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# Assessment of compressibility behavior of organic soil improved by chemical grouting: An experimental and microstructural study

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**Abstract.** Tropical organic soils having more than 65% of organic matters are named “peat”. This soil type is extremely soft, unconsolidated, and possesses low shear strength and stiffness. Different conventional and industrial binders (e.g., lime or Portland cement) are used widely for stabilisation of organic soils. However, due to many factors affecting the behaviour of these soils (e.g., high moisture content, fewer mineral particles, and acidic media), the efficiency of the conventional binders is low and/or cost-intensive. This research investigates the impact of different constituents of cement-sodium silicate grout system on the compressibility behaviour of organic soil, including settlement and void ratio. A microstructure analysis is also carried out on treated organic soil using Scanning Electron Micrographs (SEM), Energy Dispersive X-ray spectrometer (EDX), and X-ray Diffraction (XRD). The results indicate that the settlement and void ratio of treated organic soils decrease gradually with the increase of cement and kaolinite contents, as well as sodium silicate until an optimum value of 2.5% of the wet soil weight. The microstructure analysis also demonstrates that with the increase of cement, kaolinite and sodium silicate, the void ratio and porosity of treated soil particles decrease, leading to an increase in the soil density by the hydration, pozzolanic, and polymerisation processes. This research contributes an extra useful knowledge to the stabilisation of organic soils and upgrading such problematic soils closer to the non-problematic soils for geotechnical applications such as deep mixing.

**Keywords:** organic soil; compressibility; settlement; void ratio; porosity; chemical binders

## 1. Introduction

Organic soils having more than 65% of organic matters are defined as peat or peaty soils, which are usually soft and consist of partly decomposed or undecomposed fibrous organic material derived from plants and micro-bacteria (Muhamad *et al.* 2010). Since the main component of these soils is organic matters, they all share the common characteristics of high water content, high compressibility, and low stiffness (Craig 1992, Deboucha *et al.* 2008). Organic matters play a central role in the functioning of the overall soil ecosystem. As such, it is often used as a proxy for soil quality in soils undergoing reclamation (Turcotte *et al.* 2009, Quideau *et al.* 2017). Peat deposits are found in many geologic and geographic settings throughout the world and constitute 5-8% of the earth’s land surface. Two-third of the world coverage of tropical peat is located in South East Asia. In Malaysia, for example, peatlands occupy an area of about 2.6 Mha, representing about 8% of the country’s total land area (Huat *et al.* 2013, Melling 2016).

Generally speaking, settlement of soils is divided into three different main components, including initial settlement, primary consolidation settlement, and secondary consolidation settlement or creep. The settlement of organic soils, especially peaty soils, are very rapid and higher than other soils; in peat, the creep settlement plays a significant role and represents a big portion of the total settlement than other soil types (Kazemian and Huat 2009). There is also a possibility in peaty soils that the secondary compression settlement commences before the dissipation of excess pore water pressure is completed and it is often difficult to obtain the beginning of the secondary compression settlement from the consolidation curve because the preliminary consolidation occurs rapidly (Leonards and Girault 1961, Yulindasari 2006). Mesri and Ajlouni (2007) stated that the fibre content, void ratio, water content, permeability, soil nature, and arrangement of soil particles are the main factors affecting the compressibility characteristics of peat. The compression index ($c_c$) of peat is estimated to range from 2-15, whereas the ratio of secondary compression ($c_\alpha$) to compression index ($c_\alpha/c_c$) for peat is estimated to range from 0.05-0.07 (Dhowian and Edil 1980, Mesri *et al.* 1994).

Some soil deposits in their natural form, such as problematic and organic soils, are unsuitable for construction purposes and thus need some sort of prior treatment. They either need to be excavated and replaced, or their properties should be modified before they can sustain the applied loads induced by the superstructures (Ikeagwuani and Nwonu 2019). Two methods are often employed for soil stabilisation, including chemical and

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mechanical techniques. Each of these methods may be used independently or simultaneously, in an attempt to optimise the overall benefit (Soltani *et al.* 2018, Zhou *et al.* 2020). Over the last few decades or so, chemical grouting has grown and owed its separation as one of the most important ground improvement techniques in geotechnical engineering practices. The literature includes many project reports concerning chemical grouting applied to stabilization of mineral soils; however, very few projects are available concerning the application of chemical grouting on organic soils (Kazemian *et al.* 2012, Radhakrishnan *et al.* 2017). Chemical grouting is the process of injecting a chemically reactive solution into the soil and has been used frequently in different projects for improving properties of soils and controlling water movement (US Army Corps of Engineers 1995). Chemical grouts behave as water-soluble polymers and cannot contain any solid particles, which helps with being injected into the fine soils easily but reacts after a predetermined time to form a solid, semi-solid, or gel (Bolisetti 2005, Lin *et al.* 2018). Among all chemical grouts, sodium silicate grouts are so popular because of their safety, environment-friendly, and environmental compatibility (Baker 1983, Hesnawi 1996). Generally, the ingredients of sodium silicate chemical grouts include aqueous sodium silicate, water and a neutralisation reagent. Several types of reagents exist for sodium silicate grouts, including organic compounds (Malone 1996). In this research, the advantages of using different constituent amounts of a cement-sodium silicate grout system for improving organic soil, in terms of void ratio and settlement, are evaluated by performing the Rowe Cell test and using Scanning Electron Micrographs (SEM), Energy Dispersive X-ray spectrometer (EDX), and X-ray Diffraction (XRD).

Table 2 Chemical composition of cement

| Constituent | Value (%) |
|---|---|
| $SiO_2$ | 21.0 |
| $Al_2O_3$ | 5.3 |
| $Fe_2O_3$ | 3.3 |
| CaO | 65.6 |
| MgO | 1.1 |
| $SO_3$ | 2.7 |
| $Na_2O$ | 1.0 |
| Loss on ignition | 0.9 |

Table 3 Chemical composition of sodium silicate

| Constituent | Value |
|---|---|
| $SiO_2$ (%) | 28.7 |
| $Na_2O$ (%) | 8.9 |
| Silica ratio ($SiO_2/Na_2O$) | 3.22 |
| Density (kN/m$^3$) | 13.8 |
| pH | 11.3 |

Table 4 Chemical composition of calcium chloride anhydrous powder

| Constituent | Value (%) |
|---|---|
| Minimum Assay Content of $CaCl_2$ | 96 |
| Alkalinity_$Ca(OH)_2$ | 0.04 |
| Sulphate_$SO_4$ | 0.02 |
| Magnesium and Alkalis (Sulphate) | 0.6 |

## 2. Materials and method

### *2.1 Materials*

Soft organic soils obtained from various locations in Kampung Jawa (Kelang) near Kuala Lumpur, Malaysia, are selected for this research; the properties of such soils are given in Table 1. Ordinary Portland Cement is selected as the first binder with the composition given in Table 2. The second binder is a chemical binder hiving two reactors/accelerators as hydrous sodium silicate (syrupy liquid) and calcium chloride anhydrous powder ($CaCl_2$). The second chemical binder and its reactor composition (provided by the manufacturer) are summarized in Tables 3 and 4.

Table 1 Soil properties of pure organic soils

| Parameters | Method | Soil |
|---|---|---|
| Moisture content (%) | BS 1377: Part 2, Clause 3 (BS, 1990) | 192 |
| Liquid limit (%) | BS 1377: Part 2, Clause 4.3 (BS, 1990) | 171.8 |
| Specific gravity | BS 1377: Part 2, Clause 8.4 (BS, 1990) | 1.36 |
| Organic content (%) | BS 1377: Part 3, Clause 4 (BS, 1990) | 83.31 |
| Bulk unit weight (Mg/m$^3$) | BS 1377: Part 2, Clause 7 (BS, 1990) | 1.07 |
| Shear strength (kPa) | BS 1377: Part 7, Clause 3 (BS, 1990) | 10.5 |
| pH | BS 1377: Part 3, Clause 9 (BS, 1990) | 5.8 |
| CEC (meq/100g) | Gillman and Sumpter (1986) | 82 |
| Surface area (m$^2$/g) | BET technique (1938) | 93 |

### *2.2 Methodology*

This section focuses on investigating the compressibility (i.e., void ratio and settlement) and microstrucal changes of organic soil stabilised with different components of sodium silicate system grouts. The study includes the effects of the ordinary Portland cement, kaolinite, and sodium silicate on treated organic soil.

#### *2.2.1 Soil sampling and sample preparation*

To determine the basic properties of the organic soil used, disturbed samples are mixed with different grouts. To get the soil samples, firstly, the top layer of the soil is removed to get rid of any unwanted plant and root material (around 1 m). The soil is then scooped out using a shovel and transferred to a plastic bag. The collected soil samples are placed and stored in the soil laboratory at the room temperature (below 30°C). Fig. 1 shows the field location from which the soil samples are obtained, indicating

(a) (b)

Fig. 1 Soil sampling and location: (a) organic soil at MARDI, Kampung Jawa, Klang and (b) collected organic soil

Table 5 Different concentrations of compounds used for preparing grouts (Formulae and notations are by weight of wet soil)

| Sample No. | Soil (gr) | Sodium Silicate (%) | Cement (%) | Kaolinite (%) | Water (ml) | $CaCl_2$ (%) | Time (days) |
|---|---|---|---|---|---|---|---|
| 1 | 170 | 0 | 30 | 30 | 340 | 1 | 30 |
| 2 | 170 | 1 | 30 | 30 | 340 | 1 | 30 |
| 3 | 170 | 2.5 | 30 | 30 | 340 | 1 | 30 |
| 4 | 170 | 5 | 30 | 30 | 340 | 1 | 30 |
| 5 | 170 | 15 | 30 | 30 | 340 | 1 | 30 |
| 6 | 170 | 0 | 20 | 30 | 340 | 1 | 30 |
| 7 | 170 | 2.5 | 20 | 30 | 340 | 1 | 30 |
| 8 | 170 | 5 | 20 | 30 | 340 | 1 | 30 |
| 9 | 170 | 0 | 30 | 20 | 340 | 1 | 30 |
| 10 | 170 | 2.5 | 30 | 20 | 340 | 1 | 30 |
| 11 | 170 | 5 | 30 | 20 | 340 | 1 | 30 |
| 12 | 170 | 2.5 | 0 | 30 | 340 | 1 | 30 |
| 13 | 170 | 2.5 | 0 | 20 | 340 | 1 | 30 |
| 14 | 170 | 2.5 | 30 | 0 | 340 | 1 | 30 |
| 15 | 170 | 2.5 | 20 | 0 | 340 | 1 | 30 |
| 16 | Pure organic soil | | | | | | |

minimal environmental disturbances.

To evaluate the components of the cement-sodium silicate grout system of the organic soils, different ratios of materials (% of the weight of wet soil) are admixed with pure organic soil, as given in Table 5. the organic soil, kaolinite and cement are poured into a container to mix with the wet soil, and calcium chloride (0.5 mol/L) is then added. After all the components are well mixed, the mixture is poured inside a PVC mould of a fixed volume. Finally, the sodium silicate is added and mixed with the mixture in the PVC mould. The mixture was immersed in the water for curing after the samples have set. The samples are cured in the water for 30 days before carrying out any test. After curing, the samples underwent a Rowe Cell consolidation test to investigate the compressibility behaviour of treated soil concerning different ratio and curing time.

### 2.2.2 Rowe cell consolidation test

Rowe Cell is used for evaluation of soil compressibility of treated organic soil versus time. The advantage of using the Rowe Cell is that it can overcome most disadvantages of the conventional oedometer apparatus when performing consolidation tests on low permeability soils, including non-uniform deposits. It is also able to control the drainage and measure pore water pressure during consolidation. Rowe Cell test is carried out according to BS 1377 Part 6 – 1990 (BS, 1990). Linear variable displacement transducer (LVDT) with 0.001 mm accuracy and pressure transducer with an accuracy of 0.1 kPa are used as measuring devices in the Rowe Cell. LVDT is used to measure the settlement of treated organic soil, and the pressure transducer is used to measure the back-pressure, diaphragm pressure, and pore pressure of the specimens. All measured data are read and stored in a personal computer, which uses the GDSLAB program to control the testing data for saving progress. Load increment is applied at 25, 50, 100, 200 kN/m$^2$ and unloaded at 25 kN/m$^2$; each load increment is maintained for 24 hours.

### 2.2.3 Microstructural study

The presence of the aqueous phase of different composition in a pore net varying over a large range alters the microstructure arrangement. Therefore, to investigate the microstructure of the sample, SEM, EDX, and XRD tests are carried out. The SEM provides reliable visual evidence of the effect of the cementitious products at binding the soil particles and the corresponding fabric pattern of the soil. Whereas, the EDX spectrometer and XRD are used in the examined formations of cementing materials of weak to strong intensities, from which the changes of microstructure and mineralogy for grout samples can be described clearly.

The soil samples are carefully cut with a sharp knife after 90 days of curing to make sticks, about 3-5 mm long. These sticks are then frozen immediately in nitrogen slush

(a) (b)

Fig. 2 Laboratory testing setup: (a) coating sample with a thin layer of platinum and (b) SEM and EDX apparatus

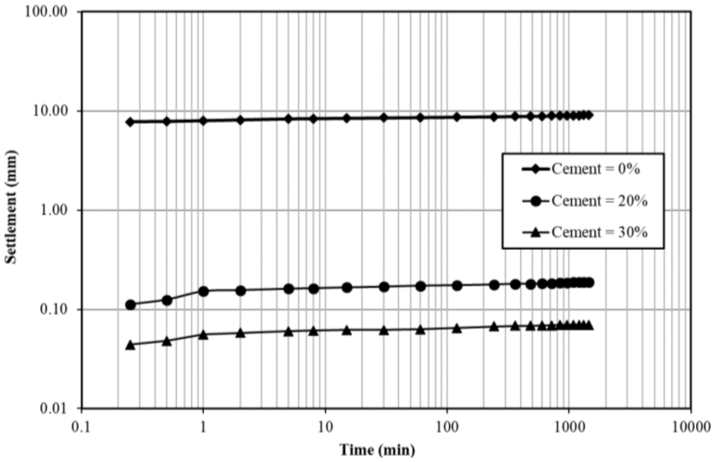



Fig. 3 Effect of cement on settlement versus time for pure and treated organic soils

at –210°C to retain the soil fabric. While the samples are still frozen, they are broken into small size clusters and placed into vacuum desiccators. Finally, the soil samples are coated (Fig. 2(a)) with a thin layer of gold–platinum for performing the SEM and EDX analyses; the coating time is 2 min with a specific electric current, producing a layer of around 30-50 nm thick on the samples. It should be mentioned that the EDX outputs are measured as the average of four measurements at the same location and microstructural studies with equipment brand Hitachi Japan (Model S3400N) are performed on each sample. Fig. 2(b) shows the SEM and EDX equipment used in this study. In addition to EDX and SEM, XRD is also conducted; the samples are ground manually in an agate mortar and then placed in sample holder with clean glass slides. The samples are then placed in the machine “X'pert high score plus” software and used to plot samples' XRD patterns.

## 3. Results and discussion

### 3.1 Effect of cement

The effect of the cement is studied for cement amounts equal to 0%, 20% and 30% by weight of wet soil, while other mixture components such as kaolinite, sodium silicate, and $CaCl_2$ remained constant. It is found that all of the compressibility parameters decrease as the amount of cement increases. As shown in Fig. 3, the settlement of the improved organic soil declines with the addition of cement, which makes the samples harder to be compressed.

The process of the cement mixing with water initiates a chemical reaction called hydration. Portland cement is a heterogeneous substance, containing minute tri-calcium silicate ($C_3S$) dicalcium ($C_2S$), tricalcium ($C_3A$), and solid solution described as tetra calcium alumino-ferrite ($C_4A$). When the pore water of the soil encounters with cement, hydration of cement occurs, and the major hydration (primary cementitious) produces hydrated calcium silicates ($C_2SHx$, $C_4AHx$) and hydrated lime $Ca(OH)_2$. Then, the secondary cementitious, known as the pozzolanic reaction, occurs when the hydrous silica and alumina react with the calcium ions liberated from the hydrolysis of cement to form insoluble compounds (Bergado 1996, Huat *et al.* 2019). The products of the secondary pozzolanic reaction are responsible for the long-term strength gain of the stabilized soil. Also, the strength increases with the increase of time (Hashim and Islam 2008).

Moreover, the strength of the cement is enhanced by the pozzolanic reaction since the cement is mixed with kaolinite and sodium silicate containing aluminous and siliceous

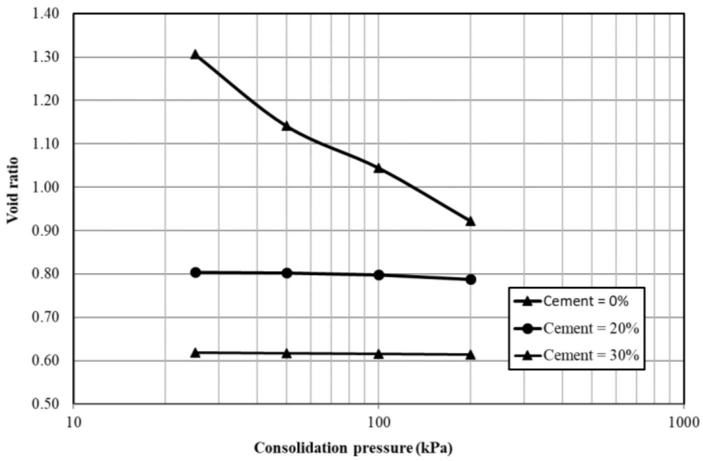



Fig. 4 Effect of cement on void ratio versus consolidation pressure for pure and treated organic soils

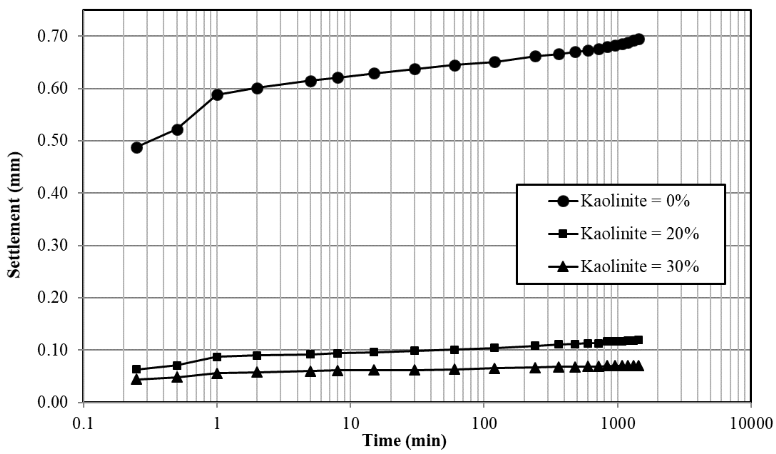



Fig. 5 Effect of kaolinite on settlement versus time for organic and treated organic soils

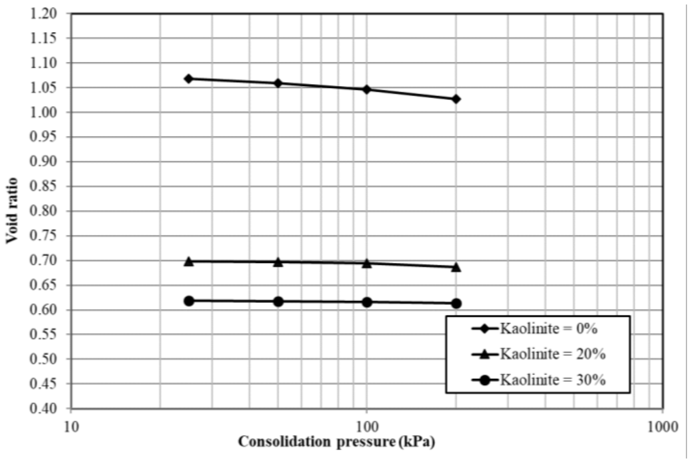



Fig. 6 Effect of kaolinite on void ratio versus consolidation pressure for pure and treated organic soils

minerals. Besides, the void ratio also decreases gradually with the increasing cement percentage (Fig. 4). Generally, the void ratio decreases with increasing cement despite the initial flocculation or structural change. This is because cement is used as a dry powder, and since cement is a hydraulic binding agent, using water to form cementation products decreases the void ratio. Other than that, it may also be due to the hardened skeleton matrix formed by the bonding of cement particles with adjacent soil particles in the presence of water, thus, improving the compressibility characteristics of treated organic soils.

### *3.2 Effect of kaolinite*

The effect of the kaolinite is investigated for ratios of kaolinite equal to 0%, 20%, and 30% by weight of wet soil, while other components remained constant. As shown in Fig. 5, the settlement declines gradually as the kaolinite

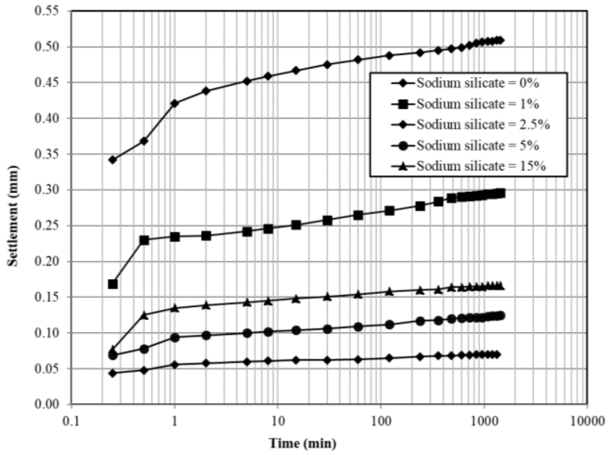



Fig. 7 Effect of sodium silicate on settlement versus time for organic and treated organic soils

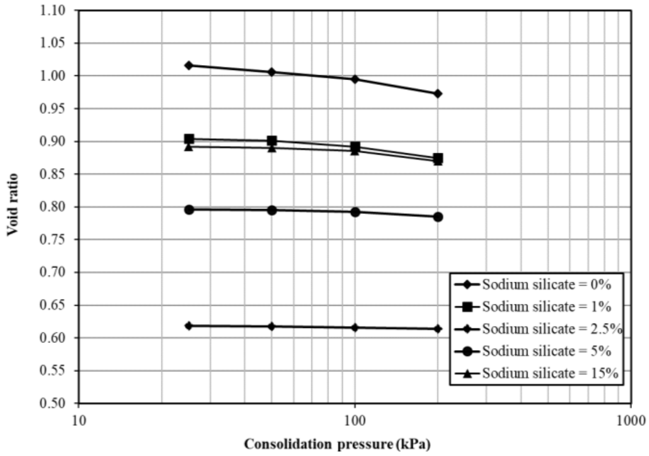



Fig. 8 Effect of sodium silicate on void ratio versus consolidation pressure for pure and treated organic soils

content increases, and this obvious when comparing the samples of 0% and 20% kaolinite. The results obtained reveal that the compressibility of organic soil decreases with the addition of kaolinite. However, the effect of the kaolinite in the compressibility behaviour is marginal compared to the effect of cement.

Due to the function of kaolinite as a pozzolanic material in the mixture, the compressibility of the sample is decreased. It enhances the strength of the cement through the pozzolanic reaction and the settlement declines as the strength increases. The pozzolanic reaction is responsible for the long-term strength gain of the stabilised soil. Besides, the ion exchange between the calcium ions from cement and calcium chloride with the ions present in the kaolinite causes an increase in the strength of the mixture. Therefore, with more kaolinite present, more ions are exchanged between the calcium ions; thus, the strength increases with the addition of kaolinite and compressibility decreases gradually. Other than that, based on the reasons mentioned above, the void ratio, as shown in Fig. 6, also decreases as the percentage of kaolinite increases.

### *3.3 Effect of sodium silicate*

The effect of the sodium silicate is investigated through ratios of 0%, 1%, 2.5%, 5%, and 15% by weight of wet soil, while other components remained constant. As shown in Fig. 7, as the percentage of sodium silicate increases, the settlement decreases until an optimum value is achieved, which is 2.5%. The sample with 2.5% sodium silicate has the lowest settlement, among other percentages. After the optimum value, the settlement increases gradually with the increase of sodium silicate content. The mixture of cement and sodium silicate in the presence of calcium chloride is intensively hydrated, and the $OH^-$ ions pass into the solution to be consumed for the reaction of depolymerisation and hydrolysis of the silicate anions of the additive. When the concentration of calcium and hydroxide ions reaches a specific value, the calcium hydroxides crystallise out of solutions, and this finally leads to the production of calcium silicate hydrate (C-S-H) and thus an increase in the shear strength. Hence, with the increase of shear strength, the compressibility decreases.

When the sodium silicate is mixed with soil, a polymerization process occurs to form a gel. This gel makes the binder behave as a glue which binds the soil particles together as a filler to reduce the void volume of the soil. The reduction of the void volume means that the densification of the soil is increased and thus, the void ratio and compression index are reduced. However, when an optimum value is achieved, the increase of the sodium silicate content will not have any effect on the densification,

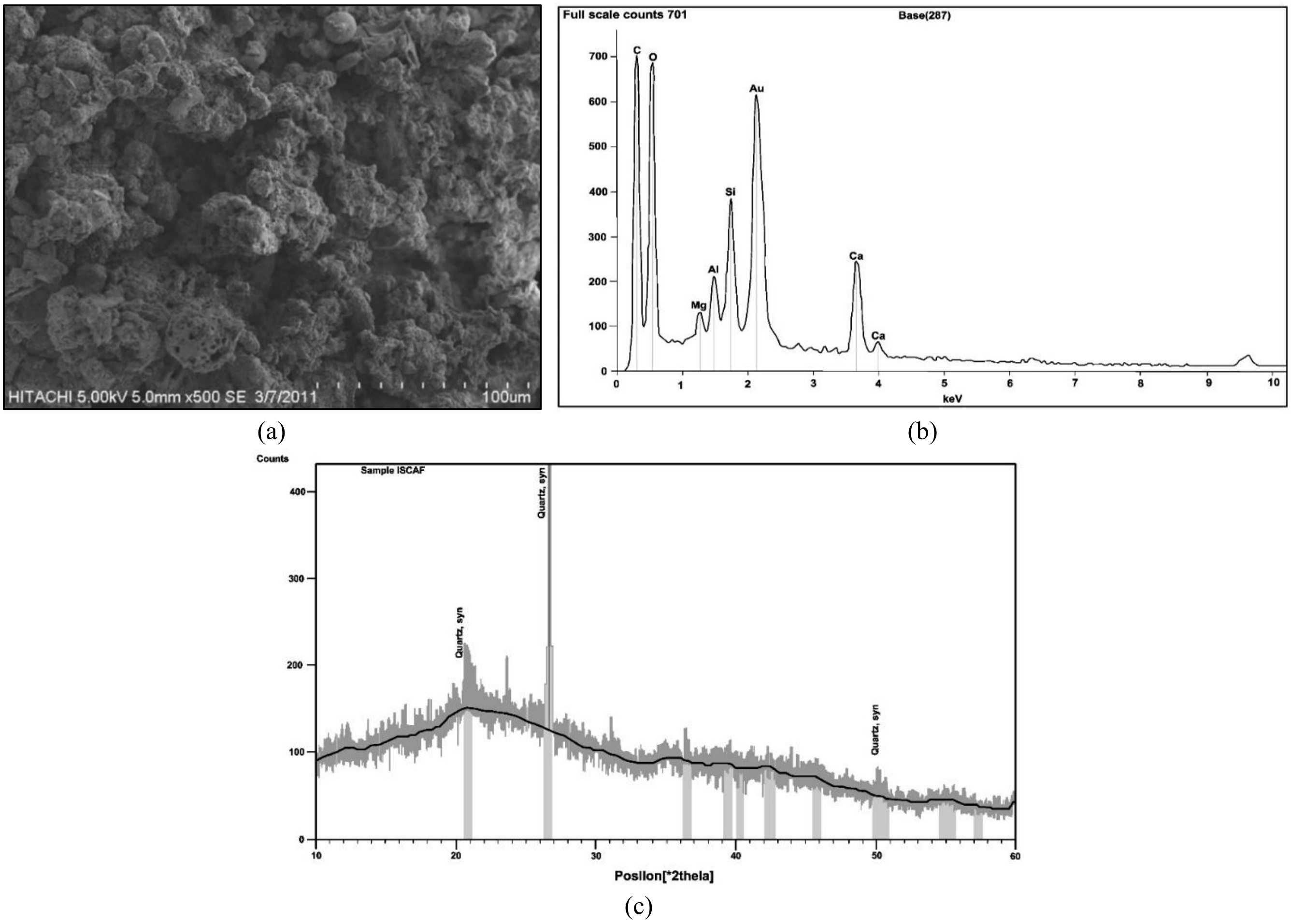



Fig. 9 Microstructure results of pure organic soil: (a) SEM, (b) EDX and (c) XRD

Table 6 Grout formulae for SEM, EDX, and XRD tests

| Grout No. | Grout Composition (% of wet soil weight) | | | |
|---|---|---|---|---|
| | Cement | Kaolinite | Sodium Silicate | Calcium chloride |
| 1 | 0 | 30 | 2.5 | 1 |
| 2 | 30 | 30 | 2.5 | 1 |
| 3 | 30 | 20 | 2.5 | 1 |
| 4 | 30 | 30 | 1 | 1 |

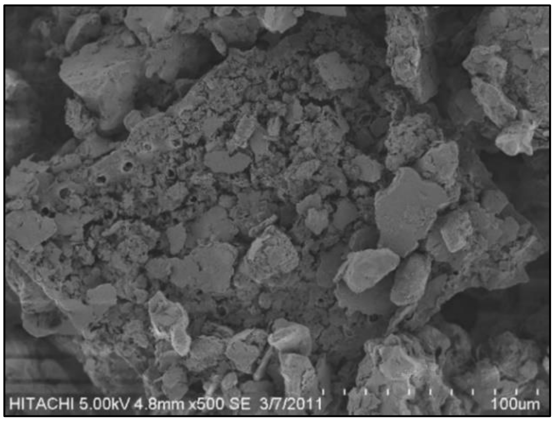
and these findings agree well with Kazemian *et al.* (2011). Hence, the void ratio and compression index increase gradually, as shown in Fig. 8.

### *3.4 Microstructure analysis*

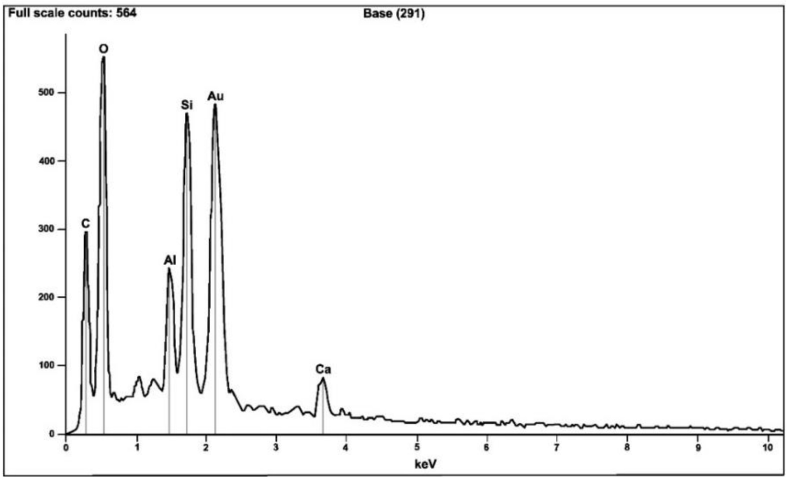
The microstructure of materials depends on some physical and mechanical properties such as water retention, compressive and tensile strength, Young's modulus, and Poisson's ratio (Gleize *et al.* 2003). Sridharan and Keshavamurthy (2016) suggested that the mineralogical identification methods are not cost-effective in nature, due to their requirements of high-level of instrumentation, complexity and expert interpretation of results. This makes the mineralogical identification methods impractical for a wider range of applications. The microstructure of cement-based materials is complex due to the following reasons: (i) presence of several hydrated phases, with the composition and microstructure characteristics varying locally; (ii) presence of an aqueous phase of variable composition in a pore net with sizes varying over a large range; (iii) change of the microstructure with the passing time and environmental conditions (e.g., relative humidity and temperature); and (iv) physical and mechanical behaviour of the material being often controlled by zones with special microstructures, which occurs in specific places within the system, instead of the prevalent general microstructure (Diamond 1986).

Taylor (1997), Malhotra and Mehta (2014) classified three types of C-S-H morphologies of Portland cement mortars based on their configuration; fibrous-acicular form (Type I), reticule or honeycomb form (Type II), and denser-almost sphere form (Type III). The explanation of these microstructural changes has been attributed to the chemistry between the sodium silicate-cement and additive systems. In the current study, thin slices of air-dried samples were tested after soaking in distilled water for 90 days, and the changes in the microstructure were studied to further validate the results obtained from the tests discussed in the previous sections.

The microstructure of an organic soil improved by sodium silicate system grout is a combination of organic soil and cementation bond. The cement-based material is




(a)

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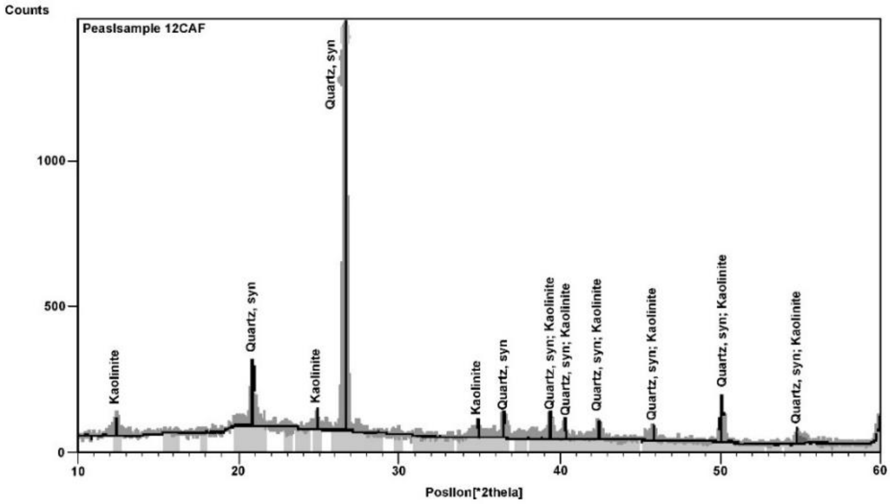
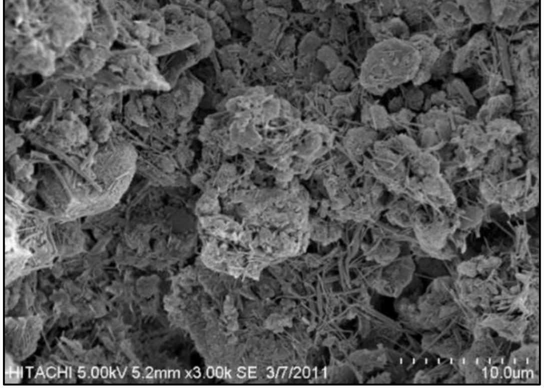



(c)

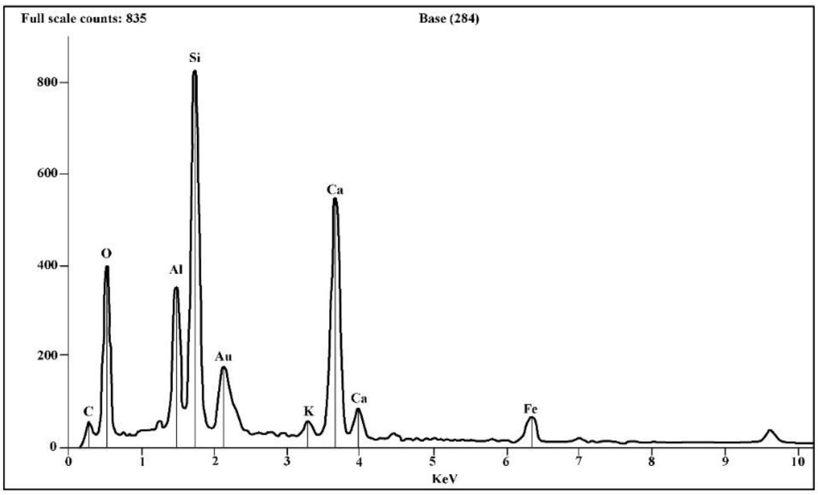
Fig. 10 Microstructure results of Grout No. 1: (a) SEM, (b) EDX and (c) XRD

complex due to several hydrated phases caused by the microstructure of the sample varying locally.

The samples used to investigate the effects of cement, kaolinite, and sodium silicate in the microstructure study

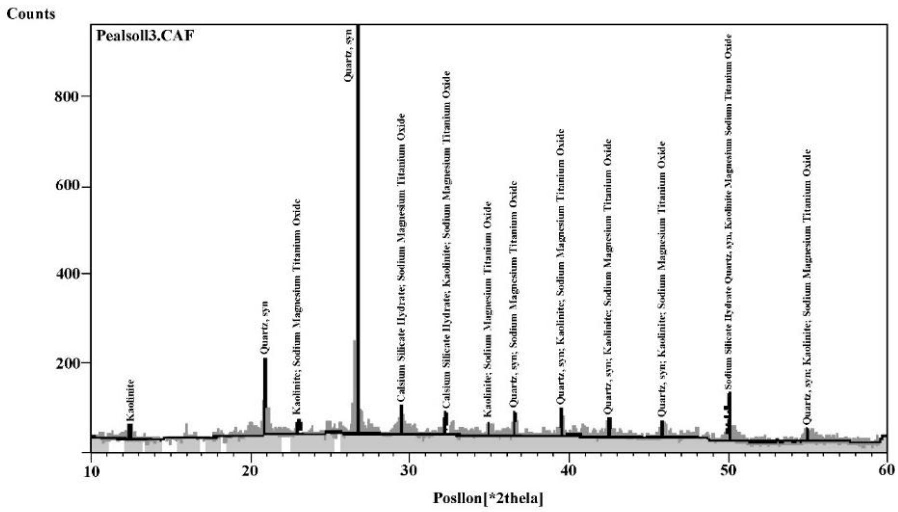



(a)



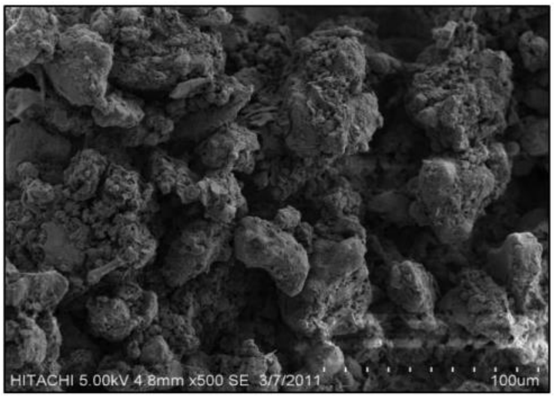

(b)

Fig. 11 Microstructure results of Grout No. 2: (a) SEM, (b) EDX and (c) XRD

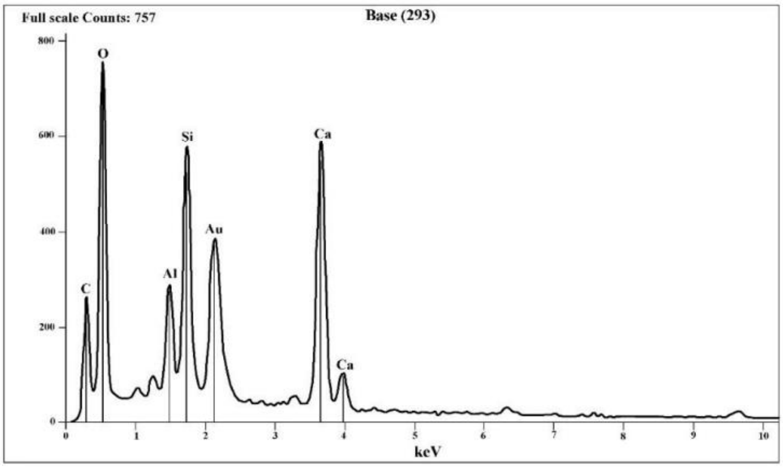



(c)

Fig. 11 Continued




(a)

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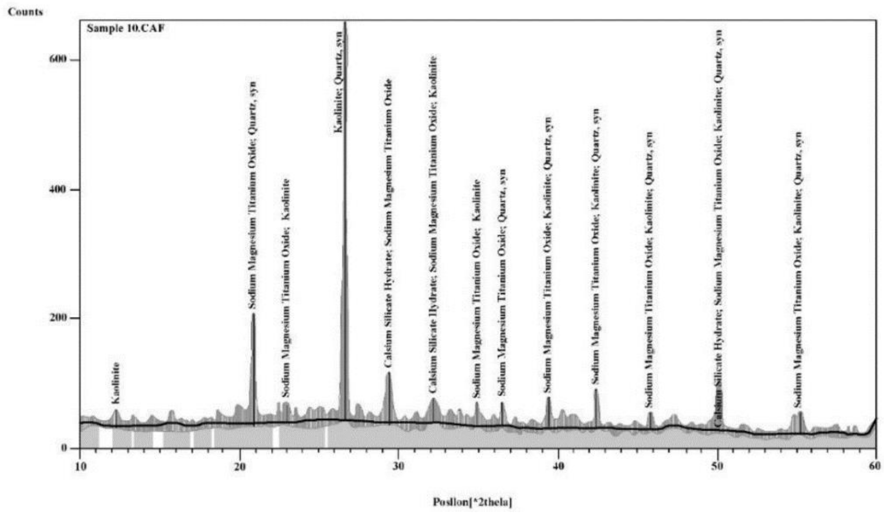
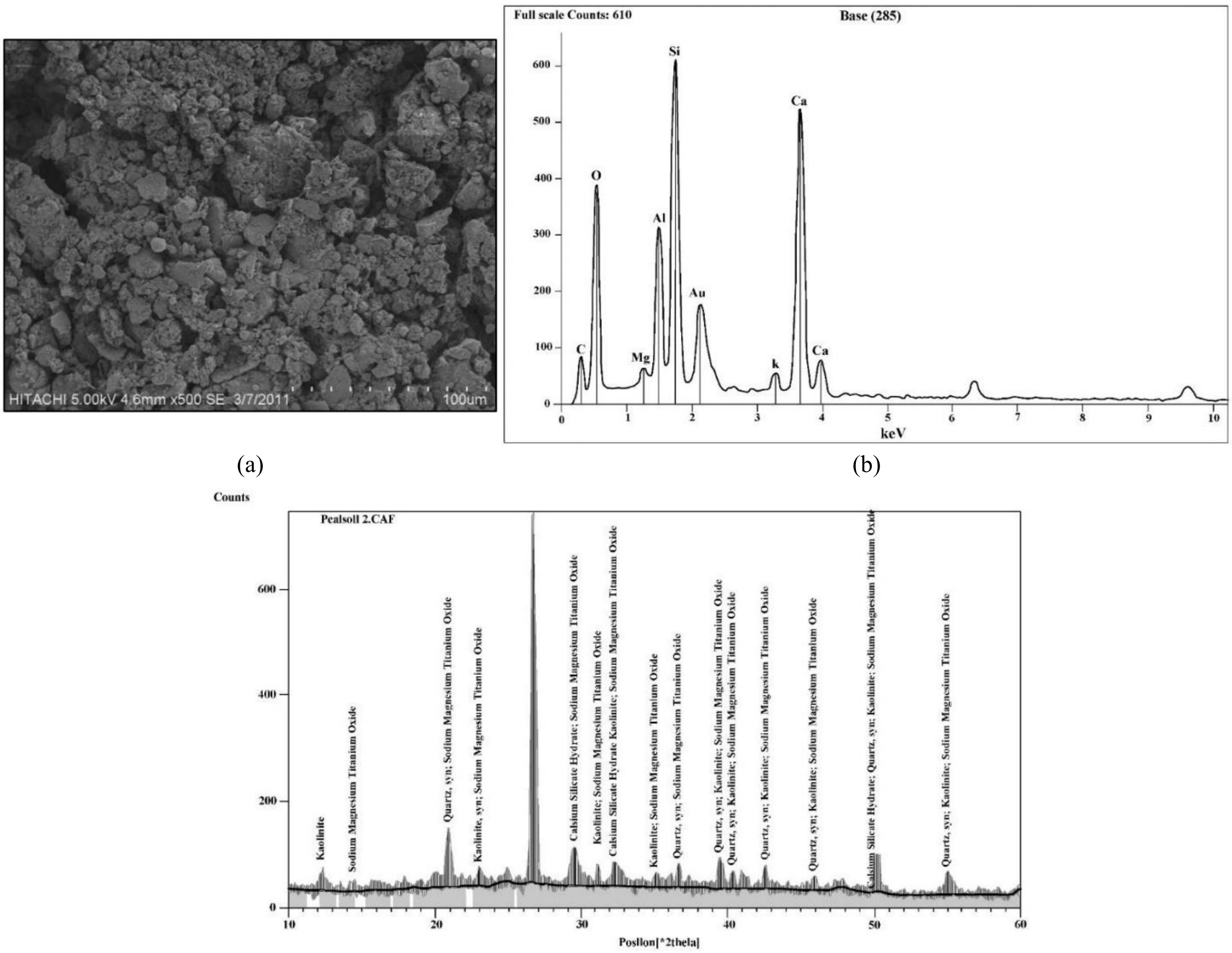



(c)

Fig. 12 Microstructure results of Grout No. 3: (a) SEM, (b) EDX and (c) XRD

are based on the information given earlier in Table 5 and the selected grouts listed in Table 6.

The results of the microstructure tests carried out on the pure organic soil used in this study are shown in Fig. 9. It can be seen from Fig. 9(a) that pure organic soil has a lot of microporous and macroporous between the soil particles.




(a) (b)

(c)

Fig. 13 Microstructure results of Grout No. 4: (a) SEM, (b) EDX and (c) XRD

This proves that natural organic soils have high porosity and consist of large pores size, which contributes to the high compressibility of organic soil. EDX result in Fig. 9(b) shows that pure organic soil has a high concentration of carbon and oxygen, indicating that the soil has a high organic content. In the XRD, Fig. 9(c), quartz can be obtained from the analysis since quartz is the most common mineral particle present in the soil.

The effect of cement is indicated by comparing Grout No. 1 (Fig. 10) and Grout No. 2 (Fig. 11), which have 20% and 30% cement, respectively. For Grout No. 2 of higher cement content, the SEM shows that the microstructure consists of denser sphere form and many spherical C-S-H particles Fig. 10(a) compared to Grout No. 1 of lower cement content Fig. 11(a). This is due to the reaction between the calcium and hydroxide ions that produces a calcium silicate hydrate gel (C-S-H). Besides, a higher percentage of cement content resulted in higher intensity of the ion calcium, as shown from the EDX result for Grout No. 2 [Fig. 11(b)]; while Grout No. 1 (Fig 10(b)) does not have any ion calcium since there is no cement present in this sample. The XRD results in Figs. 10(c) and 11(c) also reflect the same outcome since no calcium silicate hydrated is being analyzed for Grout No.1, and a few peaks are showing the presence of calcium silicate hydrated for Grout No. 2.

The effect of kaolinite is examined by comparing Grout No. 2 (Fig. 11) and Grout No. 3 (Fig. 12), which have 30% and 20% kaolinite, respectively. It can be seen from the SEM results (Fig. 11(a) for Grout no. 2 compared to Fig. 12(a) for Grout No. 3) that the porosity (or void) is reduced when the kaolinite content is increased. The reduction in the void is because of the formation of the calcium silicate hydrate (C-S-H) gel and calcium aluminate silicate hydrate (C-A-S-H) gel when they react with $Ca(OH)_2$. These gels contribute to the stronger filling effect of the organic soils. The result of the EDX test for Grout No. 2 (Fig. 11(b)) indicate a higher intensity of the ion aluminium compared to Grout No. 3 (Fig. 14(b)). This is because the higher the kaolinite content, the more ion aluminium exists in the sample. The XRD results reflect more peaks of the kaolinite for Grout No. 2 (Fig. 11(c)] compared to Grout No. 3 [Fig. 14(c)], which means higher content of kaolinite. Moreover, Grout No. 2 has a higher intensity of kaolinite of about 98 compared to only 74 for Grout No. 3.

The effect of sodium silicate is examined through Grout

No. 2 (Fig. 11) and Grout No. 4 (Fig. 13), which have 2.5% and 1% sodium silicate, respectively. The results of the SEM micrograph (Fig. 11(a) for Grout No. 2 compared to Fig. 13(a) for Grout No. 4) show that with the increase of sodium silicate, the void between the particles becomes less. This is due to the densification caused by the gel-forming from the polymerisation, which involves the exchange of ion and the presence of the hydrated calcium silicate gel. For the EDX result, a higher sodium silicate content owns a higher intensity of ion silicate, as clearly shown in Fig. 11(b) for Grout No. 2 compared to Fig. 13(b) for grout No. 4. Grout No. 2 has a higher intensity of Si compared to Grout No. 4 since it has a higher percentage of sodium silicate. For the XRD results (Fig. 11(c) for Grout No. 2 compared to Fig. 13(c) for Grout No. 4), it can be seen that Grout No. 2 shows a slightly higher intensity of sodium silicate of 98 compared to 94 for Grout No. 4., so the intensity difference is also marginal.

## 4. Conclusions

In this paper, the effects of different constituents of cement-sodium silicate grout system on the compressibility behaviour of organic soil, including settlement and void ratio, were investigated. The effects of cement, kaolinite, and sodium silicate on the compressibility characterisctis of organic soil were studied using Rowe Cell and some microstructural tests. From the current study, it can be concluded that:

• The settlement and void ratio of organic soil was decreased gradually with the increase of cement and kaolinite contents. However, the effect of cement was found to be more significant than kaolinite.

• The settlement and void ratio of organic soil was decreased gradually with the increase of sodium silicate binder until an optimum value of 2.5%, after which the increase in sodium silicate resulted in an increase in soil compressibility.

• The results of the microstructure analysis using SEM, EDX, and XRD showed that with the increase of cement, kaolinite, and sodium silicate in organic soil, the void and porosity between soil particles decreased, leading to an increase in the soil density by hydration, pozzolanic, and polymerisation processes.

• The rate of hydration process of stabilised organic soil was accelerated by adding sodium silicate, cement, kaolinite, and calcium chloride. The strength of organic soil was strengthened through the pozzolanic and polymerisation processes, by producing the C-S-H gel and hence reducing the compressibility of organic soil. This is to say that the presence of the C-S-H gel increases the strength of grout and this eventually causes a decrease in soil compressibility.

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