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Study properties of soft subgrade soil stabilized by sewage sludge/lime and nano-SiO_2

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Abstract. The pozzolanic characteristics of a sludge incinerated into ash were determined in this study. Lime is commonly used as a stabilizer for the treatment of soils, whereas sewage sludge ash (SSA) is often applied with lime to improve soft subgrade soil. In this study, a cohesive soil categorized as A-4 (low-plasticity clay) by AASHTO classifications was mixed with SSA/lime with a 3:1 ratio. Nano-SiO_2 was also added to the soil. To identify changes in the workability, strength, permeability, and shear strength of the soft subgrade soil, basic soil tests were conducted, and the microstructure of the treated soil was analyzed. The results indicate that SSA/lime mixtures improve the properties of soft subgrade soil and transform the soil from "poor subgrade soil" to "good to excellent subgrade soil" with a CBR > 8. Additionally, the addition of 2% nano-SiO_2 increases the unconfined compressive strength of soft subgrade soil treated with SSA/lime mixture by approximately 17 kPa. However, the swelling of the treated soil increased by approximately 0.1% after the addition of nano-SiO_2 and lime. Thus, soil swelling should be considered before lime and nano-SiO_2 are applied to soft subgrade soil.

Keywords: lime; sewage; sludge ash; soft subgrade soil

1. Introduction

Sewage systems are fundamental to the infrastructure of Taiwan, and the amount of wastewater treated by these systems has increased rapidly in recent years. The sludge produced by sewage systems requires further treatment before it can be released into the environment. Dewatered sludge is often dumped into oceans or landfills; however, this is not a suitable solution for an island, such as Taiwan, that possesses limited land resources. To reduce the effects of dewatered sludge on the environment, the Taiwanese government has focused on reducing and reutilizing sludge. For example, the incineration of dewatered sewage sludge into ash is a common alternative to sludge treatment. After incineration at high temperatures, moisture and organic matter have been removed from the sludge. The ash generated via incineration possesses pozzolanic characteristics and can be used as cement in engineering applications or as a treatment for soft subgrade soil. To expand the use of sewage sludge ash (SSA) in engineering applications, Luo *et al.* (2014) studied the effects of nanomaterials on cement paste and mortar specimens containing SSA; they showed

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that the addition of nano-Al_2O_3 to cement paste specimens containing SSA efficiently improved the hydration products of the specimens. Chen and Lin (2009) mixed incinerated SSA with cement at a fixed ratio of 4:1 for use as a stabilizer to enhance the strength of soft subgraded cohesive soil. The results show that the unconfined compressive strength, swelling behavior, and California bearing ratio (CBR) of treated soil specimens containing incinerated SSA/cement admixture were more improved than those of the untreated soil specimens. Thus, incineration transforms sewage sludge from waste into a useful construction material.

Nanomaterials are synthesized from fine nanoparticles, which range in size from 1 to 100 nm. Due to their small particle size, nanomaterials tend to exhibit unique characteristics, including their optical, magnetic, thermal conductivity and chemical activity properties. In this study, nano-SiO_2 and sewage sludge ash were added to soft subgrade soil and low-plasticity clay soils with low engineering potential to improve their strengths and soil characteristics to make them useful in road construction.

Nanoparticles are small; thus, when an external force is applied to a nanomaterial, nanoparticles within the material move easily, resulting in large deformations. Additionally, nanomaterials have relatively large interfaces. For example, when an external force is applied to a nanomaterial, interfacial atomic arrangements are disturbed, and surface atoms become activated. The addition of nanoparticles to a brittle material can increase the material's toughness and ductility. The incorporation of nanomaterials into concrete decreases the size and quantity of capillaries and cracks, fills pores, and decreases permeability.

Lime is commonly applied to soft subgrade soil; however, to increase the material's strength, a soil must contain sufficient amounts of silicon and aluminum to react with the lime. For example, soft cohesive clay soils can be effectively treated with lime. Alternatively, granular soils, such as sands and gravels, contain sufficient amounts of silicon and aluminum; however, the minerals present in these soils are tightly packed and are not available to react with the lime. Thus, lime is not an effective stabilization treatment for granular soils. During the stabilization process, pozzolanic materials in the soil react with lime; specifically, calcium ions react with SiO_2 to form a C-S-H gel, and soil particles and other impurities become solidified within the gel.

By adding a small amount of lime to soil, Little (1995) found that the calcium present in lime ionized and produced agglomerates, which improved the workability and shear strength of the soil. Additionally, if a sufficient amount of lime is added to a given soil, clay minerals react with the lime based on the following equations

$$\mathrm{Ca(OH)_2 + SiO_2 \;\rightarrow\; C-S-H\ gel} \tag{1}$$

$$\mathrm{Ca(OH)_2 + Al_2O_3 \;\rightarrow\; C-A-H\ gel} \tag{2}$$

Aziz *et al*. (2015) studied the engineering properties of low- and high-plasticity cohesive soils treated with 0-20% rice husk ash (RHA) and found that the decrease in the material's plasticity index and shrinkage ratio reduced the swell potential of cohesive soils treated with RHA. It helped solve problems related to placing pavement and footings on soft cohesive soils. Those authors concluded that the use of RHA was a cost-effective and sustainable alternative solution for problematic local cohesive soils in agro-based developing countries, such as Pakistan.

Canakci *et al*. (2015) applied different contents of lignin, rice husk powder (RHP) and rice husk ash (RHA) to treat expansive soils in a laboratory environment. Their tests, which included unconfined compressive strength (UCS) tests, swelling tests and Atterberg limit tests, were performed on the treated soil specimens. In that study, the additives and curing duration exhibited noticeable influence on the strength of the treated soil specimens. In general, excluding the soil sample treated with 20% RHP for 3 days, the UCS value increased as the content of the additive and the curing duration increased.

Ahmed (2015) used bassanite, which was obtained from gypsum waste materials, as an additive to stabilize soft clay soil. He mixed bassanite with different amounts of cement and lime to reduce the solubility of bassanite. Then, these admixtures were mixed with soft clay soil to manufacture test soil samples. The test results of that study indicated that the addition of bassanite waste improved the compressive strength of the test soil samples. The XRD results showed that both the amount and the ratio of the admixture with different amounts of bassanite, cement or lime had an important impact on the formation of the cementation compounds and the improvement of the compressive strength of the test soil samples. He suggested that the use of recycled bassanite obtained from gypsum waste was a low-cost and efficient stabilizer material for engineering applications in ground improvement projects.

In their study of the effect of calcium content on soil stabilization, Cristelo *et al*. (2012) used fly ash type-C (FAC, higher calcium content) and type-F (FAF, lower calcium content) to stabilize soft soils using alkaline activation with sodium-based alkaline activators. Four test soil mixtures containing FAC, FAF, cement, and lime were manufactured, and the short-term and long-term compressive strengths of the soil mixtures were determined and compared. That study's test results indicated that the short-term compressive strengths of soil mixtures containing FAC were higher than those with FAF. However, after a longer curing period, the FAF mixture reached considerably higher compressive strengths than the soil mixtures containing cement or lime. The authors thus concluded that for long-term soft-soil stabilization via alkaline activation, the low-calcium fly ash was preferred compared with the high-calcium fly ash.

To investigate the effects of cement stabilization on the geotechnical characteristics of sandy soils, Shooshpasha and Shirvani (2015) added different amounts of lime Portland cement to treated soils. Unconfined compression tests and direct shear tests were performed on cylindrical and cube-shaped, treated soil specimens. Those authors concluded that the soil specimens stabilized by the lime Portland cement exhibited improved strengths, lower displacements at failure, and brittle soil behaviors.

Calik and Sadoglu (2014) studied the engineering properties of soft soil treated with lime and perlite. Test soil mixtures were prepared by mixing lime or different contents of pertile with soft soil. Geotechnical tests investigated the Atterberg limits, compaction, swelling, and unconfined compressive strength of the materials and indicated that the geotechnical properties of soft soil stabilized by the combination of lime and perlite were more improved than those of soft soil stabilized by perlite or lime alone. When the soil strength was considered, the optimum contents of lime and perlite were found to be 8% and 30%, respectively, when stabilizing soft soil.

Al-Mahbashi *et al*. (2015) used soil water characteristic curves (SWCCs) to assess the improvement of expansive soil, including the soil's swelling characteristics and unconfined compressive strengths, after being stabilized by different amounts of lime. After curing for 7 and 28 days, lime-treated soil samples were tested to determine their SWCCs. Then, correlations between the primary features of the SWCCs and the basic engineering performance characteristics were determined. These results suggested that three factors – the initial slope, the saturated water content, and the air entry value – were important in evaluating the improvement in engineering performance achieved by lime treatment.

Harichane *et al*. (2012) investigated the influence of applying lime, natural pozzolana or a combination of both on the geotechnical characteristics of soft soil specimens. Tests including compaction tests, shear tests, and unconfined compression tests were performed and showed that the soft soil specimens were positively stabilized by the combined action of natural pozzolana and lime and resulted in a reduction in construction costs.

Fattah *et al*. (2015) studied the behavior of a square footing over soft clay treated by grouting the clay with lime-silica fume slurry. Three different percentages of lime (2%, 4% and 6%) and silica fume (2.5%, 5%, and 10%) were applied. Those authors found that the bearing capacity of soft clay stabilized by a slurry of lime-silica fume underneath or around a footing increased by between 6.58 and 88%.

Malekpoor and Poorebrahim (2014) compared the performance of lime-mortar well-graded soil (Lime-WS) columns with that of conventional stone (CS) and geogrid-encased stone (GES) columns with regard to the improvement of soft soils. Column samples that were 100 mm in diameter, 600 mm in length, and surrounded by soft soil were tested with different area ratios. Experiments evaluating the load-settlement behavior of treated ground samples were performed and showed that the installation of Lime-WS columns presented a noticeable improvement in the performance of the soft soil. The performance of these Lime-WS columns was considerably improved when the area ratio increased. The results also suggested that CS columns were not appropriate for soil improvement with extremely soft soils.

To assess the performance of soft subgrade clay base layers treated with lime and cement, both laboratory experiments and finite element analyses were performed by Azadegan *et al*. (2014). Two different granular soils – well-graded gravel and well-graded sand – were stabilized by mixtures with different amounts of lime and cement. The compressive strength and properties of the specimens were obtained and used in finite element analyses to determine the appropriate estimating function for lime-and cement-treated granular soils. Those authors concluded that at the mid-range strength of stabilized granular soils, most of the applied functions were consistent with those results found in laboratory conditions.

Kang *et al*. (2015b) applied class-C FA and lime kiln dust (LKD) as stabilizers for soft subgrade clay soils. Mechanical tests, including unconfined compression tests, proctor compaction tests, and resilient modulus tests, along with scanning electron microscopy (SEM) analyses, were performed. Those authors concluded that the dry unit weight, unconfined compressive strength, and resilient modulus of soft subgrade clay treated by FA had improved due to the addition of class-C FA. They also suggested that the soft subgrade clay stabilized by class-C FA and LKD can be cost-effective for road-base construction.

In another study, Kang *et al*. (2015a) investigated the effectivenesses of fly ash and LKD to stabilize clay pavement-base materials in laboratory conditions and found that the addition of fly ash up to 20 wt% effectively improved the dry unit weight, unconfined compressive strength, and Briaud compaction device modulus of soil. LKD was also shown to stabilize weak soil by improving its unconfined compressive strength and stiffness.

The mechanism of soil stabilization via the addition of sewage sludge ash and lime is characterized by the activity of pozzolans present in the soil. Tay and Show (1992a, b) found that the strength activity index (SAI) of sewage sludge ash ranges from 58 to 67%, which corresponds to class-C pozzolanic materials, as specified in ASTM C618. Thus, it is possible to replace a certain amount of cement with sewage sludge ash in engineering applications. Thus, sewage sludge ash and lime can be characterized as pozzolanic materials. Lin *et al*. (2007) studied the addition of sewage sludge ash to improve soft subgrade soils and also suggested future engineering applications. In this study, lime and 2% nano-SiO_2 were added to soils to improve treatment efficiency, improve soil stability, and increase the amount of sewage sludge incorporated into soft subgrade soil.

2. Materials and methods

A soil sample was obtained from the Southern Taiwan Science Park in Kaohsiung County, Taiwan and was sieved with a 4.75-mm (#4) mesh sieve. The results indicated that the soil was a finely aggregated, brownish-yellow silty soil. Nano-SiO_2, which consists of ball-shaped particles with a specific surface area of 670 ± 20 m^2/g, was added to the soil. The average particle size of the nano-SiO_2 was 30 ± 5 nm, and the hydroxyl group concentration and ultraviolet reflectance were greater than 35% and 75%, respectively. Hydrated lime with a density between 0.45 and 0.6 T/m^3 was used in this study.

To produce ash, dewatered sewage sludge samples obtained from a wastewater treatment plant in Kaohsiung City were incinerated at 800-850°C and then ground with a powder-grinding machine. The target average particle size for the SSA was 0.0137 mm. The SSA possessed a specific gravity of 2.13 and was categorized as a light aggregate. Additionally, the SSA was mildly alkaline with a pH of 7.8. The toxic characteristic leaching procedure (TCLP) test was conducted based on the procedures described in NIEA R201.14C (2009) of the Republic of China (ROC). The TCLP results indicated that Hg, Cr^{+6}, and Sc were not present in the SSA and that the concentrations of Pb, Cd, Cr, and Ba were less than 0.2 mg/L, which is less than the standard values of 5.0, 1.0, 5.0, and 100.0 mg/L, respectively. Additionally, the concentrations of As, Cu, and Zn were 0.42, 7.94, and 11.3 mg/L, respectively, which were less than the standard values specified by regulations. Thus, the concentrations of metals in the SSA met the standards specified by the Environmental Protection Agency (EPA) of the ROC.

Yang (2004) applied 0, 2, 4, 8, 16, and 22% w/w of SSA and lime to soil and found that 16% SSA/lime produced an optimal shear strength at minimum cost. In this study, 15% SSA/lime was shown to improve the characteristics of a soft, cohesive soil. Cai (2007) suggested an optimal SSA to lime ratio of 3:1; thus, this ratio was used in this study. To manufacture the soil samples tested in this study, the optimal moisture content of a soil-SSA/lime mixture was obtained. Then, to study the effects of the nano-SiO_2 additive on the subgrade soil with SSA/lime mixture treatment, a 2% nano-SiO_2 additive was added to each soil-SSA/lime sample. The samples studied were categorized as untreated soil, soil-SSA/lime, and soil-SSA/lime with the 2% nano-SiO_2 additive and marked as “soil”, “Nano 0%”, and “Nano 2%”, respectively, in the figures below.

3. Results and discussion

3.1 Soil properties

Results obtained from the Atterberg limit test indicated that the liquid limit (LL), plastic limit (PL), plastic index (PI), specific gravity, optimal moisture content (OMC), and unit weight of soil A (i.e., untreated soil) were 25.6-26.3%, 16.3-16.8%, 8.8-10.0, 2.72 g/cm^3, 13.5-13.8%, and 17.0-17.5 kN/m^3, respectively. The unconfined compressive strength of the OMC was between 29.5 and 32.5 kPa, which indicates that the bearing capacity of untreated soil is insufficient to withstand the compressive forces exerted by vehicles; thus, the untreated soil may be improved by increasing its strength.

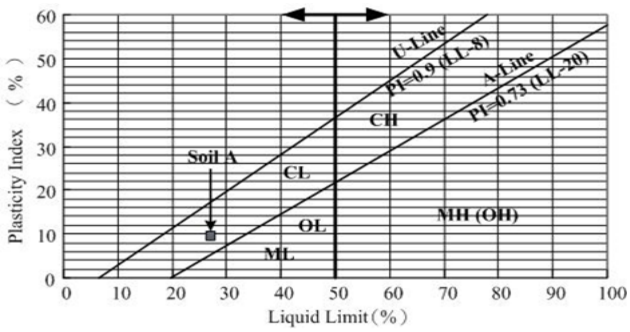


Fig. 1 Soil classifications

In this study, soil classifications followed the standards specified by the American Association of State Highway Transportation Officials (AASHTO) and the Unified Soil Classification System (USCS). As shown in Fig. 1, the untreated soil was categorized as an A-4 soil with low-plasticity clay by AASHTO and as CL (i.e., silty clay) soil based on the USCS. The particle size distribution of the soil was obtained via sieving and hydrometer analysis. The results indicated that the untreated soil contained 95% silt and clay, of which 50% to 55% was silty soil, 40% to 45% was clay, and approximately 5 to 8% was fine aggregates. Thus, the untreated soil was not suitable for subgrade materials and required improvement before being used in engineering applications.

3.2 Compaction test

In Taiwan, the accepted compactness requirement in the construction standards is set at 95% or more of the dry density when the base or sub-base layer is stabilized by cement. No standards are set for the strength of the soil or the stabilization agent used. When soil treatment is performed, the soil and stabilization agent are mixed uniformly. Then, the mixture is laid layer by layer. The thickness of each layer is less than 15 cm and is evenly compacted by a sheep's foot roller or other appropriate compaction roller until the soil layer is fully compacted. The moisture content of the mixture must be maintained to be near to the OMC throughout the compaction process. The entire compaction process must be completed layer by layer within a 2-hr period.

The OMCs of untreated soil, soil-SSA/lime, and soil-SSA/lime with 2% nano-SiO_2 additive at each optimal dry unit weight were determined using the results of compaction tests. Then, the moisture content of the soil was controlled to determine the required compactness and *in-situ* unit weight. Fig. 2 shows the results of the OMC and maximum dry unit weight obtained from the compaction tests for untreated soil, soil-SSA/lime, and soil-SSA/lime with 2% nano-SiO_2 additive. The results shown in Fig. 2 indicate that the dry unit weight of the soil-SSA/lime was less than that of the untreated soil. This disparity may have been caused by differences in the specific gravity of SSA, lime, and soil, which are equal to 2.13, 2.2, and 2.72, respectively. The specific gravity of the soil-SSA/lime increased after the addition of 2% nano-SiO_2 additive; however, this value was still less than that of the untreated soil. As shown in the figure, the OMC of soil-SSA/lime was 14.8%, which is 1.3% higher than the OMC of the untreated soil. The OMC of soil-SSA/lime with 2% nano-SiO_2 additive was 13.9%, which is 0.4% higher than the OMC of the untreated soil but smaller than that of the soil-SSA/lime. These results indicate that the addition of nano-SiO_2 lowered the effect of the SSA/lime on the OMC of the treated soil.

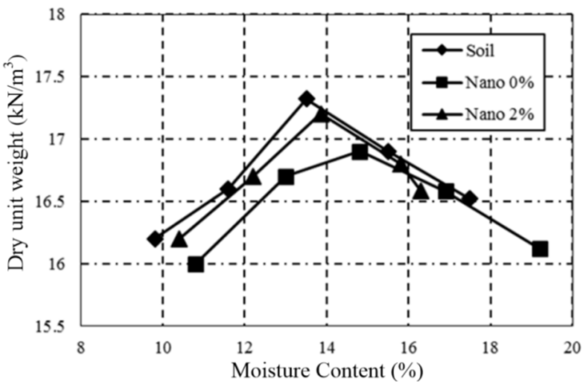


Fig. 2 The results of the OMC and maximum dry unit weight for the untreated soil, soil-SSA/lime, and soil-SSA/lime with 2% nano-SiO_2 additive

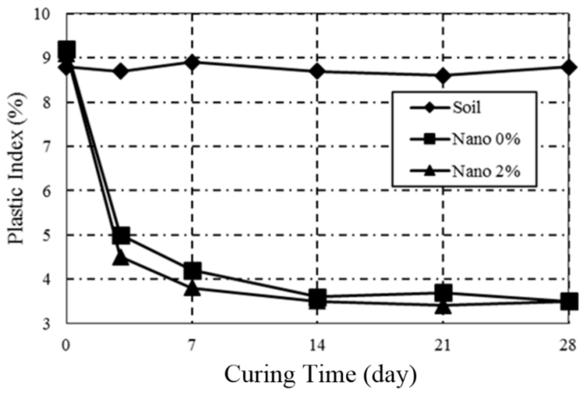


Fig. 3 The relationship between PI and the curing time for the untreated soil, soil-SSA/lime, and soil-SSA/lime with 2% nano-SiO_2 additive

3.3 Atterberg limits

The LL and PL of the soil were determined using Atterberg limit tests, where the PI was calculated from the LL and PL. As moisture permeates into a soil, constituents such as silt and clay tend to become soft, limiting the use of soil as a subgrade material in engineering applications.

Fig. 3 shows the relationship between the PI and the curing time for the untreated soil, soil-SSA/lime, and soil-SSA/lime with 2% nano-SiO_2 additive. The results indicate that the addition of SSA/lime reduced the PI of the soil; a PI between 4.9 and 5.1 was obtained after a curing time of 3 days, whereas a curing time of 7 days produced a PI between 4.1 and 4.3. Thus, the addition of SSA/lime improved the PI of a soft subgrade soil, particularly early in the curing process. After 14 days, the PI of the treated soil stabilized and reached a constant value between 3.4 and 3.7.

As shown in Fig. 3, the addition of 2% nano-SiO_2 lowered the PI of the soil-SSA/lime, particularly during the early stages of the curing process. Only a marginal difference in PI between the soil-SSA/lime and the soil-SSA/lime with 2% nano-SiO_2 additive was observed (i.e., approximately 0.3).

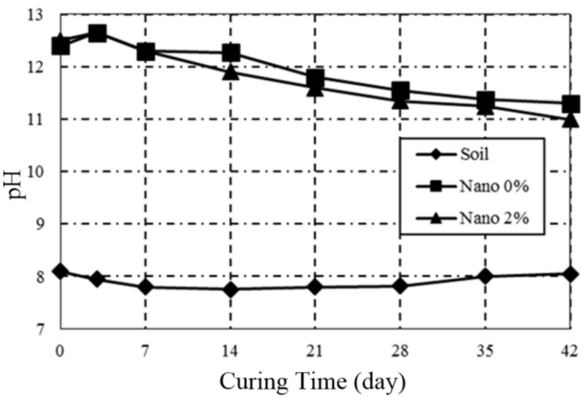


Fig. 4 The relationship between pH and the curing time for the untreated soil, soil-SSA/lime, and soil-SSA/lime with 2% nano-SiO_2 additive

3.4 pH test

Fig. 4 shows the relationship between pH and the curing time for the untreated soil, soil-SSA/lime, and soil-SSA/lime with 2% nano-SiO_2 additive. In general, the pH of the soil-SSA/lime was greater than the pH of the untreated soil. For example, after 2 hours, the pH of the soil-SSA/lime was 12.43, whereas the pH values of the lime and untreated soil were approximately 13.0 and 8.0, respectively. Thus, the addition of lime can significantly increase soil pH. After 7 and 14 days, the pH decreased slowly as the curing time increased. After 28 days of curing, the pH of the treated soil decreased to 11.54. The observed reduction in pH over time may be explained by changes in the calcium concentration of the soil. Based on the mechanism of soil stabilization, the concentration of calcium ions gradually decreases as pozzolanic reactions occur in the treated soil. As a result, the pH of the soil-SSA/lime decreased as the curing time increased.

As shown in Fig. 4, the pH of the soil-SSA/lime with the 2% nano-SiO_2 additive decreased as the curing time increased. The results indicate that the nano-SiO_2 accelerated the hydration reaction between the soil and lime, gradually reducing the concentration of calcium ions, which caused the pH to decrease. After more than 28 days of curing, the pH value of soil-SSA/lime with 2% nano-SiO_2 additive was approximately 11.3; the pH did not decrease further beyond a curing time of 28 days. The stabilization of the pH may have been caused by a loss of moisture from the treated soil, preventing the nano-SiO_2 from accelerating the hydration reaction. Thus, pH cannot be effectively reduced by extending the curing time. To fully exploit the effects of nano-SiO_2 on treated soil, the optimal ratio of SSA/lime and nano-SiO_2 should be determined.

3.5 Unconfined compressive strength (UCS) test

The UCS is typically used as an index of soil strength and as a basis for the determination of the pavement-bearing capacity. Fig. 5 shows the relationship between the UCS and the curing time of the untreated soil, soil-SSA/lime, and soil-SSA/lime with 2% nano-SiO_2 additive. As shown in the figure, the UCS of the soil-SSA/lime increased by approximately 0.8 times above that of the untreated soil during the early stages of the curing process. However, after 3, 14, and 91 days, the UCS was approximately 1.4, 4.1, and 6.2 times greater than that of the untreated soil, respectively.

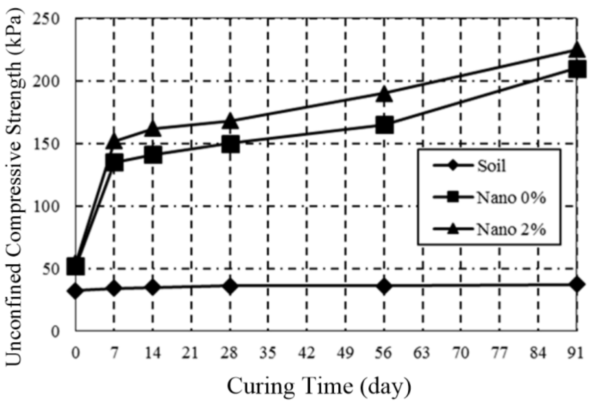


Fig. 5 The relationship between the unconfined compressive strength and the curing time of the untreated soil, soil-SSA/lime, and soil-SSA/lime with 2% nano-SiO_2 additive

The UCS of the untreated soil became stable after 28 days; however, in the soil-SSA/lime, the UCS continued to increase as the curing time increased. The results indicate that the soil pores became filled with products of the pozzolanic reactions generated by the SSA and lime, which caused the UCS to increase. Thus, the strength of the soil-SSA/lime increased as the curing time increased.

The results in Fig. 5 indicate that the 2% nano-SiO_2 improved the UCS of the soil-SSA/lime in the early stages of the curing process. Additionally, an increase in the UCS was observed as the curing time increased. After 91 days, the strengths of the soil-SSA/lime and soil-SSA/lime with 2% nano-SiO_2 additive were 210.7 and 223.2 kPa, respectively. The strength increased by approximately 5.9% compared with the untreated soil. These results indicate that the addition of 2% nano-SiO_2 to soil-SSA/lime significantly improves the UCS. However, to achieve the largest effect of nano-SiO_2 at the lowest cost, an optimal amount of additive should be identified.

3.6 Indoor permeability test

The hydraulic conductivities of the untreated soil, soil-SSA/lime, and soil-SSA/lime with 2% nano-SiO_2 additive at different stages of the curing process are shown in Fig. 6. The results indicate that the application of SSA/lime effectively improved the hydraulic conductivity (K, $\times 10^{-7}$cm/s) of the soil. In the early stages of the curing process, the value of K for the soil-SSA/lime was 79.3, which is 14.4 times greater than that of untreated soil. As the curing time increased, the value of K gradually decreased. After more than 28 days, the differences between the hydraulic conductivities of the soil-SSA/lime and the untreated soil decreased due to the hydration reactions between the SSA and lime. The products, such as calcium hydroxide and C-S-H gel, that were generated via hydration filled the pores of the soil, causing a gradual decrease in hydraulic conductivity over time. The K of the soil-SSA/lime after more than 28 days of curing was approximately 46.3, which is 7.2 times greater than that of the untreated soil, indicating that soil treated with SSA/lime becomes permeable after long curing times. Thus, SSA and lime are excellent additives for improving soil permeability.

As shown in Fig. 6, the addition of 2% nano-SiO_2 improved the permeability of the soil-SSA/lime. As stated above, the calcium hydroxide and C-S-H gel that were generated during

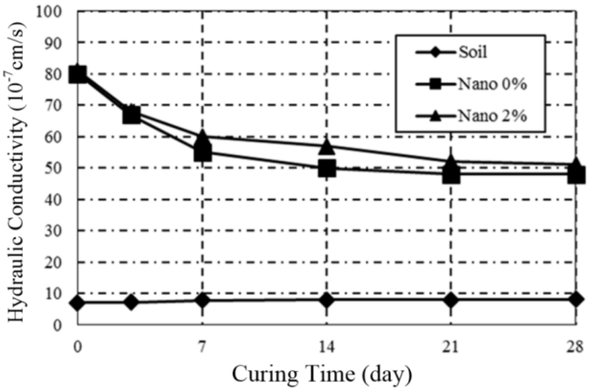


Fig. 6 The relationship between the hydraulic conductivity and the curing time of the untreated soil, soil-SSA/lime, and soil-SSA/lime with 2% nano-SiO_2 additive

hydration fill the pores of the soil; however, nano-SiO_2 decreases the thickness of the double layer and improves soil permeability.

3.7 Swell potential test

Fig. 7 shows the volumetric swelling of the untreated soil, soil-SSA/lime, and soil-SSA/lime with 2% nano-SiO_2 additive. The results indicate that the addition of both SSA/lime and nano-SiO_2 reduced volumetric swelling in the treated soil, whereas the exclusive application of lime increased volumetric swelling, which ranged from 0.57% to 0.65% in the soil treated with SSA/lime. Alternatively, the volumetric swelling of the untreated soil was found to be marginally lower than that of the treated soil and ranged from 0.7% to 0.8%. Thus, if volumetric swelling is an important factor in the performance of a soil, the addition of lime can reduce the efficiency of a soft subgrade soil treatment. Additionally, the addition of nano-SiO_2 to soil-SSA/lime does not improve soil expansion; for example, the volumetric swelling of soil-SSA/lime and soil-SSA/lime with 2% nano-SiO_2 additive ranged from 0.57% to 0.65% and 0.64% to 0.75%, respectively.

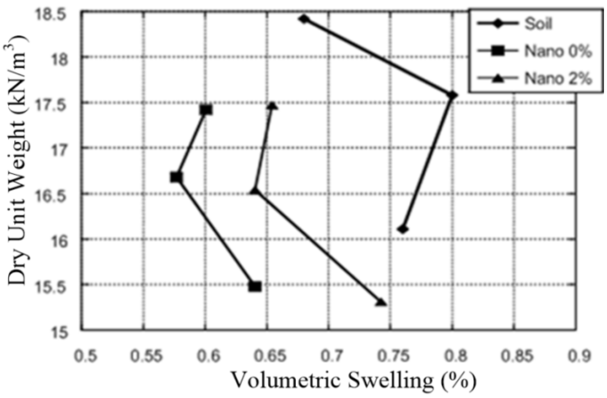


Fig. 7 The volumetric swelling of the untreated soil, soil-SSA/lime, and soil-SSA/lime with 2% nano-SiO_2 additive

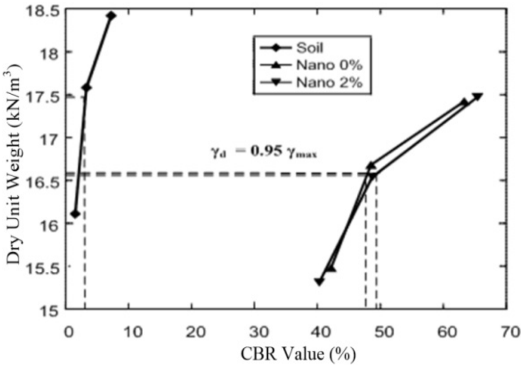


Fig. 8 The relationship between the CBR value and the dry unit weight of the untreated soil, soil-SSA/lime, and soil-SSA/lime with 2% nano-SiO_2 additive

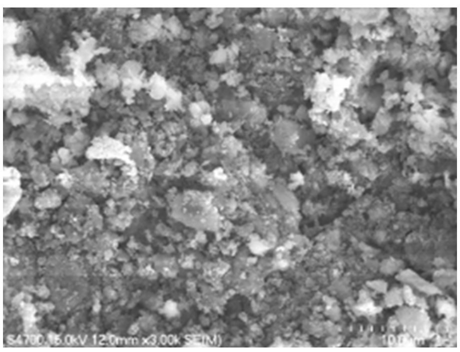
3.8 CBR test

The effect of SSA/lime on the 95% CBR value in the treated soil is shown in Fig. 8. Based on AIIS-181 specifications, a CBR ≤ 3 indicates a "poor subgrade soil", a CBR between 3 and 8 signifies a "medium subgrade soil", and a CBR > 8 indicates a "good to excellent subgrade soil". The 95% CBR of untreated soil was approximately 3.0; thus, the soil was characterized as a "poor subgrade soil". However, the 95% CBR of the soil treated with SSA/lime was approximately 48 (i.e., a "good to excellent subgrade soil").

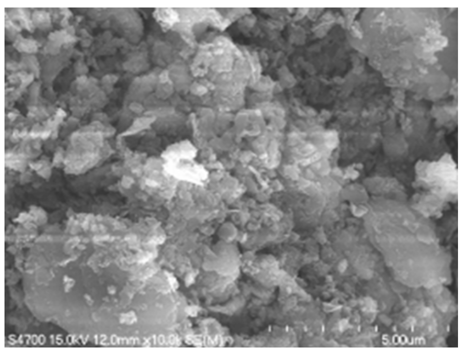
As shown in Fig. 8, the addition of 2% nano-SiO_2 to soil-SSA/lime increased the 95% CBR; however, the effect was not as strong as that observed with the addition of lime. Nano-SiO_2 increased the 95% CBR by promoting hydration reactions between the SSA and lime, which generates products such as calcium hydroxide and C-S-H gel.

3.9 SEM analysis

To understand the relationship between the microstructure and behavior of soil, SEM tests were performed on the soils treated with SSA/lime and 2% nano-SiO_2. Figs. 9 and 10 show SEM

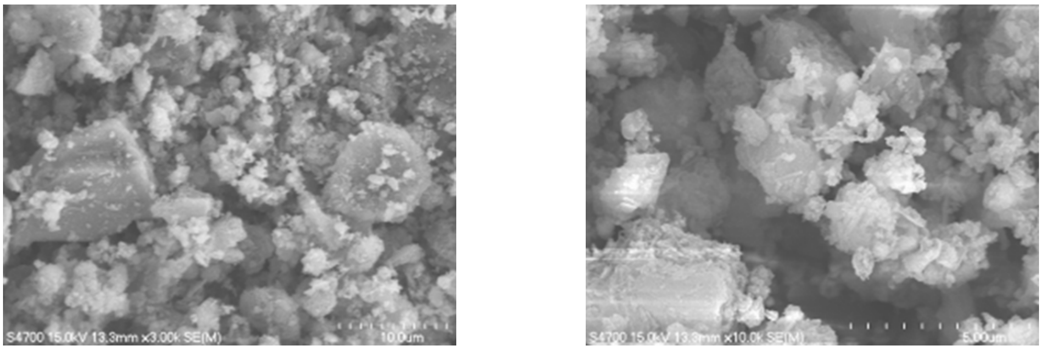


(a)



(b)

Fig. 9 SEM images of the soil treated with SSA/lime cured for 56 days (a) 3,000×; and (b) 10,000×



(a) (b)

Fig. 10 SEM images of the soil-SSA/lime with 2% nano-SiO_2 additive cured for 56 days: (a) 3,000×; and (b) 10,000×

images of soil treated with SSA/lime and soil-SSA/lime with 2% nano-SiO_2 additive after 56 days of curing, respectively. Because lime is composed of 85% calcium, many calcium-related products were observed in the SEM images of soil treated with SSA/lime, as shown in Fig. 9. The presence of calcium in the SEM images indicates that the addition of lime increased the compressive strength of the soil treated with SSA/lime. However, as stated above, lime also increases volumetric swelling; thus, the swelling behavior of a soil should be considered before lime is added to stabilize it. The effects of 2% nano-SiO_2 on soil-SSA/lime is evident when comparing Figs. 9 and 10. The images show that hydration products were present and that the pores of the treated soil were filled, which improved the strength of the soft subgrade soil.

3.10 X-ray diffraction test

Fig. 11 shows the XRD results of the soil-SSA/lime and soil-SSA/lime with 2% nano-SiO_2 additive cured after 56 days of curing. The XRD patterns show that the amount of $CaSiO_3$ increased after the addition of 2% nano-SiO_2, which has been shown to improve the strength of soft subgrade soil. SiO_2 and $Ca(OH)_2$ were gradually transformed into $CaSiO_3$, which improved the soil strength. The amount of these compounds increased as the concentration of nano-SiO_2

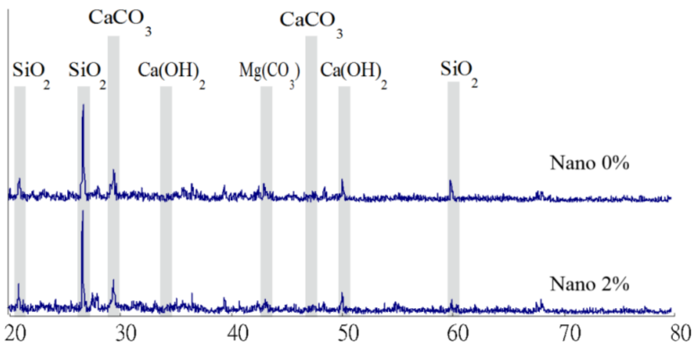


Fig. 11 XRD results of soil-SSA/lime and soil-SSA/lime with 2% nano-SiO_2 additive cured for 56 days

increased and as the concentrations of SiO_2 and $Ca(OH)_2$ decreased during the soil stabilization process.

4. Conclusions

In this study, a mixture of SSA/lime and 2% nano-SiO_2 additive was added to soft subgrade soil to improve the soil's stability. Based on the experimental results, the following conclusions were made:

(1) The hydraulic conductivity of the soil treated with SSA/lime was approximately 7.2 times greater than that of the untreated soil after more than 28 days; thus, SSA and lime are excellent materials for improving soil permeability.
(2) Based on specifications, the 95% CBR of soil treated with SSA/lime was approximately 48; thus, the addition of lime transformed a "poor subgrade soil" to a "good to excellent subgrade soil". Additionally, the bearing capacity of soil treated with SSA/lime was approximately 16 times greater than that of untreated soil. Overall, the results indicate that the addition of SSA/lime is an efficient treatment for the stabilization of soft subgrade soils.
(3) The addition of 2% nano-SiO_2 increased the unconfined compressive strength of the soft subgrade soil treated with the SSA/lime mixture by approximately 17 kPa.
(4) The SEM and XRD results showed that the addition of nano-SiO_2 accelerated and increased the production of $Ca(OH)_2$ and C-S-H gel, which indicates that the addition of nano-SiO_2 improved the 95% CBR and the unconfined compressive strength of the soil.
(5) The addition of nano-SiO_2 changed the swelling behavior of the untreated soil. Therefore, soil swelling should be considered before the application of nano-SiO_2 to the stabilization treatment of soft subgrade soils.

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