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# STABILIZATION OF LATERITIC SOIL USING FLY ASH BASED GEOPOLYMER

Current development consists of a high-rise building and heavy traffic load demands for soil with good engineering properties. Lateritic soil is commonly treated with Ordinary Portland Cement (OPC) to improve its engineering properties in order to enhance its load bearing capacity. The production of OPC however emits a large amount of carbon dioxide ($CO_2$) into the atmosphere. Geopolymer technology has been explored as an alternative replacement for the OPC. In this research, the unconfined compressive strength (UCS) of a lateritic soil treated with fly ash (FA) based geopolymer up to 40% by weight of the dry soil and activated using combination of sodium silicate ($Na_2SiO_3$) and sodium hydroxide (NaOH) was investigated by means of unconfined compression test (UCT). The effect of different molarity of NaOH (5-20 M), FA to alkali activator (AA) ratio (1-3) and different curing temperatures to the UCS of treated soil sample are being determined. In general, as the content of FA in the soil increases, the UCS increases more than 100% and almost 400% compared to the untreated soil for room curing temperature and oven curing temperature respectively. Based on the scanning electron microscopy (SEM) result, the molarity of NaOH solution reduces the pores in the treated soil sample. The geopolymerization process combines the soil particle and makes it denser, resulting in higher UCS than the untreated soil sample.

*Keywords:* Fly ash geopolymers; soil stabilization; lateritic soil

## 1. Introduction

Rapid development and increase in population demand for more transportation networks to be constructed. In the most part of the world, gravelly soil has been used for the construction of roads. However, the lateritic soil is now being used for road construction due to the availability of the soil in tropical countries to fulfil the needs together with better knowledge and consideration of environmental issues [1,2]. In addition, the lateritic soil is widely used as construction material for constructing roads, buildings, embankment dams, etc. [3]. Due to its high load bearing capacity and low plasticity index, lateritic soil has been used for the subbase layer of road [4,5]. Despite its usage for road construction, good quality lateritic soil is difficult to obtain resulted in failure to meet up the specifications for suitable material for road construction projects and required soil stabilization work [6-9].

The grain size of lateritic soil depends on the degree of weathering and laterization [10]. From the geotechnical point of view, lateritic soil with high amount of silt or clay normally deal with high settlement and foundation failure due to its high compressibility and high creep rates [1]. The low engineering characteristics of tropical lateritic soil with high clay or silt content are due to the high content of the fine grain particle [11]. The construction project on this type of soil will put the project at risk of dealing with failure caused by settlement. The situation worsens when the construction project on this type of soil is far away from the quarry sources. The limitation of suitable local material will increase the cost of transportation of the suitable material to the construction site. Hence, the practical method to solve this problem is using Ordinary Portland Cement (OPC) for soil stabilization work [12-14].

Several techniques of soil stabilization have been introduced to deal with problematic soil. The aims of the soil stabilization works is to alter the engineering properties of the problematic soil according to the construction needs. Mechanical and chemical stabilization are the most common soil stabilisation method [15-18]. In the chemical stabilization work, chemicals such as

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cement, lime, bituminous emulsions and pozzolans were added to the soil and served as compaction aids, binders and water repellents [15,19]. OPC has been used to stabilize lateritic soil [10,20]. This method has been used in many countries, including Malaysia, Thailand and Cameroon [1,2,21]. The addition of cement improves the unconfined compressive strength and the elastic modulus of lateritic soil [2,22-24]. Lime is the other material used extensively for the treatment of high plasticity soil [25-27]. It was proven that the incorporation of lime enhanced the engineering performance of the soil including the strength, physical qualities and swelling reduction [28]. Although the use of cement and lime is proven effective, the manufacturing process of these materials are well-known for contributing to the environmental issues dealing with greenhouse gas emission, air pollution and natural resources depletion [9]. Cement manufacturing emits greenhouse gas that is considered a major contributor to global warming [29,30]. In the other hand, the production of lime has been recognized with a high association of specific $CO_2$ emission [31]. In order to seek the solution, an alternative material with low $CO_2$ emission such as geopolymer were explored.

Previous research proven that the incorporation of geopolymer improved the mechanical strength of soil [4,32-36]. A recent study shows that soft clay can be successfully treated using Granulated Blast Furnace Slag (GBFS) and Basic Oxygen Furnace Slag (BOFS) activated with calcium oxide (CaO) and medium reactive magnesia (MgO). The treatment improved the soil's instability and increased the mechanical properties, especially for samples treated with BOFS. In addition, the compression index of the treated soil was reduced with the addition of geopolymer [37]. It was also reported that soil stabilization using 20% (slag and fly ash) activated using NaOH and $Na_2SiO_3$ with the mixing ratio of 2 with solid to liquid ratio of 1.5 shows the maximum UCS of 3.15 MPa for the treated soil sample [18]. The formation of calcium aluminosilicate hydrate (C-A-S-H) gel in geopolymer matrix and increase in calcium content from slag contributing to the improvement of mechanical strength [38]. In the other study performed to evaluate the UCS, CBR and resilient modulus of soil stabilization using FA based geopolymer has confirmed that the FA based geopolymer is effective for soil stabilization [39]. The addition of FA geopolymer successfully enhanced the properties of treated soil. The FA geopolymer treated sample shows better performance of CBR in soak condition compared to unsoaked condition, indicating the better performance of subgrade in extreme conditions [40]. In terms of durability, the soil stabilized with slag-fly ash based geopolymer was found to have better durability than OPC when tested for the resistance to sulphate erosion [41].

It can be summarized that most of the research on using geopolymer as potential replacement to OPC focuses on the mechanical strength and microstructural analysis related to the treatment of problematic soil. However, no specific mixture is suggested as there are differences in the material used, especially the type of soil based on its origin. Due to rapid development in Malaysia, more construction space is required to be developed involving the exploration of land with different soil properties. Hence, the soil stabilization is not limited to the treatment of problematic soil but also to enhance the engineering properties of other type of soil available at the construction site. In addition, the performance of geopolymer stabilized soil depends highly on the binder and alkaline activator content [36]. With the availability of FA and rapid construction project in Malaysia, there are needs for further investigation to explore the properties of treated lateritic soil using FA based geopolymer for subgrade improvement.

This study aims to investigate the index properties and mechanical strength of lateritic soil treated with FA based geopolymer. Treated lateritic soil using FA based geopolymer will be tested for the UCT while the microstructural of the geopolymer stabilized soil were accessed using scanning electron microscopy (SEM). The effect of different percentage of FA, concentration of sodium hydroxide and the FA to AA ratio were evaluated. The consistency limit changes will be determined using the Atterberg limit test.

## 2. Methodology

### 2.1. Materials

Lateritic soil used in this study were collected from a construction site at Kangar, Perlis, Malaysia, with geographical coordinates of 6°24'56.5''N 100°11'23.8''E. It was bagged and transported to the soil laboratory for storage. The lateritic soil was air dried for three weeks continued with 24 hours of oven drying. The soil was then grinded into smaller particles and filtered using a mesh of size 2 mm. Fig. 1 shows the lateritic soil used in this study. The soil was tested for basic properties such as liquid limit, plastic limit, specific gravity. TABLE 1 shows the details of basic properties of lateritic soil. Modified Proctor test was conducted to determine the compaction properties of the soil. It was found that the maximum dry density (MDD) and the optimum moisture content (OMC) for the soil are 1.94 Mg/m$^3$ and 12.8% respectively.

Fig. 1. Lateritic soil used for the experimental programme

TABLE 1

Basic properties of lateritic soil

| Physical Properties | Values |
|---|---|
| Specific Gravity | 2.39 |
| Atterberg Limits | |
| Liquid Limit, LL (%) | 29.0% |
| Plastic Limit, PL (%) | 15.0% |
| Plasticity Index, PI (%) | 14.0% |
| Modified Proctor Compaction | |
| Maximum Dry Density, MDD ($Mg/m^3$) | 1.94 |
| Optimum Moisture Content, OMC (%) | 12.8 |

FA was obtained from a local supplier located in Manjung, Perak. FA is a by-product from the coal combustion for electricity. The chemical composition of the FA is shown in TABLE 2. Based on the results of X-ray fluorescence (XRF), the FA is classified as a Class F FA as the total amount of $SiO_2$, $Al_2O_3$ and $Fe_2O_3$ of 89.82% and 3.51% of CaO.

The liquid alkaline activator used in this study is a mixture between $Na_2SiO_3$ and NaOH of different concentrations. The combination of $Na_2SiO_3$ and NaOH has been proven to produce a sample with better mechanical properties [42,43]. The $Na_2SiO_3$ is in liquid form and consist of 9% $Na_2O$ and 30% $SiO_2$. The NaOH with 98% purity in pellet form was mixed with water to attain the required concentration.

TABLE 2

Percentage of chemical element of fly ash

| Element | Percentage (%) |
|---|---|
| $SiO_2$ | 54.3 |
| $Al_2O_3$ | 30.7 |
| $Fe_2O_3$ | 4.82 |
| CaO | 3.51 |
| MgO | 1.32 |
| Others | 5.35 |

### 2.2. Sample preparation and testing programme

In order to determine the ability of FA based geopolymer to stabilize lateritic soil, three sets of specimens with different mix designs were prepared as shown in TABLE 3. Set 1 was performed to compare the effect of different FA content to the unconfined compression strength of treated soil. The FA content used to stabilize the soil is 10, 20, 30 and 40% by weight. The concentration of NaOH and FA/AA were kept constant at 15 and 2.5 respectively. Set 2 was determined to investigate the effect of NaOH concentration (5, 10, 15 and 20 M) on treated lateritic soil's strength. The percentage of FA used for set 2 is 20%. Set 3 was performed with different FA/AA ratio. The effect of different FA/AA ratio was evaluated with the amount of FA and NaOH concentration being constant. The FA/AA ratio varies from 1.0 to 3.0.

The sample preparation started with the preparation of AA. $Na_2SiO_3$ was mixed with NaOH solution at different concentrations and left for 24 hours to cool down. The ratio of $Na_2SiO_3$:NaOH is kept constant at 70:30 for all samples as recommended in past research [44]. Dry lateritic soil was mixed with FA for 3 minutes. The AA was added to the soil-FA mixture and mixed for another 3 minutes to achieve homogeneity. The mixed sample was then transferred to the cylindrical mould with a diameter of 38 mm and a height/diameter ratio of 2.0 and compacted in three equal layers. All samples were cured at room temperature (25 ± 2°C) except for set 1 that being cured at both room and oven (100°C) conditions. The oven cured specimen is only used for the first 24 hour continued with curing in room temperature. All samples were wrapped using plastic film and tested at 24 hours and 3 days of curing.

The UCS were performed at the axial strain rate of 0.5 mm/min. For each curing time and mixture, 3 samples were tested under the same conditions for consistency. The unconfined compression test (UCT) was performed using motorized unconfined compression according to the BS 1377-Part 7 [45]. The maximum strength and strain were recorded for analysis. The Atterberg Limit test was conducted after 7 days of curing. The treated lateritic soil was crushed and sieve using 425 µm sieving mesh and then mixed with water. The test was performed to determine the liquid limit (LL), plastic limit (PL) and plasticity index (PI) in accordance to BS 1377-Part 2 [46]. Microstructural characterization was conducted for selected treated specimens at 7 days of curing specimens using Scanning Electron Microscopy (SEM). The fraction of specimens from the UCS test were trimmed and coated with a thin layer of gold using a sputter coater to make it conductive.

TABLE 3

Summary of the testing programme

| | Set 1 | Set 2 | Set 3 |
|---|---|---|---|
| Fly ash content (%) | 10, 20, 30, 40 | 20 | 20 |
| Alkaline activator type | $Na_2SiO_3$, NaOH | $Na_2SiO_3$, NaOH | $Na_2SiO_3$, NaOH |
| NaOH (molars) | 15 | 5, 10, 15, 20 | 2.5 |
| FA/AA | 2.5 | 2.5 | 1.0, 1.5, 2.0, 2.5, 3.0 |
| Curing temperature (°C) | 25, 100 | 25 | 25 |

## 3. Results and discussions

### 3.1. Unconfined compressive strength

Fig. 2 shows the effect of FA content and curing temperature on the UCS of treated soil. Clear improvement of UCS was observed once the FA content of 10% was added to the soil with a gain in UCS of 53% and 468% for 24 hours curing and 3 days curing respectively. The improvement in terms of UCS were continued when the content of FA reached 20%. At NaOH concentration of 15 M, higher FA content will increase the geopolymerization process providing higher silica and alumina oxides [44]. The usage of FA content of more than 20% resulted in slight decrement of UCS for 24 hours and 3 days of curing. The UCS decrement may cause by the replacement of soil with FA particles which is finer during the compaction process resulting in a slight reduction in strength. In addition, adding FA at a higher percentage may decrease the UCS due to insufficient water and AA content to react with high FA content [36]. Thus, it can be seen that the maximum strength given by the sample treated with geopolymer consists of 20% FA that shows 640 kPa and 1850 kPa of UCS for 24 hours and 3 days of curing respectively.

The trend of UCS development shows that 24 hours oven-cured specimens are similar to those cured at room temperature. The highest UCS of oven-cured specimens is given by the 20% FA specimens with a slight downward trend of UCS when the FA content exceeds 20%. The effect of curing temperature on the UCS of the treated soil specimen can be observed in Fig. 2. Significant improvement of UCS is shown by the specimens cured in an oven at 100°C compared to the sample cured at room temperature. All the sample shows more than 100% improvement when cured under 100°C compared to room temperature. The finding is aligned with other research that observed a significant increment of UCS as the temperature increases as higher temperatures enhance the geopolymerization reaction [44,47].

The 40% FA specimen gives the highest increment of UCS due to temperature different. However, compared to the 3 curing days specimens, the 24 hours oven cured specimens show lower UCS except for the 10% FA specimen. Based on the overall observation on the effect of different FA content on the UCS, it can be summarized that the best soil stabilization can be achieved by using 20% FA based geopolymer regardless of the curing period and temperature.

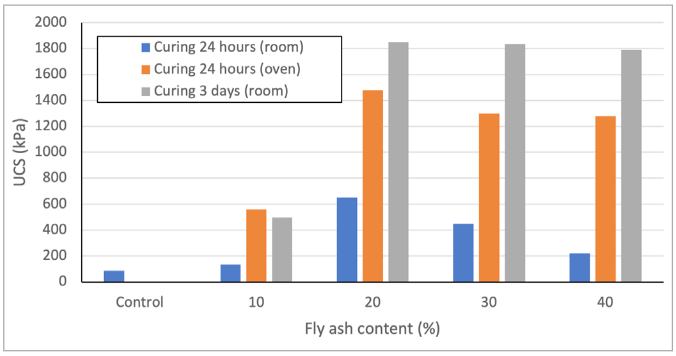


Fig. 2. UCS of fly ash based geopolymer treated lateritic soil at NaOH concentration of 15 M and FA/AA of 2.5 with different fly ash content

Fig. 3 presents the UCS for the control and FA-based geopolymer-treated samples at different molarities of NaOH cured at 24 hours and 3 days. All treated specimen shows better UCS compared to the control sample. Independently of the NaOH molarity, geopolymer treatment to the soil specimens increases the compressive strength over time. This is common as the geopolymerization process is ongoing, especially during early curing period. Significant development of UCS due to the curing period is observed for specimens with NaOH molarity of 15 M and 20 M with increment percentage over 100% for both specimens.

The increased NaOH molarity improves the UCS of treated specimens with 20 M specimen shows the highest UCS of 730 kPa and 1910 kPa for 24 hours and 3 days curing period respectively. The strength development of treated samples with increasing NaOH concentration are due to the dissolution of silica and alumina ions from FA for the geopolymerization process, resulting in a higher mechanical strength of treated specimens. The same finding was reported in other research on using geopolymer for soil stabilization [44,48].

The trend of UCS increment due to molarity of NaOH is more significant once the molarity reached 15 M. Beyond this concentration the rates of UCS development declined. The percentage of UCS increment shown by 20 M specimen compared to the 15 M specimen is only 12% and 3% for 24 hours curing and 3 days curing respectively. Hence the optimum NaOH concentration providing the best improvement of UCS is fixed at 15 M with consideration of the cost of the AA.

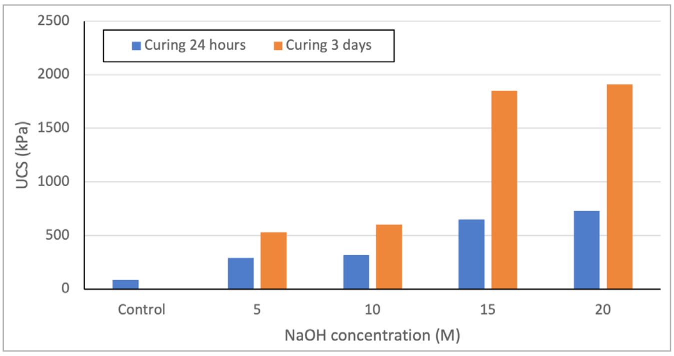


Fig. 3. UCS of fly ash based geopolymer treated lateritic soil using 20% fly ash and FA/AA of 2.5 at different NaOH concentrations

Fig. 4 shows the UCS of different FA/AA ratio at FA content of 20%, NaOH concentration of 15 M and $Na_2SiO_3$:NaOH of 70:30. The UCS of all geopolymer treated lateritic soil are higher than that of control sample. The increment of FA/AA from 1.0 to 2.5 has successfully increase the UCS from 112 kPa to 650 kPa and from 215 kPa to 1850 kPa at 24 hours and 3 days of curing. Further increment of FA/AA at 3.0 show a reduction of UCS compared to the UCS at FA/AA of 2.5. The trend of UCS development is affected by the treated specimens' compaction process, which is highly dependent on the FA/AA. Since the FA content used is constant at 20%, higher FA/AA will provide less moisture, affecting the compaction process of treated soil specimen. The increment of FA/AA value from 1.0 to 2.5 were considered as reduction of moisture that assisted the compaction process with the FA/AA of 2.5, providing the optimum moisture content in the form of AA for the soil with 20% FA additive. As the FA/AA ratio reaches 3.0, the amount of moisture is very low for the optimum compaction process leaving the compacted soil with higher air voids. At this stage, the difficulties of compaction to be conducted to the treated soil specimens was experienced. This trend of strength development with a peak value before the decrement of UCS is similar to the other research using FA based geopolymer as a chemical stabilizer as less moisture content was reported to make the compaction process difficult resulting in lower UCS [18]. The increment of UCS with the curing period can be observed for all treated specimens. The increment of UCS is more than 90% from day 1 to day 3 showed by all treated soil specimens. The FA/AA of 2.5 gives the highest improvement based on the curing period with the UCS at 3 days of curing increasing 15 times higher compared to the UCS at 24 hours of curing. More geopolymer paste were produced as time extended resulting in higher UCS and enhancing the mechanical properties of soil treated with geopolymer [18].

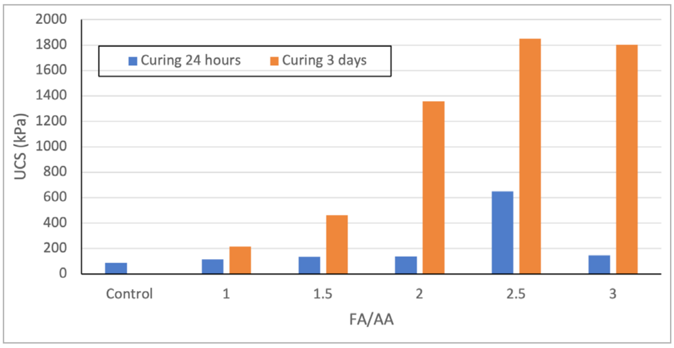


Fig. 4. UCS of fly ash based geopolymer treated specimens at different FA/AA ratio

### 3.2. Atterberg's limit

The Atterberg's limit test result of treated FA based geopolymer with different mixtures are shown in Fig. 5. In general, the LL and PI of treated specimens were decreased regardless of the FA content. This finding agrees with previous research on the effect of FA based geopolymer to the consistency limit of soil which shows reduction in LL and PI of treated soil sample [18,40,49]. At NaOH concentration of 15 M, FA/AA = 2.5 and $Na_2SiO_3$:NaOH = 70:30, the sample with 40% of FA gives the lowest liquid limit and plasticity index. The effect of NaOH concentration and FA/AA ratio on the consistency limit of treated soil are presented in Fig. 6. The increasing concentration of NaOH was found to slightly increase the LL and decrease the PI of the treated soil sample at the same FA content, FA/AA and $Na_2SiO_3$. The LL and PI was also found to decrease slightly with the increasing FA/AA ratio, with the FA content and NaOH concentration being constant.

The findings on the consistency limit agree with the previous research on clay stabilization using FA base geopolymer, which found that the decrement trend of LL and PI were resulted from cation exchange, flocculation and the agglomeration process in treated soil specimens. The cation exchange that occurs in the treated soil specimen alters the strength and texture of the soil resulting in a transition from high plasticity to friable soil which is indicated by low PI [18]. The increase of water holding capacity due to the flocculation of soil particle in the addition of FA decreases the LL. Lower LL due to the addition of FA indicated a strength increment [40]. The agglomeration process that occurs after the mixing of FA treated sample involves restructuring the negative charged soil particle enveloped by the positively charged cation shells [50].

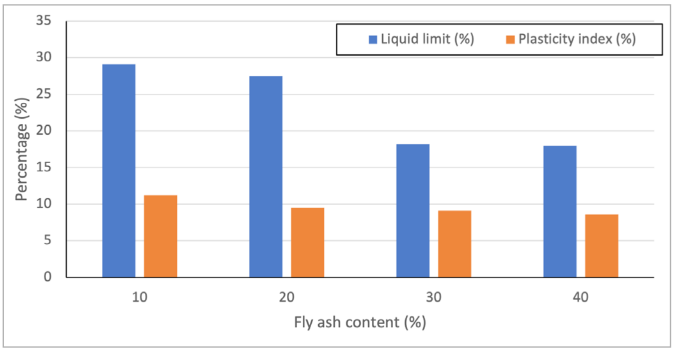


Fig. 5. Liquid limit and plasticity index of fly ash based geopolymer treated soil at different fly ash content

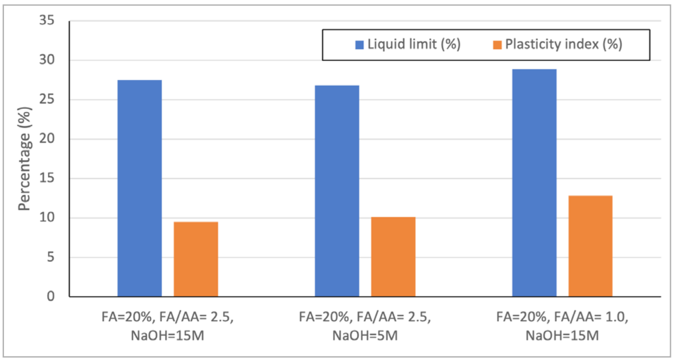


Fig. 6. Liquid limit and plasticity index of fly ash geopolymer with different NaOH concentration and FA/AA at 20% fly ash content

### 3.3. Scanning electron microscope

The formation of FA based geopolymer is begin with the decomposition of aluminosilicate in FA that activated by AA that is generated the polycondensation [51]. The UCS of FA treated soil using the FA based geopolymer comes from the reaction between AA and FA that produce the geopolymer gel [52]. Hence, higher production of the geopolymer gel will increase the UCS of FA based geopolymer treated soil.

Fig. 7A and B shows the SEM image of treated soil sample using different FA content at FA/AA = 2.5, NaOH concentration = 15 M and Na2SiO3:NaOH = 70:30. The formation of geopolymer gel can be observed for all treated specimens. The improvement in term of UCS of the treated specimen results from a denser structure combined with the binding of soil particles with geopolymer paste [40]. The results of SEM confirm the UCS development shown in the UCT. The higher amount of FA used increase the sources of aluminosilicates resulted in higher production geopolymer that contribute to the increase in strength of treated soil specimens.

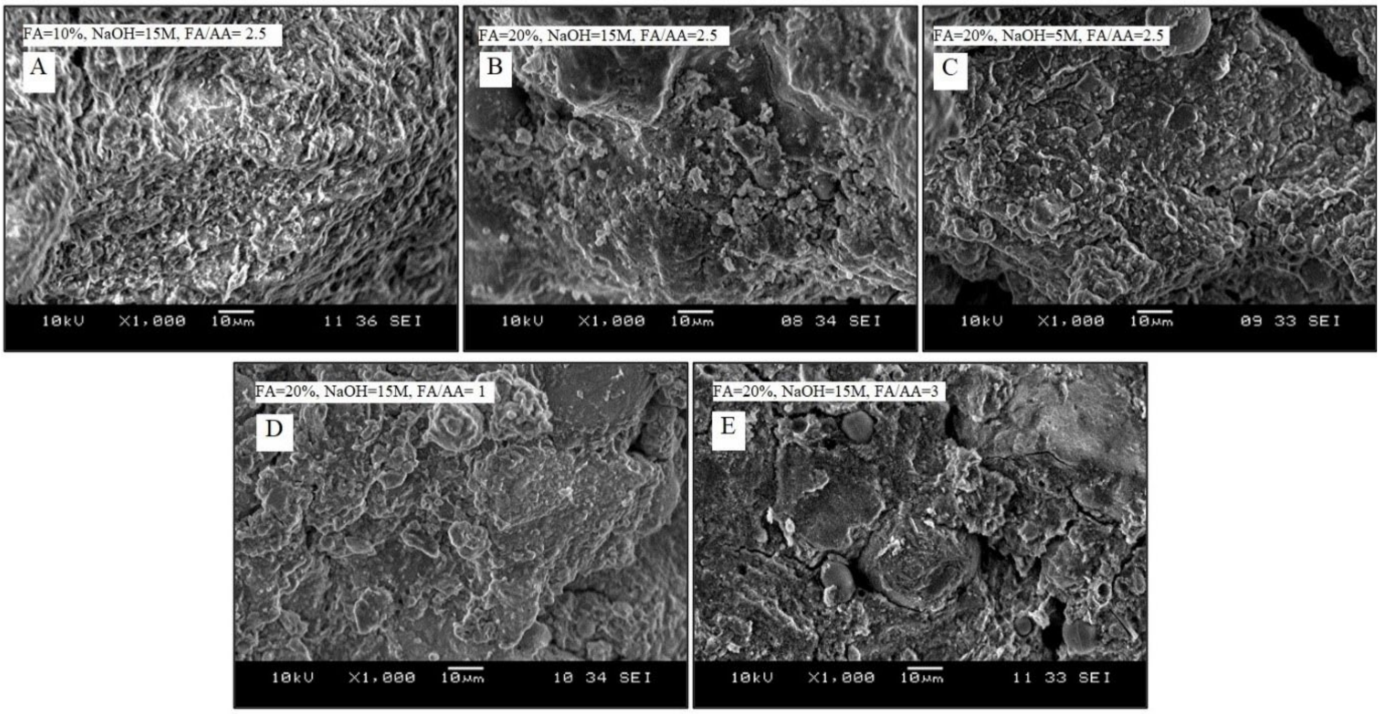


Fig. 7. SEM image of treated lateritic soil using fly ash based geopolymer at various mixture

The soil sample added with 5 M of NaOH consists of some tiny pores, cracks among the soil bonding and unreacted FA particles as shown in Fig. 7C. It might be due to the inadequate molarity of the NaOH to react with the FA particles. At 15 M of NaOH, tiny circular pores have decreased. The soil particles tended to bond together closer, with smaller pores among the soil particles. The result is aligned with the past research conducted that demonstrate a lower ability to dissolve FA particles and to leach silica and alumina from aluminosilicate source caused by low NaOH concentration [53]. Higher NaOH concentration boosts the ability to leach silica and alumina resulting in higher degree of geopolymerization [54].

The effect of FA/AA on the microstructure of treated soil at FA content of 20%, NaOH concentration of 15 M and $Na_2SiO_3$:NaOH of 70:30 is illustrated in Fig. 7B, D and E. The result shows that the FA/AA = 2.5 generates more geopolymer products than the FA/AA = 1.0 with a denser soil structure. Higher FA/AA provides denser soil structure with lower void content due to better workability at the same AA value. However, further reduction of AA at FA/AA = 3.0 cause difficulties during soil compaction resulting in decrement of UCS. Fig. 7E shows more voids and unreacted FA particles due to insufficient AA content.

## 4. Conclusions

A laboratory experiment was conducted to evaluate to possibility of using FA based geopolymer as an alternative to the OPC as chemical stabilizer for soil stabilization work. Based on the results, the following conclusions can be summarized:

- The geopolymer has been found to be effective in stabilising lateritic soil regardless of the geopolymer mixture (i.e., FA content, NaOH concentration and FA/AA).
- The 3 days UCS of geopolymer mixture at 20% FA, NaOH concentration of 15 M and FA/AA content of 2.0 is higher than 0.8 MPa as required in the Design Guideline for Alternative Pavement Structures (Low Volume Roads) of Malaysia Public Work Department (PWD) make it suitable for construction of road subgrade. The performance of treated soil sample at the early curing period will provide a solution for early strength during construction.
- At 20% of FA content, the increment of FA/AA from 2.0 to 2.5 provides a significant increment of UCS that shows better load carrying capacity, giving advantages when dealing with higher load. The increment of FA/AA beyond 2.5 will not further improve the UCS.
- 15 M NaOH gives the best UCS in terms of cost as the higher concentration will not assist in further improvement of UCS tested at 20% FA content.
- Higher curing temperatures prove to assist the strength development of geopolymer treated lateritic soil. This condition provides advantages to the country with hot climate temperature as higher temperature during soil stabilization work will help the geopolymerization process.

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