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Research Paper

Improvement of Soft Bangkok Clay using Kaolin-Quick Lime Geopolymer

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ABSTRACT

The engineering properties of C-QG geopolymer were evaluated to ascertain the viability of using this material as an embankment structure fill material and also the efficacy of geopolymer stabilization in improving mechanical behavior of soft clay. Results from strength assessments with the usage of UCS and indirect tensile strength were used to establish the performance of the C-QG geopolymer. Quicklime mixed with 6 molar NaOH gave the maximum unconfined compressive strength. q_u of the samples increases significantly to 127% as the temperature increase from 28 °C to 70 °C indicating that the optimum curing temperature was 70 °C. Elastic modulus of samples increases with curing temperature increase. The mixing ratio of C:QG 60:40 exhibited highest elastic modulus. E_{50} increases with increasing in geopolymer content and approximately equal to 869.82qu. This secant modulus can be used for pavement design in Thailand. The highest indirect strength at all curing temperatures was obtained samples with mixing ratio of C:QG 80:20.

1. Introduction

The Bangkok subsoil consists of the layer of top crust underlain by the soft to very soft clay at depth of -2.00 m to -20.00 m. The buildings or superstructures construct on this type of soil may damage due to soil bearing capacity failure during construction of long-term services. (Pongsivasathit et al., 2017) Methods for improving soft soil to be stronger commonly used various types of chemical stabilizer. Soil improvement mechanisms are widely understood and known. The most popular substances used for soil improvement are Ordinary Portland Cement (OPC) and soil treated with lime (Horpibulsuk, et al., 2012, Manandhar et al. 2014, 2019) Mechanism for soil improvement with cement is caused by hydration and pozzolanic reactions. (George, 2001; Nicholson et al., 2005) Clay particles move closer together after mixing with cement and the soil is stabilized by

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pozzolanic reactions. (Yao et al., 2009; Horpibulsuk et al, 2012) However, the use of Portland cement leads to the destruction of various natural resources to be used as raw materials in the production process. It also burns energy and releases carbon dioxide. It is estimated that 1 ton of cement production emits 1 ton of carbon dioxide into the atmosphere (Voottipruex et al., 2019). Currently, other materials are sought to improve the soil instead of using cement. development.

Geopolymer is an inorganic alumino silicate substance that is formed by the merger (polycondensation) of tetrahedral silica (SiO4) and alumina (AlO_4) which are interlinked by sharing all oxygen atoms. The chemical structure of geopolymer is generally shown as Mn {- (SiO_2) z-AlO_2-}n. M is an ion + alkaline such as potassium (K+) or sodium (Na+) that is balanced with the negative charge of aluminum (Al). n is the degree of consolidation and z is the ratio of silica to alumina (Si / Al) in molar, ranges from 1 to 15 and may be up to 300 (Davidovits, 1994; Zhang et al., 2010; Chayakrit, 2016). The general geopolymer structures are: Mn{-Si-O-Al-O-}n, Mn{-Si-O-Al-O-Si-O-}n, Mn{-Si-O-Al-O-Si-O-Si-Si}n. The geopolymer shows different physical chemical properties by varying the concentration ratio of Si/Al. Low concentration ratio (< 3) will create a three-dimensional linking network resulting in brittle and rigid materials that can be used as bonding materials same as ceramic while high concentration ratio (> 3) causes the linking network in a straight line with sticky rubber adhesion property (Kenneth et al., 2006). The geopolymerization process is divided into two main steps that interact with each other over time. Step 1: Alumina silicate amorphous material is dissolved with alkali hydroxide solution and/or alkaline silicate solution to form silica and alumina that is ready to react. Step 2: The dissolved elements are combined into amorphous materials or oligomers, which are larger molecular chains that still dissolve in the solvent that will be combined and solidified into a synthetic aluminosilicate material thereafter (Khale and Chaudhary, 2007; Mohammadjavad, 2019). The optimum temperature for polymer synthesis is in the range 25-80 °C (Sindhunata et al., 2006). If the geopolymer is used instead of Portland cement reducing in reduction in energy consumption and carbon dioxide emissions can be greatly reduced (Davidovits, 2005). In addition, geopolymer has excellent mechanical properties such as compressive strength and rigidity and resistant to heat Moreover, the geopolymer is able to carry high compressive strength and is particularly resistant to heat, acids and organic solvents. The geopolymer material can be synthesized from amino aluminum silicate with a low price or even form various types of industrial waste, such as sintered kaolin (metakaolin) furnace slag, fly ash, rice husk ash (Sukmak et al., 2013; Detphan and Chindaprasirt. 2009; Ogundiran, 2015). Considering all the advantages mentioned, geopolymer is an interesting alternative to cement replacement for civil engineering infrastructure construction. Geopolymer still has low shrinkage potential and excellent adhesion to the aggregate, indicating the potential of geopolymer to improve soil quality (Yunsheng et al., 2010; Teerawattanasuk and Voottipruex, 2019). Recently, researchers have studied the effectiveness of geopolymer from low-calcium and high-calcium fly ash to improve deep soft soil using high pressure injection (Cristelo et al., 2012). Fly ash activated by alkaline form geo-polymer precursors which can be used to improve the quality of soft soil. The fly ash geopolymer treated soil gave similar results to the cement treated soil. Now the popularity of using fly ash from coal burning is increasing making it rare and expensive.

The research aims to study soft soil stabilization using quick lime geopolymer. The geopolymer form by stimulate quick lime with NaOH to create the geopolymerization process. Then the soft Bangkok clay was improved with regard to the optimum ratio between clay and quick lime geopolymer. In the study, the mechanical properties were examined based on temperature and curing period by considering the unconfined compressive strength. The results can be used as a model for soft Bangkok clay improvement by using the geopolymerization process of quick lime instead of cement. In addition, microstructure changes in the soil were examined before and after the improvement in order to explain the mechanism of soil improvement with geopolymer.

2. Material and method

2.1 Bangkok Clay

Soft Bangkok clay samples (C) were collected at a depth of 4 to 6 meters from the original ground in Pathumthani province. The clay with natural water content, wet unit weight and specific gravity were 79.8%, 15.62 kN/m^3 and 2.78, respectively. The Liquid and plastic limits were 72.05% and 33.85% respectively. The particle size analysis of clay using X-ray diffraction technique exhibited sand, silt and clay content of 2.11%, 71.26% and 26.63%, respectively. The particle size of clay is in the range of 0.20-127 μm as shown in **Fig. 1**. Based on AASHTO classification system (AASHTO, 2012), the soil was classified as soil group A-7-5 (0), the appearance is fine granular clay with a high liquid, while based on Unified soil classification system, the soil was classified as inorganic clay with high plasticity (CH).

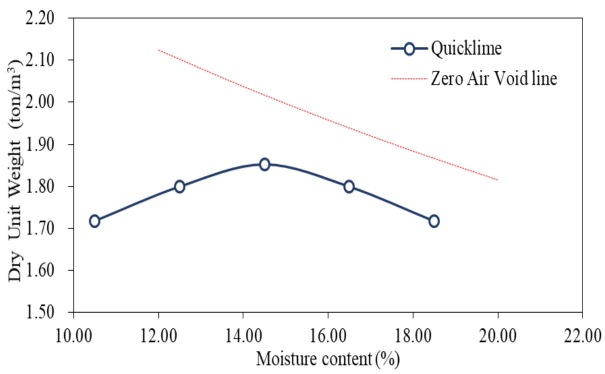

Fig. 1. Grain size distribution of Bangkok clay

2.2 Quick Lime

Quick lime was obtained from Saraburi Province, Thailand. Modified Proctor compaction effort was used to determine the maximum dry density (MDD) and optimum moisture content (OMC) of the quicklime and was performed according to AASHTO (2004), which is similar to ASTM (2012). The maximum dry density (modified Proctor density) and the optimum water content of the quicklime was 1.853 ton/m^3 and 14.5% respectively, as shown in **Fig. 2**.

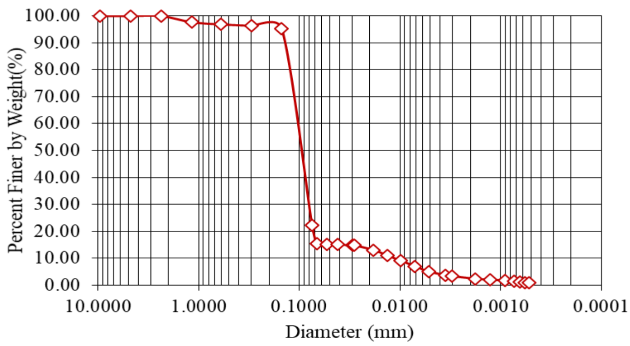

Fig. 2. Modified compaction test of quicklime

2.3 Concentration of sodium hydroxide solution

In order to find the suitable concentration of sodium hydroxide (NaOH) solution for geopolymerization process, quicklime was thoroughly mixed with NaOH solution by varying its concentration of 3, 6, 9, 12, 15 and 18 molar. The OMC of the NaOH solution was 17 %. Quick lime geopolymer samples were prepared and cured at room temperature with curing period of 7 days, 14 days and 28 days. The UCS of the samples was measured in accordance with ASTM (2016) with a strain rate of 0.5%/min at the ages of curing periods. The test results showed that quicklime mixed with 6 molar NaOH gave the maximum unconfined compressive strength of 2750, 3250 and 3500 kPa after curing period of 7, 14, and 28 days, respectively, as shown in **Fig. 3**.

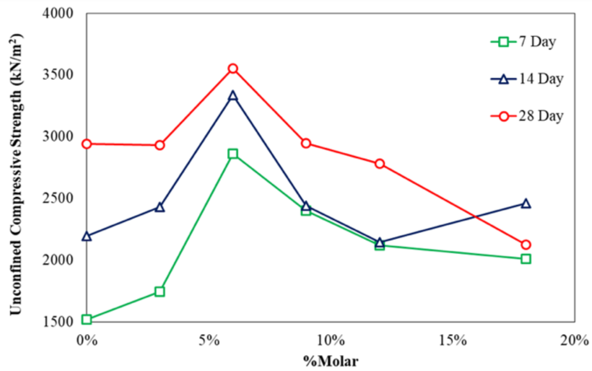

Fig. 3. Unconfined compressive strength of quicklime mixed with NaOH solution of different concentrations

2.4 Optimum moisture content of clay (C) improved by quicklime geopolymer (QG)

Different mixes of C: QG were prepared that included 100: 0, 80:20, 60: 40, 40:60, 20:80, 0:100. To determine the maximum dry density (MDD) and optimum moisture content (OMC) of clay improved by QG, modified Proctor test was conducted for each mix with NaOH solution of 6 molar as shown in **Fig. 4**.

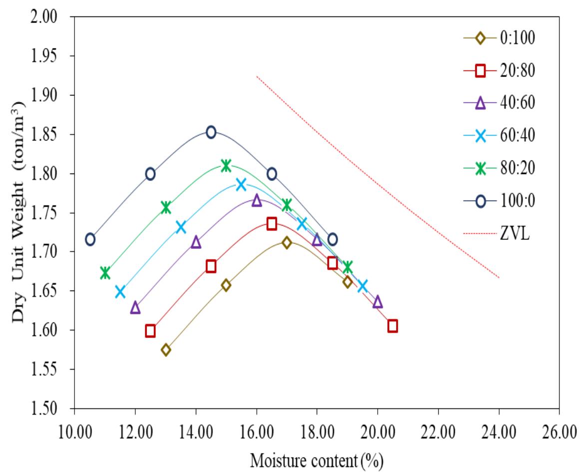

Fig. 4. Relationship between dry Unit Weight and moisture content.

After the optimum moisture content and maximum dry density in each mix was obtained, soil treated geopolymer samples were prepared as shown in **Fig. 5**. The samples were then cured for 7, 14, 28, 60, and 120 days under the controlling temperatures of 28 ˚C, 70 ˚C and 100 ˚C respectively. Afterwards, the unconfined compressive strength and indirect tensile test were conducted.

Fig. 5. Samples preparation of 3.5 cm diameter and 7.0 cm height

2.5 Unconfined compressive strength (q_u)

The strength of QG treated clay increase as the QG content increase to 40%. **Figure 6** shows that q_u of QG treated clay replaced by QA content 20% to 40% exhibited not much different. However, sample of C: QA 60:40 exhibits higher q_u than sample of C: QA 80:20 at curing age 14 and 28 days.

The q_u at curing period of 120 days are 2530.21 kPa, 5755.89 kPa, and 6820.74 kPa at temperature 28, 70,100 ˚C, respectively. With ratio of QG increase from 40% to 80%, the q_u decrease for all curing temperatures because the added amount of geopolymer more than 40 percent is not necessary for geopolymerization process but the excessive of geopolymer destroy the bonded structure instead. It can be notice that the q_u of the samples increases significantly to 127% as the temperature increase from 28 ˚C to 70 ˚C. On the other hand, the increment rate of q_u increase only 18% when the curing temperature increased from 70 ˚C to 100 ˚C, indicating that the optimum curing temperature was 70 ˚C.

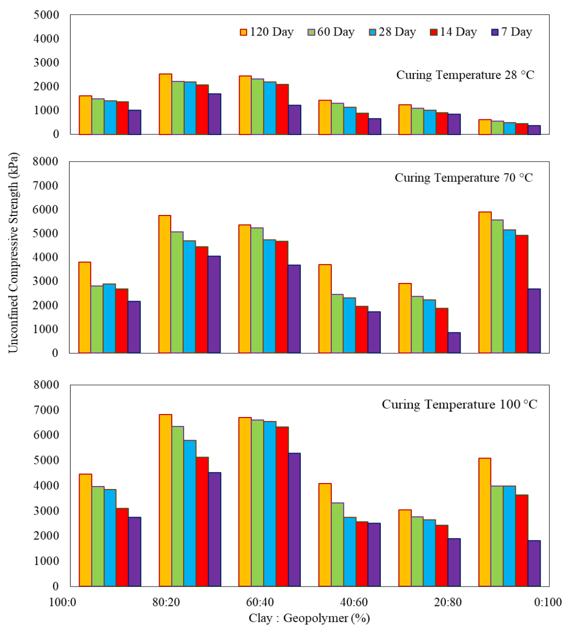

Fig. 6. Unconfined compressive strength with different mixing ratio of C:QG

2.6 Elastic modulus of the quicklime geopolymer treated clay

Elastic modulus of samples increases with curing temperature of 28°c, 70°c and 100°c. The highest elastic modulus was obtained at curing period of 120 days in every mixing ratio as shown in **Fig. 7**. The mixing ratio of C:QG 60:40 at curing temperature of 28 ˚C, 70 ˚C and 100 ˚C exhibited highest elastic modulus of 35000 kPa, 48000 kPa, and 52000 kPa, respectively.

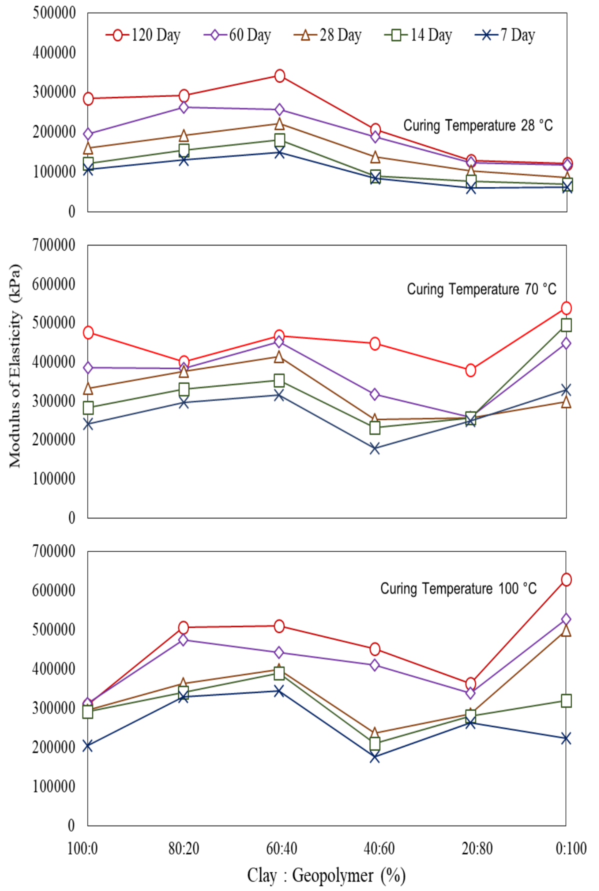

Fig. 7. Secant modulus of elasticity, E_{50}, with different mixing ratio of C:QG

Elastic modulus increased by 20 percent as the curing temperature increased from 28 ˚C to 70 ˚C while elastic modulus increased only 8 percent when the curing temperature increased from 70 ˚C to 100 ˚C therefore it confirm that the optimum curing temperature was 70 ˚C corresponded to unconfined compression strength.

Figure 8 shows the relationship between modulus of deformation at 50% strength; E50 and q_u of clay samples treated by QG. In this study, E_{50} increases with increasing in geopolymer content and approximately equal to $869.82q_u$. This secant modulus can be used for pavement design in Thailand.

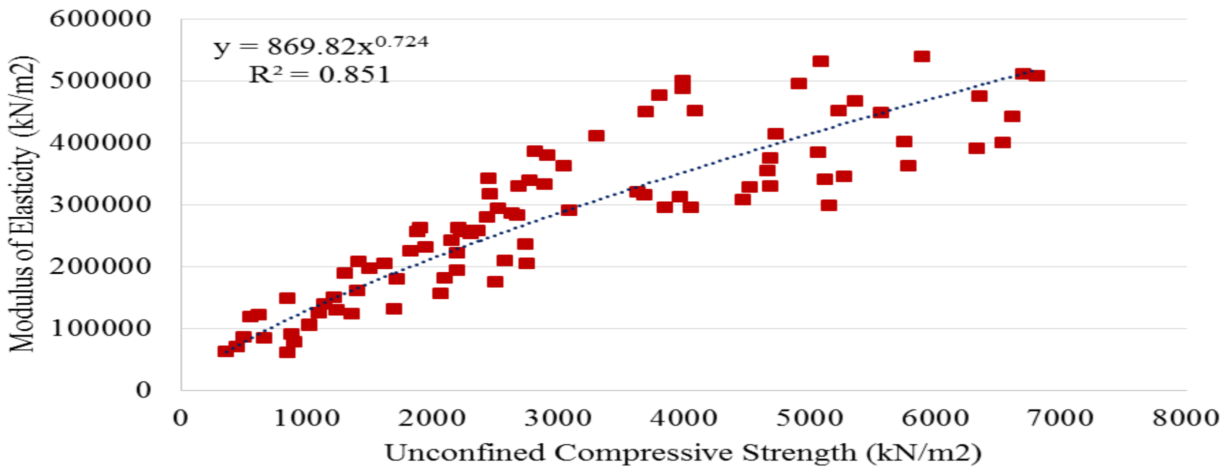

Fig. 8. Modulus of elasticity, E_{50} and unconfined compressive strength

2.7 Indirect Tensile strength

The highest indirect strength at all curing temperatures was obtained from sample with mixing ratio of C: G 80:20. Moreover the highest indirect strength was obtained at curing period of 120 days indicating that longer curing period leads to complete polymerization. At curing temperature of 28, 70 and 100 degrees, the maximum indirect tensile strength was 48, 72 and 90 kPa, respectively. However, at curing period of 28 days, the increased amount of geopolymer does not affect the reaction. The curing temperature increased from 28 ˚C to 70˚C, the indirect tensile strength increased by 50 percent. On the other hand, the curing temperature increased from 70˚C to 100˚C, the increment rate of indirect tensile strength was reduced to only 25 percent confirming that the optimal curing temperature is 70 ˚C. as shown in **Fig. 9**.

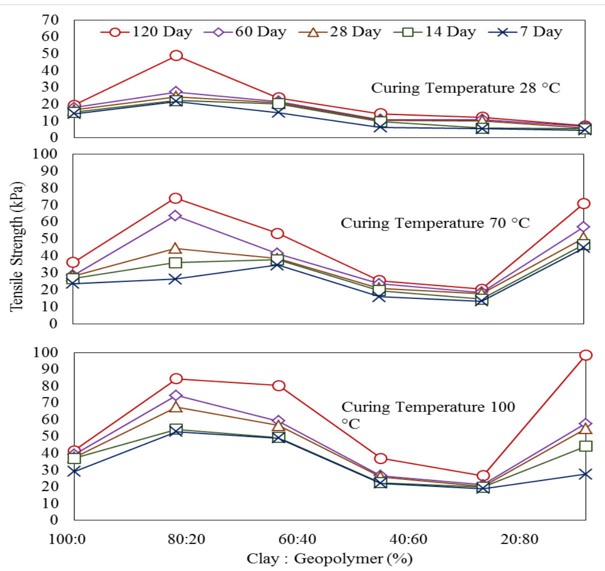

Fig. 9. Indirect tensile strength with different mixing ratio of C:QG

2.8 Temperature effects on geopolymer formation

In the geopolymering process, there is heat exchanging between the particles. Temperature therefore affects the compressive strength of the samples. In this study, the samples were cured at temperatures of 28, 70 and 100 ˚C. Higher temperatures lead to more homogeneous samples, resulting in higher compressive strength correspond to Chayakrit (2016) Mohammadjavad (2019). **Figure 10** shows the relationship between q_u of the sample and the curing temperature of the sample. C: QG 60:40. Samples with different proportions, the strength also increased with the curing temperature.

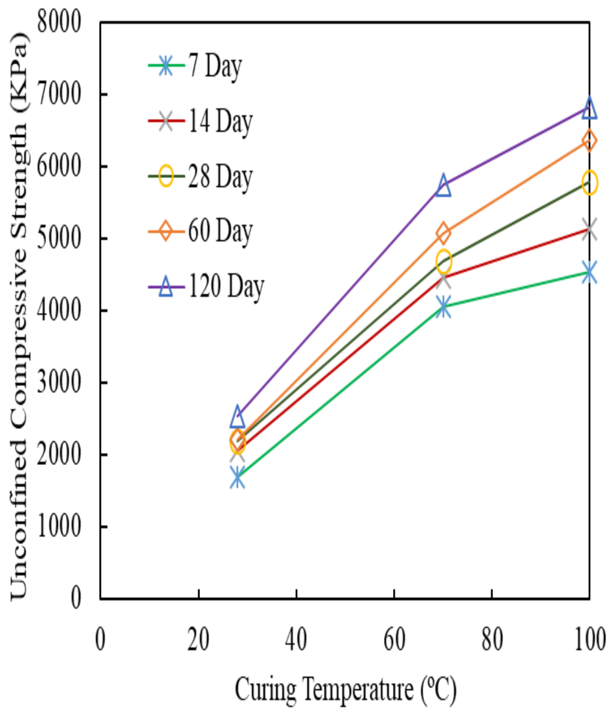

Fig.10. Unconfined compressive strength and curing temperature of C:QG 60:40

2.9 Geopolymerization reaction

Soft Bangkok clay is rich of silica and alumina. The surface of the clay sample becomes rougher after mixed with QG which contain high calcium, indicating greater reaction between QG and clay. QG react with silica and alumina in clay forming calcium silicate hydrate and calcium aluminosilicate hydrate. (Yip et al., 2005, Li et al., 2010) Similarly, pozzolanic reactions result in a more compact microstructure of the geopolymer system due to the bonding of calcium (Yip and Van Deventer, 2003). The strength development from the UCS tests demonstrates the binding properties of the QG geopolymers. **Figure 11** shows sample of C: QG 60:40 at 28 days, curing different temperatures. At curing temperature of 70 ˚C, the sample exhibit denser particle arrangement than the sample curing under 28 ˚C. However, there are no significantly different of particle arrangement between samples curing under 70 ˚C and 100 ˚C. Therefore, it can be anticipated that the curing temperature of 70 degrees is suitable for polymerization reaction.

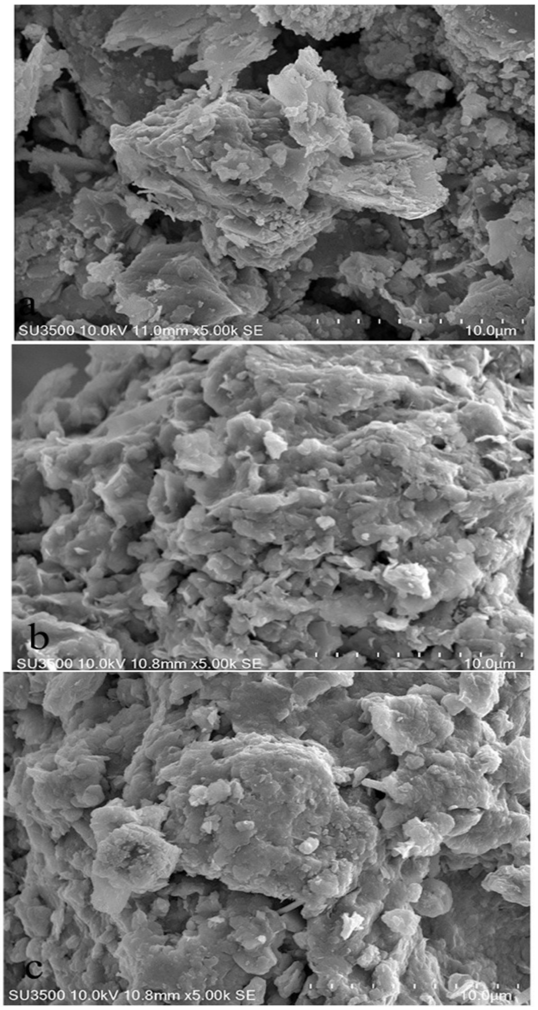

Fig. 11. SEM image of C: QG 60:40 (a) 28 °C, (b) 70 °C and (c) 100 °C

3. Conclusions

Soft clay is a problematic soil with poor engineering properties. In this research, soft clay was treated by using quicklime as a precursor, and with alkali activators. This approach will bind the soil particles within the geopolymer paste, thus rendering it as a stable material. The strength development from the UCS tests demonstrates the binding properties of the C-QG geopolymers.

a. Quicklime mixed with 6 molar NaOH gave the maximum unconfined compressive strength after curing period of 7, 14, and 28 days, respectively. The strength treated clay increase as the QG content replacement increase to 40% and the sample of C: QA 60:40 exhibits higher q_u than sample of C: QA 80:20 at curing age 14 and 28 days. It can be notice that the q_u of the samples increases significantly to 127% as the temperature increase from 28 ˚C to 70 ˚C, On the other hand, the increment rate of q_u increase only 18% when the curing temperature increased from 70 ˚C to 100 ˚C, indicating that the optimum curing temperature was 70 ˚C.
b. Elastic modulus of samples increases with curing temperature of 28 ˚C, 70 ˚C and 100 ˚C. The mixing ratio of C:QG 60:40 exhibited highest elastic modulus. The optimum curing temperature was 70 ˚C corresponded to unconfined compression strength. E_{50} increases with increasing in geopolymer content and approximately equal to 869.82q_u. This secant modulus can be used for pavement design in Thailand.
c. The highest indirect strength at all curing temperatures was obtained samples with mixing ratio of C: QG 80:20. At curing temperature of 28, 70 and 100 degrees, the maximum indirect tensile strength was 48, 72 and 90 kPa, respectively. However, the curing temperature increased from 28 ˚C to 70 ˚C, the indirect tensile strength increased by 50 percent indicating that the optimal curing temperature is 70 ˚C.
d. The strength development from the UCS tests demonstrates the binding properties of the QG geopolymers. At curing temperature of 70 ˚C, the sample exhibit particle arrangement denser than the sample curing under 70 ˚C and there are no significantly different of particle arrangement between samples curing under 70 ˚C and 100 ˚C.

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