

GYPSUM STABILIZATION OF ORGANIC SOIL: STRENGTH AND COMPRESSIBILITY

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Abstract

Organic soil exhibits poor engineering characteristics including high compressibility, high moisture content, and low strength. Its mechanical properties must be improved using a widely accepted chemical stabilization method before commencing with any engineering work. A laboratory testing program was carried out to examine the development of strength of organic soil stabilized using gypsum. The standard Proctor test was performed to determine the maximum dry density and optimum moisture content of the organic soil to prepare the stabilized samples for the unconfined compression strength (UCS) at different percentages of gypsum and curing times. Additionally, a standard oedometer test was performed at the efficient gypsum content, which yields the highest UCS. An increase in the gypsum content and curing time led to a significant increase in the UCS of the organic soil. Furthermore, the compressibility of the organic soil was significantly reduced by the addition of gypsum. Micro-level assessments were performed on stabilized soil samples at 11% of gypsum content via energy-dispersive X-ray spectrometry and field emission scanning electron microscopy techniques. The pores of the stabilized soil were filled by new cementitious products, confirming that a pozzolanic reaction occurred between the organic soil and gypsum during the stabilization process and hence strength improvement.

Keywords: Unconfined compressive strength, organic soil, gypsum; curing time, stabilization

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Introduction

According to Abu Hassan *et al.* (2013), peat soil constituted 8% of the total land area in Malaysia, and more than 60% of the peat is found in East Malaysia. Peat or organic soil is formed from the process of decay and breakdown of trees, sedges, mosses, and other vegetations that thrive in wetlands, marshland and other lowland places in the absence of oxygen (Zainorabidin *et al.*, 2007; Zainorabidin and Wijeyesekera, 2008; Kazemian *et al.*, 2011). Based on the amount of organic content, the three basic soil types, namely clay, silt, or sand are classified as slightly organic when their organic content ranges between 2% to 20% while soils with organic contents between 25% and 75% are classified as organic soil, and soils are classified as “peat” when the organic content exceeds 75% (Bujang *et al.*, 2009; Huat *et al.*, 2014).

Replacing peat with other soil types in several cases can be costly, time-consuming, and unfeasible (Nikookar *et al.*, 2013). The effective soil improvement technique consists of physical processes such as compaction, preloading, earth reinforcement and soil replacement, and chemical processes (Horpibulsuk *et al.*, 2009; Rashid *et al.*, 2015; Wu *et al.*, 2015; Phummiphan *et al.*, 2016; Hoy *et al.*, 2017; Udomchai *et al.*, 2017; Sukmak *et al.*, 2019). Nevertheless, soil stabilization or chemical process is popular because it is cost-effective when compared with other methods of soil improvement. Soil stabilization is widely used over the last 20 to 25 years for problematic soil (Adon *et al.*, 2012). Chemical reaction between soil and admixtures improves engineering, chemical and physical properties of soils such as pH, permeability, compressibility, and shear strength (Kolay and Pui, 2010; Awg Shahminan *et al.*, 2014; Borthakur and Stephen Singh, 2014; Raftari *et al.*, 2014; Latifi *et al.*, 2015; 2016a; 2016b; 2018a; 2018b; Dehghanbanadaki *et al.*, 2017; Rashid *et al.*, 2015; 2017). Several studies examined the stabilization of organic soil by using cement (Huat *et al.*, 2005; Deboucha *et al.*, 2008), fly ash (Kolay and Pui, 2010; Rahman *et al.*, 2011), and lime (Said and Taib, 2009; Nikookar *et al.*, 2013; Vishwanath *et al.*, 2014). Huat *et al.* (2005) stated that the addition of cement and lime improves the engineering properties of tropical peat soils. When the cement and lime content increased, the liquid limit and optimum water content decreased, maximum dry density increased, and unconfined compressive strength (UCS) increased significantly. Hassan *et al.* (2017) indicated that the strength increased approximately 3 to 5 times after 7 days of stabilization with magnesium chloride. Nikookar *et al.* (2013) observed that a UCS test on peat hydrated

with lime and cured for 28 days in the laboratory achieved the highest strength when 12% lime was used. However, there is a paucity of studies on potential improvement in the physical and geotechnical properties of organic soil stabilized with a gypsum admixture.

Yilmaz and Civelekoglu (2009) and Latifi *et al.* (2018) revealed that gypsum contains a very low content of clay, calcite, and anhydrite and is effectively used as a stabilizing agent. Furthermore, the cost of gypsum is approximately 2-3 times cheaper than that of lime. Gypsum waste can be produced from the manufacturing process, construction, and demolition activities. Generally, gypsum waste consists of calcium sulfate dihydrate (Rahman *et al.*, 2015). The use of recycled gypsum in ground improvement is not widespread due to the solubility of gypsum and especially when water is introduced. Chemical compositions of gypsum can produce the cementation bonding in soil-gypsum mixture, and thereby facilitate its use as a stabilizing agent (Ahmed *et al.*, 2011).

Based on Ahmed *et al.* (2011), the recycled gypsum (Bassanite) improved the early strength of clay in the early stage up to 7 days. The effect of curing time was insignificant beyond 7 days. The unit weight and compressive strength of clay-gypsum mixture increased with increasing the gypsum content. Clay-gypsum mixture exhibited brittle behavior during unconfined compression, and the failure strain decreased with the addition of recycled gypsum. Additionally, Ahmed *et al.* (2012) stated that the strength and mechanical properties of soft organic clay increased with increasing the content of gypsum-lime admixture. The flexural and compressive strength of the compressed earth blocks (CEBs) was found to be improved by the presence of gypsum (Amin Maher, 2013).

Though the performance of a peat (organic content >75%) stabilized by gypsum has been investigated (Kolay and Pui, 2010; Saberian and Rahgozar, 2016; Vasu *et al.*, 2017), the study on strength and compressibility of the organic soil (organic content range between 25%-75%) stabilized with gypsum is very limited. Therefore, this research investigates the visibility of using gypsum to enhance the strength and compressibility of problematic organic soil in Sarawak, Malaysia. Additionally, the microstructural analyses (energy-dispersive X-ray spectrometry (EDAX) and field emission scanning electron microscopy (FESEM)) were performed to investigate micro-structural changes with the addition of gypsum and enlighten the strength and compressibility improvement.

Materials

Soil samples were taken from BC2 Ulu Sikat, Mukah, Sarawak where the project of coal mining (extraction and transportation) and rehabilitation of mines were performed. The soil samples were excavated at a depth of 0.5 m below the ground surface. Gypsum or calcium sulfate dihydrate in a powder form was obtained from Qrec (Asia) Sdn. Bhd. Malaysia. Table 1 shows the engineering and chemical properties of gypsum material used in this study.

Table 1. Engineering and chemical properties of gypsum

Parameters	Results
pH	10.16
Specific gravity, G_s	2.32 Mg/m ³
SiO ₂ (%)	4.15
Al ₂ O ₃ (%)	2.73
Fe ₂ O ₃ (%)	0.64
Na ₂ O (%)	0.23
CO ₂ (%)	2.15
CaCO ₃ (%)	36.43
P ₂ O ₅ (%)	0.80
SO ₃ (%)	52.87

Sample Preparation and Testing Program

The disturbed samples were taken to the laboratory, oven-dried at 60°C and subsequently passed through a 2 mm size sieve to remove the large fiber contents such as wood (Brendan, 2005; Hassan *et al.*, 2017; Hassan *et al.*, 2019). The soil passing through the 2 mm sieve was utilised in this research.

Several tests were performed using BS 1377: Parts 2, 3, 5, and 7 standards to determine the soil classification, compaction properties, compressibility characteristic, and UCS, respectively. The soil specific gravity was determined by the use of method of density bottle, and kerosene was used instead of distilled water since the soil contained organic material (British Standard Institution, 1990). The loss of ignition (LOI) test was also performed; the soil was heated at 440°C for more than 3 h, and loss on ignition was taken as the mass of the organic content.

The standard Proctor test was performed to determine the maximum dry density (MDD) and optimum moisture content (OMC) of the organic soil (Liu and Evett, 2005). The strengths of the unstabilized and stabilized soils were obtained from the UCS test. All the stabilized samples for the UCS tests were prepared based on the MDD and OMC of the unstabilized soil. The influence of compaction characteristics was considered as trivial with respect to the stabilizer content (Rashid *et al.*, 2015). Six different ranges of gypsum were prepared: 1%, 3%,

5%, 7%, 9%, and 11% (wt.%) of organic soil as advised by Indiana Department of Transportation (2008) where suggested stabilizer quantity is less than 10%. The organic soil was thoroughly manually mixed with gypsum and a palette until the mixtures were homogeneous. Subsequently, the organic soil mixed with gypsum was transferred into a cylindrical UCS mold with a diameter of 38 mm and a height of 76 mm. Samples were compressed via a compression machine and extruded via steel plunger, and subsequently trimmed and cured in a plastic bottle for 3, 7, 14, and 28 days at room temperature (20°C) and humidity exceeding 90% prior to the UCS test (Latifi *et al.*, 2016a). A loading rate of 1.52 mm/min was employed until the sample failed. The test data was used to plot deviator stress versus strain, and thereby the compressive strength was obtained.

Standard oedometer consolidation tests were performed only on the stabilized sample at the efficient gypsum content, providing the highest UCS. The dimension of oedometer sample was 75 mm diameter and 20 mm height. Applied loads were 12.5, 25, 50, 100, 200, 400, and 800 kPa. The vertical compression under each load was recorded in a 24 h period. Subsequently, the coefficient of consolidation (C_v), compression index (C_c), and the initial void ratio (e_0) were determined from the e-log p curve.

Additionally, topographic features, morphological changes, and major elemental composition on the surface associated with organic particles before and after stabilization were examined via FESEM and EDAX. Approximately 1-g sample was obtained from the center of the UCS sample after the testing was completed based on the assumption that the entire sample was uniformly mixed. The stabilized samples with the efficient gypsum content providing the highest UCS were examined via FESEM and EDAX.

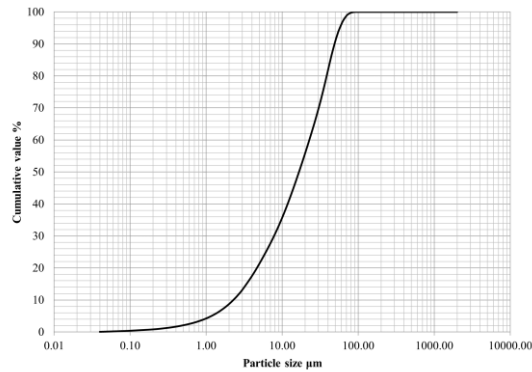
Results and Discussion

Physical and Geotechnical Properties of Organic Soil

The physical and geotechnical properties of the soil sample are shown in Table 2. The organic soil is classified based on the degree of humification (known as the Von Post scale), and the test was performed based on the appearance of soil water that was extruded when the soil was manually squeezed. It was observed that a small amount of muddy water was presented between the fingers when the soil was squeezed. The organic soil is in the range H5, which is moderately decomposed. Based on the loss of ignition (Table 2), organic soil corresponds to

Table 2. Physical and geotechnical properties of organic soil

Parameters	Results
Natural Moisture Content, %	850
Von Post humification	H5
Specific gravity, G_s	1.6 Mg/m ³
Liquid limit, LL	128.25%
Plastic limit, PL	Non-plastic
Loss on ignition, LOI (%)	53.16
Optimum Moisture Content, OMC	75.63%
Maximum Dry Density, MDD	0.649 Mg/m ³
Unconfined compressive strength, UCS	13 kPa

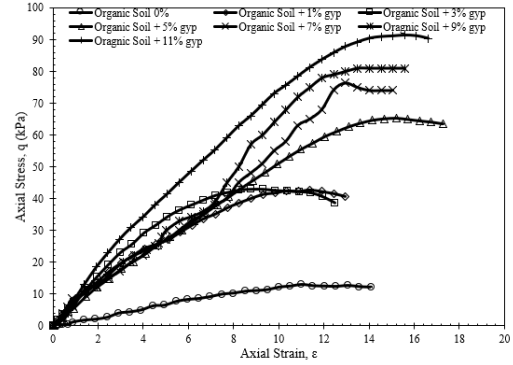
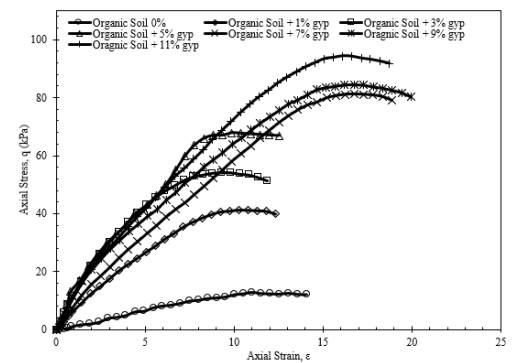
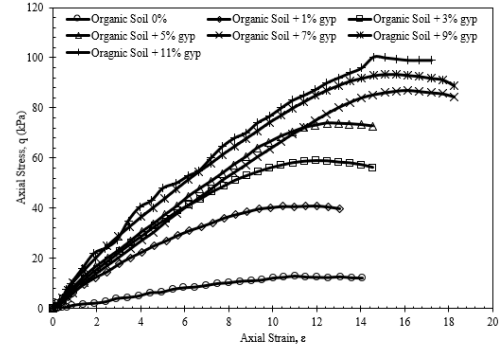
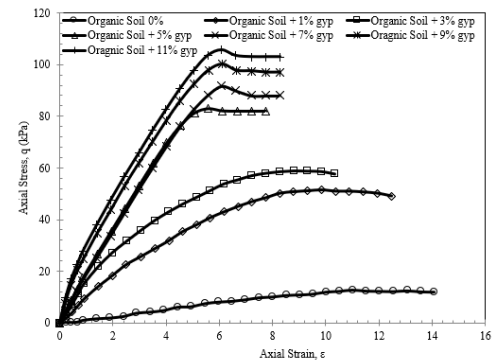
**Figure 1. Particle size distribution of organic soil**

fibrous peat with a specific gravity of 1.6 and an organic content of 53.2%. Soil with organic content between 20% and 75% is classified as organic soil (Bujang *et al.*, 2009). The value of the liquid limit is high because of high water absorption of present fibers.

Figure 1 shows the gradation curve of the soil sample. Based on the sieve analysis and particle size analyzer (CILAS 1180) analysis, the studied soil consists of 5.6% sand, 86.6% silt, and 7.8% clay. The dominant soil particle is the silt-sized material.

Stress-Strain Behavior

The stress-strain plots in Figure 2, for the early curing period, show that with higher gypsum content, the stabilized soil exhibits higher strength and failure strain. The failure strain decreases with increasing curing time showing the more brittle behavior over curing time. The failure strain for unstabilized samples and stabilized samples with low gypsum contents (1% and 3%) is nearly identical and approximately 14%. The failure strain for the stabilized soil with higher gypsum contents (5%, 7%, 9%, and 11%) increases by up to 20% for curing periods <14 days. Conversely, the failure strain for all the stabilized soils at 28 days of curing decreases when compared with that of the unstabilized soil due to higher stiffness. The secant

**a) 3 days of curing****b) 7 days of curing****c) 14 days of curing****d) 28 days curing****Figure 2. Particle size distribution of organic soil**

stiffness at 2 of axial strain increased by 95% on average after 28 days as compared to the 14 days of stabilized soil.

Unconfined Compressive Strength

Figure 3 shows the plots of UCS of organic soil with 0% gypsum content and with six various percentages of gypsum at 3, 7, and 28 days of curing. The gypsum and curing time enhance the UCS of the stabilized soil. For 1% gypsum, the 3-day UCS is 3 times UCS of the unstabilized soil, and the UCS increases from 39 kPa to 52 kPa for curing time increasing from 3 days to 28 days.

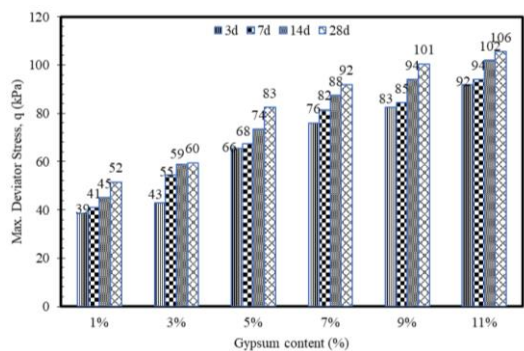


Figure 3. Maximum deviator stress with various gypsum contents

The UCS increments respect to the unstabilized organic soil in terms of percentages for each amount of gypsum at 28 days correspond to 300% (1% gypsum), 362% (3% gypsum), 538% (5% gypsum), 608% (7% gypsum), 677% (9% gypsum), and 715% (11% gypsum). The maximum UCS is found to be 106 kPa at 11% gypsum (maximum content tested) and 28 days of curing. This maximum UCS is 8 times that of the unstabilized organic soil (13 kPa). Therefore, only 11% of gypsum contents are considered to study the compressibility of stabilized soil and the microstructure and chemical composition of the treated soil.

Compression

Based on e-log p curve shown in Figure 4, the values of compression index (C_c), recompression index (C_r) can be obtained for the unstabilized, and 11% gypsum stabilized soil at 28 days of curing. For the unstabilized sample, the C_c value is 0.365 while the C_r value is 0.052. Conversely, for the stabilized sample, the C_c value is 0.093, and the C_r value is 0.032. The lower compression index of the stabilized sample confirms the improvement of resistance to compression. The values for the void ratio, e_0 of unstabilized and stabilized with 11% gypsum are 3.121 and 1.417, respectively. The

coefficient of consolidation, c_v values for the unstabilized sample is between 146 to 816 m^2/year while they are between 12 and 314 m^2/year for the stabilized sample. The obtained strength of 11% gypsum content could be used a temporary platform during the construction of the organic area.

FESEM and EDAX

EDAX analysis was performed on the organic soil, gypsum, and stabilized organic soil to obtain the surface composition of particles and presented in Figures 5 to 7. The EDAX spectrum of the

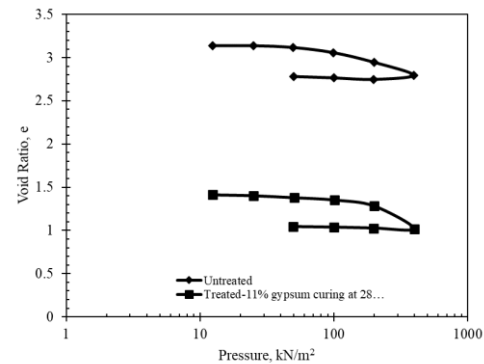


Figure 4. Graph of e-log p curve of unstabilized and stabilized with 11% gypsum curing at 28 days of organic soils

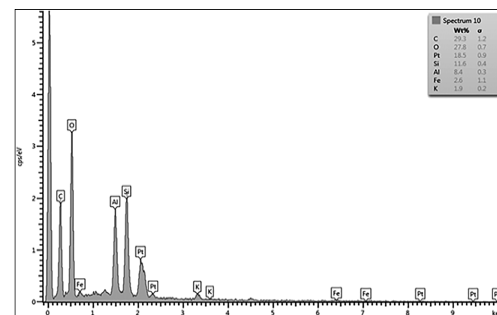


Figure 5. Elemental composition of used soil from EDAX

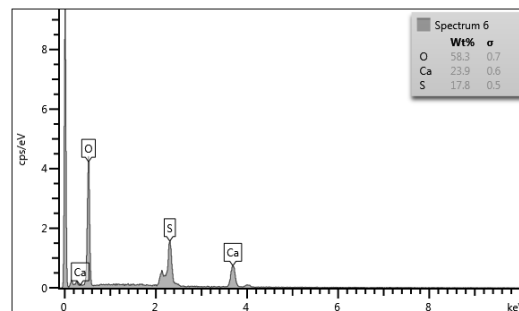


Figure 6. Elemental composition of gypsum from EDAX

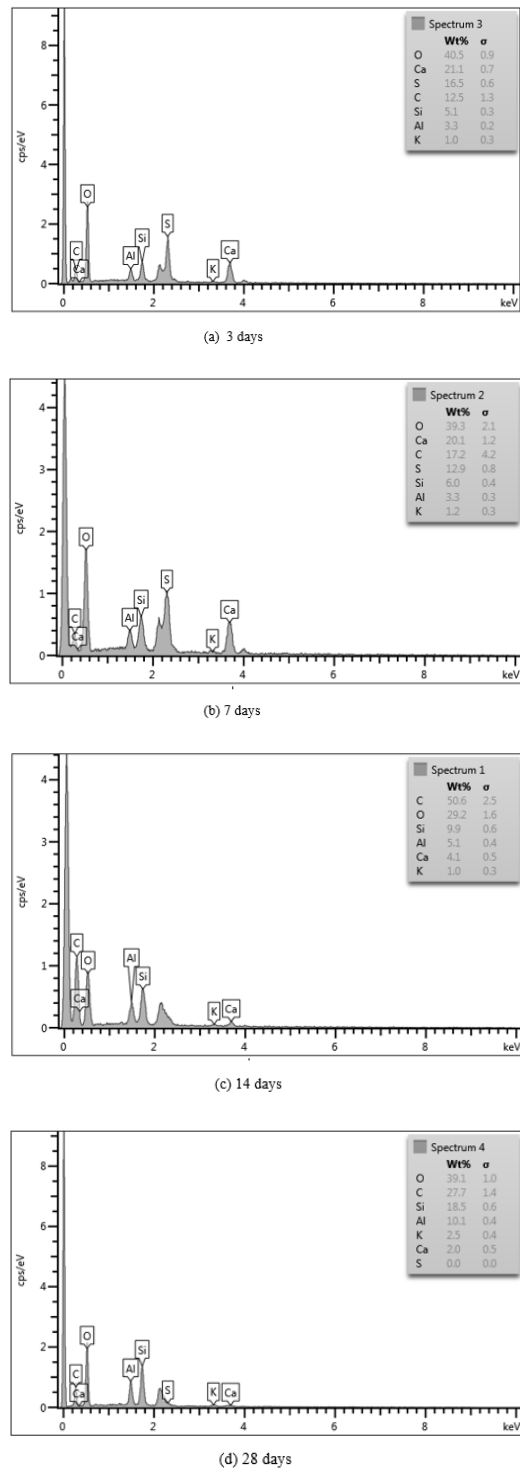


Figure 7. EDAX spectrum of 11% gypsum stabilized organic soil after (a) 3 days, (b) 7 days (c) 14 days and (d) 28 days

unstabilized organic soil (Figure 5) is primarily characterized by a high weight percentage of carbon and oxygen (i.e., 57%), and the remaining 43%

corresponds to the total elemental weight of aluminium (Al), silicon (Si), iron (Fe) and potassium (K). A similar finding was reported by Leong *et al.* (2012) in that organic soil exhibited a high elemental concentration of C and O and low elemental concentrations of Si, S, Al, Ca, and Fe. Gypsum contains very high CaO content of 82.2% (Figure 6). The engineering properties of $\text{Ca}(\text{OH})_2$ rich materials stabilized soil are ascribed to three basic reactions, namely pozzolanic reaction, aggregation and flocculation, and cation exchange. The influence of the three reactions are basically liable for the changes in shrinkage and plasticity (Horpibulsuk *et al.*, 2010; Kampala and Horpibulsuk, 2013; Kampala *et al.*, 2013). The shear strength of the stabilized soil slowly rises with time and is majorly because of the pozzolanic reaction. Gypsum with high CaO content can react with the silicates and aluminates (natural pozzolanic materials) in the organic soil to produce cementitious materials. The formation of cementitious products is confirmed via microstructural analysis in this research.

Figure 7(a-d) shows the EDAX results for stabilized organic soil (11% gypsum) cured for 3, 7, 14, and 28 days. The figure revealed the existence of new elements, such as calcium (Ca), confirming the formation of a cementitious compound after stabilization. The peak intensities of Ca exhibit significant reduction with increasing curing time. The decreases in Ca with time indicates the occurrence of chemical reactions between soil particles and gypsum. The resulting compound is identified as calcium aluminate hydrate (CAH) via the energy-dispersive X-ray spectrometer (EDAX) technique. Table 3 displays the corresponding changes in the ratios of Ca:Si and Al:Si for various curing times. There is a significant change in Ca:Si and Al:Si ratios for the gypsum stabilized samples when the curing time increases from 3 to 28 days.

Table 3. Al:Si and Ca:Si ratios for unstabilized and stabilized soil by 11% gypsum at various curing times obtained from the EDAX analysis test result

Al:Si and Ca:Si	Unstabilized Soil	Curing Periods			
		3 days	7 days	14 days	28 days
Al/Si	0.72	0.65	0.55	0.52	0.55
Ca/Si	0	4.14	3.35	0.41	0.11

FESEM equipment at high magnification (10,000 x times) is used to investigate the morphology of the stabilized soil. Figure 8 indicates the FESEM results for unstabilized organic soil (Figure 8(a)), 11% gypsum stabilized soil after 3 days (Figure 8(b)), 7 days (Figure 8(c)), 14 days

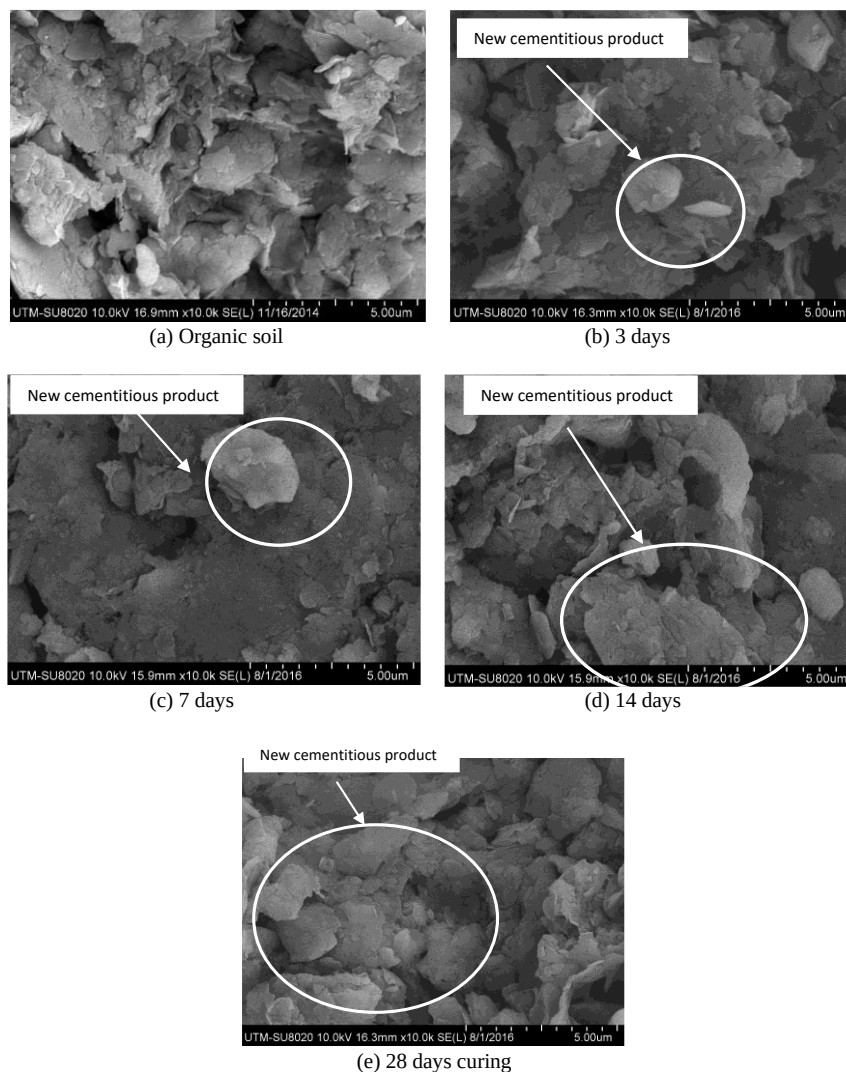


Figure 8. FESEM images of (a) organic soil and 11% of gypsum stabilized organic soil after (b) 3 days, (c) 7 days, (d) 14 days and (e) 28 days

(Figure 8(d)), and 28 days (Figure 8(e)) of curing. The microstructural changes between stabilized and unstabilized soil are conspicuously shown. New mineralogical phases are seen in the gypsum stabilized soil after 3, 7, 14 and 28 days of curing. The unstabilized sample (Figure 8(a)) has a more disjointed structure in which voids and porosity are obvious when compared with the stabilized soil (Figures 8(b) to 8(e)). The white particles in the images show the presence of gypsum in the organic soil, and their size increases with increasing the curing time. A new cementitious product in the form of white lumps (crystal), web-shaped cementitious compounds is observed over curing time. The increase in the curing time results in a higher degree of chemical reaction that leads to particle reorganization and stronger interparticle forces. The

encapsulation reaction between the organic soil and the gypsum stabilizer is shown in Figures 8(b) to 8(e).

Conclusions

This research investigated the physical and engineering properties of a soil sample in Ulu Sikat, Mukah, Sarawak. The soil sample contained 53.16% organic content and was therefore classified as organic soil. The UCS of the organic soil significantly increased with increasing the gypsum content, especially after a long curing period. The compression index, C_c , of the 11% gypsum stabilized sample was low when compared to that of the unstabilized sample. The mechanical test results

show that the gypsum stabilization reduced the compressibility and enhanced the UCS of the organic soil. The FESEM and EDAX analysis results revealed that the pozzolanic product between soil particles and gypsum is mainly calcium aluminate hydrate (CAH). It filled the pores and led to stronger interparticle forces and finally denser soil matrices. This study potentially contributes to the advancement of knowledge on the effectiveness of gypsum in improving problematic organic soils to be an engineered material.

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