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CHEMICAL STABILIZATION OF SARAWAK CLAY SOIL WITH CLASS F FLY ASH

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Abstract

Chemical stabilization of Sarawak clay soil was studied via Fly Ash (FA) due to their potential benefit. FA is a by-product produced from thermal power plant and disposal of FA causing an environmental hazard. Investigation on the feasibility of FA as a potential stabilizer to stabilize the Sarawak clay soils was performed via Unconfined Compression Strength (UCS) and Triaxial Consolidated Isotropic Undrained (CIU). From the compaction results, the Maximum Dry Density (MDD) and the Optimum Moisture Content (OMC) for all mixtures increased and decreased respectively compared to natural soil. Based on the UCS test, the addition of 20% FA and 40% FA achieved a significant improvement in compressive strength and recommended as optimum stabilizer amount. The plasticity index and linear shrinkage for the FA stabilized soil decreased compared to the natural soil. The triaxial test was performed for the optimum amount of stabilizer and obtained significant improvement in effective cohesion and effective internal friction angle compared to natural soil. The deviator stress for FA stabilized soil also increased compared to the natural soil corresponding to the confining pressure. The morphology of stabilized soil shows the existence of cementitious product, which contributed to strength increased as observed via Scanning Electron Microscopy (SEM).

Keywords: Fly Ash, SEM, Soil Stabilization, Triaxial, UCS.

1. Introduction

Due to rapid development and scarcity of good land and desirable soil for civil infrastructure, several development projects have shifted to site with problematic soil such as soft soil, which is also widely deposited in the state of Sarawak [1].

Soft soil is typically well known for their low strength, high water content, high void ratio, high compressibility, high deformability and low permeability, which are causing difficulties in geotechnical applications [1, 2]. Therefore, ground improvement techniques such as densification technique, reinforcement technique and stabilization technique are needed to improve the soil engineering properties especially in strength [3].

Soil stabilization is an effective technique to enhance the engineering properties of problematic soil especially in soft soil [1]. In addition, soil stabilization is also able to increase the bearing capacity and strength of the soil [4]. Soil stabilization is achieved via blending and mixing the stabilizer material with the problematic soil to improve the soil properties [5]. The technique is generally divided into two categories, which are mechanical and chemical stabilization [6].

Chemical stabilization involves soil modification typically performed to improve the soil's engineering characteristic in term of strength and stiffness via chemical reaction when the problematic soil is blended with the stabilizer [7, 8]. When calcium-based stabilizers such as cement and lime are been used, typically four reactions take place in the soil chemical stabilization, which are cementitious hydration, cation exchange, flocculation and agglomeration and pozzolanic reaction.

Hydration process can be continued for long periods of time as long as the calcium hydroxide can be produced continuously and the pH level is maintained high. When the $Ca(OH)_2$ dissolves in the water, it will increase the concentration of calcium ion Ca^{2+} and the hydroxyl ion OH^- [9]. Then, cation exchange occurs between the monovalent alkali ions attached on clay with dissociated divalent calcium ions in the pore water and Ca^{2+} becomes the only interlamellar cations [10].

Cation exchange causes the density of the electrical charge surrounding the clay particle to change and undergo flocculation by attracting the particles closer to each other and form flocs [11]. Flocculation is a process where clay particles rearrange their flat, parallel structure to the more random edge to face orientation. The effect of flocculation will increase the workability, cause a reduction in the clay plasticity, and potentially increase the clay strength and stiffness [12]. It also implied stronger attraction forces between layers and stacking of greater number layers [13].

Typically, the strength of the soil increases with time mostly due to the pozzolanic reactions. The dissolved $Ca(OH)_2$ causes a high concentration of OH^-, which also causes high pH environment that dissolves silica and alumina from the soil into the water [9]. Then the dissolved silica and alumina from soil react with calcium ion to form Calcium Silicate Hydrate (CSH) and Calcium Aluminate Hydrate (CAH) respectively [14] as shown in the Eqs. (1) and (2).

$$Ca^{2+} + 2[OH]^- + SiO_2 \text{ (silica)} \longrightarrow \text{CSH(gel)} \quad (1)$$

$$Ca^{2+} + 2[OH]^- + Al_2O_3 \text{ (alumina)} \longrightarrow \text{CAH (gel)} \quad (2)$$

According to Van Impe and Flores [14], the CSH and CAH are stable products and will not dissolve into the water as long as the calcium ion exists and pH environment is maintained high. These CSH and CAH are capable to turn the soil into a hardened solid with high strength and stiffness [9]. Currently, chemical stabilization is receiving more attention because the technique has the potential to increase soil strength parameters and load-bearing capacity compared to other conventional methods [15].

Based on research by Basha et al. [16], typically, cement and lime are the traditional stabilizers used for soil chemical stabilization. To add, traditional calcium based stabilizer has also obtained good recognition due to their robustness and easy adaptability [17]. Hence, chemical stabilization has been implemented in various engineering projects especially in the geotechnical sector such as road construction, slope stabilization, erosion control and embankment improvement [15].

However, the traditional stabilizers such as cement and lime are expensive in cost [18] due to the rapid increase in price [19] whereas FA, which is typically being disposed of in the landfill, can be obtained at a cheaper price or even at no cost. Rapid industrialization and urbanization have also led to massive by-products or waste materials to be produced such as FA. This waste material has caused a serious environmental hazard and recycling the waste is a great challenge [20].

Generally, these by-product ashes are divided into two major categories, which are self-cementing and not self-cementing. Self-cementing ashes and not self-cementing ashes are classified as class *C* and class *F* respectively [21, 22]. FA is classified as artificial pozzolan [23]. According to ASTM International [24], pozzolan is a siliceous or aluminous material, which itself has little or none cementitious value and when chemically react with $Ca(OH)_2$ in the presence of moisture at ordinary temperature shall form products with cementitious properties.

In addition, in some other cases, by-products may have attributed to better performance than the traditional earthen material [25]. Therefore, FA also can become an attractive alternative if adequate performance can be obtained due to its lower cost [16].

2. Materials

2.1. Soil

Clay soil is widely deposited in Sarawak. Clay soil from Kuching, Sarawak, Malaysia was used in this study. Table 1 presents the properties of the soil.

2.2. Fly ash

The Fly Ash (FA) from Sejingkat Power Plant, Kuching was used in this study. Based on the chemical properties obtained from the XRF test for FA and are tabulated in Table 2, the FA was classified as class *F* ashes according to ASTM C 618 [26]. Cement was used as an activator for the FA to initiate the chemical reaction.

Class *F* FA has the potential to be used as a soil stabilizer although it needs a small amount of activator such as cement. The stabilizer is able to reduce the amount of traditional stabilizer, which is costly. By utilizing this type of locally available FA, the amount of disposal can be reduced and shall save the environment.

Table 1. Soil properties.

Parameters	Clay soil
Natural moisture content (%)	59.3
Particle density (g/cm^3)	2.57
Particle size distribution:	
Sand (%)	2.0
Silt (%)	45.0
Clay (%)	53.0
Atterberg limits:	
Liquid limit (%)	65.0
Plastic limit (%)	30.0
Plasticity index (%)	35.0
Soil classifications	
USCS classification	CH
Standard proctor test:	
Maximum dry density (Mg/m^3)	1.527
Optimum moisture content (%)	22.5
Average UCS (kPa)	268.9

Table 2. Chemical properties of FA.

Compound formula	FA (%)
Al_2O_3	23.500
SiO_2	52.900
SO_3	0.290
CaO	6.250
Fe_2O_3	8.361

2.3. Cement

The cement used was Ordinary Portland Cement (OPC). Since cement is expensive in cost, only small and sufficient amount of cement was used to activate the FA. In this study, 6% of cement was used in all the mixtures. According to ACI Committee 230 [27], the cement percentage recommended being used is 10 - 16% by weight to stabilize the high plasticity clay in the field. Thus, 6% is considered as minimal quantity for stabilization of high plasticity clay.

3. Laboratory tests

3.1. Compaction test

The standard proctor compaction test performed was according to BS 1377-1990: Part 4 [28] that is to determine the MDD and OMC of the natural soil and FA-Cement stabilized soil. The first series of test conducted was on natural soil and the second series was on the FA stabilized soil with a varying amount of FA.

3.2. Sample preparation

The air-dried soil specimen was sieved in a 2 mm mesh in order to ensure uniformity of the soil particle size in all samples. The achieved targeted compressive strength was a minimum of 800 kPa in this study as suggested by the Malaysian Public Work Department [29]. Thus, 10%, 20%, 30%, and 40% of FA and constant 6% of cement was added to all mixtures by dry weight of soil to determine the mix proportion that able to produce the targeted strength.

Each mixture was prepared with respective MDD and OMC. The samples were then compacted in 50 mm diameter and 100 mm height mould under constant compactive effort based on BS 1924-1990: Part 2 [30]. Then the samples were wrapped with the thin plastic film and stored in a room with a constant temperature of approximately (27 ± 2 °C) and cured for 7, 14 and 28 days prior to testing.

3.3. Unconfined compression strength (UCS) test

The UCS test was conducted based on ASTM D 2166-00 [31]. The UCS test was performed at a strain rate of 1.27%/min for both natural and stabilized samples. Triplicate samples were tested to make sure adequate quality control and the average of the triplicate samples is reported as compressive strength.

3.4. Atterberg limit test

Based on British Standard Institution [32], the atterberg consistency limits were determined based on BS 1377-1990: Part 2. Atterberg limit includes the liquid limit, plastic limit and linear shrinkage. The clay soil was sieved through 425-micron sieve.

3.5. Triaxial CIU test

A series of triaxial compression test was performed on natural and stabilized soils to evaluate the improvement of soil strength. The CIU triaxial test was performed according to ASTM D 4767-95 [33].

All specimens were fully saturated with a minimum measured B value of 0.95. The triaxial load test with a strain rate of 0.1 mm/min under confining pressure σ_3 equal to 40 kPa, 80 kPa and 160 kPa was used to define the shear strength parameters.

3.6. Scanning electron microscopy (SEM)

SEM was conducted to observe the morphology of the natural soil and FA-Cement stabilized soil. The observation was done via a Hitachi Tabletop microscope TM3030 at a magnification of 5,000.

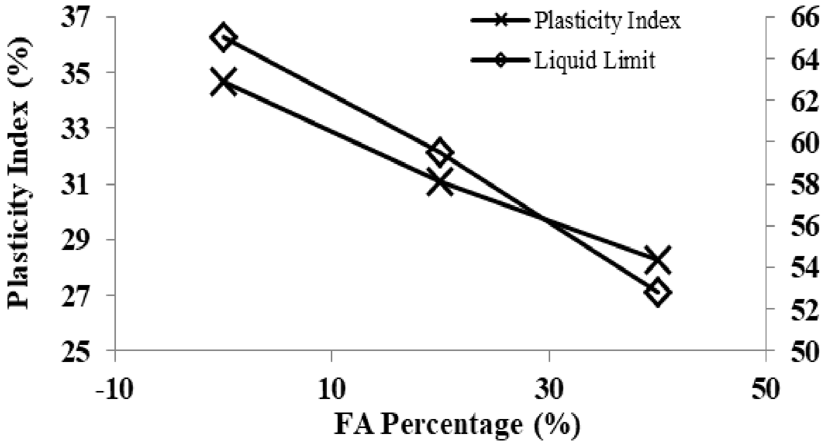
4. Results and Discussion

4.1. Effect on the consistency limit

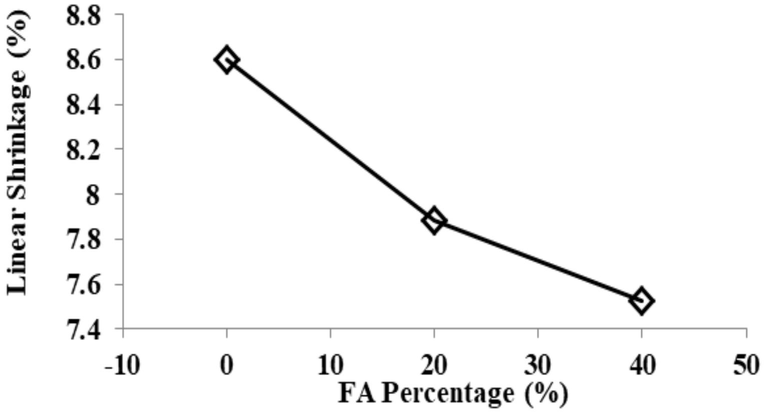
The consistency limit test in term of liquid limit, plastic limit and linear shrinkage was performed for natural soil and for stabilized soils with optimum mixtures of 20% FA - 6% OPC and 40% FA - 6% OPC. The results of the liquid limit with plasticity index and linear shrinkage are shown in Figs. 1(a) and (b) respectively.

From the results, the liquid limit, plastic index and linear shrinkage reduced significantly compared to the natural soil. The decrement in the plasticity index of the stabilized soil was due to the improvement of the workability of the clay and increment in the pH value promotes rapid pozzolanic reaction to take place [34].

The reduction in the plasticity index also is a sign of improvement with the addition of FA into the soil [17]. The reduction of liquid limit, linear shrinkage and plasticity index is probably due to the flocculation and agglomeration of stabilized soil particle, which reduced clay's water affinity and surface area of clay particle [35].



(a) Liquid limit-plasticity index.



(b) Linear shrinkage.

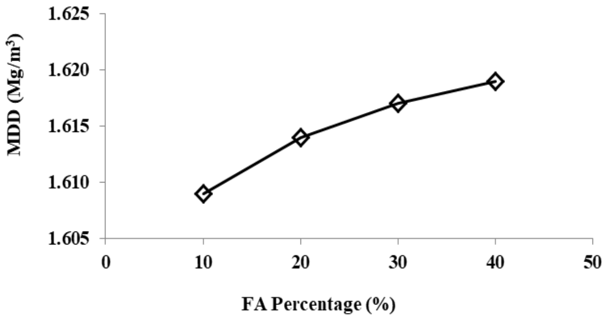
Fig. 1. Atterberg limit for natural soil and FA - 6% OPC stabilized soil.

4.2. Effect on the compactability

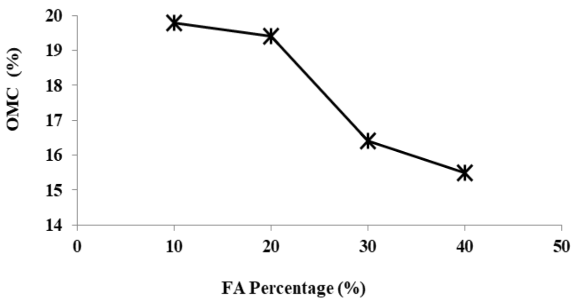
The general pattern of the Proctor compaction test was increased in MDD and decreased in OMC for all mixtures of FA stabilized soil compared to the natural soil. Results for the MDD and OMC are shown in Figs. 2(a) and (b) respectively. For FA stabilized mixture, the MDD and OMC increased and decreased respectively with an increment of the FA dosage. Lower dosage of FA stabilized soil has higher OMC compared to the higher dosage amount of FA.

The increase in MDD is probably due to the effect of particle size and specific gravity of soil and stabilizer [8]. To add, the stabilizer with low fineness and the specific area will coat the soil particle to form large aggregates that shall occupy larger spaces. Initially, the tendency of the clayey soil is to reduce the dry density until the stabilizer, which tends to increase the dry density, compensates for the larger spaces [36].

It is also a good sign of improvement of the soil properties when the MDD is increased [16]. The OMC for all mixtures were lower than the natural soil. When the FA dosage increased, the OMC decreased gradually. According to Zha et al. [37], the decreased was due to increment in the electric double layer thickness and the soil particles undergo flocculation via ion exchange. Then the flocculated soil enables the mixture to be compacted with lower OMC.



(a) MDD.



(b) OMC.

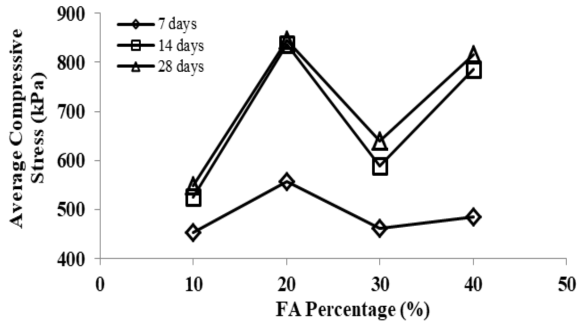
Fig. 2. Compaction characteristic of variation of FA dosage with 6% OPC stabilized soil.

4.3. Effect on the compressive strength

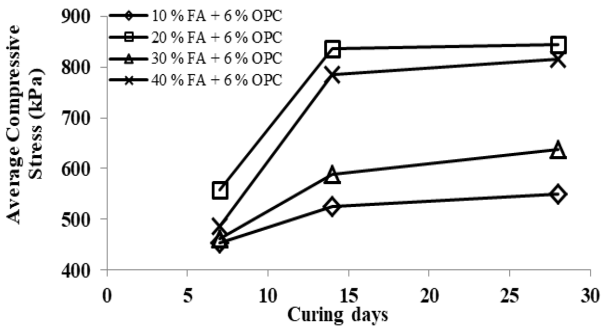
The results of the UCS test were shown in Figs. 3(a) and (b) on the effect of the curing period and effect of FA dosage respectively. From Fig. 3(a), it was shown that the longer the curing period, the higher is the compressive strength for all the stabilized soil mixtures. The 28 days curing period achieved the highest strength followed by 14 and 7 days for the stabilized soil. In addition, Fig. 3(b) shows that 20% of FA stabilized soil achieved the highest strength followed by 40% FA, 30% FA and 10% FA.

The 20% FA stabilized soil achieved the highest strength probably due to the effect of moisture content because the mixture has the highest OMC compared to other mixtures. The more water added, the more cementitious products produced via the hydration reaction and causing higher strength achieved [7]. It is because the excess water content will dissolve more Ca^{2+}, which can react rapidly with the silica and alumina of the soil to produce more CSH and CAH.

The 40% of FA stabilized soil also achieved significant strength improvement due to the effect of stabilizer dosage and presence of extra $Ca(OH)_2$, which readily reacts with moist soil and dissolves in the soil and to cause high pH value, which is favourable to the pozzolanic reaction. The 28 days curing achieved higher strength because pozzolanic is a time-dependent reaction and long-term process [35]. Hence, the CSH and CAH will continuously be produced with time as long the presence of $Ca(OH)_2$, water and high pH is maintained.



(a) Effect of curing period.



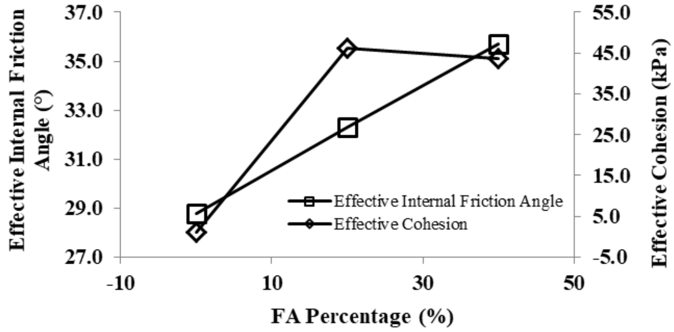
(b) Effect of FA content.

Fig. 3. Compressive strength of variation of FA dosage with 6% OPC stabilized soil.

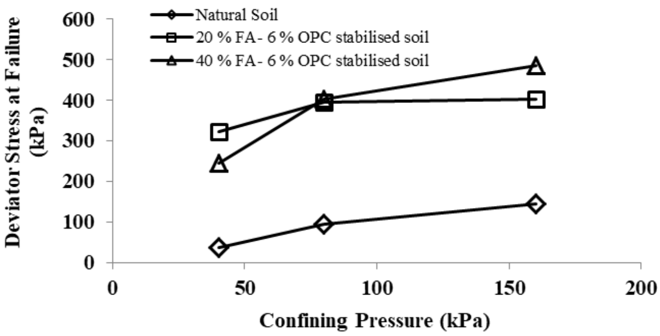
4.4. Effect on the triaxial test

The triaxial CIU test was performed on natural soil and on optimum mixtures, which are 20% FA - 6% OPC and 40% FA - 6% OPC stabilized soil cured for 28 days. The results of a triaxial test under CIU condition are shown in Figs. 4(a) and (b) for shear strength parameter and deviator with corresponding confining cell pressure respectively. Figure 4(b) shows that the deviator stress at failure increased with the increment of confining pressure for natural soil and stabilized soil. Both 20% FA - 6% OPC and 40% FA - 6% OPC stabilized soils show increment in deviator stress compared to the natural soil.

The 20% FA and 40% FA stabilized soil have higher deviator stress compared to natural soil and deviator stress increased gradually with increased of confining pressure. The increased pattern is indicating improvement for the stabilized soil. The effective cohesion increased significantly for 20% FA - 6% OPC and 40% FA - 6% OPC stabilized soil compared to the natural soil. The effective internal friction angle had slight increment for both 20% FA - 6% OPC and 40% FA - 6% OPC stabilized soil compared to the natural soil.



(a) Shear strength parameters.



(b) Deviator stress at failure.

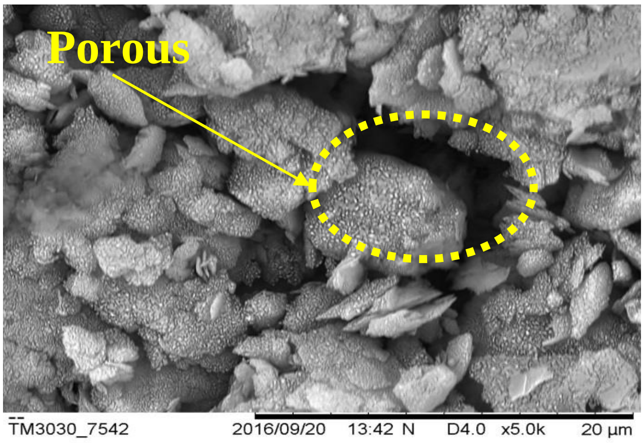
Fig. 4. Triaxial CIU for natural soil and FA with 6% OPC stabilized soil.

The increment of deviator stress for the FA stabilized soil compared to natural soil and improvement in shear strength parameter such as effective cohesion and effective internal friction angle are mainly due to the formation of new cementitious products, which are the CSH and CAH from hydration and pozzolanic reactions [38].

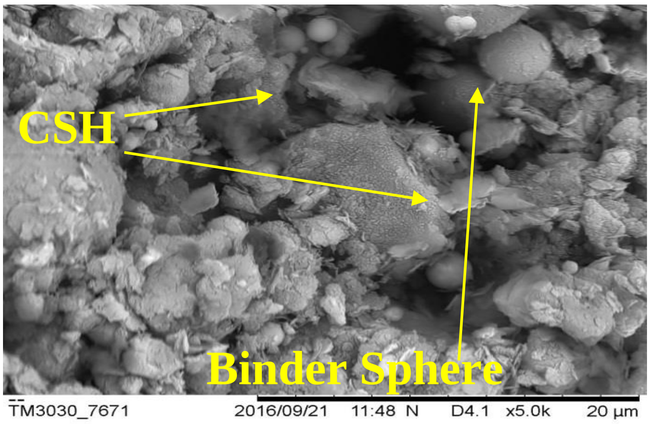
4.5. Scanning electron microscopy (SEM)

The SEM test was performed on the natural soil and the 20% FA - 6% OPC cured 28 days and 40% FA - 6% OPC cured 28 days images are shown in Figs. 5(a) to (c) respectively at 5,000 magnification. Figure 5(a) shows that porous structure was observed in the compacted natural soil.

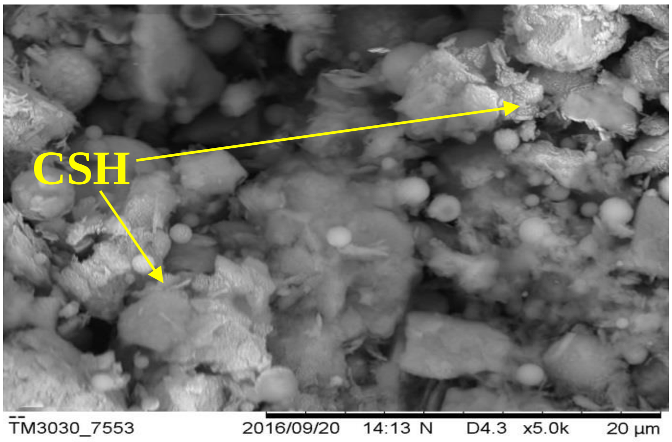
Figures 5(b) and (c) show the existence of cementitious product such as CSH within the stabilized soil. Moreover, denser morphology was observed in the stabilized soil and most of the voids are filled with cementitious products compared to natural soil.



(a) Natural soil.



(b) 20% FA - 6% OPC stabilized soil.



(c) 40% FA - 6% OPC stabilized soil.

Fig. 5. Morphology observation at 5,000 magnification.

5. Conclusion

In this study, class *F* FA activated with 6% cement has been used to stabilize Sarawak clay soil. The following conclusions can be drawn based on the test results.

- The MDD and OMC of the FA stabilized soil increased and decreased respectively compared to the natural soil for various FA dosages.
- The UCS of FA stabilized soil increased significantly with curing period compared to the natural soil. The optimum content of the FA for the effective stabilization found to be 20% FA and 40% FA activated with 6% OPC.
- The liquid limit, plasticity index and linear shrinkage reduced significantly for the 20% FA - 6% OPC and 40% - 6% OPC stabilized soil compared to the natural soil.
- The effective cohesion increased significantly for the 20% FA - 6% OPC and 40% - 6% OPC stabilized soil compared to the natural soil.
- The effective internal friction angle for the 20% FA - 6% OPC and 40% - 6% OPC stabilized soil had slight increment compared to the natural soil.
- SEM shows that cementitious product such as CSH was found in the stabilized soil and denser morphology was observed for the stabilized soil.
- Class *F* FA can potentially stabilize the Sarawak clay soil effectively and the activation with 6% cement is considered a minimum amount in this study. Utilizing the class F FA as a stabilizer is a potential alternative to decrease the construction cost especially in the rural areas.

Nomenclatures

Al_2O_3	Aluminium oxide
C_3S	Tricalcium silicate
$C_3S_2H_3$	Hydrated calcium silicates
$Ca(OH)_2$	Calcium hydroxide
Ca^{2+}	Calcium ion
CaO	Calcium oxide
Fe_2O_3	Iron oxide
OH^-	Hydroxide ion
SiO_2	Silicon dioxide
SO_3	Sulfur trioxide

Greek Symbols

σ_3	Confining cell Pressure (kPa)

Abbreviations

CAH	Calcium Aluminate Hydrates
CIU	Consolidated Isotropic Undrained
CSH	Calcium Silicates Hydrates
FA	Fly Ash
MDD	Maximum Dry Density
OMC	Optimum Moisture Content
OPC	Ordinary Portland Cement
XRF	X-ray Fluorescence

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