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Effect of fly ash on the behaviour of a high plasticity clay

Effect des cendres volantes sur le comportement d'une argile de haute plasticité

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ABSTRACT: Artificial cementation of clays has been studied and applied in soil improvement using various methods and techniques for several years. Although considerable work has been done to develop advanced machinery and techniques for the implementation of artificial cementation, less knowledge is available on the mechanisms involving the formation of the artificial structure and the resulting mechanical behaviour by mixing a low cost binding agent as fly ash to a soft soil. The primary objectives of this research were to investigate the formation of microstructure in artificially cemented clay materials of high plasticity, by using Ptolemais type C fly ash as the main binding agent without using lime or cement as the second additive for quicker development of pozzolanic reactions within the soil matrix. A large number of laboratory soil tests on mixtures with varying fly ash content and curing time was also performed as well as the determination of relationship between cementitious bonding and the mineral composition of clay. The engineering properties measured, included strength and compressibility properties; while the microstructure was investigated by Polarised Light Microscopy (PLM) analysis.

RÉSUMÉ: La cimentation artificielle des argiles a été étudiée et appliquée dans l'amélioration du sol en utilisant diverses méthodes et techniques depuis plusieurs années. Bien que des travaux considérables aient été réalisés pour mettre au point des machines et des techniques avancées pour la mise en œuvre de la cimentation artificielle, on dispose de moins de connaissances sur les mécanismes impliquant la formation de la structure artificielle et le résultat comportement mécanique en mélangeant un agent de liaison à faible coût comme cendres volantes à un sol mou. Les principaux objectifs de cette recherche étaient d'étudier la formation de microstructures dans des matériaux argileux cimentés artificiellement de haute plasticité, en utilisant des cendres volantes de type C Ptolémaïs comme agent de liaison principal sans impemation de chaux ou de ciment comme on le voit dans littérature pour un développement plus rapide des réactions pouzzolanique dans la matrice du sol. Un grand nombre d'essais de sol en laboratoire sur des mélanges à teneur variable en cendres volantes et en temps de durcissement a également été effectué, ainsi que la détermination de la relation entre la liaison cimentaire et la composition minérale de l'argile. Les propriétés d'ingénierie mesurées comprenaient les propriétés de résistance et de compressibilité; alors que la microstructure a été étudiée en polarisant l'analyse par microscopie photonique (PLM).
Keywords: fly ash; soft soil; compressibility; soil improvement; artificial cementation

1 INTRODUCTION

Artificial cementation is used in civil engineering practice as an effective method to improve the behaviour of soft soil sites with low shear strengths and high settlements. Many additives such as lime, cement, fly ash and different chemicals are being used for the stabilization of these soils. The term ‘fly ash’ is often used to describe any fine particulate material precipitated from the stack gases of industrial furnaces burning solid fuels. The amount of fly ash collected from furnaces on a single site can vary from less than one ton per day to several tons per minute. The characteristics and properties of different fly ashes depend on the nature of the fuel and the size of furnace used.

The quantity of fly ash produced is a function of several factors. The parameters more likely to affect the engineering and physical properties of fly ash are free lime and unburnt carbon. The former influences the age of hardening of fly ash when it is compacted, while the latter influences its compaction and strength characteristics. ASTM C 618 categorizes coal combustion fly ash into two classes: Class F and Class C. The Class F fly ashes are normally generated due to combustion of anthracite or bituminous coal. The Class C fly ashes are produced due to burning of lignite or subbituminous coal. Therefore, Class C fly ashes are classified as cementitious and pozzolanic admixtures/additives and Class F fly ashes as normal pozzolans for use in concrete.

2 SCOPE OF INVESTIGATION

Since fly ash is a waste material from thermal power plants and shows pozzolanic characteristics, it is valuable to use fly ash for stabilization where easily and economically available. An experimental program was conducted to evaluate the effect of fly ash (class C) as the main binding agent on the plasticity, consolidation, compressibility characteristics as well as the unconfined compression strength of a high plasticity clay for different amounts of fly ash and various curing periods up to 720 days of specimen curing.

Also a microlevel investigation was carried out using Polarised Light Microscope (PLM) in order to elucidate the stabilization mechanism and the formation of microstructure within the specimen matrix.

3 MATERIALS AND METHODOLOGY

3.1 Materials used

The clay used for this study was collected from clay pits and piled excavated clay in Agios Stefanos, an area on the east side of Attiki. More specifically this clay is used for brick production for the local ceramic facility “Flessiopoulos”.

Table 1. Properties of Agios Stefanos clay

Properties	Value
Liquid Limit, LL (%)	72
Plastic Limit, PL (%)	26
Plasticity Index, PI (%)	46
In-situ Moisture Content., w (%)	31
Liquidity Index, I_L	0.11
Initial Void Ratio, e_o	2.29
Specific Gravity, G_s	2.78
Grain Size Distribution:	
Sand (%)	8
Silt (%)	23
Clay (%)	69
Wet Unit Weight, γ_{sat} (kN/m^3)	15.1
Dry Unit Weight, γ_d (kN/m^3)	8.4

On the basis of its mineralogical composition, the clay sample was characterized by a generally high content in illite (approximately 20%-30%) and by low content in kaolinite, chlorite and montorillonite. High contents in carbonate minerals were also found in the pits where the clay sample was collected with a mean value of 17.1%. The content in organics lied between 1.5% to 4%. The basic properties of the Agios Stefanos clay are summarized in Table 1.

In Greece, most lignite deposits are located in the Florina – Ptolemais – Kozani basin, a large intensively exploited area, in northern Greece. This area is exploited by open-cast mining and feeds nearby lignite – fired power stations. The Greek fly ash which is produced at the electrical power stations of Ptolemais belongs to type C fly ash. The type C Ptolemais fly ash has high lime content (10%-35%), it is both pozzolanic and cementitious and presents hydraulic attributes.

The particle size distribution of Ptolemais fly ash is similar to that of silt (less than a 0.075 mm or No. 200 sieve). The specific gravity of Ptolemais fly ash is 2.3, while its specific surface area may vary from 170 to 1000 m^2/kg. The colour of fly ash can vary from tan to grey to black, depending on the amount of unburned carbon in the ash.

3.2 Specimen preparation

A wide range of six different mix proportions were used in this study. Untreated clay of Agios Stefanos area was prepared from its natural wet state without pre-dying. Lee et al. (2005) noted that the pre-drying causes largely irreversible changes to the Atterberg's limits of the clay, which are indicated of chemical changes. The selected additive, i.e. fly ash of Ptolemais, was finely pulverized into a powder (oven drying and passing Sieve No. 40), in order to create a uniform bond with the soil matrix.

For a given binding agent content, the shear strength of the treated soil depends on the total clay water content. There exists an optimum clay water content at which the shear strength is the maximum (Lorenzo et al., 2004).

In order to determine the optimum clay water content for the six fly ash treated samples, experiments were conducted for water contents ranging from 1.1 to 1.6 times the liquid limit of the untreated clay depending on the fly ash amount added to the soil-water mixture. Additionally, the fly ash content is defined by the ratio of the weight of the fly ash to the weight of natural clay and the amount of water used for the specimen preparation, expressed as a percentage. Soil-fly ash mixtures were prepared from the slurry clay and powdered fly ash.

The procedure for mixture preparation is similar to that described by Chew et al., (1997). The prescribed amount of water was first added to the clay and mixed thoroughly by a large scale mixing machine to obtain clay slurry with water content of 82% to 115%. Fly ash was then added slowly to achieve a uniform mixing. A range of 4% to 25% of fly ash was added to the water-soil slurry (Table 2). All mixing was done within 15 min to avoid loss of the final water content through the hardening process of the clay-fly ash mixture.

The treated mix was then placed in a stainless steel type rigid walled mould measuring 150mm diameter and 120mm height. The bottom end of the mould was covered by a metallic perforated plate to allow the trapped air and excessive water to escape during the pre-consolidation stage and curing period. Filter papers were placed on both ends of the mould.

After the mixture preparation and its placement on the metallic prefabricated mold, a 50kPa constant vertical load was applied on the mixture in order to stabilize the mixture, allow the trapped air in the soil-fly ash matrix to escape and enhance the homogeneity of the mixture. When the pre-consolidation stage was over, the treated clay with the metallic mold were placed in a bath tab full of distilled water for curing time of 28 days. Then, the treated clay was extracted from the metallic mould, carefully wrapped and placed in a constant humidity chamber ready to be used for oedometer and triaxial specimen formation. One specimen was compacted without any additives for the purpose of comparison with the treated specimens.

Table 2. Fly ash – Agios Stefanos clay mixtures

Mixture	**Fly ash content (%)**	**Initial water content of mixture before pre-consolidation and curing (%)**
1	4	82
2	6	85
3	8	87
4	10	90
5	15	95
6	25	115

3.3 Experimental program

The current study consisted of laboratory tests as follows, investigating the improvement of physical and mechanical properties due to the existence of fly ash (Class C) as the binding agent and the influence of curing time for each mixture:

i. Oedometer consolidation tests: to determine the consolidation characteristics of the treated and untreated clay. For six fly ash contents between 4% to 25% at curing periods of 28, 56, 112, 224 and 365 days. A comparison of the results of the fly ash treated specimens was made with the untreated specimen.

ii. Unconfined compression tests: mainly to determine the variation of strength of the improved clay with the addition of six different fly ash contents from 4% to 25% for curing periods of 28, 56, 84, 112, 168, 224, 365 and 720 days. A comparison of the results of the fly ash treated specimens was also made with the untreated specimen.

iii. Polarised Light Microscopy (PLM) analysis: to examine the microsructure of fly ash-clay mixtures with 10%, 15% and 25% fly ash content as well as to compare the results with the microfabric of the untreated clay.

4 TEST RESULTS AND DISCUSSION

4.1 Oedometer consolidation tests

In this study, a set of three manual oedometers was used to run the consolidation tests for the six mix proportions of fly-ash treated clay as well as the untreated clay. For the consolidation curves shown in $e\text{-}\log\sigma'_v$ relationship, an incremental loading ($\Delta p/p=1.0$) of vertical stresses of 12.5kPa up to 3200kPa was applied as well as unloading of the specimen.

Figures 1 – 5 show the $e\text{-}\log\sigma'_v$ relationship of untreated and treated clay samples. Test results show that the pressure of 50kPa, which was initially applied to each mixture (pre-consolidation pressure) increases significantly when the fly ash content is ≤10% but always taking under consideration that fly ash is not a cement binder as strong as cement or lime. The aim of the study was to investigate the light improvement on mechanical properties of a high plasticity clay by adding a cement agent with low strength properties, like fly ash (Class C). The increase in yield stress of the untreated clay owing to the inclusion of fly ash were also observed by other researchers (e.g. Uddin et al., 1997, Miura et al., 2001). Test results also suggested that at low percentage of fly ash content (i.e. 4%, 6%), there was minimal cementation effect in the treated clay matrix. It seems to suggest that a certain amount of fly ash is required to complete the interaction between fly ash and clay in order to form the primary and secondary cementitious materials. The increase of pre-consolidation pressure is due to the effect of structuration (i.e. creation of cementation bonds) of treated clay particles.

At consolidation stress less that the respective pre-consolidation pressure of 50kPa, the initial void ratio of the treated samples increases with the increase of fly ash content. It is also found that the change of void-ratio is very small for the stress values less that the respective pre-consolidation pressure of 50kPa. This implies to the effect of structuration within the stress range after the initial application of 50kPa to the mixture and hence the behavior of the sample is found to be relatively ductile.

Furthermore, beyond the pre-consolidation pressure of 50kPa, the reduction of void ratio with the increase in consolidation pressure is noticeable for all values of fly ash content. This is due to the apparent destructuration (i.e. breaking of cementation bonds) of the treated clay matrix, when it is stressed beyond the pre-consolidation pressure. At this stage the effect of cementation bonding is minimum and the fabric of the treated clay plays a dominant role on the compressibility characteristics. Results also show that beyond the pre-consolidation pressure, the treated curves shifted parallel with the increase of fly ash content having higher void ratios. This leads to the conclusion that the yield surface and failure envelope of the treated clay increases with the increase of a cement binder content.

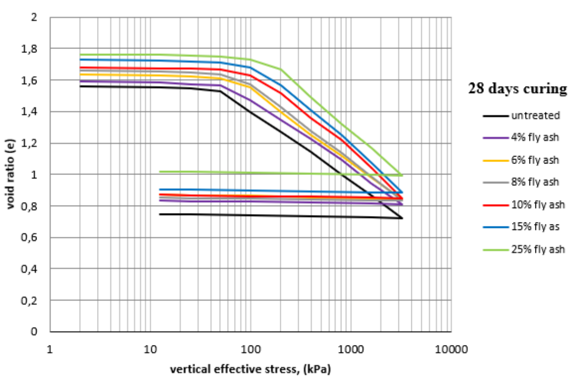

Figure 1. Void ratio- axial stress relationship for various fly ash contents at a curing time of 28 days

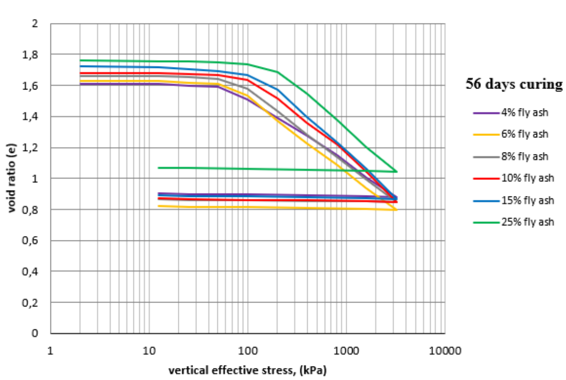

Figure 2. Void ratio- axial stress relationship for various fly ash contents at a curing time of 56 days

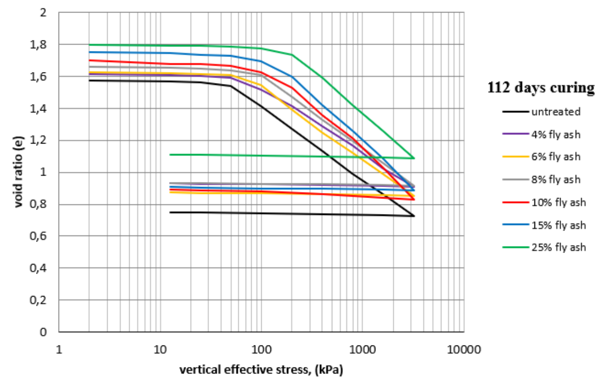

Figure 3. Void ratio- axial stress relationship for various fly ash contents at a curing time of 112 days

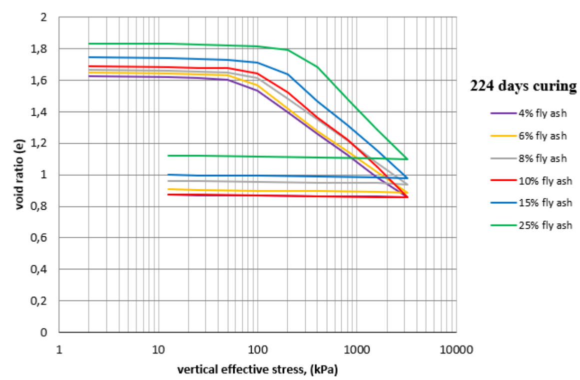

Figure 4. Void ratio- axial stress relationship for various fly ash contents at a curing time of 224 days

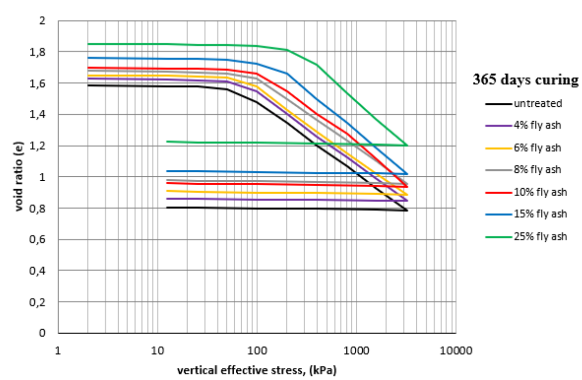

Figure 5. Void ratio- axial stress relationship for various fly ash contents at a curing time of 365 days

4.2 Unconfined compression tests

A wide number of unconfined compression tests were performed to establish a general trend for the gain in strength using fly ash as the main binding agent to a soft clay soil in different curing periods of time. The fly ash content varies from 4%-25%, while the curing periods vary from 28 days to 720 days.

As Figs. 6-8 show, even at very low fly ash content there is a level of increase in strength and stiffness which is evident. At low fly ash content, (i.e. ≥15%), ductile behavior is manifested, with the post-peak stress decreasing gradually with stain in the same manner similar to that exhibited by untreated clay. At higher fly ash content (i.e. 25%), the treated specimen becomes more brittle, with abrupt drops in the post-peak stress; which is more akin to that of highly structured or sensitive natural soils (Leroueil and Vaughan, 1990). This behavior is more consistent with the findings of many other researchers on different cement treated clays (e.g. Uddin et al., 1997; Miura et al., 2001).

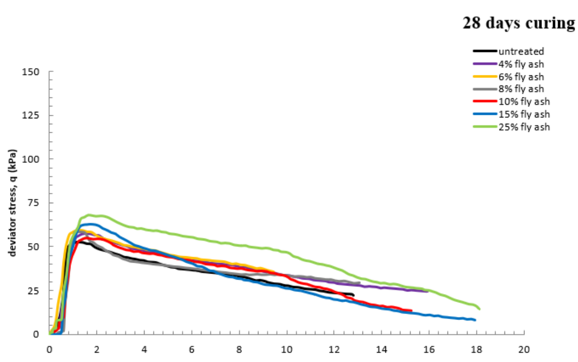

Figure 6. Effect of fly ash content on stress-strain behaviour of treated and untreated clay mixtures at a curing time of 28 days

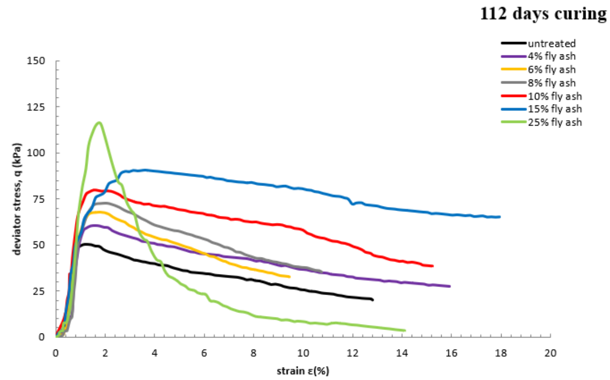

Figure 7. Effect of fly ash content on stress-strain behaviour of treated and untreated clay mixtures at a curing time of 112 days

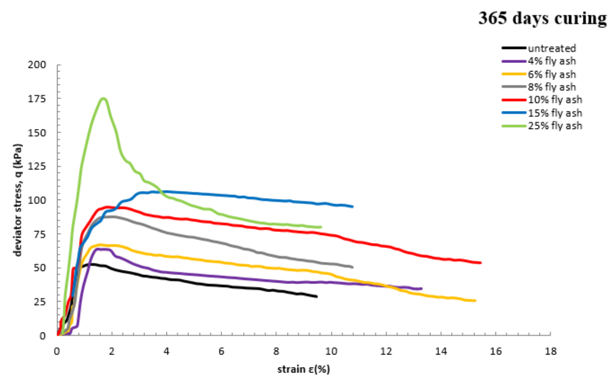

Figure 8. Effect of fly ash content on stress-strain behaviour of treated and untreated clay mixtures at a curing time of 365 days

The shear behavior of the treated soil in unconfined compression test up to the peak failure state depends on the cementation bond, and thus the shear behavior of pre-failure state is predominantly elastic in nature. The ductility is much more pronounced for mixtures with low fly ash contents at can been seen in Figs. 6-8. It is interesting to note that the behavior of fly ash treated clay at conventional 28 days curing periods and at prolonged curing periods (i.e. 365 days) is very similar to clay mixtures with fly ash not greater than 10% and quite different for clay mixture with fly ash content of 15%.

The formation of cementitious product due to the hydration and pozzolanic reaction increases with the increase of curing time, and thus the rate of development of strength also increases. This can be explained from the comparison of the development of strength both in short term as well as prolonged curing time as can been seen in Figure 9. Test results suggest that the pozzolanic reaction is very significant at prolonged curing time and even continues up to 2 years (720 days). This can be explained with the fact that at 720-day curing period, significant portion of Ca^{2+} ions diffuses within the treated clay matrix to permit the pozzolanic reaction. The difference in strength between 28 days and 56 days strength increases and after this curing period remains almost constant. Similar behavior is also observed in 224 days and 365 days strength at sample with fly ash content ≥15%. The notion can be explained with the fact that even at prolonged curing time, the rate of pozzolanic reaction does not increase for all ranges of fly ash content. Beyond a certain percentage of fly ash content, it is easier for calcium ions to be diffused within the treated clay matrix due to the power of cement particles to form stronger bonds, even at short term curing periods.

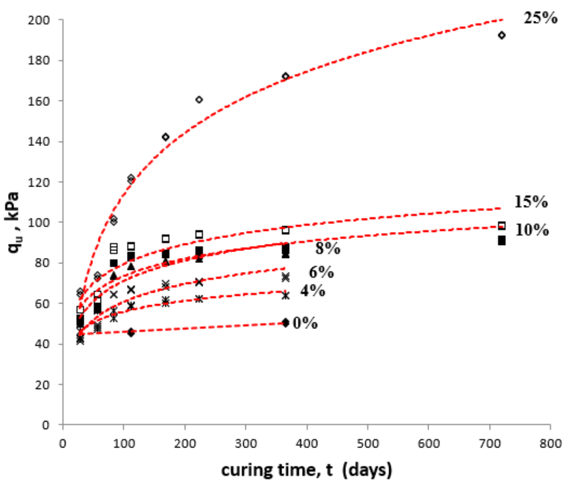

Figure 9. Effect of fly ash content on unconfined compressive strength of treated and untreated clay mixtures

4.3 Polarised light microscope (PLM) analysis

The PLM analysis has been carried out to study the microstructural effects of untreated clay and fly ash treated Agios Stefanos clay with the addition of 10%, 15% and 25% of fly ash of Ptolemais after a curing time of 365 days using a ZEISS Axio Scope.A1 Polarised Light Microscope at Institute of Geology and Mineral Exploration (I.G.M.E) in Athens, Greece.

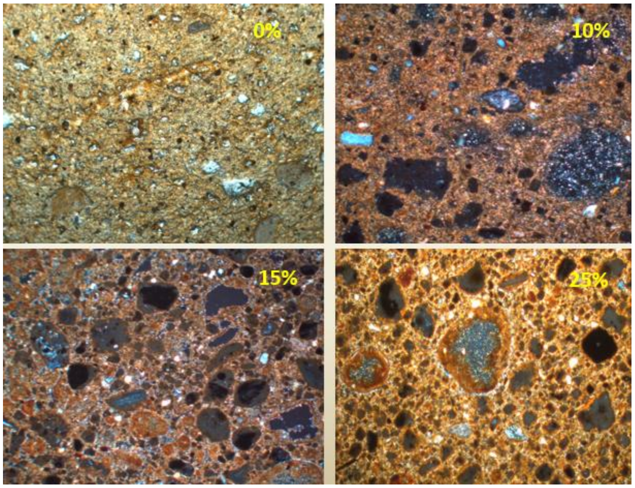

Figure 10. PLM images of fly ash treated and untreated clay mixtures

As shown in Figure 10, the micrograph of untreated clay reveals the existence of clay minerals and aggregates having a not homogeneous particle size with grain morphology from euhedral to anhedral and the mineralogical composition of tested untreated clay sample show the presence of abundant quartz, chlorite and oxides of iron.

The PLM analysis of 10% of fly ash treated clay exhibits a fairly open type of microstructure, with the platy fly ash particles assembled in a dispersed arrangement. The micrographs of the treated clays for fly ash content of 25% show no evidence of a clear formation of clay-fly ash clusters. The fabrics of the clay particles are found to be reticular in nature, which is likely to form the clay-fly ash clusters with time when higher fly ash content is added to the clay sample.

The platiness of the structure becomes more evident and degree of reticulation appears to increase as the fly ash content increases. As it can been seen, at 15% and more significantly at 25% of fly ash content, fine reticulation becomes quite evident. The increase in the degree of reticulation can be attributed to the increase in the amount of calcite (e.g. Locat et al., 1990). This also gives rise to the improvement of strength as well as compressibility behavior of fly ash treated high plasticity clay.

5 CONCLUSIONS

The foregoing discussion shows a significant increase in apparent pre-consolidation pressure from the oedometer consolidation tests as the fly ash content and curing time increases. This was due to structuration (existing cementation bond) of treated clay particles. At higher stress beyond the apparent pre-consolidation pressure the e-logσ'_v curves of the treated clay shifted at higher void ratio than the untreated clay with the same pre-consolidation pressure. This sifting was almost parallel with the virgin consolidation line of the untreated clay and was more significant with higher fly ash content and longer curing periods.

The unconfined compressive strength of fly ash treated clay increased with the increase of fly ash content and curing time. The pozzolanic reaction was found to equalize within a short period of time for an addition of fly ash lower than 15%. It was shown that the reaction was still very significant at prolonged curing time up 720 days. In such long curing periods, significant portion of Ca^{2+} ions diffuses within the treated clay matrix to promote pozzolanic reaction. On the other hand, 112 curing period - for treated clay with the addition of lower than 15% fly ash only a small portion of Ca^{2+} ions was used up by the soil leading to a more usable for further testing sample.

Polarised Light Microscope analysis on treated clay showed a dispersed placement of clay particles in untreated clay. However, due to liberation of calcium ions from the hydration reaction, the fabric of treated clay changed to flocculated type, forming clay-fly ash clusters scattered within the matrix of sample by preventing the formation of a strong and uniform structure.

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