Improvement of Marine Clay Soil Using Lime and Alkaline Activation Stabilized with Inclusion of Treated Coir Fibre

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Abstract: Waste products have recently been used as one of the techniques in soil stabilization. The material is not just environmentally friendly, but also cheap. In this study, two different types of soil stabilizer—lime and alkaline activator (AA) with the inclusion of treated coir fibre as soil reinforcement in marine clay soil—were examined. The inclusion of fibre in the treated soil has had a positive impact in increasing the strength of the soil. Therefore, to assess the effectiveness of the soil treatment, mechanical tests such as indirect tensile strength, flexural test and unconfined compressive strength test were performed at three different curing periods (7, 28 and 90 days) on both untreated and treated soil. From the results, the inclusion of fibre in both lime and alkaline activation indicates an enhancement on post-peak behaviour from brittle to more ductile. Microstructural analyses of Field Emission Scanning Electron Microscope (FESEM) and Energy Dispersive X-ray (EDX) were also conducted after shearing to evaluate the changes of the soil before and after the treatment. Overall, results indicate that the treatment transformed the structure of the soil to become denser where it filled the large pores compared to untreated soil.

Keywords: marine clay soil; soil stabilization; lime; alkaline activators; compressive strength; indirect tensile strength; flexural test

1. Introduction

Vast deposits of marine clay soil are typically linked with poor engineering properties such as low shear strength, high compressibility and low permeability [1–4]. The marine clay soil is usually found at the coastal area in Peninsular Malaysia especially at Alor Setar, Penang, Klang and Malacca. These types of soil mainly posed a significant challenge and problems in designing, construction of building and infrastructure. Recent development nowadays is concerned with obtaining better performance of stabilization by reducing the usage of cement-based binder with a minimal environmental cost. A variety of stabilization soil techniques have been applied to address the problems where one of the major techniques uses chemical stabilization.

Lime is one of the traditional chemical stabilizers that has been extensively used internationally. A stabilizer known as a calcium-based binder is a common technique used to improve the performance of soil due to its robustness, easy adaptability and obvious cost effectiveness [5]. Usage of lime as soil
treatment resulted in increasing the concentration of pore water which changed the texture of the soil particles to form aggregates [6]. The benefits of applying the lime in marine clay soil have been widely reported by many of the past researchers [7–9]. The application of lime in the soil has been reported to have a strong bonding between the soil particles, which, through the reactions, results in a reduction of the compressibility of the soils, swelling, shrinkage, plasticity and makes the soil mixture more resistant [6,10].

Alkaline activation (AA) has grown as one of the binders that were introduced as a replacement of cement due to the environmentally friendly materials and low emission of carbon dioxide. It is also known as one of the “geopolymers”, where it is touted for its high performance (in terms of durability and strength), low energy consumption and low CO2 emission [11]. [12,13] stated that the binders are formed by the reaction of amorphous aluminosilicate source with alkali which is usually either alkali-earth (Ca) metals, potassium(K) or sodium hydroxide (Na) that was included in the dissolution of the mineral aluminosilicates and followed by the condensation and hydrolysis of the silica (Si) and alumina (Al) components which are consequential in the formation of a three dimensional, essentially aluminosilicate gel and are amorphous. Particularly, usage of the waste material as a precursor for AA is due to the element that is rich with silica (Si) and aluminium (Al), which helps in binding gel in soil voids and thus perform a formation of sodium aluminium silicate hydrate (N-A-S-H) or calcium aluminium silicate hydrate (C-A-S-H) [5]. Many past studies [5,14–18] have reported on the effectiveness of the AA as the stabilizer which significant in the improvement of the soil strength, helps in compacting the microstructures as well as filling the voids inside the soil.

Presently, fibre has also been used as a mixture in the soil to improve the behaviour of the soils. However, the focus nowadays is on environmental and sustainability awareness which is more likely to involve natural fibre that is used as reinforcement in the soil matrix. Many past researches have conducted a test by including different types of fibre such as geo- fibre, jute, nylon, sisal fibre, kenaf fibre, palm fibre and many other types of fibre at different types of soil. They concluded that inclusion of the fibre in the soil increased the ductility, compressive strength, and moisture content, and reduced the maximum dry density of soil, increased tensile strength and enhanced the strength of the California Bearing Capacity (CBR) [17,19–22]. Coir fibre is one of the natural fibres that is found to have a good strength characteristic and resistance to biodegradation over a long period of time [23]. Coir fibre usage was discovered and made popular as soil reinforcement property as it has the advantages of increasing the tensile strength and durability of the soil. According to [24], there are many advantages of using coir fibre as soil reinforcement which is due to the ability to absorb water, the environmentally friendly materials, good durability and high tensile strength. It is also noticeable that fibre with lime treated soil is better than the untreated soil [25]. Other than that, a study by [26], wherewith the fibre inclusion in the soil increases the efficiency in transferring the load matrix to the fibre especially after 6 months of curing dates. Subsequently, the usage of coir fibre increases the strength and stiffness of soil which is attributed to an improvement in the effect of reinforcing fibre [26].

Therefore, in this study, both lime and AA are used as a stabilizer in improving the strength of the marine clay soil. Stabilization using the lime and fly ash has proved to increase the strength and stiffness of the soil. However, the utilisation of the chemical agents itself was not solving the brittleness of the treated marine soil. Therefore, the inclusion of fibre treated as a soil reinforcement has commonly been recognized as one of the methods in improving the brittleness of soil. The main objective of this study is to evaluate the effect of soil marine clay treated with lime and AA inclusion fibre. Comparisons between the untreated and treated soil using the chemical stabilizer were made with a series of Unconfined Compression Strength tests (UCS), Indirect Tensile Strength tests (ITS), and Flexural Strength tests (FS). Understanding the mechanism of the soil fibre matrix was also conducted using the field emission scanning electron microscope and energy dispersive X-ray.
2. Materials and Methods

2.1. Materials

2.1.1. Marine Clay

In this study, marine clay soil sample was obtained from Jeram, Selangor. The sample was collected near the coastal area at a depth of 2 m from the ground surface. The soft clay soil was excavated using a backhoe and the condition of the soil while excavating was observed to be high in moisture content. Tables 1 and 2 listed the physical properties and analysis of the chemical composition of the marine clay soil used in this study, respectively. According to the [27], the natural clay is classified as clay with high plasticity (CH). For the X-ray diffraction (XRD) analysis, the dominant mineral on the clay soil shows that the clay soil is rich with montmorillonite-illite, quartz, mica and halloysite materials.

| Parameter          | Values   | Method Standard       |
|--------------------|----------|-----------------------|
| Moisture Content   | 72%      | BS 1377-2-1990        |
| Specific Gravity   | 2.59     | BS 1377-2-1990        |
| Particle Size      | Clay—31% | BS 1377-2-1990        |
| Distribution       | Silt—67% | BS 1377-2-1990        |
|                    | Sand—2%  | BS 1377-2-1990        |
| Plastic Limit      | 32%–40%  | BS 1377-2-1990        |
| Liquid Limit       | 57%–72%  | BS 1377-2-1990        |
| Plasticity Index   | 25%–37%  | BS 1377-2-1990        |
| pH                 | 7.5      | BS 1377-3-1990        |
| Organic Content    | 6.88%    | BS 1377-3-1990        |

Table 2. Chemical Composition of Clay.

| Compound Oxides | (%) by Weight |
|-----------------|---------------|
| SiO₂            | 75.84         |
| Al₂O₃           | 12.09         |
| Fe₂O₃           | 3.47          |
| K₂O             | 1.51          |
| MgO             | 1.33          |
| Na₂O            | 1.13          |
| CaO             | 0.72          |
| TiO₂            | 0.68          |
| P₂O₅            | 0.092         |
| LOI             | 3.14          |

2.1.2. Coir Fibre

The fibre that was used in this study was coir fibre which is a fibrous material from coconut husk. The coir fibre is known as a material that is lighter, has high tensile strength, high hemicellulose, cellulose and lignin, which gives it lower degradation compared to other natural fibres. The material is also known to be environmentally friendly which benefits, nature where it can be used as soil reinforcement. The coir fibre was obtained from a factory at Batu Pahat, Johor with diameter of 0.15–0.45mm. Table 3 below presents the chemical and physical analysis of coir fibre.
Table 3. Chemical and physical analysis of coir fiber.

| Basic Properties | Value |
|------------------|-------|
| **Chemical Analysis** |       |
| Ash (%)          | 2     |
| Cellulose (%)    | 44    |
| Lignin (%)       | 48    |
| Water Soluble (%)| 6     |
| **Physical Properties** |       |
| Diameter (mm)    | 0.15–0.40 |
| Unit Weight (kN/m³) | 14    |
| Breaking elongation (%) | 30  |
| Length (mm)      | 50–200 |
| Tensile Strength (MPa) | 50–118 |

2.1.3. Additive

**Lime**

Calcium hydroxide (CaOH)₂ was used as one of the additives for the soft clay stabilizer. The reagent was supplied by Evergreen Engineering, Selangor in powder form where the purity of the content is more than 90%. The lime was kept in a tight container to preserve the originality of the content.

**Fly Ash**

Fly ash (FA) was obtained from Lafarge Sdn Bhd company in Selangor as a residue from the coal-burning process. Table 4 summarizes the chemical composition of fly ash using XRF testing. The major oxides presented below in Table 4 have a total chemical composition that is more than 70%, which is a standard requirement in accordance with [28] for fly ash (class F).

Table 4. Chemical composition of fly ash.

| Major Oxides | (%) by Weight |
|--------------|---------------|
| SiO₂         | 57.471        |
| Al₂O₃        | 15.365        |
| Fe₂O₃        | 4.707         |
| CaO          | 3.317         |

**Activator**

As for the activator, a potassium hydroxide (KOH) solution with 10 Molar was chosen as it has been proven as an effective molarity to be employed as alkaline activators. Potassium hydroxide in pellet form with the purity of more than 90% was also used. The solution was first diluted with one litre of distilled water and stirred for about 10 min to make sure it was fully dissolved. The solution was then left for about 24 h to cool down before it could be used.

2.2. Method

2.2.1. Sample Preparation

Two types of main sample were prepared in this investigation study. One with lime and the other one with AA for the soil stabilization. The sample preparation was done after getting the optimum moisture content for the soil specimen (Table 5). First, the marine clay soil was dried for 24 h in an oven and was ground until soil passed through a 2 mm sieve. For lime treatment, the soil was mixed with 5% of dry weight lime and 1% of modified coir fibre with an appropriate water content. The usage of
5% of lime was considered based on the experience as lime fixation for gaining the maximum strength at which the considerable increase of workability can be obtained [29–31]. The percentage of lime was also related to the montmorillonite- rich clay which normally does not exceed 8% of the usage in soil stabilization [29]. As for alkaline, effective fly ash is 60% [17] with 10 molar potassium hydroxide (KOH). KOH solution was first diluted with 1 L of distilled water in order to achieve the effective concentration of 10 molar KOH. The solution was then left to cool for about 24 h before being added to the soil mixture. The preparation of 10 M concentration was based on the past finding of researcher’s studies [29,32,33]. Table 5 shows the mixture proportion of the various testing done in this study.

Table 5. Mixture proportion of the various test.

| Group Series | Test Number | Samples | Optimum Moisture Content (OMC) (%) | UCS/ITS/ FS Curing Days |
|--------------|-------------|---------|------------------------------------|------------------------|
| C            | C           | Natural Soil | 31                                  | 7, 28 & 90             |
| CLF          | CL          | Clay + Lime + | 30.5                               | 7, 28 & 90             |
|              | CLF         | Clay + Lime + Fiber | 35                                  | 7, 28 & 90             |
| CFA          | CFA         | Clay + FA(60) + 10 KOH | 23                                  | 7, 28 & 90             |
|              | CFAF        | Clay + FA(60) + 10 KOH + Fiber | 22.4                              | 7, 28 & 90             |

Where, C = Natural Soil (Clay), CL= Clay + Lime, CLF= Clay + Lime + Fibre (1%), CFA= CFA + Activator, CFAF= CFA + Activator + Fibre (1%).

2.2.2. Geotechnical Testing

Unconfined Compression Strength Test

Unconfined Compressive Strength (UCS) is defined as load per unit area where the maximum unit axial compressive stress was compressed until it failed. In this study, the UCS test was conducted based on the guidelines outlined in [34]. A cylindrical sample was prepared with 50 mm diameter and 100 mm height using a 45 mm diameter steel rod applied as a static load in three layers, similar to the compaction method. Then, the cylindrical sample was extruded using the extruder and immediately was wrapped with a plastic cover and aluminium foil to prevent moisture loss. The sample was then cured for the selected curing time, which was for 7, 28 and 90 days prior to testing. When the respective curing period had elapsed, the sample was then subjected to axial compression (UCS) at a rate of 1 mm/min until failure occurred.

Flexural Test (Three Point Bending)

The preparation of the soil specimen was the same as the previous test. For the flexural test, the soil was placed on the simply supported span with a length of 60 mm as shown in Figure 1. The test was conducted according to [35] with a loading rate of 0.1 mm/min until the specimen experience failure in the test. The result of the flexural test was determined by using Equation (1) below:

\[
\sigma_f = \frac{PL}{\pi r^3}
\]  

where \( P \) is maximum load of the stress (N), \( L \) is the distance between the support which is 60 mm and \( r \) is the radius of the specimen (mm).
Figure 1. Three-point bending test.

Indirect Tensile Strength Test

The behaviour of cylindrical soil mixtures with 50 mm diameter and 100 mm length were diametrically loaded between two platens in order to determine the tensile strength of the soil as shown in Figure 2 below. The specimens were tested until it reached its strength limit which was adapted based on [36] and as well as described by [37]. The loading rate of the test was 1.0 mm/min and when the specimen reached the peak or failure in which the condition usually split along the loaded plane, the ITS test was calculated based on [38] (Equation (2)),

\[ \text{ITS} = \frac{2P_{ult}}{\pi t D} \]  

(2)

where \( \text{ITS} \) is indirect tensile strength test, \( P_{ult} \) is applied as ultimate load at which the failure occurred (N), \( t \) is thickness of the soil specimen (mm) and \( D \) is the diameter of the soil specimen (mm).

Figure 2. Indirect Tensile Strength Test.
2.2.3. Microstructural Analysis

Field Emission Scanning Electron Microscope (FESEM) and Energy Dispersive X-Ray (EDX) analysis were done to assess the morphology and chemical composition for the specimen before and after testing was done on untreated and treated soil. The specimen was using Hitachi SU8010 machine for both of FESEM and EDX analysis. Once the specimen dried, it was mounted at the platinum plate using a carbon tape before being sputter coated. The function of the sputter coating is to increase electrical conductivity on the surface of the specimen and thus reduce the charges.

3. Results and Discussion

3.1. Unconfined Compressive Strength

Figure 3 depicts the compressive stress versus compressive strain behaviour of untreated and treated soil specimen at different curing periods, which are at 7, 28 and 90 days. Untreated and treated soil mixed with lime and alkaline activation with the inclusion of fibre were examined. It is clearly observed that the strength of the soil radically increased after 7 and 28 days curing period (Figure 3a,b) with 0.85 and 1.19 MPa (lime) and 3.21 and 7.90 MPa (AA) for the treated soil respectively. However, the result continues to increase higher after a longer curing period (90 days) with 1.57 (lime) and 10.96 MPa (AA) for both treated soil as shown in Figure 3c compared to untreated soil with the strength of 0.15, 0.20 and 0.21 MPa for all of the three curing periods. As reported by [39,40], the improvement of the soil strength is also contributed to by the curing period and the addition of fibre. This is mainly due to the interaction of calcium chloride (lime) and the ion in the KOH activator (AA) that allowed dissolution of the chemical and a higher degree of ionization to happen.

Figure 3a and Table 6 show that the specimens of untreated soil show higher ductile behaviour at a failure strain of 11.96% compared to treated soil specimen. As for the CLF and CFAF specimen, the failure strain shows 4.05% and 1.75%, respectively. This indicates that the ductility of the soil behaviour changes from brittle to ductile which can be explained by the sudden strength reduction that occurred after the peak axial stress value reached the maximum limit. According to [41], this occurrence due to the movement of the fibre tensile strength occurred upon loading and the following
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| Mixture | Curing Period (Days) | Failure Strain (%) | Secant Modulus (E_s) MPa | Deformability Index (I_D) |
|---------|----------------------|--------------------|--------------------------|--------------------------|
| Clay    | 7        | 11.96              | 0.013                    | -                        |
|         | 28       | 10.98              | 0.018                    | -                        |
|         | 90       | 23.00              | 0.0091                   | -                        |
| CLF     | 7        | 4.05               | 0.21                     | 0.34                     |
|         | 28       | 1.75               | 0.68                     | 0.16                     |
|         | 90       | 3.25               | 0.48                     | 0.14                     |
| CFAF    | 7        | 1.75               | 1.83                     | 0.15                     |
|         | 28       | 1.90               | 4.16                     | 0.17                     |
|         | 90       | 4.19               | 2.16                     | 0.18                     |

Secant Modulus (E_s) and Deformability Index (I_D)

The result of secant modulus and deformability index that obtained from the unconfined compressive strength test (UCS) for the untreated and treated specimen after 7, 28 and 90 days curing period were tabulated as in Table 6. The secant modulus is a parameter in identifying the elasticity of the stiffness of soil. Secant modulus is also known as Young Modulus (E_s) by [43,44] were the compressive strength was divided towards the strain in the stress–strain curve (elastic part). The test is conducted in order to characterize the elasticity or stiffness of the soil. From the results, it can be seen that the specimen encounters an increasing trend for all of the specimens at 7 and 28 days curing periods. The increment of the secant modulus for both 7 and 28 days curing period for both stabilized soil with lime and alkaline activation are roughly 15.15 and 36.77 (lime) and 139.77 and 230.11 (alkaline activation) times greater than compared to the untreated soil specimens, respectively. The increment of the secant modulus for both additives with fibre inclusion associate with the past research that has been carried out by [39,45]. Meanwhile, for the 90 days curing periods, the result shows decrement for the secant modulus with about 29% and 48% for both lime and alkaline activation compared to the 28 days curing periods, respectively. This might be due to the fact that the longer curing periods decrease the stiffness or elasticity of the soil for both treated soil with lime and alkaline activation. This trend of decrement also can be seen similar to the untreated soil specimen at 90 days curing period. The decrement of the secant modulus for the treated soil (lime and alkaline) can be correlated to the strength of the soil obtained from the UCS test (Figure 3b,c) where the increment in the soil strength between 28 days curing period and 90 days curing period is not too significant.

The deformability index is defined as the maximum axial strain occurs at the peak of UCS for treated soil towards the axial strain at the peak of UCS for untreated soil specimen. This parameter is used to determine the deformation behaviour that occurs on soils [44,46]. It can be clearly seen in Table 6, where the deformability index decreases as an increase of the curing periods for the treated with lime from 0.34 to 0.14. The decrement can be seen due to the less pozzolanic reaction that at the first stage of 7 days curing period which contribute to forming the specimens towards the more brittle condition. This trend is similar with findings by [44] which were that increasing the curing period and degree of saturation decreased the deformability of the soil specimens, which shows the specimen to
be more brittle. Other than that, as the curing period increased towards 90 days curing period, the lesser the deformability index obtained which shows the bonding between the stabilized soil and fibre inclusion helps in strengthen the soil thus reducing the deformation behaviour. For the deformability index of treated soil with alkaline activation, the results show a not significant increment over of the curing periods with 0.15 to 0.18. This may be due to the higher compressed loading towards the soil that contributes to increasing the strain thus increasing the deformability index. Hence, lime and alkaline activation stabilizer with fibre inclusion have consequently caused an effect to compressibility behaviour of soil such as for the UCS test, failure strain, secant modulus and deformability index. This finding also similar to findings by [44,47].

3.2. Flexural Strength Test

Figure 4 presented load versus vertical displacement of flexural strength test performed on untreated soil (C) and treated soil matrix of CLF and CFAF for 7, 28 and 90 days. The results were evaluated right after the soil specimens reached the ultimate load from the computed flexural strength. From the figure, it can be observed that the displacement increases with an increase of curing period. This was due to the increase of the soil specimen strength during the curing period and at the same time increase the displacement of the soil specimen. The peak flexural load was observed to have significant increment of strength with the addition of fibre as reinforcement in the soil treated. The increment with the addition of fibre is by 0.42, 0.48 and 0.65 MPa (lime) and 0.87, 2.97 and 4.56 MPa (AA) compare to untreated soil with only 0.05, 0.07 and 0.08 MPa for 7, 28 and 90 days curing period.

Other than that, as commonly known, lime and fly ash can disperse the admixture particles that improve soil strength. A good dispersion of the admixture particles will lead to better filling of the pores between soil particles with the inclusion of fibre in making a soil matrix more stiff. The statement was the same trend with [48–50] in which the usage of cement is a good dispersion as it will lead to a better filling of spaces between the soil particles making the solid matrix more resistant.

![Figure 4. Load versus Displacement (Flexural) for (a) 7 days, (b) 28 days and (c) 90 days.](image-url)
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3.3. Indirect Tensile Strength Test

A plot of load against displacement for the curing period of 7, 28 and 90 days was shown in Figure 5. The continuous reduction in displacement is observed with the treated soil samples with fibre. At the curing period of 7 day, the load keeps increasing with 165.63 N, 1066.85 N and 4023.85 N respectively by decreasing the displacement to 1.74, 1.00 and 0.36 mm for all specimens. The trend on increasing load with the decreasing displacement was same as the 28 and 90 days which applied to 234.93, 1966.31 and 10,115.89 N to 1.50, 1.05 and 0.62 mm for 28 days and 280.33, 2269.21 and 12,841 N to 1.66, 0.82 and 1.12 mm for 90 days curing. Meanwhile, it is noticeable that there is a high contrasting obtained for CFAF for all curing period compared to untreated soil which indicates soil stiffness. It can be explained due to the inclusion of treated fibre with alkaline activation resulting in changes of the behaviour of soil and improvement of soil strength. According to [51], the tensile strength of modified fibre with lime soil can be explained by the altered surface morphology which results in the soil strength enhancement.

![Figure 5](image)

**Figure 5.** Load versus displacement (indirect tensile strength) for (a) 7 days, (b) 28 days, and (c) 90 days.

3.4. Microstructural Analysis

A series of micrograph study was conducted on three different specimens which were untreated soil (C), stabilized soil mixture with lime (CLF) and stabilized soil mixture with alkaline activation (AA) after 28 days of curing by using the field emission scanning electron microscope. It is clearly seen from Figure 6a that, the untreated clay soil shows a discontinuous and fractured structure with a presence of voids and macropores. At this view, it can be observed that there is high porosity qualified
as inter-agglomerate between the clay particles. As the specimen was being zoomed, it can clearly be seen that the clay particles have huge large coated aggregated soil particles among it (Figure 6b).

Figure 6. FESEM images for untreated soil.

![FESEM images for untreated soil.](image)

Figure 7 shows the FESEM images for the stabilized soil with lime inclusion fibre, after 28 days curing period. The treated soil matrix with lime (Figure 7) depicts the pozzolanic reaction that occurs to produce cementitious products resulting in compacted soil particles as can be seen by the presence of white cementitious gel around the soil matrix. As can be observed in Figure 7, there are only smaller pores appearing after the soil treatment which indicates that the lime and fibre help in coating the agglomerate particles thus increasing the strength of the soil. Other than that, this is due to the reaction between the soil and fibre in filling the voids inside. The filling of the voids is attributed to the significant increase in strength similarly noted by [52], in soil treated with 6% of lime at 28 days curing periods, causing an increase in strength with a reduction in the coefficient of permeability. The surface treatment with 5% lime and the inclusion of fibre shows a significant result from the untreated soil in Figure 6 which improves the mechanical properties due to the development of the C-A-S-H compound that covered the surface area.

![FESEM images for treated soil with inclusion of fibre (CLF).](image)

Figure 7. FESEM images for treated soil with inclusion of fibre (CLF). (a) Compacted soil matrix with treated lime and fibre, (b) Soil particles were coating by white cementitious gel. FESEM images for treated soil with inclusion of fibre (CLF).

Figure 8a,b shows micrographs of the fly ash and soil treated with AA, respectively. The microstructural of fly ash illustrated in Figure 8a shows that there is an irregular round shape
particle. As the fly ash particles mixed with the activator (Figure 8b) shows a distributed spherical shape attributed to having bonded with the parent soil. The AA with the fibre binds and coats together with the aggregated soil particles thus leading to a compacted and dense structure that reflects in consumption of the cementitious gel filling inside the voids. Although there are still some voids or pores appearing as in Figure 8b, the soil matrix shows an increase of the soil strength with the absence of the additive relative to the untreated clay soil. This can be confirmed by the UCS result for the treated soil with alkaline activation for 28 days curing periods.

Other than that, this can also be supported with the EDX analysis (Table 7) result where the chemical composition of Si and Al elements were detected in the alkaline activator treated clay soil, as clearly seen in Figure 8 which signals that the alkali activator had taken place in treated clay soil with the presence of SiO₂ and Al₂O₃ in the soil lime and alkaline activator. The result signifies that large voids in the untreated soil (Figure 6) have diminished with the filling of fly ash and lime in those voids with the admixtures. As it can be seen, the formation of Si-O-Al and Si-O-Si bonds occurs from the dissolution of the fly ash contributing to the overall aluminosilicate gel, typically low- Ca AA blends. Other than that, the presence of high Si elements on the surface of the coir fibre has enhanced the formation of the bond that is strongly wrapping around the admixture. This is in line with the high increase in strength registered by the soil stabilization mixture, relative to the untreated soil specimen.

![FESEM images for treated soil with inclusion of fibre (CFAF).](image)

**Figure 8.** FESEM images for treated soil with inclusion of fibre (CFAF).

Table 7 shows the weight percentages and the corresponding ratios of all the major elements found in the samples for EDX test. Of all of the element composition, the major relative concentrations found are alumina (Al), silica (Si) and sodium (Na) for the untreated soil clay which are elements existing in nature. From Table 7, it can be observed that the presence and increment percentage of Si for the treated specimens with lime and alkaline activation confirms that there is formation of cementitious compound occurring caused by the pozzolanic reaction after 28 days curing periods compared to the untreated clay soil. Similarly, the percentage of Al for the treated sample happens to be increased in contrast to the untreated clay soil. In addition, from the calculated ratio of Ca:Si, and Al:Si illustrate that there be changes on the compositions for the surface particles due to the coating of pozzolanic reaction or new minerals products formed between the soil with lime or with alkaline activation interactions.

### Table 7. Energy Dispersive X-Ray Element for All Specimens.

| Element | Si   | Al  | Ca  | Si/Al | Ca/Si | Al/Si |
|---------|------|-----|-----|-------|-------|-------|
| Clay    | 21.49| 7.86| 0.99| 2.73  | 0.05  | 0.37  |
| CLF     | 19.87| 3.85| 4.73| 2.88  | 0.72  | 0.35  |
| CFAF    | 24.36| 6.19| 3.33| 3.3   | 0.31  | 0.3   |
The increment of the chemical percentage was due to the commencement of the pozzolanic reaction in conjunction with the time elapse through dissolution of alumina and silica discovered in the soil and calcium presented in lime and alkaline activation stabilizer at higher pH value (>10) for both, confirming the significant increase in strength. This observation similarly was reported by [52]. In addition of lime attributed to the increment of chemical percentage after 7 days curing period. Besides that, the ratio of the Ca:Si, and Al:Si show increase and decreases with the curing periods relative to the untreated clay soil. This was enclosed with the cementitious reaction products of calcium- silicate hydrate (C-S-H), calcium aluminate hydrate (C-AH) and calcium aluminium silicate hydrate (CASH) in which the reaction indicates high peak element of Si, Al and Ca from EDX analysis. This observation on cementitious reaction is similar to that reported by [53,54]. Ratio of Ca/Si was found to be in the range of 0.24 to 1.73 by [54] where it contributes to the reduction in linear shrinkage values and where the changes in plasticity properties of clay could be predictable.

4. Conclusions

Having an environmentally friendly and green technology are an important aspect in overall development these days. In line with this, an approach of using coir fibre treated in marine clay soil stabilization was investigated. A positive finding of this research study has proven that existence of combination action among the lime and alkaline activation on soft clay soil has overcome the problems in stabilizing. From the experiment work, the summarize detailed conclusions are as follows:

- Inclusion of fibre in treated soil for lime and alkaline stabilized soil increases the compressive strength, tensile strength and indirect tensile strength test for both chemical agents.
- The inclusion of fibre in the treated soil enhances the post-peak behaviour at the different curing period of 7, 28 and 90 days.
- There is an important pozzolanic reaction that occurred after 28 days curing period for treated soil with lime and alkaline activation compared to the untreated clay soil.
- Stabilization on soil using reinforce alkali activation shows higher strength compared the utilization by lime for all curing periods. The noticeable is clearly seen after 90 days of curing periods. The interfacial interlocking of treated soil and fibre shows a good bonding compared to the untreated soil.
- Analysis of FESEM and EDX shows that, reaction occurs between the treated soil with lime and alkaline activation contributes to denser soil. The reaction also seems to bind the soil particles around and strengthen the soil.
- Cementitious reaction products of calcium- silicate hydrate (C-S-H) and calcium aluminium silicate hydrate (C-A-S-H) for lime and formation of Si-O-Al and Si-O-Si bonds for alkaline activator shows that interaction between fibre and treated soil contribute in enhance the behaviour of reinforced mixtures.

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