stabilization [3]. Chemical stabilization involves the utilization of chemical binders to improve the properties of soils. Chemical stabilization is an effective method due to its ease of adaptability [4]. After the chemical reaction of soil particles and the chemical additives, strong bond is created between soil particles, improving the soil structure [5].

The most commonly used chemical binders in soil stabilization are lime and cement [6]. Many waste materials are also used as the alternative materials for the stabilization such as fly ash, bottom ash, and rice husk ash, owing to the many environmental benefits [3].

Fly ash is a waste material obtained from burning of coal and generated from thermal power plants [7]. The use of fly ash for soil stabilization is encouraged by many researchers based on understanding of its effective characteristics such as pozzolanic reactions, ease of adaptability and economic viability and many other benefits [8].
Fly ash has been generally utilized in subbase or base layers of road construction, railway or highway embankments, and as an aggregate or mineral filler in the construction industry [9].

The advantages of using fly ash are:

- The amount of coal fly ash in the world is estimated at approximately 500 million tonnes annually. At present, a large amount of ash is still discarded into landfills [9]. Thus, the use of fly ash in geotechnical projects can decrease the disposal costs of fly ash.
- The disposal of considerable amounts of fly ash creates huge environmental problems, such as, air, surface water and ground water pollution due to the leaching of its heavy metals to underground water, surface and deep soil. In addition, fly ash disposal in ponds or sea can create significant damage to aquatic life [10].
- The use of fly ash in soil stabilization can help to reduce CO_2 emissions. If fly ash is used for soil stabilization instead of cement, CO_2 emissions could be significantly reduced [11].
- Fly ash stabilized soil is an effective material for geotechnical applications [12].

From the geotechnical point of view, the advantages of using fly ash in construction industry are:

- Significant decrease in swelling-shrinkage and plasticity potential of high plasticity soil [13].
- Improvement in compressive and tensile strength, and bearing capacity of fine-grained soils [7].
- Better performance under ‘wet and dry cycles’ based on durability tests [10].
- Decrease of permeability and improvement of transfer properties of soils [9].

In this paper, the effects of fly ash in improving the mechanical properties of a clayey soil is investigated through a program of laboratory tests. The liquid limit and plastic limit, compaction characteristics, and strength, and swelling behaviour are presented for different fly ash contents.

LITERATURE REVIEW

Laboratory and field studies have been carried out by many researchers to improve the understanding of the effects of fly ash in improving the properties of soils.

Phani Kumar and Sharma [14] assessed plasticity, strength, swelling potential, hydraulic conductivity, and compaction characteristics of a clayey soil stabilized with 0 %, 5 %, 10 %, 15 %, and 20 % fly ash. It was revealed that both plasticity index and swelling characteristics of the stabilized soil decreased by about 50 % with addition of 20 % of fly ash. With fly ash content beyond 20 %, there was no significant decrease in swelling potential. In addition, undrained shear strength increased by approximately 27 % with inclusion of 20 % fly ash. Based on compaction test results, it was concluded that the optimum moisture content decreased by about 25 % and the maximum dry unit weight increased by about 5 % with 20 % fly ash inclusion. The results from variable-head permeability tests revealed that the hydraulic conductivity decreased with the inclusion of fly ash. Cokca [15] studied the effects of 3 stabilizers, including high calcium and low calcium class C fly ash, lime, and cement, on the swelling potential of an expansive soil. The amounts of lime and cement used were at 0 - 8 % while amount of fly ash used was between 0 - 25 %. Both fly ashes were cured for 7 and 28 days. It was concluded that the plasticity index and swelling potential of all the stabilized soils decreased significantly. Furthermore, there was a remarkable decrease in swelling potential of fly ash stabilized soil from 7 to 28 days curing times. Prabakar et al [4] conducted a number of experiments with addition of different percentages of fly ash from 9 % to 46 % on different soil types. Compaction, shear strength, CBR, and swelling characteristics were evaluated on CL (inorganic clay with low plasticity), OL (organic soil with low plasticity), and MH (inorganic silt with high plasticity) soils. Based on the experimental results, dry density of all soil types reduced by between 15 % and 20 % by addition of the fly ash. The shear strength of the soils increased non-linearly with the addition of fly ash. Another important finding was that the swelling behaviour of the soils decreased due to the particle size, shape, and non-expansive structures of fly ash. Moreover, the CBR values of the soils improved with the addition of fly ash in comparison with the pure soil. Brooks [16] investigated the impacts of class C fly ash and rice husk ash on high plasticity clayey soil by conducting unconfined compressive strength (UCS), California bearing ratio, compaction, and swell-shrinkage tests. According to the UCS tests results, the failure stress increased about 106 % with the addition of 25 % fly ash, although the stress decreased with adding over 25 % of fly ash. The swelling potential of the stabilized soil also decreased in consolidation tests. It was recommended that 12 % of rice husk ash or 25 % of fly ash are the best ratios for stabilization of the clayey soil.

In general, there is some evidence from laboratory and field tests indicating that the use of fly ash can be effective in stabilization of soils. The main benefits of using fly ash for soil stabilization include improvement in compressibility and strength, and decrease in the swelling behaviour.

This paper presents some results from a comprehensive program of experiments to study the effects of fly ash and alkali activators in improving the mechanical properties of a clay soil.

The experiments include Atterberg limits, compaction, uniaxial compressive strength, and consolidation/swelling tests on samples stabilized with different fly ash contents. In what follows the results from some of the experiments are presented and discussed. This is an ongoing project and more results will be available and presented at the conference.

MATERIALS AND METHODS

Soil

The soil used in this study was kaolinite, China clay. Its properties are presented in Table 1.

Scanning electron microscopy (SEM) analysis was also carried out on pure kaolinite with different magnification factors (Figure 1). The results show that the kaolinite has a flat structure.

Table 1 Kaolinite clay properties

GEOTECHNICAL PROPERTIES OF KAOLINITE	
Cone penetrometer	
Liquid limit (%)	54
Plastic limit (%)	27.15
Liquidity index (%)	26.85
Classification	CI-CH
Specific gravity (g/mL)	2.6
Maximum dry unit weight γ_{dmax} (kN/m^3)	1.51
Optimum moisture content w_{opt} (%)	21

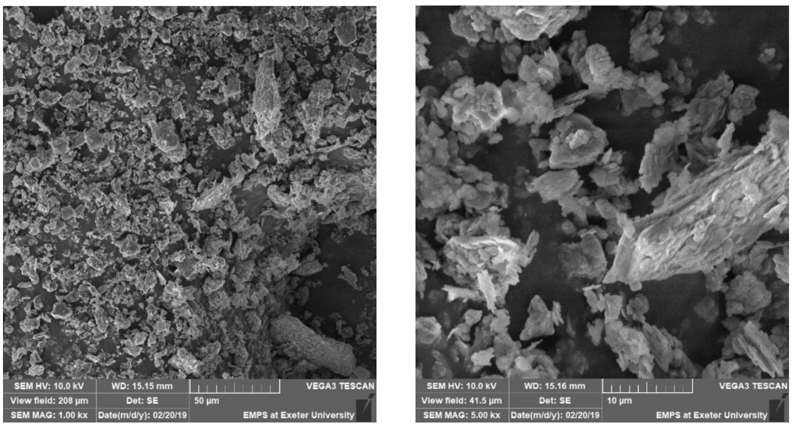

Figure 1 SEM images of pure kaolinite with 50 µm and 10 µm magnification factors

Fly Ash

The fly ash used in this study was obtained from the MUEG Company in Germany. Its chemical composition is presented in table 2. The fly ash has 32.4 % CaO (high calcium content) and is classified as a class C fly ash according to ASTMC 618 standard.

SEM analysis was carried out on the pure fly ash with different magnification factors (Figure 2). It is seen that the morphology of fly ash is spherical.

Table 2 Fly ash chemical compositions

PARAMETERS	AVERAGE	MINIMUM	MAXIMUM
SiO_2 (%)	28.3	16.3	40.4
CaO (%)	32.4	23.7	43.2
Fe_2O_3 (%)	6.6	3.7	10.8
Al_2O_3 (%)	15.8	8.2	22.5
K_2O (%)	0.5	0.3	0.9
MgO (%)	4.2	2.5	6.6
Na_2O (%)	0.31	0.19	0.76
P_2O_5 (%)	0.72	0.38	1.26
SO_3 (%)	8.6	5	13.2
TiO_2 (%)	0.9	0.5	1.5

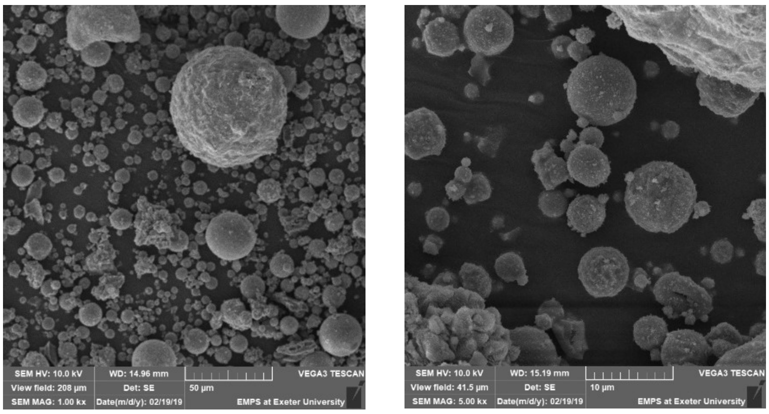

Figure 2 SEM images of pure fly ash with 50 µm and 10 µm magnification factors

EXPERIMENTAL PROGRAM

The program of experiments included Atterberg limit tests, compaction tests, unconfined compressive tests, and consolidation tests.

Atterberg Limit Tests

Atterberg limit tests were conducted on fly ash stabilized soil with 0 % to 30 % fly ash to determine the liquid limit, plastic limit, plasticity index of the soil based on the British standard (BS 1377-2).

Compaction Tests

Standard Proctor (compaction) tests were carried out to determine the dry density and moisture content relationships of the fly ash stabilized soil. Compaction tests (BS 1377-4) were applied using 2.5 kg rammer and 1 L compaction mould. For the tests, dried kaolinite powder (China clay) was mixed with different percentages of fly ash binder considering dry weight of the soil as the first step. After that, water was added to obtain a homogenous mixture which was then left for one day in a sealed bag to allow for the uniform absorption of water into the soil.

Compaction tests were conducted with different percentages of fly ash;
Control sample (pure kaolinite), 5 % of fly ash + soil, 10 % of fly ash + soil, 15 % of fly ash + soil, 20 % of fly ash + soil, 25 % of fly ash + soil, and 30 % of fly ash + soil.

Unconfined Compressive Tests

For the strength tests, specimens of the fly ash stabilized soil were prepared by static compaction in layers in an Instron 3382 Floor Model Universal Testing System which provides a constant loading up to a specified load. The prepared specimens were 50 mm in diameter and 100 mm high. The samples were also sealed and cured for 1 day.

Consolidation Tests

One-dimensional consolidation tests were conducted in oedometer to evaluate swelling and compressibility indices of the fly ash stabilized soil with 0 %, 15 %, and 25 % fly ash and with 1 day curing time. The volume change of the sample against time was recorded during the oedometer tests. The results showed that there was no considerable volume change after 24 hours. Thus, each stage of the consolidation test was conducted for 24 hours. The loading was sequenced in the order of 100 kPa, 200 kPa, 400 kPa, 800 kPa, 400 kPa, 100 kPa. The loading stage was done to determine the compression index, while the unloading stage was conducted to determine the swelling index.

PRELIMINARY RESULTS

Atterberg Limit Tests

The results of plastic limit and liquid limit tests are presented in Figure 3. Plasticity index was calculated as the difference between liquid limit and plastic limit. The value of plasticity index is a critical indicator of the swelling characteristics of the soil; the lower the plasticity index value, the less is the swelling potential [17]. It is seen that the plasticity index of clay (and the potential of swelling) decreased with the addition of fly ash. In this way, it could be said that the potential of swelling also decreased. According to the plasticity chart, the classification of the soil changed from CH to ML with addition of 25 % fly ash.

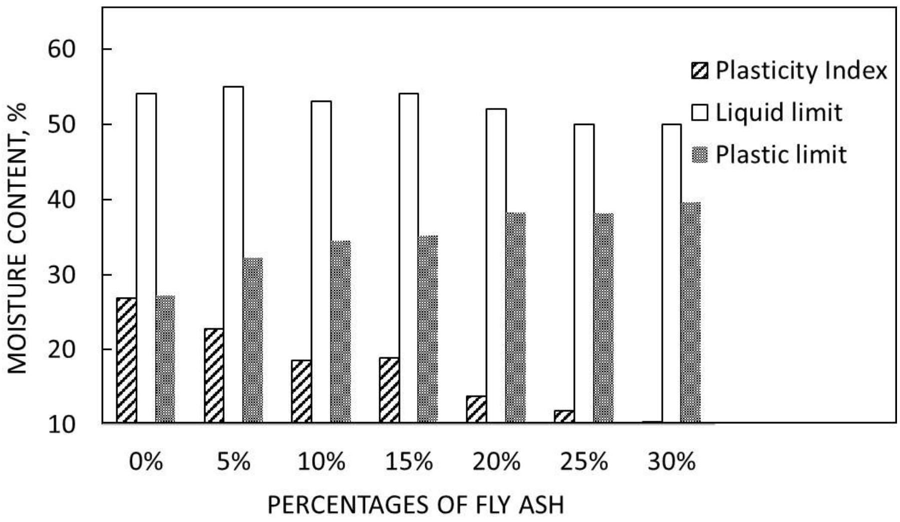

Figure 3 Consistency limits of fly ash stabilized soil

Compaction Behaviour

Table 3 and Figure 4 demonstrate optimum moisture content and maximum dry density relationships for the soil stabilized with different fly ash contents. It is seen that the maximum dry density initially decreased at 5 %. The initial decrease may be caused due to the difference of the particle density between kaolinite and fly ash. However, there was a gradual increase with addition of fly ash, from 5 % to 30 %. This may be due to the fly ash particles starting to fill the voids of kaolinite resulting in higher density. Nonetheless, the mixtures, up to 15 % of fly ash, still had a lower density than pure kaolinite. The optimum moisture content increased with 5 % of fly ash, thereafter, it generally decreased with further increase in fly ash content. This could be due to chemical reactions starting with enough fly ash that leads to excess heat and loss of water.

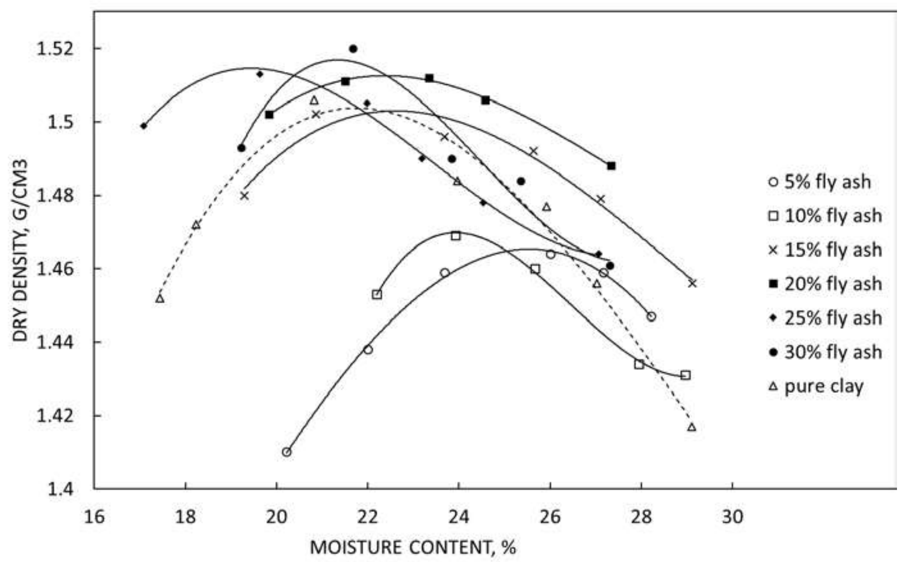

Figure 4 Compaction curves of the fly ash stabilized soil

Table 3 Compaction properties of the fly ash stabilized soil

Properties	0%	5%	10%	15%	20%	25%	30%
Optimum moisture content (%)	21	25.5	24	23.5	22.5	19.8	21.5
Maximum dry density (g/cm^3)	1.51	1.464	1.47	1.502	1.512	1.513	1.518

Unconfined Compressive Strength Tests

The effects of fly ash on improving the strength of the stabilized soil with different percentages of fly ash are shown in Figures 5 and 6. The results of the UCS tests show a gradual increase in peak compressive stress of 226, 237, 242, 254.2, 270.7, 275, and 294.5 kPa with one day curing with addition of 0, 5, 10, 15, 20, 25, and 30 % fly ash, respectively. The values of the elastic modulus of the soil were obtained from the gradient of the linear-elastic part of stress-strain curves and they were 9.5, 16.7, 20.5, 19.1, 22.8, 22.1, and 25.1 MPa for 0, 5, 10, 15, 20, 25, and 30 % fly ash, respectively.

The results of the UCS test demonstrate that class C fly ash improved the strength of the soil. The fly ash was found to be an effective stabilizing material owing to its pozzolanic and cementitious characteristics.

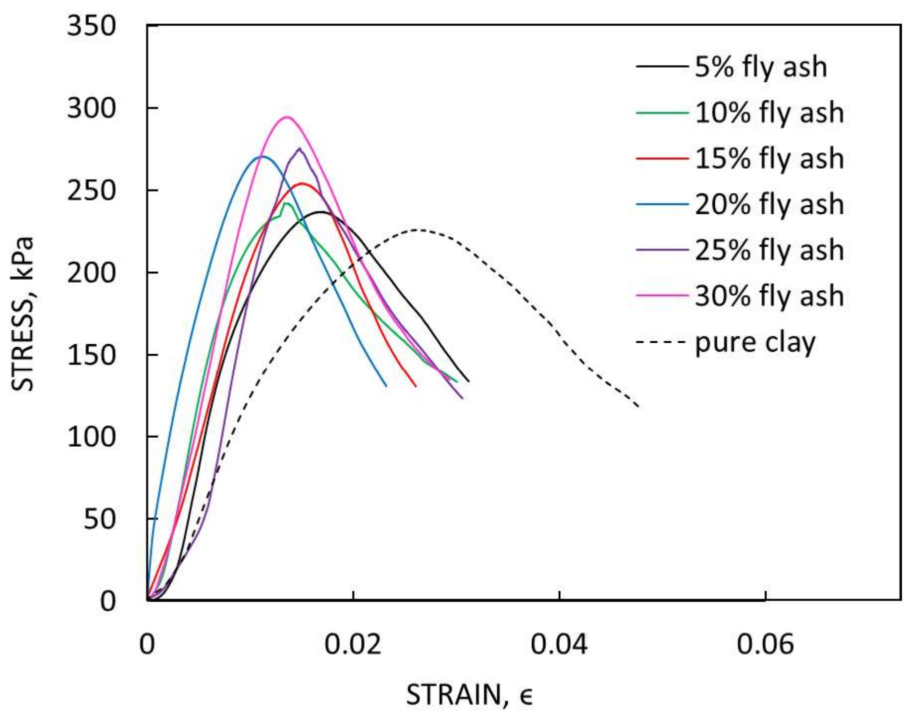

Figure 5 Stress-strain relationships of fly ash stabilized soil

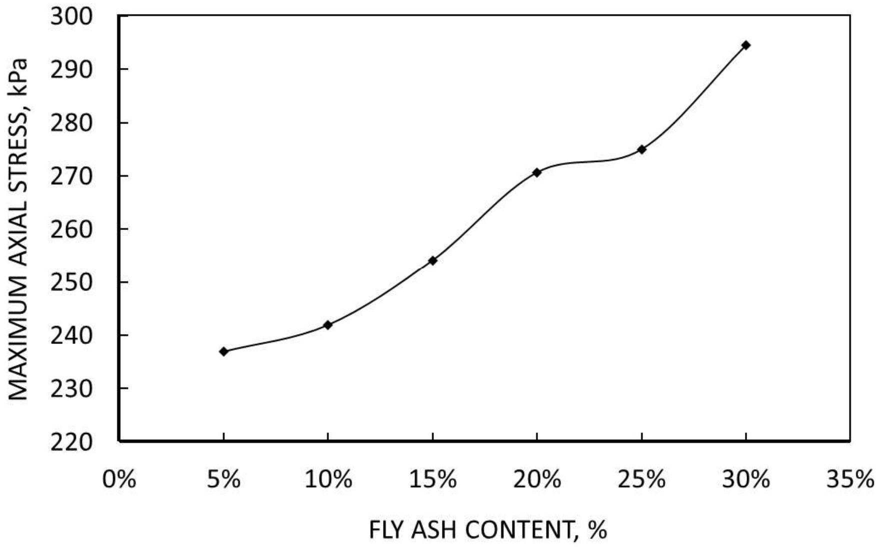

Figure 6 Effects of fly ash content on unconfined compressive strength of the soil

Consolidation Tests

Stabilization of the soil with 15 % and 25 % fly ash showed a decrease in compressibility, indicating lower rate of settlement in the soil compared to the unstabilized soil (Figure 7). The reason of decrease in Cc and Cs values could be that the fly ash and soil particles compact well due to the morphology of the soil and fly ash.

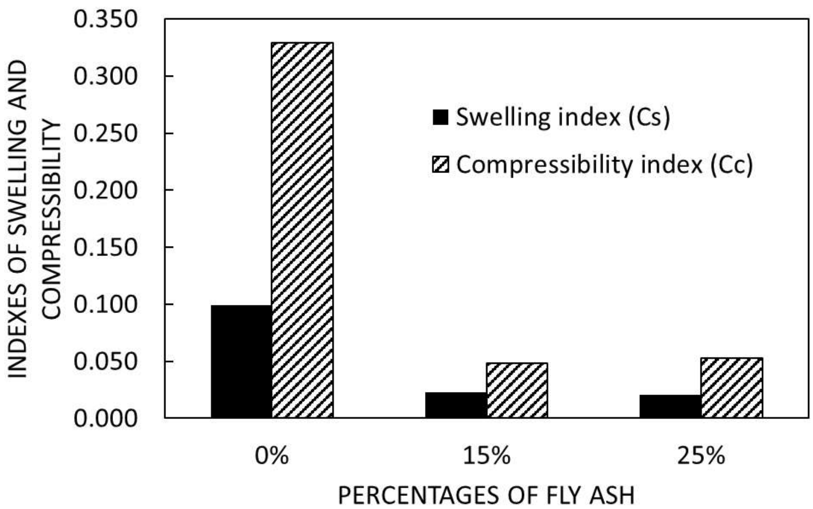

Figure 7 Compression and swelling indices of pure clay and fly ash with 15 % and 25 %

CONCLUSIONS

In this paper, the effects of consistency, swelling and strength characteristics of class C fly ash with one day curing period were determined. The following conclusions can be drawn from the results:

- The values of the plasticity index decreased with inclusion of fly ash.
- The maximum dry density of the soil decreased with addition of 5 % fly ash, and thereafter increased. The optimum moisture content increased with 5 % of fly ash, and showed a decrease with further increase in the fly ash content.
- Unconfined compressive strength of fly ash stabilized soil with 1 day curing time increased gradually with increasing the fly ash content.
- Swelling and compressibility indices of fly ash stabilized soil generally decreased.

These findings show that fly ash would be an effective method for decreasing swelling potential and increasing strength parameters of soils.

The results presented here are part of a large program of research on the effects of fly ash and alkali activators on the mechanical behaviour of fine grained soils.

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