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Strength Development of Soft Marine Clay Stabilized with Cement and Fly Ash

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ABSTRACT

This study combined the concepts of chemical ground improvement technique with environmental geotechnics for improvement of a soft marine clay. The objectives were to study strength development of the cement stabilized soils and to illustrate potential use of the fly ash obtained from a vegetable oil factory as a cement replacement material. Attempt was also made in order to elucidate contributions of fly ash as well as reaction products to the development of strengths. Hardening effects were investigated through unconfined compressive strength. In order to elucidate strength development and its correlations to reaction products, X-ray diffraction analysis (XRD) were also performed after strength tests.

Based on the experimental results, strengths were markedly increased when mixed with OPC and OPC with 10% fly ash replacement. Soil mixtures with fly ash content higher than 20% exhibited relatively lower strengths at short term, however, steady gains in strength could be observed at long term. In addition, correlations between reduction on strength and fly ash content were proposed and prediction on strengths for the predetermined fly ash content could be made. It could be concluded that strength development was attributed to the hydration and pozzolanic reactions. It was also found that increase in compressive strength was directly proportional to amounts of the major reaction product such as calcium silicate hydrate (CSH).

Key words: soil improvement, clay, cement, fly ash, X-ray diffraction analysis (XRD), calcium silicate hydrate (CSH)

INTRODUCTION

For many decades, engineers and researchers have attempted to solve problems posed by various types of soft ground. Constructions on such grounds may encounter with unstabilities arisen from low shear strength, substantial total and differential settlement, excessive seepage and liquefaction. Therefore, various methods of ground improvement have been developed in order to improve such unfavorable properties. The developed technics are based on the basic concepts of ground improvement which include the effects of densification, cementation, reinforcement, and drainage. Among many successful projects, it has been reported that ground improvement method using cement and lime is suitable to improve soft clayey ground having high water content and high compressibility. The technics such as deep cement mixing method and soil cement columns have become widely used recently (DOH and JICA, 1998).

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In addition, researchers from various fields have focused on solving environmental problems due to the production of wastes. Gidley and Sack (1984) suggested methods of utilization of wastes such as fly ash, iron slag, waste rock, mill tailing, and sludge in construction. Kamon *et al*. (1991) also pointed out that utilization of wastes as construction materials would be more effective when performed in accordance with the proposed NICE criteria (**N**on-hazardous, high **I**mprovability, **C**onsistency and compatibility, and **E**conomically feasible). Stabilization of these wastes could considerably reduce environmental risks due to emission of wastes such as dusting and leaching. Material recovery from waste utilization not only has environmental benefits, but also may conserve natural resources as well as energy by creation of new materials. Consequently, it is not surprising that studies on the potential utilizations of wastes have been of great interest and have been progressively carried out in the past several decades (Kamon, 1996).

As main objective of this study, the concepts of chemical ground improvement combined with environmental geotechnics were introduced to improve strength of a soft marine clay. Ordinary Portland Cement (OPC) was main stabilizers used in this study. In addition, the fly ash obtained from a vegetable oil factory was used as partial substitutions for cement. In the past, this fly ash was used as fill embankment and cement concrete block purposes. Since there were only a few studies that reported on effective utilizations of such fly ash, it is therefore beneficial to explore more value added of this new-type industrial waste. This study also focused on elucidation on how strengths were improved. Correlations between reaction products and the developed strengths were observed.

Experimentally, the approaches used in this study consisted of unconfined compressive strength test and subsequent X-ray diffraction analysis (XRD) to investigate the main chemical compounds of materials and reaction products in order to evaluate hardening effects.

MATERIALS AND METHODS

1) Materials

The clayey soil used in this study was sampled from a construction site at Klong Lat Pho, Samut Prakarn province. The soil was taken from a depth of 3.0 m in order to obtain a natural soil having uniform compositions. At this depth, the soil was located below the weathered zone and the ground water level which was about 1 m to 2.5 m.

Upon visual inspection, the soil had greenish to dark gray color, containing some organic fractions. Further data on their physical and engineering properties are given in Table 1. The soil can be classified as clay with high plasticity (CH) according to the Unified Soil Classification System.

Investigations on chemical compositions of the untreated soils were tested in accordance with ASTM C 323. The results showed that the soils consisted of 0.8 % calcium oxide (CaO), 1.7 % magnesium oxide (MgO), 1.0 % sodium oxide (Na_2O) and 0.08 % sulphate ion ($SO_4^{\ 2-}$). The remolded strength of untreated soil at its average natural moisture content (63.53%) was within a

Table 1 Physical and engineering properties of untreated soil.

Properties	Soft marine clay
Liquid limit (%)	85.80
Plastic limit (%)	32.70
Plasticity index (%)	53.10
Shrinkage limit (%)	32.91
Wet unit weight (kg/m^3)	1,650
Specific gravity	2.76
Natural moisture content (%)	63.53
Permeability (cm/sec)	6.706×10^{-6}
Untreated strength (kg/cm^2)	0.07-0.10
pH	6.64

range of 0.07-0.10 kg/cm^2. Based on the test results, the soil was conformed to soft marine clay.

On the other hand, the fly ash used in this study was derived from burning coals mixed with waste oil bleached clay in the fluidized bed system of the vegetable oil factory at Pathumthani province, Thailand. The fly ash is residue generated from burning such solid fuels at temperature of 600-800°C. Fly ash of approximately 8-10 tons is produced daily. The fly ash contained various compositions, but mainly consisted of oxides such as silicon (SiO_2), aluminum (Al_2O_3), ferric (Fe_2O_3), calcium (CaO) and magnesium (MgO). In accordance with chemical compositions and ASTM C 618-94, the fly ash could be classified as Class F fly ash (ASTM, 2002). Table 2 shows the major chemical compositions of cement and fly ash used in this study in comparison with those of coal fly ash from Mae Moh (data from Jirathanathaworn, 2003). The fly ash was composed of fine-grained particles equivalent to a silt grain size. The specific gravity of the fly ash was 2.11 which was much lower than that of cement grains (2.96).

2) Specimen preparation and tests

Selection on appropriate stabilizer and mix proportion was done as suggested by previous researches. DOH and JICA (1998) recommended that cement had beneficial effects to improve properties of soft Bangkok clay, i.e. ground improvement by cement column. Suitable cement content was within a range of 80-200 kg/m^3 and appropriate water to stabilizer ratio should be within a range of 0.8-1.2, based on required design strength of each project. Therefore, Ordinary Portland Cement (OPC) with a stabilizer content of 200 kg/m^3 was used in this study to stabilize the soft marine clay. OPC partially replaced with 10-30% fly ash by dry weight were also used as soil stabilizers. In addition, water to stabilizer ratio was set to be 0.80 as suggested by DOH and JICA (1998) and used in our previous study (Nontananandh and Amornfa, 2002). Specimens were prepared by mixing the soft marine clay with these stabilizers at a mix proportion of 200 kg/m^3. Mixing and preparation of specimens was performed in accordance with the method of making and curing noncompacted-stabilized soil specimens.

From each soil mix, cylindrical specimens of 5 cm diameter by 10 cm long were prepared for strength tests. After de-molding, the specimens were sealed tightly in plastic sheets to prevent loss of moisture due to surface evaporation and then cured for periods of 3, 7, 14, 28 and 90 days before strength tests. Unconfined compressive strength test was performed in accordance with ASTM D 2166-91.

Investigation on reaction products such as calcium silicate hydrate (CSH) and ettringite ($3CaO \cdot Al_2O_3 \cdot 3CaSO_4 \cdot 32H_2O$) in the mixtures was performed on the failures of specimens that were previously performed with strength test, using a Philips X'Pert Diffractometer with an input energy of 40 kV and 30 mA and a scanning speed of 2 degrees/min. This study identified CSH and ettringite at d-spacings of 3.02 Å and 3.88 Å,

Table 2 Major chemical compositions of cement and fly ash used in this study and Mae Moh fly ash.

Materials	Chemical compositions (% by dry weight)				
	SiO_2	Al_2O_3	Fe_2O_3	CaO	Ignition loss
Cement in this study	20.0	6.0	3.36	66.0	1.5
Fly ash in this study	53.5	20.2	7.5	4.3	4.8
Mae Moh fly ash	26.7-34.4	19.4-23.4	20.4-24.3	10.5-16.0	0.4-1.6

respectively, where strong reflection were prominent and did not overlap with other phases.

RESULTS AND DISCUSSION

1) Strength characteristics of the stabilized soils

The characteristic curves showing the development of strength against curing time is presented in Figure 1. Mix-1 represents the stabilized soil that was mixed with cement only while Mix-2, Mix-3 and Mix-4 represent the stabilized soils that were mixed with cement and substitutions of cement with fly ash 10, 20 and 30% by dry weight.

Experimental results showed that strength for all mixtures were significantly increased when compared with strength of the untreated soil. Strengths increased with curing time for all mixtures. For Mix-1, strength significantly increased during the first two weeks and markedly increased during 14 to 28 days, while, at long term, strength almost remained constant. For Mix-2, strength markedly increased at short term and steadily increased with curing time. Strengths of Mix-2 were relatively lower than Mix-1, however, gain in strength at long term was prominent. As it could be clearly observed, strength of Mix-2 for 90 days curing time developed close to that of Mix-1, i.e. 21.84 kg/cm^2 and 22.75 kg/cm^2, respectively.

Mix-3 and Mix-4 had relatively lower strengths at short term than Mix-1 and Mix-2, however, steady gains in strength over the passage of curing time could also be observed. At 90 days, strength of Mix-3 also developed close to that of Mix-2. As it was evident from results of strength test, therefore, the fly ash used was comparable with the Mae Moh fly ash (Jirathanathaworn, *et al*., 2003).

Based on the results of strength tests, the stabilized soils with 10%-20% of fly ash content could obtain preferable strengths and therefore showed potential uses for ground improvement purposes such as soil cement column or subbase materials for roads. However, subsequent experimental tests should be considered for each specified application.

2) Deformations of soil cement with fly ash

Modulus of elasticity (E_{50}) is one of the important parameters in determining the properties of soil and its interaction with an applied load. It is required for such calculations as settlement of footing, modulus of subgrade reaction, and vertical displacement of soil. For soil cement, hardening effects establish cementing characteristics, resulting in an increase in modulus of elasticity (E_{50}).

As observed in Figure 2, moduli of elasticity

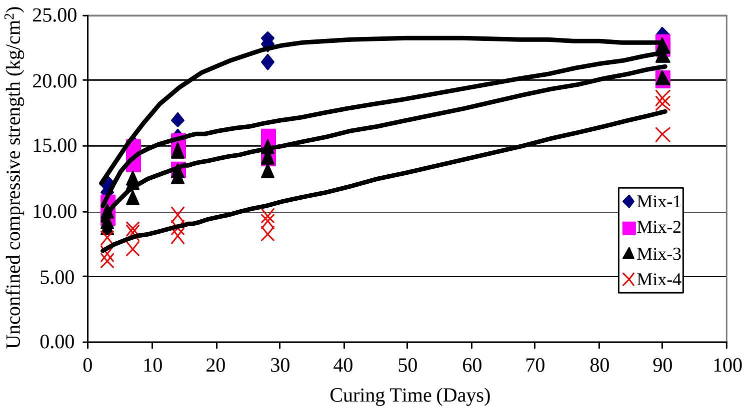

Figure 1 Unconfined compressive strengths against curing time for all mixtures.

(E_{50}) of the stabilized soils for all mixtures were markedly improved with curing time. An increase in modulus of deformation with curing time implies that the soils with high plasticity were changed into materials with high rigidity. For example, Mix-1 and Mix-2 could obtain superior E_{50} values of approximately 1,600 kg/cm^2, which was equivalent to dense sand. It could also be observed that modulus of elasticity was developed similarly to strength development. As it could be seen in Figure 3, the plot of strengths and E_{50} of the stabilized soils for all mixtures exhibit linear correlation as fitted using the method of least squares.

3) Effects of fly ash on strength development

Results from strength tests revealed that reductions on strength could be observed when 10-30% fly ash replaced cement, particularly at the early age. However, long term strengths for Mix-2 and Mix-3 gave favorable results. It is therefore beneficial for practical uses if prediction on strength as a function of fly ash content can be made. On the other words, if the target strength is assigned, a suitable mix proportion of fly ash can thus be predetermined. Correlations of reductions on strength per cement content and percentage of fly ash replacement for all curing time are illustrated in Figure 4 to Figure 8.

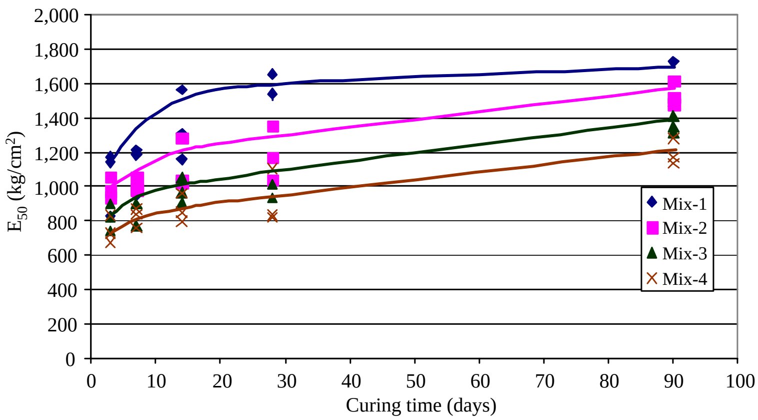

Figure 2 Modulus of Elasticity (E_{50}) against curing time for all mixtures.

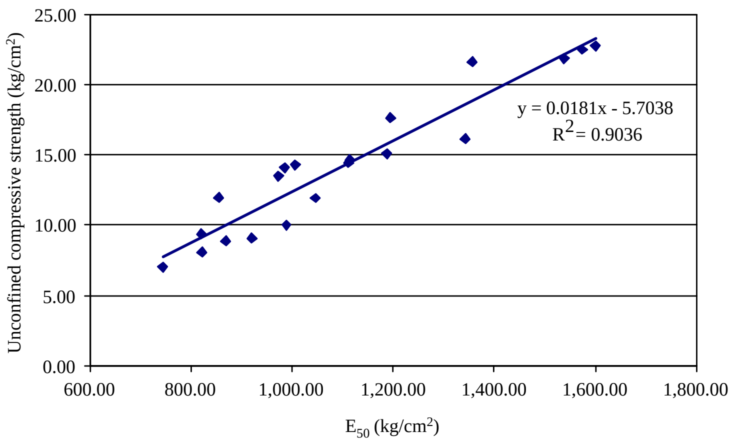

Figure 3 Relationship between unconfined compressive strengths and modulus of elasticity (E_{50}) for all mixtures.

It is apparent that strengths decrease as a function of fly ash content. Based on the curve fitting by the method of least squares, the data for mixtures at specified curing times of 7, 14, and 90 days agree well with the polynomial functions while the correlations of mixtures cured at 3 and 28 days can be either linear or polynomial function. The polynomial functions are therefore proposed, as summarized in Tables 3.

4) Reaction products in relation to strength development of the stabilized soils

The XRD pattern of the untreated soil, as illustrated in Figure 9, indicates that the soil is composed of large amount of silica in the form of quartz, montmorillonite, illite, and kaolinite as predominant minerals. Identifications reveal that the untreated soil contains no cementing materials. Figure 10 illustrates chemical compositions of the untreated fly ash based on the XRD analysis. The diffraction pattern indicates that there are various chemical compositions, but it mainly consists of combined oxides such as the oxide of quartz (SiO_2), magnetite (Fe_3O_4), hematite (Fe_2O_3) and perliclase (MgO) as dominant chemical compositions.

Preliminary tests based on the XRD analysis

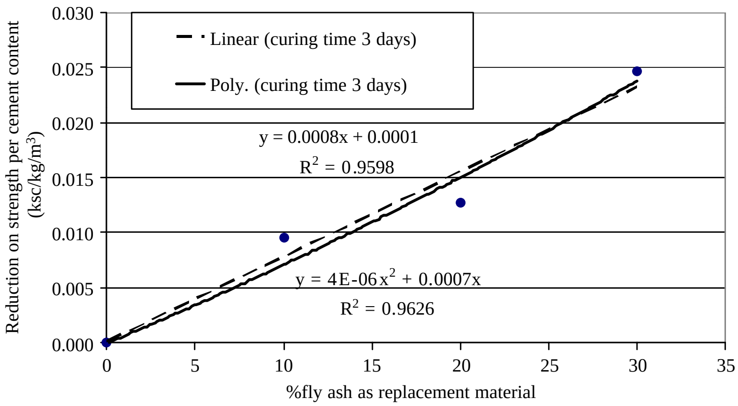

Figure 4 Reduction on strength per percent cement content with fly ash contents for strength prediction at 3 days curing time.

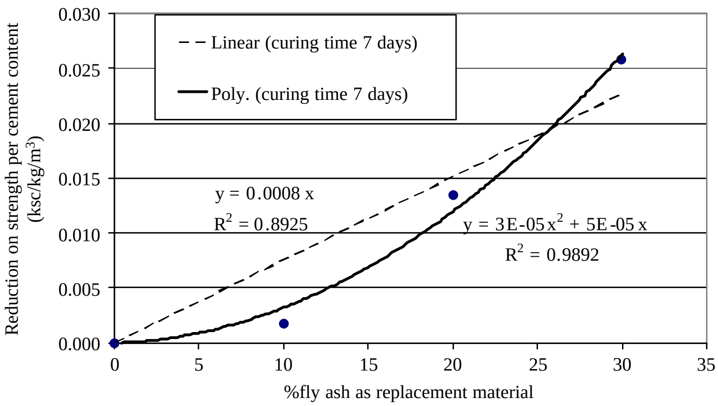

Figure 5 Reduction on strength per percent cement content with fly ash contents for strength prediction at 7 days curing time.

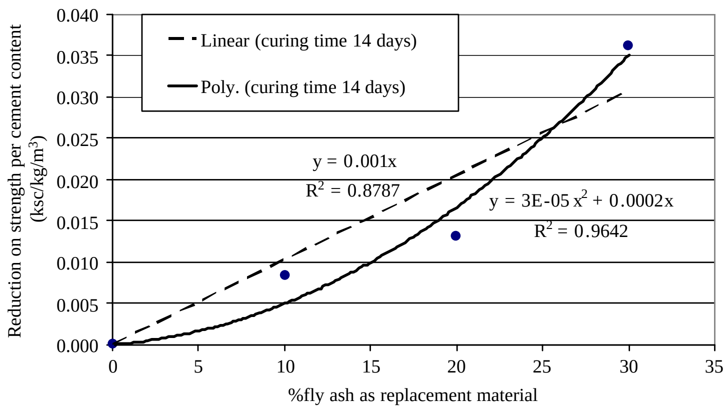

Figure 6 Reduction on strength per percent cement content with fly ash contents for strength prediction at 14 days curing time me.

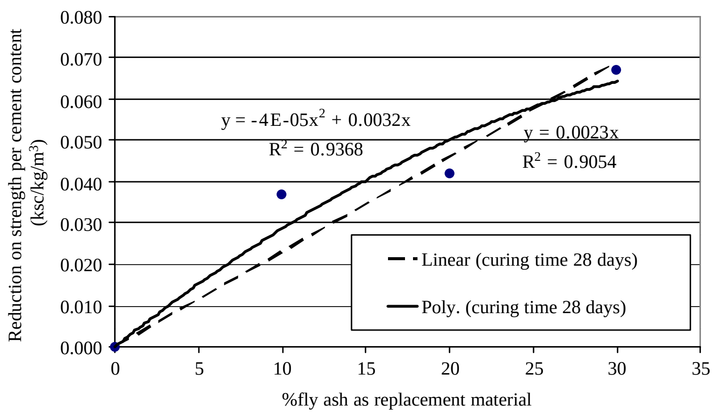

Figure 7 Reduction on strength per percent cement content with fly ash contents for strength prediction at 28 days curing time.

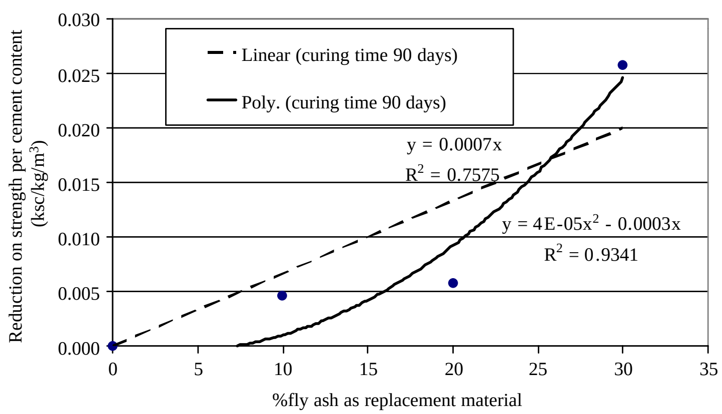

Figure 8 Reduction on strength per percent cement content with fly ash contents for strength prediction at 90 days curing time.

Table 3 Proposed equations for strength prediction.

Curing time (days)	Proposed equations	R^2
3	$Y = 4E\text{-}06\ X^2 + 0.0007\ X$	0.9626
7	$Y = 3E\text{-}05\ X^2 + 0.00005\ X$	0.9892
14	$Y = 3E\text{-}05\ X^2 + 0.0002\ X$	0.9642
28	$Y = -4E\text{-}05\ X^2 + 0.0032\ X$	0.9368
90	$Y = 4E\text{-}05\ X^2 - 0.0003\ X$	0.9341

where: Y = reduction of strength per cement content, $ksc/kg/m^3$ ($ksc = kg/cm^2$)
X = fly ash replacement content, %

of cement pastes illustrated that calcium silicate hydrate (CSH), calcium hydroxide ($Ca(OH)_2$) and ettringite were the major reaction products, as illustrated in Figure 11. Consequently, as shown in Figures 12 and 13, the diffraction intensities of CSH and ettringite increased with increase in cement content and curing time. It could be observed that their intensities markedly increased during the first two weeks and then slightly increased or became almost constant at long term.

Typical XRD patterns of the stabilized soils for Mix-1 and Mix-2 at 3 and 90 days curing time Figure 14 to Figure 17, showed growths of major reaction products which could be identified as CSH and ettringite. As obviously seen in Figures 18 and 19, X-ray intensities of CSH products and ettringite for all mixtures illustrated their formations similar to strength characteristic curves. In addition, the developed strength exhibited general trend to increase proportionally with amounts of CSH and ettringite. This can be observed as shown in Figure 20 and Figure 21. In essence, the higher reflections were obtained from the mixtures having relatively higher strength. It could therefore be concluded that these reaction products mainly contribute to strength development of the stabilized soils.

Another essential role of ettringite ($3CaO{\cdot}Al_2O_3{\cdot}3CaSO_4{\cdot}32H_2O$) was attributed to the fact that large amount of water was combined in its crystals, resulting in significant decrease in moisture content at the early age. Extracting water that existed in the pore spaces by ettringite provided a reduced water to cement ratio that aided further hardening. The previous works done by Ariizumi *et al.* (1977) and Kamon *et al.* (1989) assumed that the formation of ettringite significantly improved the leachate characteristics of the stabilized soil by combining metallic ion such as Fe^{3+} or heavy metal such as Cr^{3+}, and fixing them in its crystal. Based on the environmental geotechnical viewpoint, this confirmed the potential uses of the fly ash from vegetable oil factory combined with cement to stabilize soft marine clay.

The XRD patterns as shown in Figure 14 to Figure 17 revealed that peaks of calcium hydroxide could not be detected since the early curing time. It was therefore assumed that calcium hydroxide dissolved rapidly as Ca^{2+} and $(OH)^-$ into pore solutions after cement hydration. Increase in pH also enhanced dissolution of some silicate and aluminate from clay minerals. It could be considered that secondary reaction, generally regarded as pozzolanic reaction, between Ca^{2+} and the fly ash particles and some dissolved silicate and aluminate slowly occurred and thus substantially produced additional CSH which contributed to long term strengths. This evidence was prominent for the soils that stabilized with cement containing some appropriate proportions of fly ash. The proposed mechanisms were agreeable with the investigations performed by Ogawa *et al.* (1980) and He *et al.* (1984).

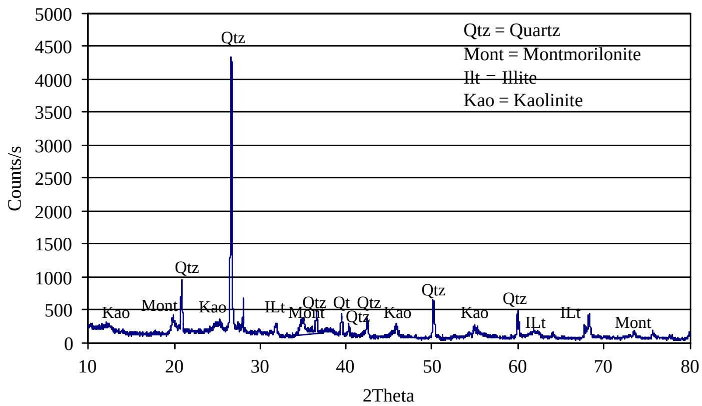

Figure 9 X-ray diffraction pattern of untreated soil.

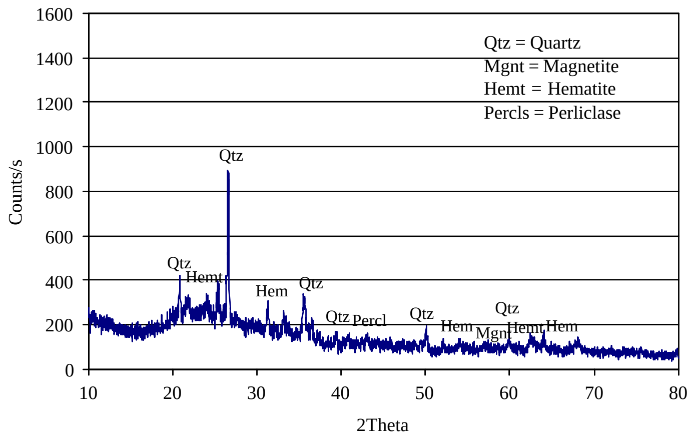

Figure 10 X-ray diffraction pattern of untreated fly ash.

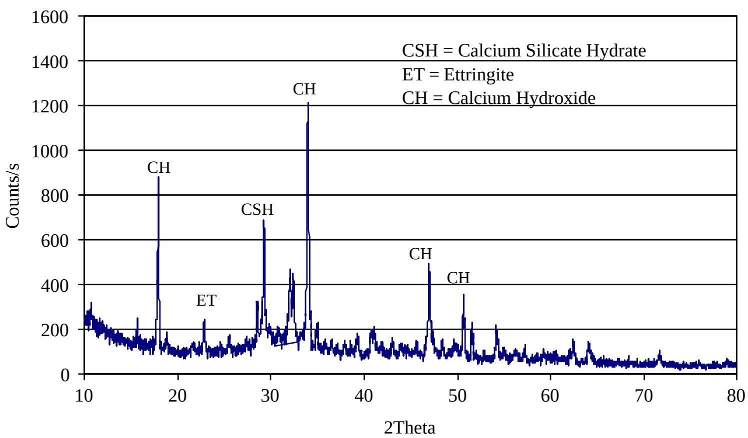

Figure 11 X-ray diffraction pattern of cement paste 250 kg/m^3 at 3 days curing time.

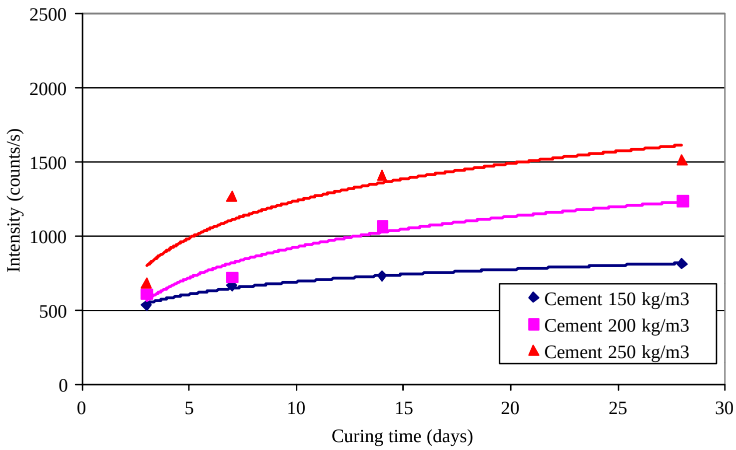

Figure 12 Intensity of calcium silicate hydrate (CSH) of cement paste at various cement contents against curing time.

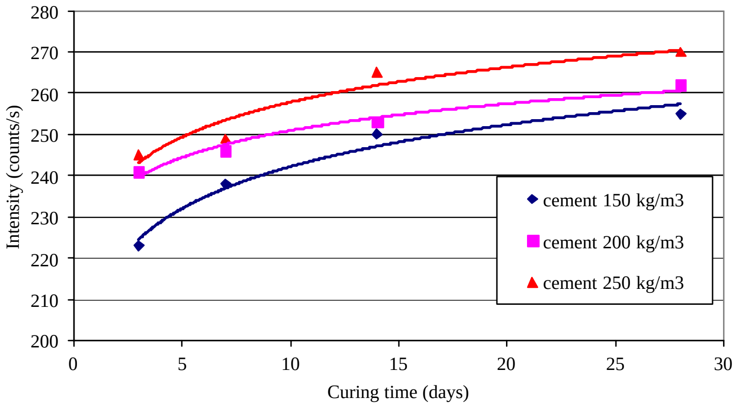

Figure 13 Intensity of ettringite of cement pastes at various cement contents against curing time.

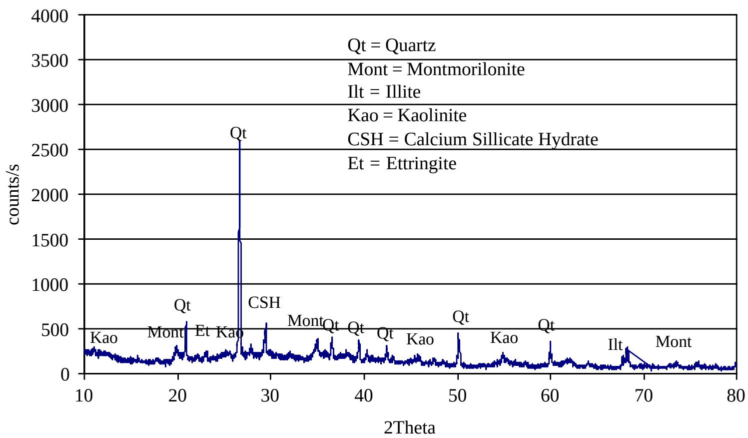

Figure 14 X-ray diffraction pattern of Mix-1 at 3 days curing time.

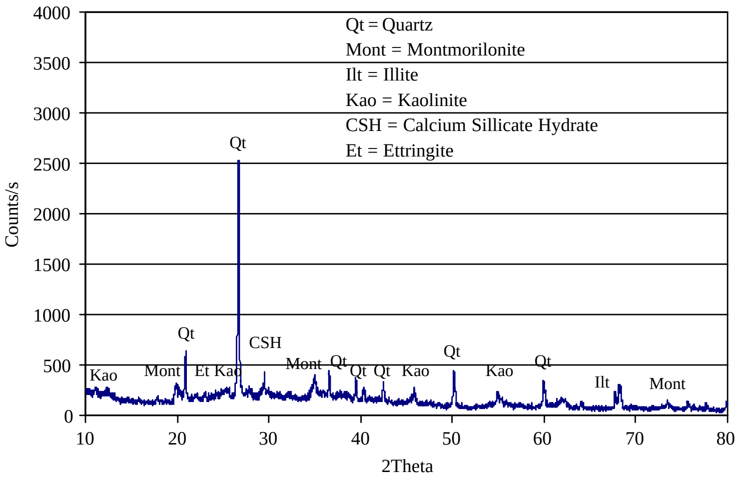

Figure 15 X-ray diffraction pattern of Mix-2 at 3 days curing time.

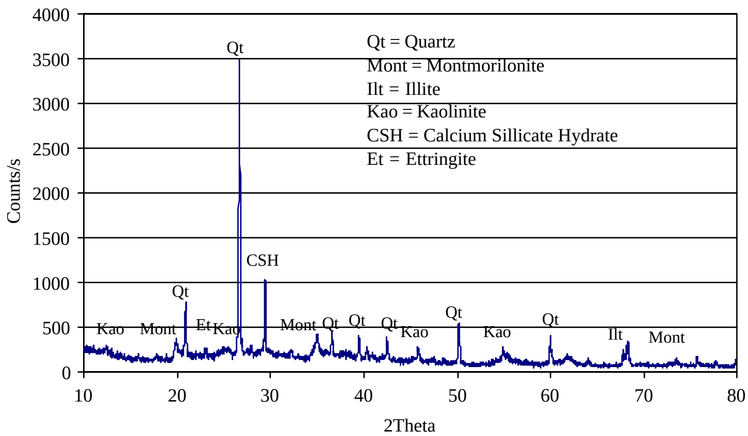

Figure 16 X-ray diffraction pattern of Mix-1 at 90 days curing time.

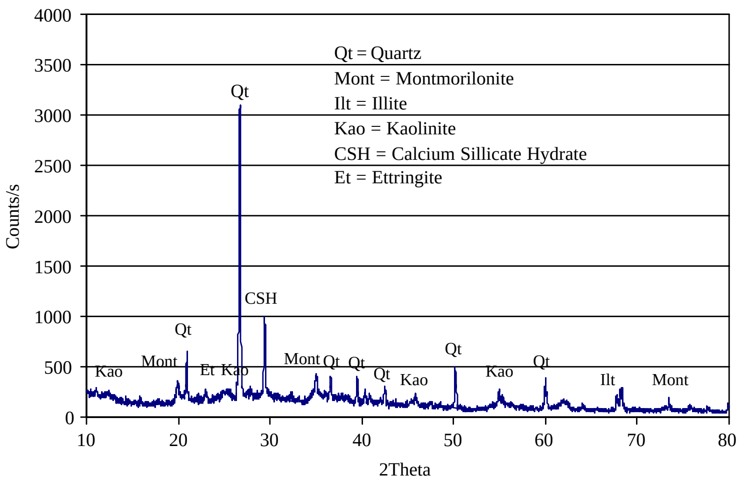

Figure 17 X-ray diffraction pattern of Mix-2 at 90 days curing time.

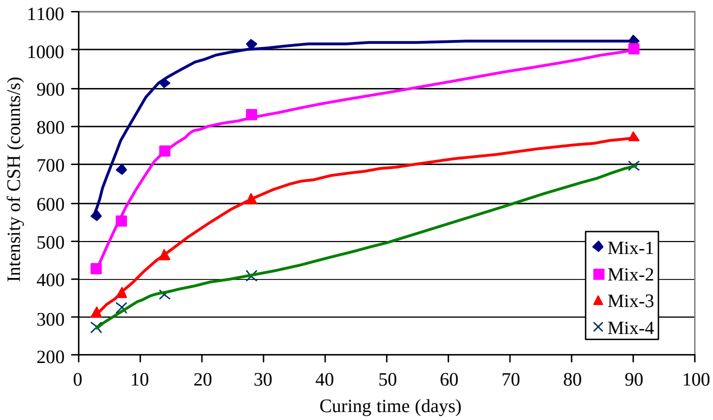

Figure 18 Intensity of calcium silicate hydrate (CSH) against curing time.

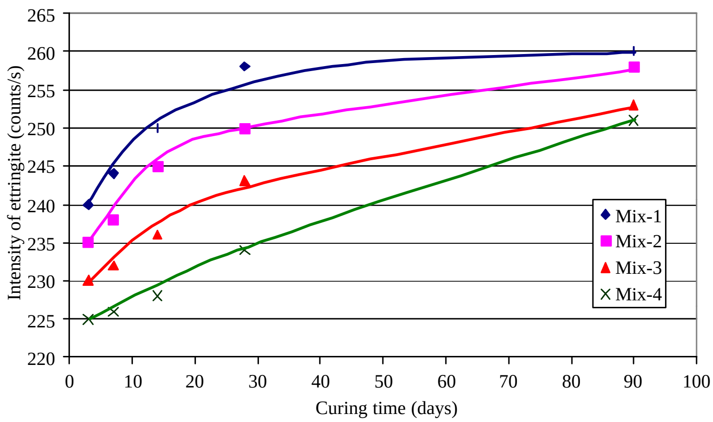

Figure 19 Intensity of ettringite intensity against curing time.

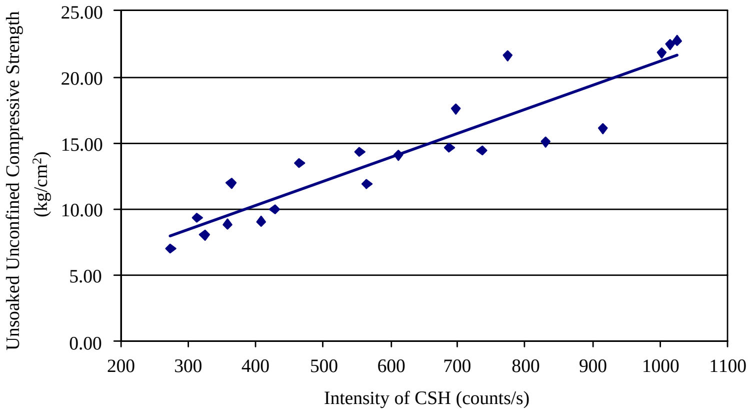

Figure 20 Relationship between calcium silicate hydrate intensity of the stabilized soils for all mixtures and unconfined compressive strengths.

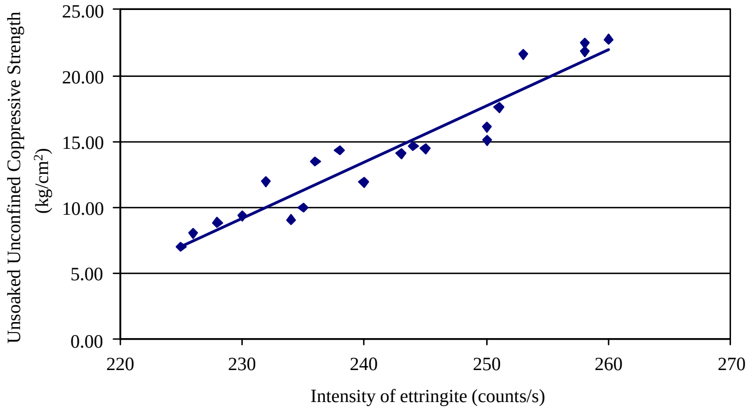

Figure 21 Relationship between ettringite intensity of the stabilized soils for all mixtures and unconfined compressive strengths.

CONCLUSIONS

Based on the results of this study, it could be concluded that strengths of the stabilized soils significantly increased when mixed with cement and cement partially replaced with fly ash. It was also found that the strength hardening effect of the stabilized marine clay was substantially influenced by the fly ash content. The fly ash derived from a vegetable oil factory could be potentially used as a cement replacement material when the fly ash content was approximately 20 percent or less. Stabilized soils appeared satisfactory for extensive ranges of applications due to the preferable strengths obtained. Prediction on strength could be accomplished using the proposed correlations with the predetermined fly ash content.

Identification of the major reaction products such as calcium silicate hydrate (CSH) and ettringite as well as elucidation on contribution of fly ash on strength development could be accomplished by XRD analysis. It was found that growths of CSH and ettringite with curing time were similar to strength characteristic curves. Addition of suitable amount of fly ash into cement considerably improved strength development in the long term. Increase in strength at long term was attributed to the pozzolanic reactions. It was also realized that strength developed was proportional to amounts of the major hydration products such as CSH and ettringite formed.

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