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Sludge ash/hydrated lime on the geotechnical properties of soft soil

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Abstract

In this study, an effort to improve the properties and strength of soil, sewage sludge ash (SSA) and hydrated lime are applied to stabilize soft cohesive subgrade soil. Five different ratios (in weight percentage), 0%, 2%, 4%, 8%, and 16%, of sludge ash/hydrated lime are proposed for mixture with cohesive soil. Then, the effects of the different proportions of SSA/hydrated lime on soft cohesive soil are studied. Test results indicate that the unconfined compressive strength of specimens with additives was raised from three to seven times better than that of the untreated soil, and swelling behaviors were also effectively reduced for those specimens. Results of triaxial compression test indicate that the shear strength parameter, *c*, rose with an increased amount of additives and improved from 30 to 50–70 kPa. On the whole, SSA/hydrated lime could particularly improve the geotechnical properties of cohesive subgrade soil.

Keywords: Fly ash; Hydrated lime; Sewage sludge; Soft soil

1. Introduction

Fly ash, a common soil stabilizer, contains large amounts of pozzolanic materials which are important components used to stabilize soft subgrade soil. It could cement ions in soil to improve the relative stress among soil particles and further increase the strength of soil. Meanwhile, with the quick growth of wastewater sewage sludge in city, landfilling shortages, and strict requirements in environmental protection, the reclamation and volumetric reduction of sewage sludge have been encouraged world wide. Many research results have found that sewage sludge ash (SSA) possesses similar pozzolanic material properties as fly ash and also has the potential application to stabilize soft subgrade soil. This is possible only if soil test results such as compaction test, California bearing ratio (CBR) test, unconfined compressive strength test (UCS), and triaxial compressive test can be improved [1]. Hence, this study proposes that SSA be used to replace traditional fly ash and be mixed with hydrated lime as an admixture to stabilize soft subgrade soil.

In general, untreated soil strength can be improved by adding high proportions of fly/lime ash. However, when the admixture added reaches a certain level, the strength of soil improved by lime could be reduced. Little [2] applied Eades and Grim's method by assessing pH values to evaluate amounts of lime needed for use as a stabilizer. He found that when pH value was about 12.4, the amount of lime needed ranged between 4% and 8%. Evans [3] disclosed that pH values increased with specific amounts of lime added for the application of soil stabilization. The maximum pH value was reached when 7% of lime was added. Parsons et al. [4] mixed different quantities of lime with soil for road tests in Kansas. They revealed that large swelling potential was generated when 5% and 2.5% of lime were added to CH soil and CL soil, respectively. In addition, smaller plasticity indices were observed for all soils tested for the case of 2.5% of lime. Non-plastic behaviors were also noticed for four out of five soils with 5% of lime admixture added. Further, they found that strengths of lime-soil specimens became better and 95% relative compactions were easily obtained for specimens tested. This was due to the control of mutual influences between lime

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and clay soil under the condition of high moisture content. They also found that the optimum moisture content were between 8% and 10% for using lime as admixture in the stabilization of subgrade soil.

SSA and hydrated lime can be applied as a stabilizer for soft subgrade soils by improving basic soil properties such as compaction, shear strength, and bearing capacity, etc. Due to the characteristics of pozzolanic reaction in sludge ash and lime, calcium in those two materials can produce either calcium silicate or aluminum silicate hydrates in the process of polymerization. Further, mechanisms used to generate these hydrates are similar to the hydration mechanisms for Portland cement. Misra [5] believed both mechanisms had the same effects chemistry-wise. The pozzolanic chemical equations are described as:

$$Ca(OH)_2 + SiO_2 \rightarrow \text{C–S–H} \quad \text{gel} \tag{1}$$

$$Ca(OH)_2 + Al_2O_3 \rightarrow \text{C–A–H} \quad \text{gel} \tag{2}$$

The other mechanism of stabilization that could improve the properties of soft subgrade soil is the occurrence of flocculation-agglomeration. This is done by a process, after the calcium in stabilizer has dissolved in water, where divalent calcium ion (Ca^{2+}) would replace monovalent hydrogen ion of the double layer on the surface of clay particles, restrain diffusive double layer from expansion, lower water absorption of soil, and result in larger soil particles by reducing repulsive forces among soil particles. Not only were soil structures improved, but the effects stated above could make clay particles cohere and produce low plasticity soil such as silt. Further, main improvements on soil performances including plasticity, workability, instant non-curing soil strength, and load deformation are noticed [6].

The application of sewage sludge to manufacture construction building materials is most seen in practice as demonstrated by Tay and Goh [7], Tay and Show [8], Lin and Weng [9], and Lin and Tsai [10]. Hence, the object of this study is to utilize SSA as a soft subgrade soil stabilizer, evaluate its effects on soil, and provide more potential applications of sludge ash in the future.

2. Test programs

In this study, sewage sludge samples were collected from a local municipal wastewater treatment plant at Kaohsiung City. Before being ground into fine particles to pass #200 sieve, sludge samples were incinerated in a furnace at 800 °C. In order to have more SSA replace pozzolanic materials and more sewage sludge recycled as well as to maintain or increase the strength of improved soil, the admixture was assigned in the ratio of 4:1 for SSA and hydrated lime, respectively. Five admixtures according to weight percentages of 0%, 2%, 4%, 8%, and 16%, were proposed for mixture with cohesive soil. Tests such as pH values, Atterberg limits, compaction tests, unconfined compressive strength tests, swelling potential, CBR, and triaxial compression tests for stabilized cohesive soil samples were carried out to study the engineering performances of improved soils. Other tests like pH values, EDS analysis, X-ray diffraction, and TCLP tests were performed for sludge ash.

The stabilized cohesive soil samples were air-cured and Atterberg limits tests that are compliant with ASTM D4318 standard were accomplished to obtain liquid limit (LL), plastic limit (PL), and plasticity index (PI). Variations of PI for untreated soil before and after admixtures added were then studied. pH value tests were regulated by 27038-S410.60T specification set by Environmental Protection Agency in Republic of China. Tests were carried out by maintaining the solid-to-liquid ratio (soil + admixture/deionized water: 20 g/20 ml) at 1:1 and samples were cured for 3 h, 3, 7, 14, 21, and 28 days to obtain variations of pH values for untreated soil both with and without ash/hydrated lime added. Compaction tests can find maximum dry unit weight (γ_{dmax}) and optimum moisture content (OMC) of SSA/hydrated lime soil specimens at various moisture contents. Furthermore, the amount of water was controlled by the OMC obtained in unconfined compressive strength tests, which were performed at different curing ages (3 h, 3, 7, 14, 28, 56, and 90 days). Once again, OMC was used in swelling potential and CBR tests were performed to find the amount of volumetric swell and bearing capacity of soil specimens, respectively. Finally, triaxial compression tests were carried out under the conditions of unconsolidated, undrained, and unsaturated (UUU tests) to obtain the shear strength parameters, c, and friction angles, φ, for ash/hydrated lime soil specimens at different simulated confined pressures.

3. Results and discussion

3.1. Characteristics of materials

3.1.1. Sewage sludge ash (SSA)

Tests such as TCLP and basic physical and chemical analyses were performed for SSA. Results for TCLP showed that leached metal concentrations of SSA (dried at 105 °C) were 0.03, 0.25, 0.24, 0.54, and 16.75 mg/L for Cd, Cu, Cr, Pb, and Zn, respectively. The study indicates that test results of TCLP were met by the Environmental Protection Agency in Republic of China. The current regulatory thresholds for Cd, Cu, Cr, and Pb are 1.0, 15, 5.0, and 5.0 mg/L, respectively.

In general, the more calcium present in oxides for materials used as a stabilizer, the quicker the pozzolanic reactions. Misra [5] showed the different levels of improvement in clay after fly ash were added. He found that the bearing capacity of fly ash–clay soil was effectively enhanced. On the one hand, the amount of calcium in admixture affected improvement on soil. On the other hand, calcium in SSA (8%) was more than in fly ash (3–5%). Hence, it is expected that SSA would have better efficiency than fly ash in the application of cohesive soil improvement. Moreover, according to the quasi-quantitative analysis of EDS for SSA and hydrated lime, it indicates that the main components in SSA were Si, Al, and Fe, which were related to the three major oxides, SiO_2, Al_2O_3, and Fe_2O_3, that are used for carrying out pozzolanic reactions. This observation coincided with studies found in other related research references.

Table 1
Properties of untreated soil

Gravel (0.4 mm)	0
Sand (0.4–0.08 mm)	17
Silt (0.08–0.005 mm)	46
Clay (0.005 mm)	37
Gs	2.75–2.77
ω (%)	27.7–30.6
Liquid limit (LL)	30.3
Classification (USCS)	CL
Classification (AASHTO)	A-4
Maximum unit weight (kN/m^3)	1.66
Optimum moisture (%)	17.8
Unconfined compressive strength at optimum moisture (kPa)	33.1
Hydraulic conductivity (cm/s)	3.17E−07
Plasticity index (PI)	9.7

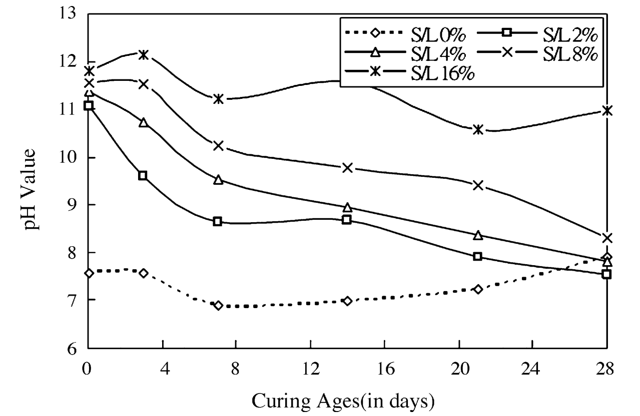

Fig. 1. Relationships between pH values and curing ages for different amounts of sludge ash/lime additives.

3.1.2. Lime

It is difficult for hydrated lime to react with water in the slake process and would generate high thermal heat (15.3 kcal). As such, hydrated lime is selected as part of a stabilizing admixture. In addition, hydrated lime is easy to transport (Gs = 2.2) and is also a low cost material. Results of X-ray diffraction indicate that hydrated lime contained 84–95% of $Ca(OH)_2$ and 5% of CaO.

3.1.3. Untreated cohesive soil

Table 1 shows the basic properties of untreated cohesive subgrade soil. The untreated soil in this study contained 60–70% of silt and clay, and was categorized as CL soil in accordance to USCS classification. Moreover, AASHTO grouped the untreated soil into the category of A-4 and identified it as low plasticity silty clay. Following the classification method of AIIS-181, where subgrade soils were divided into three grades in accordance with strength, the untreated soil was distinguished into grade 1 for CBR $\leqq 3$, as the CBR value of untreated soil equals to 2. This implies that the untreated subgrade soil was characterized as very poor soil.

3.2. pH values

In this study, the amounts of calcium found in SSA and hydrated lime were 8% and 85%, respectively. Fig. 1 shows that pH values became acidity as the extensions of curing got longer after SSA/hydrated lime were added to untreated soil. In fact, with the help of the saturation principle of calcium and the mechanism of stabilization in pH values, it is clear that calcium was gradually used up as the stabilization was being processed. Therefore, pH values reduced with a decrease in calcium levels. Further, Fig. 1 demonstrates that as more amounts of admixture (such as 16%) were added to untreated soil, a smaller decrement and a smoother variation of pH values were noticed. This led to the fact that hydrated lime contained rich calcium and could provide sufficient calcium for reaction. Further, aluminosilicates in the untreated soil (70%) and SSA (40%) could react with calcium hydroxide in hydrated lime to create pozzolanic reactions. pH values found from pozzolanic reactions at different curing ages were similar to those obtained from the optimum modification mixture proposed by Eades and Grim in the 1970s. Further, decrements in pH values became larger for small amount of admixtures (2%, 4%, and 8%) since sulfur dioxide and calcium silicate continuously reacted with each other and consumed lots of calcium in the mixture. Results also indicate that pH values of specimens with 2% and 4% SSA/hydrated lime added were less than untreated soil that were cured at 28 days. They also had the tendency of decreasing pH values.

3.3. Atterberg limits

Atterberg limits could provide information regarding LL, PL, and the hardened properties for soil at critical states. In general, soil with smaller PI has better workability in engineering applications. Fig. 2 displays the relationships between PI values and curing ages for different amounts of SSA/hydrated lime added. As shown in Fig. 2, PI values for all samples with different amounts of admixture were clearly reduced after being cured for 3 days, while low plasticity untreated CL soil turned into low plasticity stabilized ML soil (as illustrated in Fig. 3). This indicates that the application of admixture to stabilize the soil samples was very efficient in terms of time. On the whole, PI val-

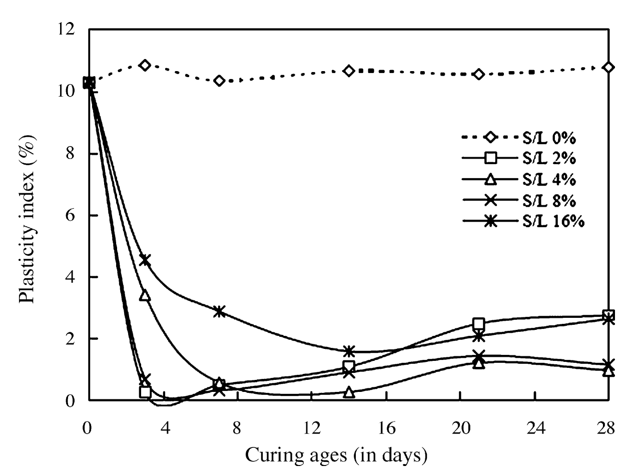

Fig. 2. Relationships between plasticity indices and curing ages for different amounts of sludge ash/lime additives.

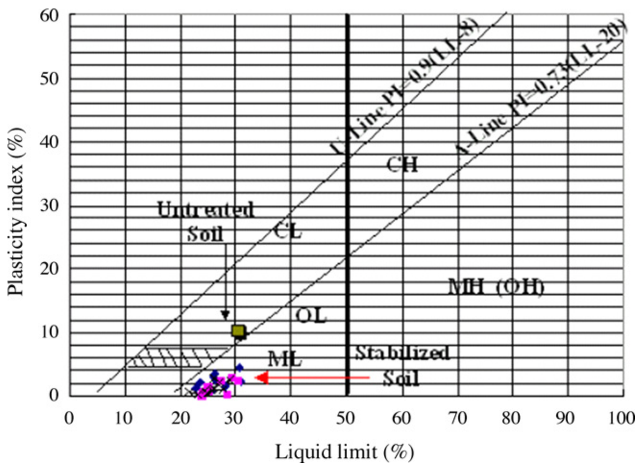

Fig. 3. Location of untreated soft soil and sludge ash/lime soil in plasticity chart.

ues were reduced quite a lot for stabilized soil, although PI values recovered a little as a result of the loss of moisture after longer extension of air curing. Moreover, based on the soil classification of Casagrande, seen in Fig. 3, the untreated soft subgrade soil had become a better soil in the application of engineering after treatments.

3.4. Compaction test

Soil compaction is a process of re-arranging and condensing soil particles by mixing water with soil and adding external energy to soil. Hence, soil can reach its densest condition with the aid of wetting and re-arranging particles by water molecule and compaction energy. Fig. 4 shows the influences of SSA/hydrated lime on the compaction properties of untreated soil. As displayed in Fig. 4, the maximum dry unit weight, γ_{dmax}, were between 16.6 and 16.9 kN/m^3 and OMC were between 16.5% and 18.0% when different amounts of SSA/hydrated lime were added to specimens. Test results indicate that the utilization of SSA/hydrated lime as a soil stabilizer had very small impact on the compaction of soft subgrade cohesive soil. Puppala and Hanchanloet [11] mixed sulfuric acid and lignosulfonate chemicals (SA-44/LS-40, or DRP) with lime to produce three different groups of soil stabilizers in order to improve soft subgrade soil. They found that each group of stabilizer showed its own compaction behaviour with different OMC and γ_{dmax} values. However, variations of OMC and γ_{dmax} with different amounts of admixture added in each group demonstrated little changes. Similar results were noticed in this study. It is believed that effects of cluster resulted in changes of properties in untreated soil. Therefore, as more admixtures were added to untreated soil, soil mixtures became looser. Further, effects of cluster and compaction counterbalanced the influences of different amounts of admixtures that were added to soil.

3.5. Unconfined compressive strength test (UCS test)

The purpose of a UCS test is to evaluate the strength of pavement by assessing the uniaxial bearing capacity of soil tested. Fig. 5 shows the relationships between UCS of specimens at different curing ages and with various amounts of SSA/hydrated lime added to soil. Results signify that the untreated soil could be effectively improved in 2 h after admixtures have been added. Furthermore, the strength of soil specimens increased with more amounts of SSA/hydrated lime added when cured at 3 days. The increased strength ranged between 1.0 and 1.5 times of the original strength. Since SSA and hydrated lime are light weight materials with specific gravity equaling to 2.13 and 2.2, respectively, more admixtures could be added to soil specimens by using gravimetric method. It could also provide more free hydrated calcium to carry out the cementation between lime and pozzolans. In Qubain's research (1999), he mentioned that the unconfined compressive strength (qu) increased effectively between 2.5 and 3.0 times of its original strength with the proportions of lime added for specimens cured at 7 days. Furthermore, strengths clearly improved as more amounts of lime were added at longer extension of curing time. In this study, similar results

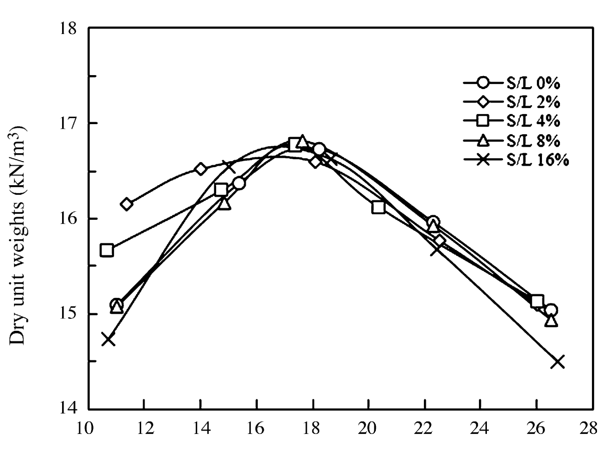

Fig. 4. Influences of different amounts of sludge/hydrated lime ashes on the compaction properties of untreated soil.

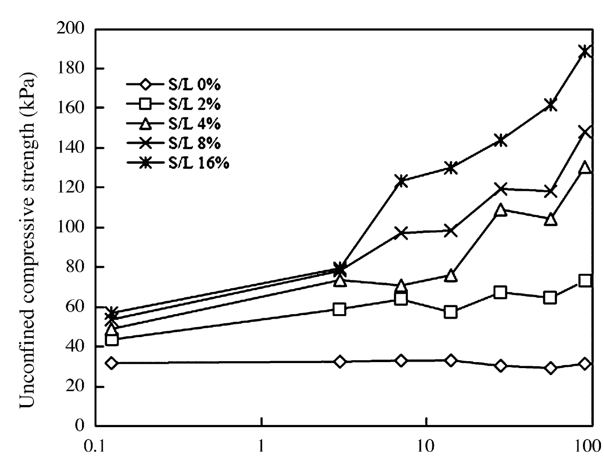

Fig. 5. Relationship between unconfined compressive strength of specimens at different curing ages and various amounts of sludge ash/hydrated lime added to soil.

were observed. When specimens were cured between 7 and 14 days, the UCS increased ranging from 1.0 to 4.3 times of soft subgrade soil (about 100.0–130.0 kPa) with increased amounts of SSA/hydrated lime added. Among them, 16% admixture gave the best improvement in strength. Further, similar strength improvements were observed for curing ages between 14 and 28 days. When cured at 56 days, strengths also showed improvements with all amounts of admixtures added. In addition, at 90 days of curing, increments of strength were the largest among all extension of curing time for different amounts of admixtures added. In contrast, for the case of 2% admixture, the increment was relatively small when compared to other amounts of admixtures.

3.6. *California bearing ratio test (CBR test)*

3.6.1. *Swell potential*

In this study, with the help of quasi-quantitative analysis of EDS, the main components in SSA were from 2 or 3 valence charged ions such as Si, Al, Fe, and Ca, and Ca for hydrated lime. Note that since the release of Ca^{2+} in SSA and hydrated lime were able to clearly replace hydrogen bonding and increased the transformation ability of negative charges on the surface of cohesive soil, the development of diffusive double layer of soil could be effectively reduced.

In general, as the volumetric stability of material improves, the engineering application becomes effectively. Fig. 6 shows that the swelling potential of untreated soil (A-4 soil) was between 0.9% and 1.0% for 120 h of soaked time when compaction energy was assigned at 10, 25, and 55 blows. The swelling phenomenon of soil was observed noticeably. Yet, when SSA/hydrated lime was added to soil, the mitigation in soil expansion was not noticed. As more admixtures were added, the less improvement in soil expansion was observed. The volumetric swelling resulted from small amounts of calcium oxide

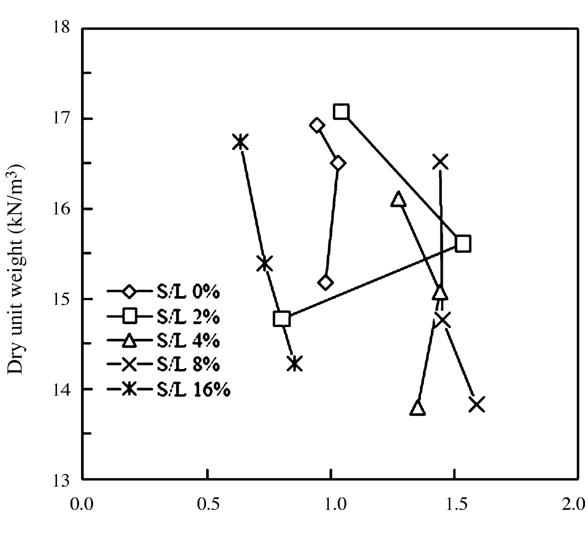

Fig. 6. Relationship between volumetric swelling and dry unit weight for the untreated soil specimens with different amounts of sludge ash/hydrated lime added.

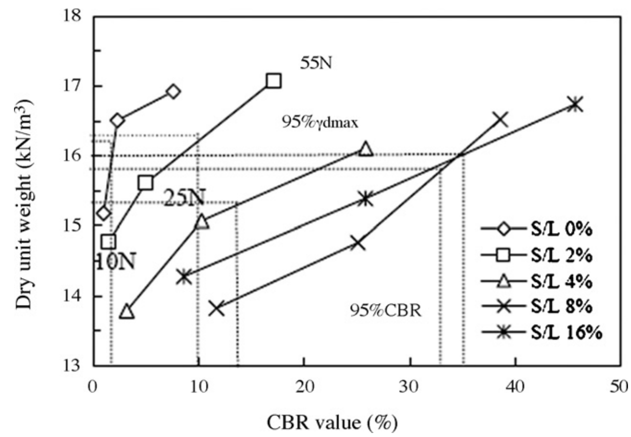

Fig. 7. Relationship between 95%CBR values and dry unit weight for the untreated soil specimens with different amounts of sludge ash/hydrated lime added.

in hydrated lime that reacted with water to generate calcium hydroxide. However, the volumetric swelling decreased to 0.7% at 16% of admixture added to soil, which was the result of the gradual growth of Ca–Si and Al–Si hydrates in SSA/hydrated lime. This phenomenon led to the large quantities of soil particles bonding together and hence reduced the amount of volumetric swelling.

3.6.2. *CBR value*

In practical application, pavement structure is usually designed according to values such as CBR, R, and modulus. In this study, CBR tests followed the specification of ASTM D1883-87. Test results indicate that 95%CBR values of untreated soil equaled about 2.0, as shown in Fig. 7. According to the classifications set by AIIS-181, if the CBR values are less than or equal to 3, the tested soil is classified as type 1 and characterized as poor subgrade soil. As illustrated in Fig. 7, 95%CBR values improved to 10, which corresponded to good subgrade soil in accordance with AIIS-181 standard, when 2% of SSA/hydrated lime was added to untreated soil. Additionally, even more improved CBR values fell between 15 and 35 for other higher proportions of admixtures added. Test results have shown that 95%CBR values of soil mixture were close to high bearing capacity subgrade soil materials when admixtures were added to untreated soil. Hence, SSA/hydrated lime additives can potentially and effectively improve soft subgrade soil from poor to good conditions.

3.7. *Triaxial compression test*

UUU (unconsolidated, undrained, and unsaturated) triaxial tests are performed following regulations set by the ASTM D2850-87. When SSA/hydrated lime soil specimens failed due to the loading of axial force, shear force and deviator stress were found in the failure surface. In general, the confining pressure would first act on the specimens in the test. Then, axial stress would shear the soil samples to failure. Following the failure, shear stress in the failed surface and Mohr-Coulomb failure envelope are obtained. In this study, tests were conducted

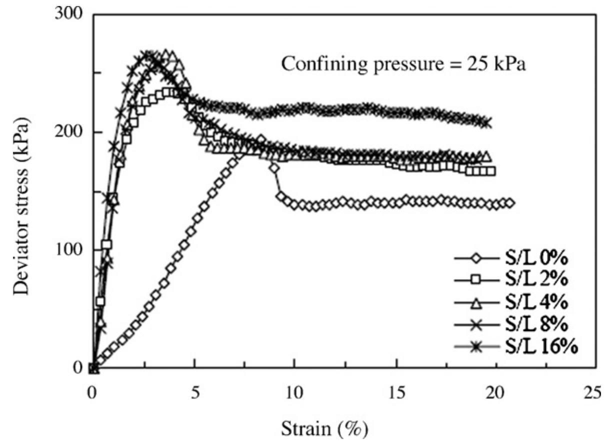

Fig. 8. Stress–strain relationships of UUU tests for the untreated soil specimens with different proportions of sludge ash/lime added when effective confining pressure was designated at 25.0 kPa.

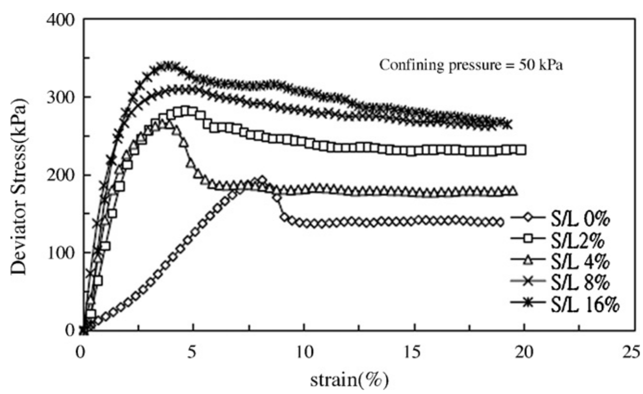

Fig. 9. Stress–strain relationships of UUU tests for the untreated soil specimens with different proportions of sludge ash/lime added when effective confining pressure was designated at 50.0 kPa.

with the effective confining pressure at 25 and 50 kPa in order to find shear stresses under the action of corresponding axial stresses. Figs. 8 and 9 illustrate the stress–strain relationships for SSA/hydrated lime soil specimens with different proportions added when effective confining pressures were designated at 25

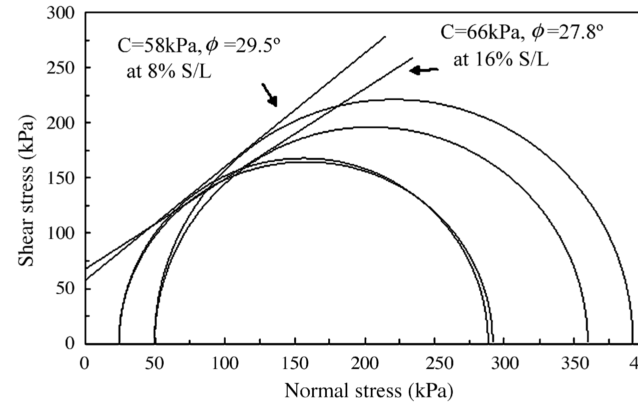

Fig. 10. Mohr circles and failure envelopes of UUU test results for the untreated soil specimens with 8% and 16% sludge ash/lime added.

and 50 kPa. As shown in the figures, peak shear stresses and failure behaviors similar to brittle materials were observed in the shear failure mode for specimens. Furthermore, Mohr's circles were plotted to find the Mohr-Coulomb failure envelopes, as illustrated in Fig. 10. Results in the figure indicate that the cohesion, c, and friction angle, φ, for the case of 8% admixtures were 58.8 kPa and 30.9°, respectively; 47.5 kPa and 36.8°, respectively, for the case of 16% admixture. On the whole, cohesion, c, increased with increased amounts of admixtures. On the contrary, friction angle, φ, reduced as more admixtures were added. This implies that more interactions among particles resulted in the increase of shear stress of soil mixtures.

3.8. Microstructure behavior

Both untreated soil and lime must have aluminosilicates components as the pre-required conditions for hydrated lime to be considered a soil stabilizer. In Evans' report [3], he indicated that aluminosilicates in untreated soil would respond with cementitious calcium materials to carry out a long term pozzolanic reactions. In the meantime, the extra pozzolanic materials in the SSA are very beneficial to the stabilization of soft subgrade soil. In this study, SEM and XRD were performed in order to observe the changes of soil after being stabilized by SSA/hydrated lime.

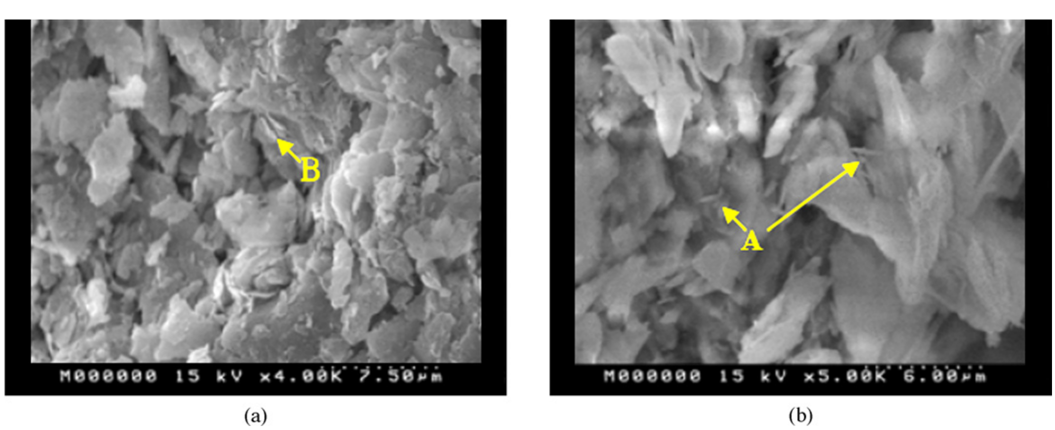

Fig. 11. Results of SEM analysis for 16% sludge ash/lime soil specimen cured at (a) 28 days (4000×), and (b) 56 days (5000×) (A = ettringite and thaumasite, B = Afm).

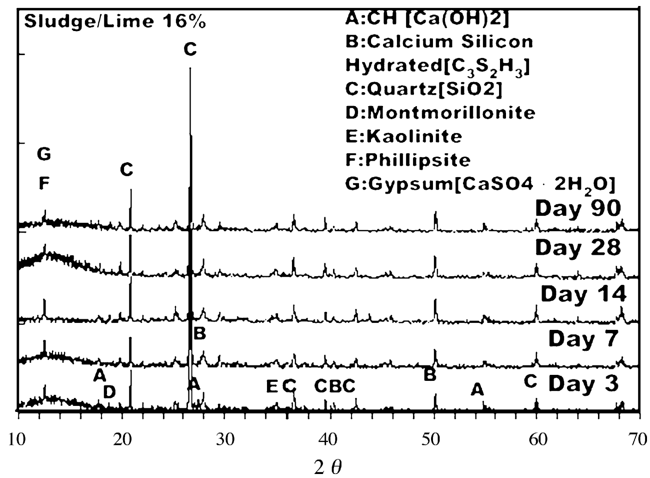

Fig. 12. Diffraction peak values of reaction products for 16% sludge ash/lime soil specimen under different curing ages obtained from X-ray diffraction.

Crystallized phases (needlelike) such as ettringite hydrates were noticed after the addition of SSA/hydrated lime to soil as displayed in Fig. 11. Fig. 12 illustrates those diffraction peaks of C–S–H hydrates obtained from X-ray diffraction as they became higher at various extensions of curing ages. Moreover, diffraction peak values of reaction products at different curing ages were obtained from X-ray diffraction and JCPD database. It is found that, with the help of overlay map analysis, the diffraction peak values for CH and C–S–H varied noticeably as marked in the figure. In addition, calcium hydroxide could produce stronger hydration with increasing duration of reaction. Calcium hydroxide could also react with aluminosilicates contained in sludge ash or clay. This pozzolanic reaction can produce hydrates of calcium silica and aluminum silica. Further, Fig. 12 also indicates that the diffraction peak for calcium hydroxide that reacted with calcium silica hydrates were observed at the diffraction angles, 2θ, equaling to 18°, 26.5°, and 50°. Note that higher peak values of CH were detected at the extension of shorter curing time. However, when curing ages were between 28 days and 90 days, the diffraction peak values at various diffraction angles were clearly lower for different CH hydration products. Moreover, results obtained from EDS analysis show that the relative amount of calcium left was about 6% after 56 days. This suggests that calcium was gradually reduced during the stabilization of soft subgrade soil. This phenomenon was also clearly shown at age of 90 days. Hence, it pointed out that Ca^{2+} reacted with aluminosilicates to produce calcium silica and aluminum silica hydrates, which implies that stabilizer could make soil particles denser.

4. Conclusions

In this study, in order to improve the stabilization of soil, SSA and hydrated lime are applied to soft subgrade soil. Test results indicate that, after SSA/hydrated lime were added to soil samples (A-4 soil), PI values of the untreated soil decreased and the type of soil improved from CL soil to ML soil. It implies that SSA/hydrated lime could stabilize the engineering properties of soft cohesive subgrade soil. As for the improvement of swelling potential, it is found that volumetric swelling of A-4 soil was not effectively reduced at small amounts of SSA/hydrated lime additives. However, the quantities of swelling were still lower than the allowable safety value. Furthermore, SSA/hydrated lime could improve 95%CBR values, triaxial shear strength, unconfined compression strength, and shear strength parameter, *c*, of A-4 soil. This indicates that the admixture of SSA/hydrated lime was helpful in stabilizing soft subgrade soil. In this study, test results also illustrate that the optimum amount of SSA/hydrated lime additive for dealing with swelling behaviour of soil was 8%. Moreover, when other engineering properties of soil were taken into consideration, 8% SSA/hydrated lime additive could effectively improve the basic properties of soft subgrade soil. Hence, the 8% of admixture can potentially change untreated soil from poor subgrade soil to good subgrade soil, and have positive influences on the treatment of stabilization of soil.

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