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Stabilization treatment of soft subgrade soil by sewage sludge ash and cement

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ABSTRACT

In this study, incinerated sewage sludge ash (ISSA) is mixed with cement in a fixed ratio of 4:1 for use as a stabilizer to improve the strength of soft, cohesive, subgrade soil. Five different ratios (in wt%: 0%, 2%, 4%, 8%, and 16%) of ISSA/cement admixture are mixed with cohesive soil to make soil samples. In order to understand the influences of admixtures on the soil properties, tests of the pH value, Atterberg limits, compaction, California bearing ratio (CBR), unconfined compressive strength, and triaxial compression were performed on those samples. The study shows that the unconfined compressive strength of specimens with the ISSA/cement addition was improved to approximately 3–7 times better than that of the untreated soil; furthermore, the swelling behavior was also effectively reduced as much as 10–60% for those samples. In some samples, the ISSA/cement additive improved the CBR values by up to 30 times that of untreated soil. This suggests that ISSA/cement has many potential applications in the field of geotechnical engineering.

1. Introduction

Reclamation of sewage sludge has been progressing positively in different research areas and, through many applications, this material has been turned into useful building construction materials. Tay and Goh [1] replaced cement with incinerated sewage sludge ash in making concrete, thereby improving the workability and compressive strength of concrete. Results obtained by Yaque et al. [2] showed that silica and calcite were observed in dry sewage sludge crystallization using DRX analysis. Therefore, the addition of sewage sludge ash to mortar could slow hydration processes of the cement. Lin et al. [3] utilized 0–45% of incinerated sewage sludge ash as a substitute for clay to manufacture glaze tile. They found that incinerated sludge ash was suitable for manufacturing glaze tile. Although less gaining of water absorption and bending strength were noticed, the sludge ash glaze tiles were met the requirement of CNS standard for floor tile earthenware. Furthermore, Lin et al. [4] applied nano-SiO_2 as an additive to improve the properties of sludge ash tiles. They showed that the bending strength of sludge ash tiles increased with the increasing amounts of nano-SiO_2. However, reductions in bending strength were also noticed and correlated with increasing amounts of nano-SiO_2 added at temperature of 1150 °C or higher.

In order to widely utilize sludge for different practical applications, Tay and Goh [5] also investigated the chemical and physical properties of ash residues and evaluated possible applications in geotechnical areas. In their study of a mixture of coal cinder and fly ash later mixed with soil, properties of this treated soil were stable. They also pointed out that soil characteristics such as shear strength and settlement were greatly improved. In applying cement to stabilize subgrade soil, K'ezdi [6] found that mixing cement with untreated soil generated hydration reactions which lessened the pH values, the amount of Ca^+, and the free $Ca(OH)_2$ of the mixture, which can be attributed to pozzolanic reactions (Little [7], K'ezdi [6]). The plasticity index (PI) of the treated soil decreased with increasing cement additions. The PI value also decreased with the increase of the hardening times of admixtures. Additionally, the cement curing time affected the unconfined compressive strength of the treated soil and was found to be the main factor in the strength development of the stabilized soil. In general, the cohesion, c, and the shear strength of the stabilized soil improved with increasing cement additions. Lin et al. [8] applied sewage sludge ash and hydrated lime to improve the properties and strength of soft cohesive subgrade soil. Results indicate that the properties such as unconfined compressive strength, swelling behaviors, and shear strength parameter (or cohesion), c, were improved for soft soil. They suggested that the sewage sludge ash-hydrated lime can mostly improve the geotechnical properties of soft cohesive subgrade soil.

Fly ash can be used as pozzolana and react with calcium materials in manufacturing calcium silicate or aluminum silicate hydrates

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during the process of polymerization. Processes used in making those hydrates are similar to the hydration mechanisms of Portland cement, and both result in the same chemical effects (Misra [9]). Incinerated sewage sludge ash also has this pozzolanic reaction nature [10–12] and so was used in this study to replace the functions of fly ash in the improvement of soft subgrade soil. The chemical formulae of the pozzolanic reaction are:

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

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

When Portland cement blended with water, the initial hydration reaction began and resulted in a fast accumulation of calcium in the soil. Then, the clay soil was effectively stabilized as calcium ions (Ca^{2+}) were released from the mixture. The amount of calcium decreased 12 h after placing the cement mixture into the soil. Consequently, calcium and water were eventually decreased and C-S-H and $Ca(OH)_2$ were produced. Hence, the calcium in the cement met the soil's initial needs. Unbound cement was formed until the calcium was fully used (Prisinski and Bhattacharja [13]).

Resource regeneration and utilization of sewage sludge is being aggressively promoted in Taiwan. However, very few studies make use of incinerated sewage sludge ash as a soil stabilizer to improve the strength of soft soil. In this article, incinerated sewage sludge ash is utilized as an alterative admixture to replace the conventional soil stabilizer, fly ash. The influences of incinerated sewage sludge ash additions on the properties and strength of soft subgrade soil were investigated. We are optimistic that this study can potentially provide further beneficial uses of the sewage sludge ash.

2. Test methods

Sewage sludge samples were first collected from a local wastewater treatment plant at Kaohsiung City in southern Taiwan. These were then incinerated in an electric furnace at 800 °C and ground into fine particles to pass through a #200 sieve. Tests of pH values, energy dispersion spectra (EDS), X-ray diffraction (XRD), and toxic characteristic leaching procedures (TCLP) which are regulated by US EPA [14], were performed to analyze the properties of incinerated sewage sludge ash (ISSA). Portland cement (type I) was also applied as an additive in this study. Hence, the admixture was manufactured with ISSA and cement in a fixed ratio of 4:1. Then, five admixture proportions of 0%, 2%, 4%, 8%, and 16% (by weight) were proposed for mixture with cohesive soil. Experiments on the pH values, Atterberg limits, compaction test, California bearing ratio (CBR), unconfined compressive strength test (UCS), and triaxial compression test were again carried out for the ISSA/cement soil specimens in order to understand the affects of admixtures on the strength of soft subgrade soil.

The ISSA/cement soil specimens were air-cured. The Atterberg limits tests follow the ASTM D4318 specifications [15] in order to obtain the liquid limit (LL), plastic limit (PL), and PI of the specimens. Variations in the PI of untreated cohesive soil before and after the addition of ISSA/cement were evaluated. The optimum moisture content (OMC) and maximum unit weight (γ_{dmax}) of ISSA/cement soil specimens were measured by the compaction test, which is regulated by ASTM D698-78 specifications [16]. After determining the OMC and γ_{dmax} from the compaction test, cylindrical ISSA/cement soil specimens of size 5 cm × 10 cm were prepared for unconfined compressive strength tests using an improved Harvard compaction hammer to compact the specimens, layer by layer. Compressive strengths were obtained at the curing age of 3 h and at 3, 7, 14, 28, 56, and 90 days.

In general, swelling potential is an index obtained to detect potential damage to the subbase, base, and subgrade of pavements after plastic soils are backfilled and compacted. In this study, swelling potential tests, which are regulated by the ASTM D1883 standard [17], measured changes in the volumetric swell of ISSA/cement soil specimens at different compaction energies by using swelling sensors. ISSA/cement soil swellings were compared with those taken from moisture-cured specimens that were soaked for 120 h. Next, triaxial compression tests were carried out according to the ASTM D2850-87 specifications [18]. Finally, the unsaturated, unconsolidated, and undrained (UUU) tests performed in the triaxial compression tests were conducted with effective confining pressures at both 25 and 50 kPa.

Table 1
Chemical compositions of Portland cement (type I)

	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	Na_2O	K_2O
Chemical Compositions (%)	20.5	6.5	3.2	62.5	0.95	<0.01	<0.01	<0.01

3. Results and discussion

3.1. Characteristics of materials

3.1.1. Soil

In this study, untreated soft subgrade soil that is 60–70% composed of clay and silt is categorized as silty clay. Soil categorization tests that follow the standard of ASTM D1883-87 [17] and the classifications of AASHTO refer the untreated subgrade soil to the A-4 category, which stands for low-plasticity silty clay. In accordance with the AIIS-181 standards [19], subgrade soil is distinguished into three grades. Based on the 95% CBR value of untreated subgrade soil, soil obtained from tests conducted in this study was graded a 2. As such, the untreated subgrade soil was grouped into grade 1. This means that the subgrade soil is very poor insofar as engineering applications are concerned.

3.1.2. Cement

Portland cement (type I) was used in this study and its chemical compositions are shown in Table 1.

3.1.3. Sludge ash

The main components of sewage sludge ash as determined by EDS analysis are shown in Table 2. It is known that the oxides which primarily carry out pozzolanic reactions are SiO_2, Al_2O_3, and Fe_2O_3, which are related to these main components of sludge ash. Misra [9] noticed that increasing the calcium contained in the oxide for fly ash accelerated the pozzolanic reaction. He also showed that fly ash improved the strength of clay. In this study, the amount of Ca in ISSA is about 8%, which is greater than that in fly ash (2–5%). This implies that ISSA has the potential to improve properties of cohesive soil. Furthermore, the test results of TCLP for sewage sludge ash dried at 105 °C are shown in Table 3. The study showed that the TCLP test results are much lower than the maximum solubility limit set by the Environmental Protection Agency in the Republic of China.

3.2. pH values

As proposed by Eades and Grim in early 1970, the optimum modification mixture (OMM) is obtained after combining the soil

Table 2
Results of EDS analysis for sewage sludge ash (in wt%)

Elements	Fe	Al	Si	Pb	Mg	K	Ca	O
Sludge Ash	7.34	10.47	24.88	5.35	2.03	2.52	7.76	39.65

Table 3
Results of TCLP for the sewage sludge ash

Heavy metals	TCLP (105 °C) (mg/L)	TCLP (800 °C) (mg/L)	TCLP allowable leached concentration (mg/L)	Total amount (105 °C) (mg/kg)
Cd	0.03	0.03	1.00	4
Co	0.25	0.21	–	31
Cr	0.24	0.06	0.50	1197
Cu	1.95	8.24	15.00	5010
Fe	2.12	0.47	–	28106
Ni	6.52	1.97	–	774
Pb	0.54	0.37	5.00	310
Zn	16.75	8.14	25.00	2950

and the admixtures and evaluating the variations in pH values. The admixture in this article was mixed by ISSA and cement with a fixed ratio of 4:1. Then, using the weight percentages of 0%, 2%, 4%, 8%, and 16%, five different admixture proportions were mixed with cohesive soil. The liquid-to-solid ratio (deionized water/soil with admixture) was kept at 1:1 for the pH value tests, which were performed for test specimens cured at 3 h and at 3, 7, 14, 21, and 28 days to find the optimum admixture ratio. Fig. 1 displays the relationship between pH values and curing ages for cohesive soil with different amounts of ISSA/cement added. For all solutions tested, the pH values increased with increasing amounts of ISSA/cement added at the initial setting period. For example, the pH value for 2% admixture was 8.7, greater than that in untreated cohesive soil by 1.2; the pH was 11.2 for the 4% admixture, which was much higher than that in untreated soil. However, the pH value for the 16% admixture showed very limited increase. Moreover, the pH values for different admixtures are reduced with the extension of curing age. This phenomenon was caused by the calcium saturation principle of pH values and the mechanism of stabilization. The study showed that amounts of calcium oxide found in ISSA and cement are 9% and 62%, respectively. Calcium gradually decreased as the stabilization progressed. Hence, pH values decreased with the decrease in calcium. As a result of decreases in the amount of calcium, the initial high level of calcium received from the admixture slowly decreased to a state of low calcium in the ISSA/cement soil specimens. This also resulted in a decrease of calcium saturation. Meanwhile, the properties of the reaction products of silica and calcium silicate corresponding to a weak alkaline, which caused a reduction in pH values as curing time increased. Hence, the pH values at 28 days kept decreasing for all the cases studied. Among these, pH values for the 2% admixture were even less than that of the untreated soil at 28 days.

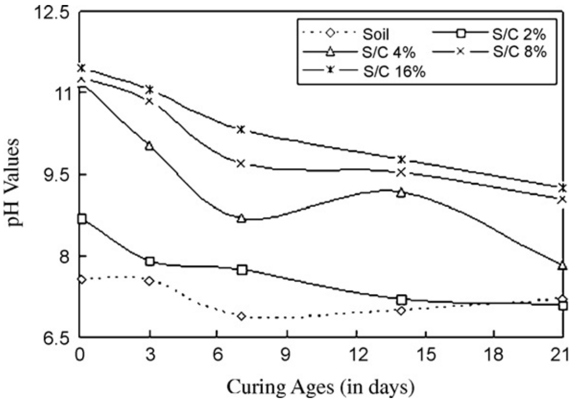

Fig. 1. The relationship between pH values and curing ages for cohesive soil with different amounts of ISSA/cement added.

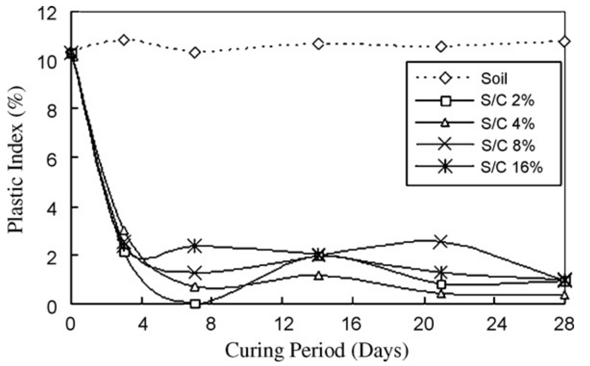

Fig. 2. The relationship between PI and the curing ages for cohesive soil with different amounts of ISSA/cement added.

3.3. Atterberg limits

In order to assess the effects of the sewage sludge ash/cement admixture on the physical properties of soft cohesive subgrade soil, the liquid limit test and plastic limit test were performed under air-drying conditions according to the ASTM D4318 standard [15]. Fig. 2 shows the Atterberg limits test results for ISSA/cement soil specimens. Plasticity indices for all specimens are noticeably decreased after curing for 3 days. The admixtures turn the low-plasticity, untreated, CL soil into low-plasticity, stabilized, ML soil, as displayed in Fig. 3. In addition, since the specimens are air-dried and the moisture in the air is insufficient to process the soil stabilization, the specimens with a high content (16%) of ISSA/cement have a relatively smaller decrease in PI values due to the serious moisture shortage at 7 days. However, as the curing time increased, the PI values of specimens with large amounts of admixture reduce noticeably because the un-reacting ISSA/cement is obtaining moisture from air. In general, the PI values of specimens with 2% admixture have fewer variations and range from 0.5 to 2.0 after being cured for 3 days.

3.4. Compaction tests

A compaction test is to re-arrange soil particles by mixing water with the soils. Soil can reach its densest condition by wetting and re-arranging the particles by water molecules and compaction. Fig. 4 displays the effects of the ISSA/cement admixture, which is used as a stabilizer for untreated soil, on the post-compaction properties of the soil. For these soils with the admixtures, the maximum dry density, γ_{dmax}, is between 16.6 and 16.9 kN/m^3. The optimum moisture content is between 16.0% and 18.3% for different amounts

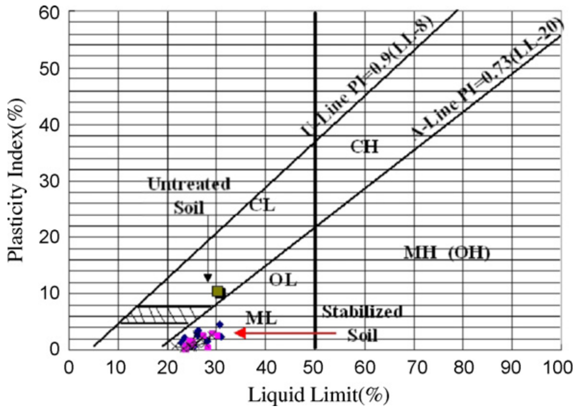

Fig. 3. Location of untreated soft soil and ISSA/cement soil in a plasticity chart.

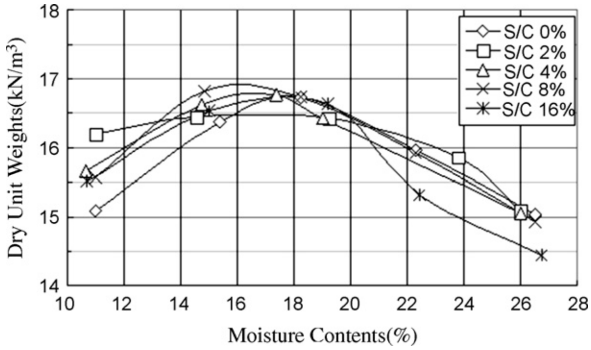

Fig. 4. Effects of the ISSA/cement admixture on the properties of the soil after compaction.

of ISSA/cement added to soil. If the dry side of the compaction curve is studied, the maximum dry densities of the specimens increase as more admixture (between 2% and 8%) is added. However, the dry side density is decreased for the 16% admixture. Similar observations are made for the wet side of the compaction curve.

Furthermore, when the peaks of the compaction curves for different admixtures are examined, the admixture is seen to efficiently reduce the over-absorption of moisture caused by the untreated soil. This moisture over-absorption phenomenon correlates with the reduction in bearing capacity of the soil. In addition, the interlocking forces among soil particles on the dry side of the compaction curve increase slightly, which is attributed to the increase in the strength of the specimens. Additionally, while the ISSA/cement additives lower the optimum moisture content and the total stresses are conserved among the soil particles, the effective soil stress rises with the decrease of water-generated stress. Therefore, the admixture of ISSA/cement improves the interlocking forces among soil particles.

3.5. *Unconfined compressive strength (UCS) test*

The relationships between various amounts of ISSA/cement additions and the unconfined compressive strength of specimens at different curing ages are shown in Fig. 5. The unconfined compressive strength of ISSA/cement soil specimens increased with admixture amount for curing ages below 3 days. The increased strength is between 2 and 4 times that of the strength of untreated soil. On the one hand, for large amounts of ISSA/cement admixtures (8% and 16%), the unconfined compressive strengths of specimens improve with the help of air moisture; on the other hand, for smaller amounts of admixtures (2% and 4%), the unconfined compressive strength of the specimens increase less as the curing time increases. However, with the help of the reaction caused by the pozzolanic materials in the ISSA and the product of hydrated cement, calcium hydroxide (CH), large increments of the unconfined compressive strengths of the specimens with small amounts of admixtures were obtained at 56 days. Miller and Zaman [20] studied the effects of three different kinds of cement kiln dusts (CKD) on the stabilization treatments. They found that, when cured for 14 days, the unconfined compressive strengths of specimens with four proportions of CKD additives were 2% less than those of untreated specimens. However, the rate of increase in strengths developed slowly for those specimens with CKD additives, yielding results similar to those specimens with small amounts of admixtures added in this study. Moreover, Fig. 5 indicates that, when the curing time reaches 90 days, the rate of increase in strength will have increased greatly for all specimens tested. The best increments are seen for specimens with 2% and 4% admixtures added. Yet again, the strength increments are attributed to the accelerated reaction between the pozzolanic materials in the ISSA and CH.

3.6. *California bearing ratio (CBR) test*

3.6.1. *Swelling potential*

The pozzolanic reaction initiated by combining the hydration of cement with the aluminosilicates in ISSA can provide the necessary products to stabilize soft cohesive subgrade soil, when that soil is mixed with the stabilizer made by the admixture of ISSA/cement. The mechanism of soil swelling is characterized by the volumetric changes in the moisturized soil and is also directly correlated with the organic material, the varieties and amounts of clay minerals, and the natures of the cations adsorbed. Valence charges in components of the admixture include: Si, Al, Fe, and Ca with 2 or 3 valence charged ions, as determined by quasi-quantitative analysis of EDS for ISSA. When these charges are greater than the bonding forces between the hydrogen ions (H^+) and the negative charges on the surfaces of the clay soil, it could enhance the exchanges and substitutions for hydrogen bonding and the surface negative charges of the clay. In this study, the ISSA contains about 40% aluminosilicates and 8% calcium; about 62% calcium oxide is in the cement. As shown in Fig. 6, before the stabilizer was applied to the untreated A-4 soil, the swell of the soil at 120 h was between 0.9% and 1% under the compaction energy of 10, 25, and 55 blows and swelling behavior was clearly observed. However, after different amounts of ISSA/cement stabilizers were added to the untreated soil, the swelling potential of the soil was effectively improved. In fact, soil with 2% admixture reduced the swelling behavior up to 40%. The restraint in swelling behavior of the clay soil resulted

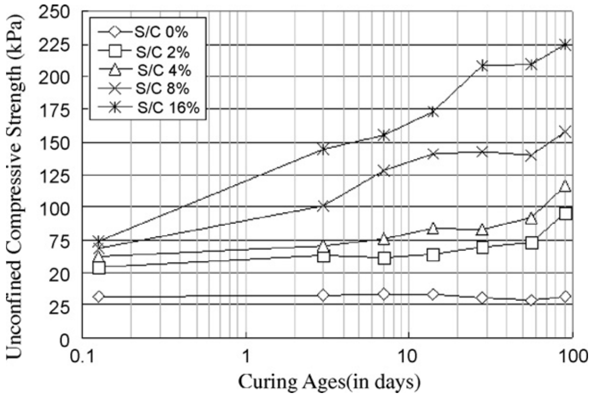

Fig. 5. The relationship between ISSA/cement and the unconfined compressive strength of specimens at different curing ages.

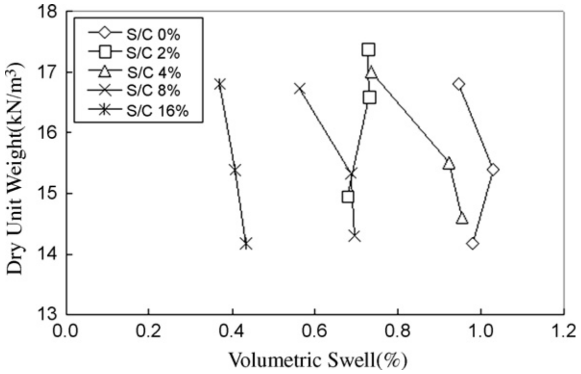

Fig. 6. The relationship between volumetric swelling and dry unit weight for the ISSA/cement soil specimens.

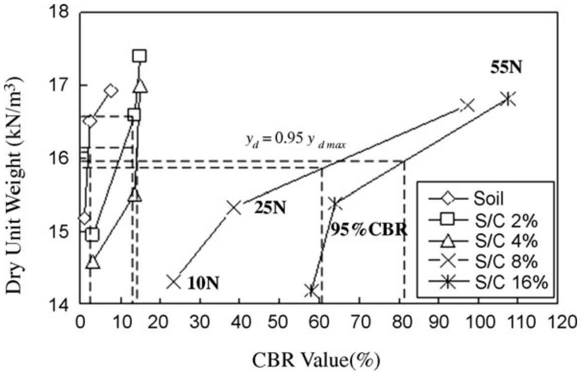

Fig. 7. The relationship between the 95%CBR value and the dry unit weight for the ISSA/cement soil specimens.

largely from the cement and the C-S-H gel produced. Furthermore, the efficacy of restraint in the swelling of clay soil increases with the increasing amount of ISSA/cement admixture, since more soft untreated soil is surrounded by the cement and gel. Fig. 6 also indicates that untreated soft soil with 16% ISSA/cement added gives the best reduction in the swelling of the clay soil; the swelling reduces to 1/3 of the original swelling of the untreated soil. The study also shows that the time needed to restrain the swelling behavior of soil increases as more ISSA/cement is added to the soil. This could result from the hardening and the phenomena of dry-shrinkage in the cement. This also relates to whether or not the cement is fully reacted in the soil when more cement is added during the stabilization treatment process.

3.6.2. CBR values

In the practical application of pavement structure design, values such as CBR, R, and the modulus are needed. In this article, CBR tests are regulated by the ASTM D1883–87 specification [17]. Fig. 7 indicates that values of 95%CBR for untreated soil equal about 2.0. Hence, based on the specifications set by AIIS-181 for CBR values less than or equal to 3, the soil is categorized as type I and characterized as poor subgrade soil, which is commonly seen for typical roads in Taiwan. When 2% and 4% ISSA/cement were added to soil, values of 95%CBR were improved to 12 and 15, respectively, which indicate that soil conditions were bettered from poor to excellent subgrade soil (CBR > 8) in accordance with the AIIS-181 standard. Furthermore, when 8% and 16% ISSA/cement were added to soil, values of 95%CBR were improved even more, to between 65 and 85; here, the soil is improved to be even better than excellent subgrade soil. This high 95%CBR of the soil indicates the soil is strong enough to replace higher bearing-capacity subgrade/base soil materials when admixtures are added to the untreated soil. Hence, admixture with ISSA and cement can effectively stabilize soft subgrade soil.

3.7. Triaxial compression tests

UUU triaxial tests were carried out following the ASTM D2850-87 specifications [18]. Soil samples with admixtures of ISSA/cement were axially loaded to an effective confining pressure of 25 and 50 kPa. Stress-strain relationships are shown in Fig. 8 for the confining pressure at 25 kPa. When stress reaches its maximum for untreated soil, the strain is about 10%. However, after admixture is added to soil, the shear failure mode of the ISSA/cement soil samples is close to brittle failure. Furthermore, the shear stresses for samples with 0% and 2% admixtures nearly equal. The maximum stresses obtained for 8% and 16% admixtures are also nearly equal. Similar stress–strain relationships for the confining pressure at 50 kPa are illustrated in Fig. 9. The maximum shear stress is observed for samples with 8% admixture added. Moreover, results for specimens with 16% admixture added are comparable to those samples with 8% admixture. Minimum strains for both additive amounts are seen where the maximum stresses are observed. On the whole, maximum shear strengths are observed for soft subgrade soil with 8% and 16% admixtures.

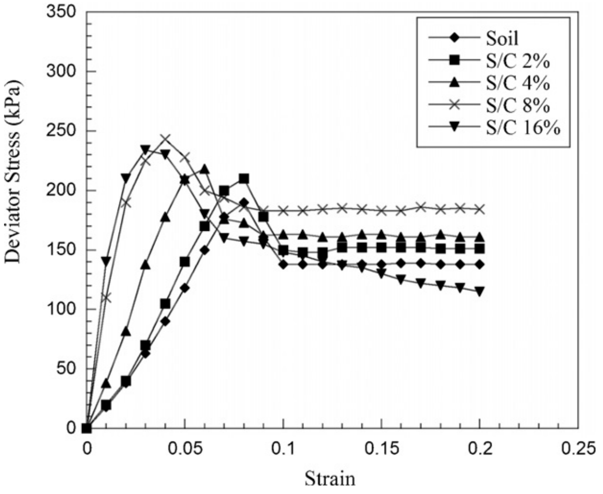

Fig. 8. Stress–strain relationships of UUU tests for the ISSA/cement soil specimens for an effective confining pressure of 25 kPa.

3.8. Analysis of microstructure

In this study, an admixture of ISSA/cement is used as a stabilizer to improve soft subgrade soil and, since ISSA contains SiO_2, Al_2O_3, and Fe_2O_3 and possesses the properties of pozzolana, it can also better the engineering characteristics of the untreated soil. Fig. 10 displays the results of the SEM analyses for the 16% and 2% ISSA/cement samples. Crystalline phases such as ettringite and monosulfoaluminate hydrates are seen after the admixture of ISSA/cement is added to the soil. Using X-ray diffraction together with JCPD database and the map-overlay method, Fig. 11 displays the diffraction peak values of reaction products for 16% sludge ash/cement added at different curing ages. The diffraction peak values of CH differed as marked. Also, as stated in Lin and Tsai's

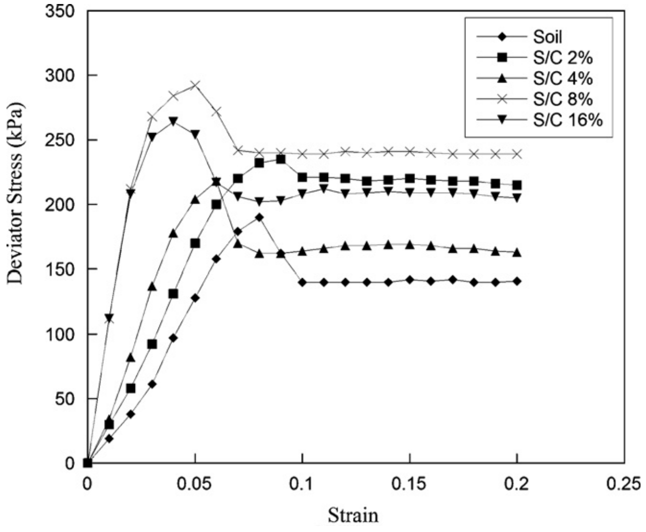

Fig. 9. Stress–strain relationships of UUU tests for the ISSA/cement soil specimens for an effective confining pressure of 50 kPa.

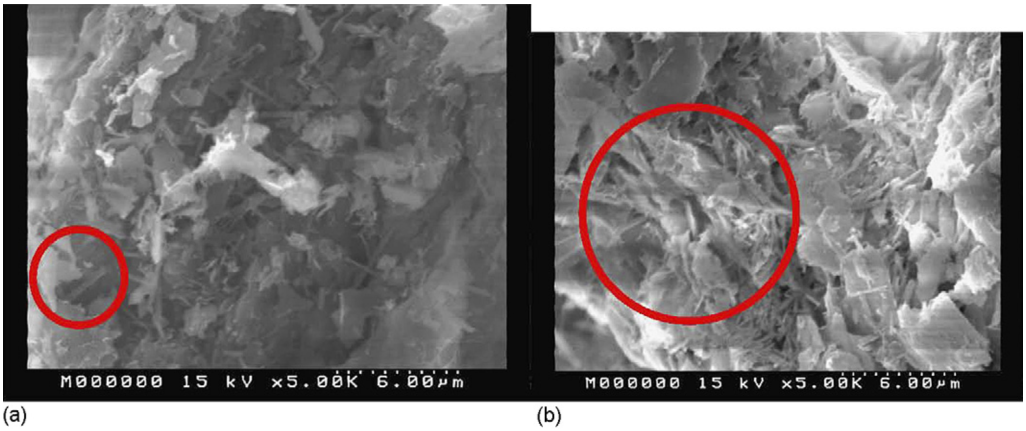

Fig. 10. Results of SEM analysis for ISSA/cement soil specimens (a) 16% ISSA/cement and (b) 2% ISSA/cement (×5000).

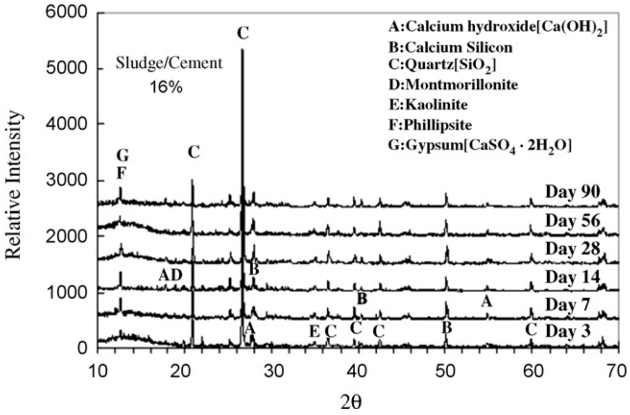

Fig. 11. Diffraction peak values obtained from X-ray diffraction for reaction products of a 16% ISSA/cement specimen under different curing ages.

research [21] and a result caused by the pozzolanic reaction, the strengths of hydrates produced by C-S-H and others reduced with an increase in curing age. The diffraction peak for CH products is observed at diffraction angles, 2θ, of 18°. Higher peak values were detected at shorter curing ages. Moreover, when the cure time was between 28 and 56 days, 2θ was equal to 55° and the CH hydration products as well as the peak values clearly decreased. The peak value even dissipated when the sample was cured for 90 days. Thus, Ca^{2+} provides a source which gradually produces calcium silica hydrates, which enhances the bonding forces among soil particles.

4. Conclusions

In this study, the ISSA/cement is utilized as a soil stabilizer to improve the basic properties of soft subgrade soil. Results based on the experimental data can be summarized as follows:

1. After the ISSA/cement admixture added to the soft subgrade soil, the PI values decrease and the soil type changes from mid-to-low plastic soil (CL) to CH soil. This indicates that the basic properties of soft subgrade soil are effectively improved.
2. Test results of swelling potential test show that soil swelling is clearly improved as more ISSA/cement admixtures are added. Among all, the swelling of untreated soft soil with 16% ISSA/cement added reduces to 1/3 of the original swelling of the untreated soil. Hence, the ISSA/cement admixture is helpful in the volumetric stabilization of soft subgrade soil.
3. The unconfined compressive strength of ISSA/cement soil specimens increases with admixture amount. This indicates that the ISSA/cement admixture can be used as a soil conditioner agent.
4. Results of CBR test show that the ISSA/cement admixture can effectively improve the soft subgrade soil from poor to excellent. In some cases, the level of soil improved is even better than excellent subgrade soil specified by the regulation. This concludes that the ISSA/cement admixture can increase the soil strength of soft subgrade soil.

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References

[1] J.H. Tay, A.T.C. Goh, Clay-blended sludge as lightweight aggregate concrete material, J. Environ. Eng. 117 (6) (1991) 834–844.
[2] A. Yague, S. Valls, E. Vazquez, Use of cement Portland mortar of stabilized dry sewage sludge in construction applications, Waste Manage. Environ. (2002) 527–536.
[3] D.F. Lin, H.L. Luo, Y.N. Sheen, Glazed Tiles Manufactured From Incinerated Sewage Sludge Ash and Clay, J. Air Waste Manage. Assoc. 55 (2) (2005) 163–172.
[4] D.F. Lin, H.L. Luo, S.W. Zhang, Effects of nano-SiO2 on tiles manufactured with clay and incinerated sewage sludge ash, J. Mater. Civil Eng., ASCE 19 (10) (2007) 801–808.
[5] J.H. Tay, A.T.C. Goh, Engineering properties of incinerator reside, J. Environ. Eng. 117 (2) (1991) 224–235.
[6] A. Kezdi, Stabilized Earth Roads, Elsevier, North-Holland, 1979, 327 p.
[7] D. Little, Stabilization of Pavement Subgrades and Base Courses with Lime, Kendall Hunt Publishing Company, 1995.
[8] D.F. Lin, K.L. Lin, M.J. Hung, H.L. Luo, Sludge ash/hydrated lime on the geotechnical properties of soft soil, J. Hazard. Mater. 145 (1–2) (2007) 58–64, doi:10.1016/j.jhazmat.2006.10.087.
[9] A. Misra, Stabilization characteristics of clays using class C fly ash, Transport. Res. Rec. 1611 (1998) 46–54.
[10] W.H. Zhu, Y.F. Yin, L.H. Jiang, L.M. Che, Study of micropore size distribution and its effect on the strength of silica fume cement paste, J. Build. Mater. 7 (1) (2004) 14–18.
[11] M. Davraz, L. Gunduz, Engineering properties of amorphous silica as a new natural pozzolan for use in concrete, Cement Concrete Res. 35 (7) (2005) 1251–1261.
[12] L. Turanli, B. Uzal, F. Bektas, Effect of material characteristics on the properties of blended cements containing high volumes of natural pozzolans, Cement Concrete Res. 34 (12) (2004) 2277–2282.
[13] J.R. Prisinski, S. Bhattacharja, Effectiveness of portland cement and lime in stabilizing clay soils, Transport. Res. Rec. 1652 (1999) 215–227.
[14] USEPA (United States Environmental Protection Agency), Test Methods for Evaluating Solid Waste Physical/Chemical Methods, SW-846, 3rd ed., Method 1311, 1992.
[15] American Society for Testing and Materials, ASTM D4318, Standard Test Method for Liquid Limit, Plastic Limit and Plasticity Index of Soils.

[16] American Society for Testing and Materials, ASTM D698-78, Moisture Density Relations for Soils and Soil-Aggregate Mixtures.
[17] American Society for Testing and Materials, ASTM D1883, California Bearing Ratio (CBR) of Laboratory-Compacted Soils.
[18] American Society for Testing and Materials, ASTM D2850-87, Standard Test Method for Unconsolidated, Undrained Compressive Strength of Cohesive Soils in Triaxial Compression.
[19] AIIS-181, Asphalt Pavement Thickness Design, Information Series No. 181, Asphalt Institute (AI), 1981.
[20] G.A. Miller, M. Zaman, Field and laboratory evaluation of cement kiln dust as a soil stabilizer, Transport. Res. Rec. 1714 (2000) 25–32.
[21] D.F. Lin, M.C. Tsai, Mineralogy and microstructure from the influence of the nano-composite additives on sewage sludge ash mortars, J. Air Waste Manage. Assoc. 56 (2006) 1146–1154.