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Research Article

Utilization of Cementitious Material from Residual Rice Husk Ash and Lime in Stabilization of Expansive Soil

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Geological disasters often occur due to expansion and shrinkage properties of expansive soil. This paper presents a cementitious material combined with rice husk ash (RHA) obtained from biomass power plants and lime to stabilize expansive soil. Based on compressive and flexural strength of RHA-lime mortars, blending ratio of RHA/lime was adopted as 4 : 1 by weight for soil stabilization. When mix proportion of RHA-lime mixture varied from 0% to 20%, specific surface area of stabilized expansive soil decreased dramatically and medium particle size increased. The deformation and strength properties of stabilized expansive soil were investigated through swelling test, consolidation test, unconfined compression test, direct shear test, and so on. With increase in RHA-lime content and curing time, deformation properties including swelling potential, swelling pressure, compression index, crack quantity, and fineness of expansive soil lowered remarkably; meanwhile, strength properties involving unconfined compressive strength, cohesion, and internal friction angle improved significantly. Considering engineering performance and cost, mix proportion of 15% and initial water content of 1.2 times optimum moisture content were recommended for stabilizing expansive soil. In addition, effectiveness of RHA-lime to stabilize expansive soil was achieved by replacement efficiency, coagulation reaction, and ion exchange.

1. Introduction

Expansive soil, rich in strong hydrophilic mineral like montmorillonite and illite, is a special kind of clay soil formed in natural geological process. Expansive soil is characterized by expansion, shrinkage, and superconsolidability [1]. The volume of expansive soil varies with water content. Change in volume will result in swelling pressure or contraction stress, consequently causing cracking and breaking up of foundations, pavements, railways, roadways, and channels [2]. At the same time, hazards of expansive soil are often accompanied by recurrent and long-term latent features, so expansive soil is well known as “engineering cancer” [3]. How to stabilize expansive soil has become one of the global engineering problems in the field of engineering geology and geotechnical engineering today.

Expansive soil is widely distributed in China. About one-third of the country’s land is covered with expansive soil, with nearly 400 million people living in these places [4]. According to relevant reports, annual economic losses caused by expansive soil problems in China exceed 10 billion RMB, which indicates seriousness of the hazards. Especially in Yunnan, Guangxi, and Henan provinces, expansive soil has a high swelling and contraction potential, and accidents caused are often reported.

In order to reduce damage caused by expansive soil, it is necessary to take certain treatments for expansive soil during construction. There are many stabilized measures for expansive soil, commonly involving soil replacement, chemical modification, humidity controlling, and special foundation systems [5]. Due to significant improvement effect and low engineering cost, the chemical modification is favored by engineers.

Traditional chemical binders in soil stabilization are lime, cement, or lime/cement (i.e., a mixture of lime and cement) [6, 7]. Due to robustness and easy adaptability, incorporation of these traditional binders has gained popularity [8–10]. Lime is the most usual modification material in expansive soil. Soil stabilization using lime is achieved through cation exchange, flocculation and agglomeration, lime carbonation, and pozzolanic reactions [11]. However, the traditional binders in soil stabilization are controversial, not only for their negative environmental effects during manufacture but also for their costs.

In recent years, as environmental protection issues have drawn increasing attention, scholars have started to use various types of solid wastes as additives for expansive soil stabilization [12], such as fly ash [13], blast furnace slag [14, 15], cement kiln dust [16, 17], waste foam particle [18], alkali residue [19], and so on. Sometimes, some wastes can also be mixed with cementitious material during stabilization of expansive soil, for example, fly ash and lime [20, 21], bagasse ash and lime [22], natural volcanic ash and lime [23], phosphogypsum and lime [24], ground granulated blast-furnace slag and lime [25], iron tailing sands, and calcium carbide slag [26]. These mixtures can achieve better results than cementitious material alone.

In countries that produce rice, like China, Indonesia, Malaya, Pakistan, and so on, there is a kind of solid waste called rice husk ash (RHA), which has received attention in recent years. Rice husk ash is resulting from burnt rice husk, which is an abundantly available agricultural by-product material. RH production is about 20% by weight of the rice. When rice husk is burnt, cellulose and lignin are removed leaving behind silica ash. A number of researchers have studied physical and chemical properties of rice husk ash [27, 28]. Chemically, rice husk ash consists of 82–95% silica under condition of controlling burning temperature [29, 30].

Thirty years ago, it was considered that rice husk ash cannot be used alone for stabilization of soil because it lacks cementitious properties [31]. Based on pozzolanic activity, recent research studies found that rice husk ash could be a potential material for soil improvement [32–34]. The research results obtained indicate a general decrease in the maximum dry density (MDD) and increase in optimum moisture content (OMC) with increase of the RHA content [35, 36]. At the same time, the effect of RHA stabilized soils on the plasticity limit (PL), liquid limit (LL), and plasticity index (PI) was analyzed [37]. There was also slight improvement in the CBR and UCS with increase of the RHA content [38].

Although rice husk ash can improve soil, the improvement effect is not significant. Recent research studies have found the soil will be improved effectively using additives combined with pozzolanic material and cementitious materials [39–45]. As a natural pozzolana, RHA can substitute conventional pozzolanic materials in soil stabilization with cementitious materials like lime. For different soil, such as clayey subgrade [46], residual granite soil [47], and marine clay [48], good results have been achieved after stabilized by rice husk ash and lime. It is worth noting that this stabilization method is particularly suitable for expansive soils [49–53]. After adding RHA-lime, their swelling potential and swelling pressure would decrease obviously; meanwhile, CBR, cohesion, internal friction angle, and bearing capacity would increase drastically.

In short, using RHA-lime composite stabilizing technology, performance of expansive soil can be improved. However, most of the rice husk ash used in previous studies was burned in a specific incinerator with controlled temperature. In this way, although the silicon content of RHA can be obtained in high levels, the production process is complicated and not conducive to engineering applications. In recent years, more than 100 biomass power plants have been built in China. Rice husks are often used as fuel for power generation. Rice husk ash is a conventional by-product of biomass power plants, but its application is currently limited to agricultural fertilizers. Can rice husk ash from biomass power plants be used as a stabilization material? So far, there are no related research reports.

Therefore, residual rice husk ash from biomass power plants, combined with lime, is adopted to stabilize expansive soil in this paper. First, blending ratio of rice husk ash and lime will be determined by a mortar strength test. Then, the influences of mixing proportion of RHA-lime, curing time, initial water content on particle size distribution, swelling properties, compressibility, strength, and cracking characteristics of expansive soil will be analyzed through a series of tests. Finally, effectiveness of using RHA-lime as a cementitious material to stabilize expansive soil can be evaluated.

2. Materials and Methods

2.1. Materials

2.1.1. Expansive Soil. Expansive soil in this study is collected from a construction site situated at about 10 km southeast of Xuanfeng town in Jiangxi Province, China. The expansive soil was extracted at a depth of about 2m. After air-drying, expansive soil is crushed into particles and sieved with sieve size #10 (2 mm). Specific gravity, limit moisture content, compaction characteristic, free swelling ratio, and swelling potential were carried out and are listed in Table 1. Particle size of expansive soil is shown in Figure 1. The soil is classified as CH clay with high plasticity. Because PI > 35% and swelling potential >10%, the tested soil can be categorized as expansive soil with very high swelling potential [54].

The chemical composition of expansive soil was also tested by polycrystalline X-ray fluorescence spectrometer, as listed in Table 2. Its main components are SiO_2 and Al_2O_3.

The scanning electron micrograph (with a magnification of 3000x) of dry expansive soil is shown in Figure 2. It can be seen that there are various sizes of particles in the expansive soil.

2.1.2. RHA. RHA in this research was obtained from biomass power plants in Huai'an, Jiangsu Province, China. RHA is gray-black, implying that carbon in this RHA is not fully burned. Surface structure and morphology of natural RHA are shown in Figure 3 with SEM. The outer surface of

Table 1: The physical properties of expansive soil.

Specific gravity	Liquid limit (%)	Plastic limit (%)	Plasticity index	Free swelling ratio (%)	Swelling potential (%)	Maximum dry density ($g \cdot cm^{-3}$)	Optimum moisture content (%)
2.61	77.6	36.9	40.7	132.0	26.21	1.47	28.0

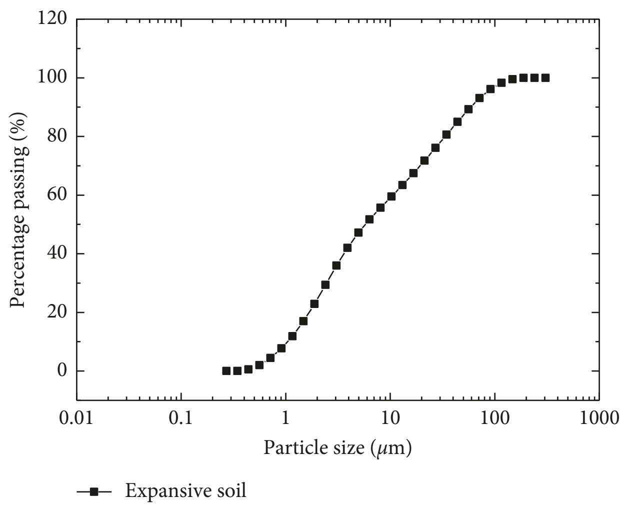


Figure 1: Particle size of expansive soil.

Table 2: Composition of materials.

Chemical composition	Mass fraction (%)		
	Expansive soil	RHA	Lime
CaO	5.76	1.54	92.25
SiO_2	58.71	72.34	0.06
Na_2O	1.08	0.75	0.26
MgO	2.02	0.98	0.03
Al_2O_3	18.44	4.43	0.56
Fe_2O_3	7.11	1.21	0.45
K_2O	3.45	3.54	0.00
LOI	3.43	15.21	6.39

LOI: loss on ignition.

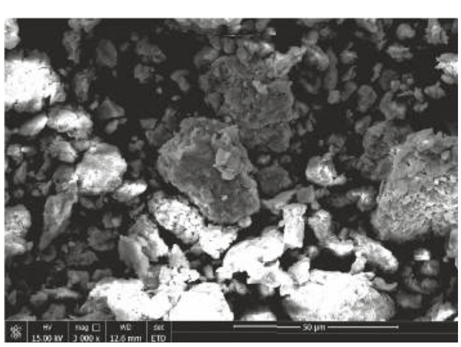


Figure 2: Microstructure of the expansive soil (3,000x).

RHA is slightly thick and the inner surface is thin. There is a sandwich between the inner and outer surfaces. The interlayer is composed of criss-crossed plates, and arrangement direction is basically similar. It shows a loose honeycomb structure. Further enlargement of sheet revealed that sheet contained a large number of holes. These holes that are called as honeycomb holes have a scale between 5 and 10 μm. For this reason, rice husk ash is a typical porous material and has a high surface area.

The grinding of rice husk ash was carried out in the XQM-20 vertical planetary ball mill made by Tianchuang Powder. After comprehensive consideration [55], grinding time was 5 minutes. After grinding, the sample was immediately filled in a sealed bag and stored. The microstructure of ground RHA is shown in Figure 4. It can be found that the ground RHA particles after grinding are very small, and most of them are less than 10 μm.

The specific surface area and particle size analysis of RHA was tested using a laser particle size analyzer. The specific surface area is about 5910 cm^2/g, and particle size distribution is shown in Figure 5.

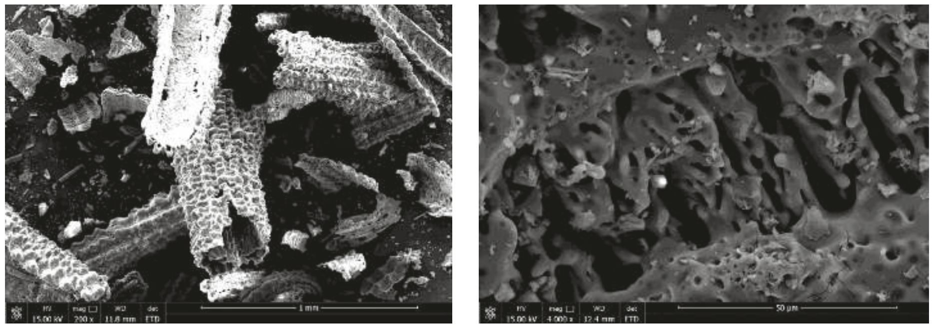
The chemical composition of RHA was also tested by XRF, as listed in Table 2. Its main component is SiO_2 as same as most of the other RHA. However, the silicon content is lower than others. In addition, loss on ignition (LOI) is up to 15.21, denoting that the rice husk is not fully burned and carbon content is relatively high.

2.1.3. Lime. The lime was used in powder hydrated lime, from local lime plant. The specific surface area of lime is 13880 cm^2/g, and the particle size is shown in Figure 6 . The chemical composition of lime is illustrated in Table 2, and the main ingredient is CaO. The microstructure of lime is reflected by SEM (12,000x) in Figure 7, indicating that its particles are very fine and uniform.

2.2. Experiment Methods. The experiment is mainly divided into two parts. First, regarding mixture of RHA and lime as a cementing material, the ratio between RHA and lime is determined according to the results of mortar strength test. Second, regarding RHA-lime as a stabilizer and mixing it with expansive soil, effects of amounts of RHA-lime, curing time, and initial water content on the strength and deformation properties of the solidified soil are studied.

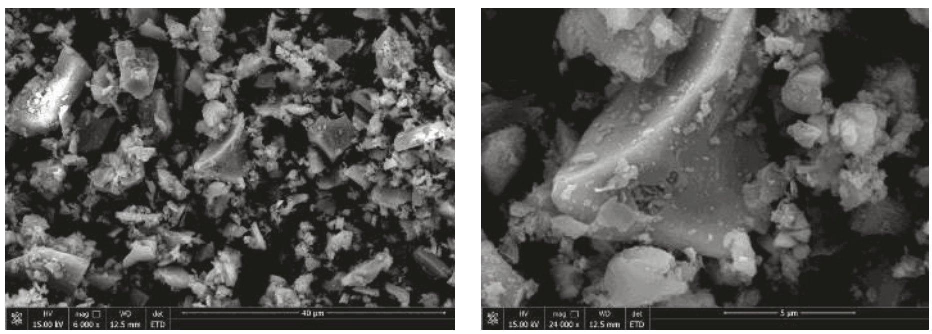
2.2.1. Preparation of Experimental Materials. Expansive soil, RHA, and lime were dried, ground, and sieved (through different sieves).

2.2.2. Mortar Test of RHA-Lime. In order to obtain the best ratio of rice husk ash-lime, six proportions of samples were designed. Meanwhile, these samples are compared with cement mortar (P.O 32.5) in different curing times. The mortar composition in parts by weight is included in Table 3. The ratio of water and cementitious material (W/C) was kept at a constant of 0.7 in all mixtures. Superplasticizer was applied to maintain the flow of mortar between 180 ± 5 mm



(a) (b)

Figure 3: Microstructure of the natural RHA. (a) RHA particle at low magnification (200x); (b) RHA particle at magnification (4,000x).



(a) (b)

Figure 4: Microstructure of the ground RHA. (a) RHA particle at low magnification (6,000x); (b) RHA particle at magnification (24,000x).

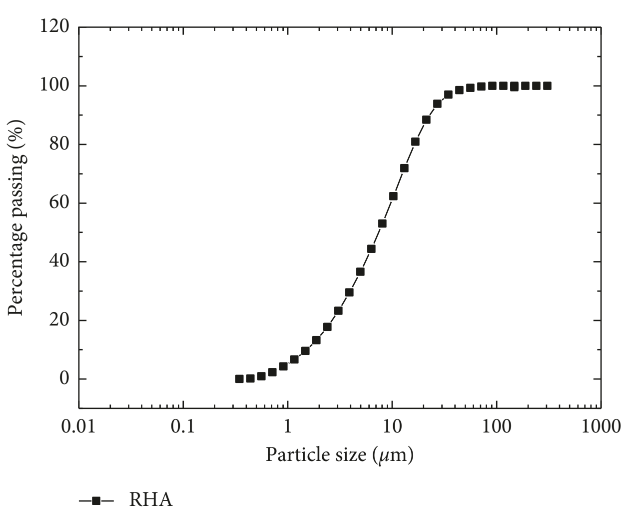


Figure 5: Particle size of RHA.

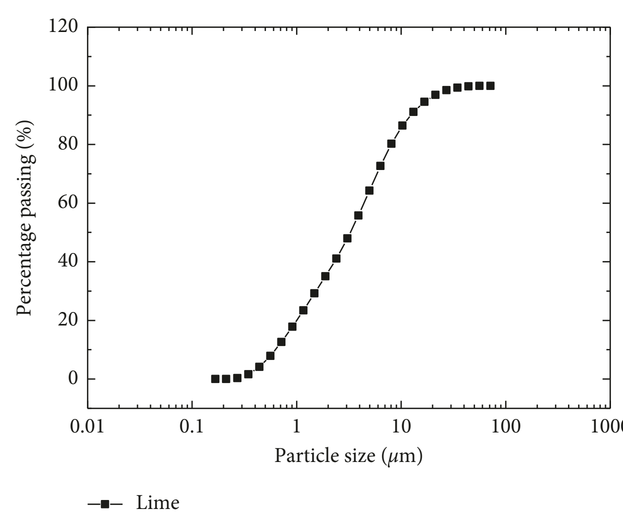


Figure 6: Particle size of lime.

since the mixture of RHA-lime mortars required more water to achieve the target flow.

A siliceous sand was used and dried prior to mixing. Its particle size distribution was established according to IS0679 (Chinese standard about testing sand). Mixing, molding, and compaction were carried out according to cement mortar test requirements. The specimens remained in a curing chamber at 20°C and 95% humidity until tested at 7, 14, 28, and 56 days. Curing time was lengthened in order to allow plenty of time for the pozzolanic reaction to take place.

The best ratio of RHA-lime by weight will be obtained after comparing the strength of six mortar samples.

2.2.3. Samples Manufacture. First, soil samples will be blended with RHA-lime (with best ratio). The mix proportion, which is the dry mass ratio between RHA-lime and expansive soil in this paper, is designed as 0%, 5%, 10%, 15%, and 20%. Second, water is added to act as a medium for the reaction process. In order to compare the effect of water

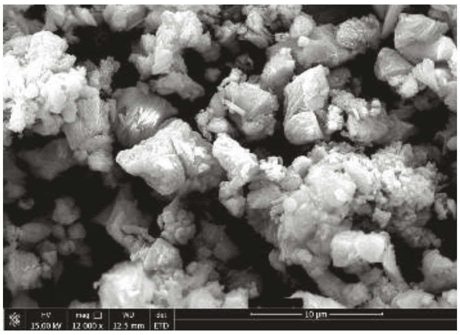


Figure 7: Microstructure of lime.

Table 3: Mortar composition in parts by weight.

Mortar type	RHA/lime	RHA (g)	Lime (g)	Cement (g)	Sand (g)
M0	—	—	—	450	1350
M1	0	0	450	0	1350
M2	1 : 4	90	360	0	1350
M3	2 : 3	180	270	0	1350
M4	1 : 1	225	225	0	1350
M5	3 : 2	270	180	0	1350
M6	4 : 1	360	90	0	1350

content on the reaction, three initial water contents were prepared. They are 1 times, 1.2 times, and 1.4 times of optimum moisture content (OMC), respectively. The mixtures are stirred with water, then placed in a sealed bag, and allowed for stewing for 24 h. Third, samples are pressed out by self-made sampler [56]. The sampler adopts half-and-half type, connected by bolts. The tester can obtain standard samples conveniently and efficiently. Fourth, soil samples will be cured at 20°C and 90% humidity until 7, 14, 28, and 90 days.

2.2.4. Testing of Soil Samples. In order to understand the effect of RHA-lime on stabilized expansive soil, the following experiments were carried out.

(1) Grain size distribution
(2) Swelling test, including swelling potential and swelling pressure
(3) Consolidation test
(4) Unconfined compression test
(5) Direct shear test
(6) Observation of crack development

All tests were conducted in the Geotechnical Laboratory, Department of Civil Engineering, Huaiyin Institute of Technology.

3. Results and Analysis

3.1. Compressive, Flexural Strength of RHA-Lime Mortars. The pozzolanic reaction between RHA and lime generates hydrate cements, inducing hardening and strength development. Compressive strength R_c and flexural strength R_f are important index of pozzolanic reaction. Figures 8 and 9 show the effect of increasing RHA content in compressive and flexural strength of RHA-lime mortars in different curing time. As shown in the figures, on the 7th day, mortar already had certain strength, demonstrating pozzolanic reaction had already began for a while. In addition, the results evidence that RHA significantly increases early strength of lime mortars. On the contrary, the effect of curing time on mortar strength is obvious, but it is also time-phased. Before 28 days, compressive and flexural strength increased rapidly with curing time, but after 28 days, the increase speed was very slow.

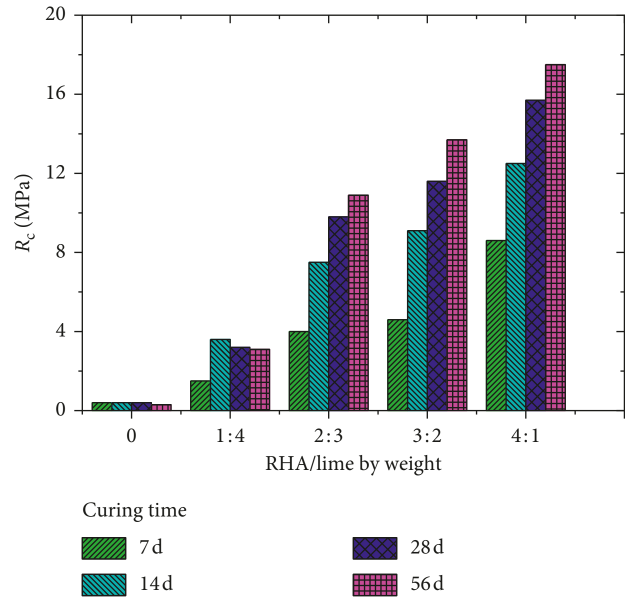


Figure 8: Compressive strength of mortars with different ratio of RHA/lime.

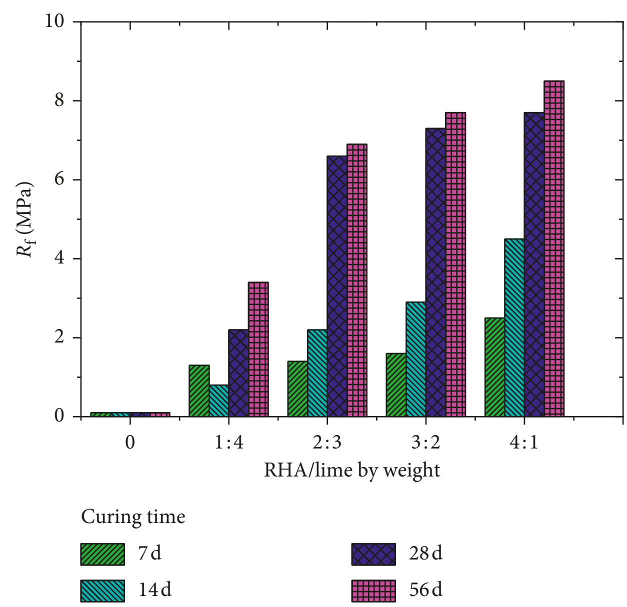


Figure 9: Flexural strength of mortars with different ratio of RHA/lime.

As is revealed in Figures 8 and 9, both compression and flexure strength increase with the RHA content, and mortars with highest RHA content (RHA/lime = 4 : 1) are about 40 times in compressive strength and approximately 80 times in flexural strength than lime mortar on the 28th day. It was also noted that rate of strength increase is higher at low-level replacements. For example, on the 28th day, the 1 : 1 (RHA/lime) mortar is over 26 times in compressive strength and 70 times in flexural strength than lime mortar, whereas the 4 : 1 (RHA/lime) mortar is only 1.5 times in compressive strength and 1.1 times in flexural strength than 1 : 1(RHA/lime) mortar.

Furthermore, strength comparison between cement mortar and RHA-lime mortar is shown in Figure 10. The cement used is P.O 32.5 cement. It can be found that the compressive strength of RHA-lime mortar is about half that of the cement mortar, and flexural strength of RHA-lime mortar is more than half that of the cement mortar. This shows that cementation of RHA-lime gelling material is very strong.

According to the above analysis, the ratio of 4 : 1(RHA/lime) can gain best result. As a result, in subsequent process of stabilized expansive soil, the ratio of rice husk ash to lime adopts 4 : 1.

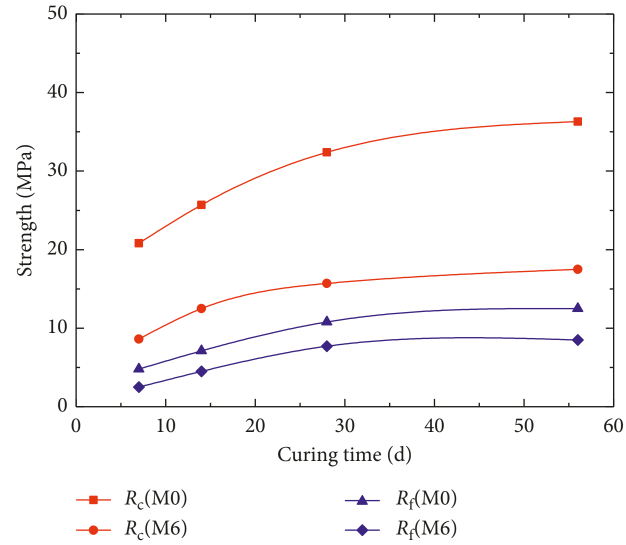


Figure 10: Strength comparison between cement mortar and RHA-lime mortar.

3.2. Particle Size Distribution of Expansive Soil Stabilized by RHA-Lime. Particle size distribution of expansive soil stabilized by RHA-lime is tested, and typical phenomenon can be found that after mixing of RHA-lime, the fine particles of expansive soil are reduced and the coarse particles are correspondingly increased. Figures 11 and 12 also reflect this phenomenon. As the amount of RHA-lime becomes larger, specific surface area of the mixture is remarkably lowered; at the same time, medium particle size D50 is improved. Since soil is cured for a certain period, a large amount of silicate mineral is produced, and the distribution of soil particles is difficult to measure by laser particle size analyzer, so the soil particle size in curing period is not analyzed.

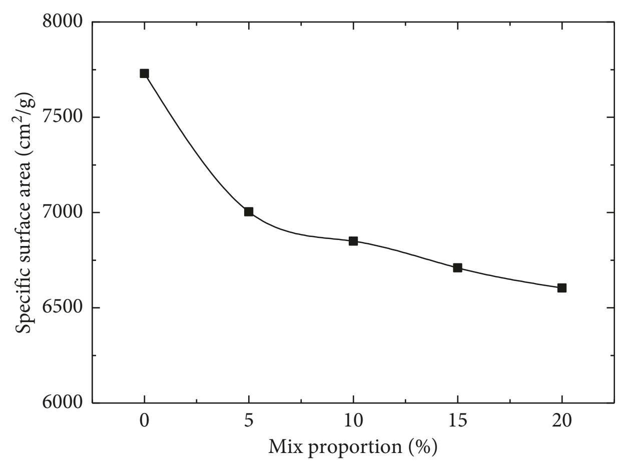


Figure 11: Effect of RHA-lime on the specific surface area of expansive soil.

3.3. Swelling Properties of Expansive Soil Stabilized by RHA-Lime. The effects of RHA-lime content on swelling potential and swelling pressure of stabilized expansive soil are presented in Figures 13 and 14. There are several rules that can be found as follows:

(1) With increase in mix proportion of RHA-lime content, swelling potential and swelling pressure of expansive soil go on decreasing gradually. For example, in Figure 13(a), swelling potential decreases from 26.21% to 14.30% when RHA-lime proportion increases from 0.0 to 20.0%. It is counted that reduction rate in swelling potential varies from 6.9% to 45.4% at different percentage of RHA-lime as compared to untreated soil. Meanwhile, swelling pressure decreases from 422.1 kPa to 174.8 kPa when RHA-lime content is increased from 0.0 to 20.0% in Figure 14(a). The reduction rate of swelling pressure varies from 12.9% to 58.6% as compared to natural soil.

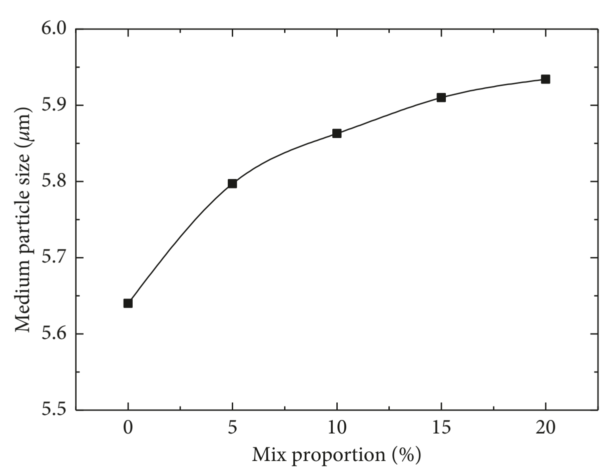


Figure 12: Effect of RHA-lime on the medium particle size of expansive soil.

The reduction in swelling potential and swelling pressure values of stabilized soils is due to addition of low-plastic

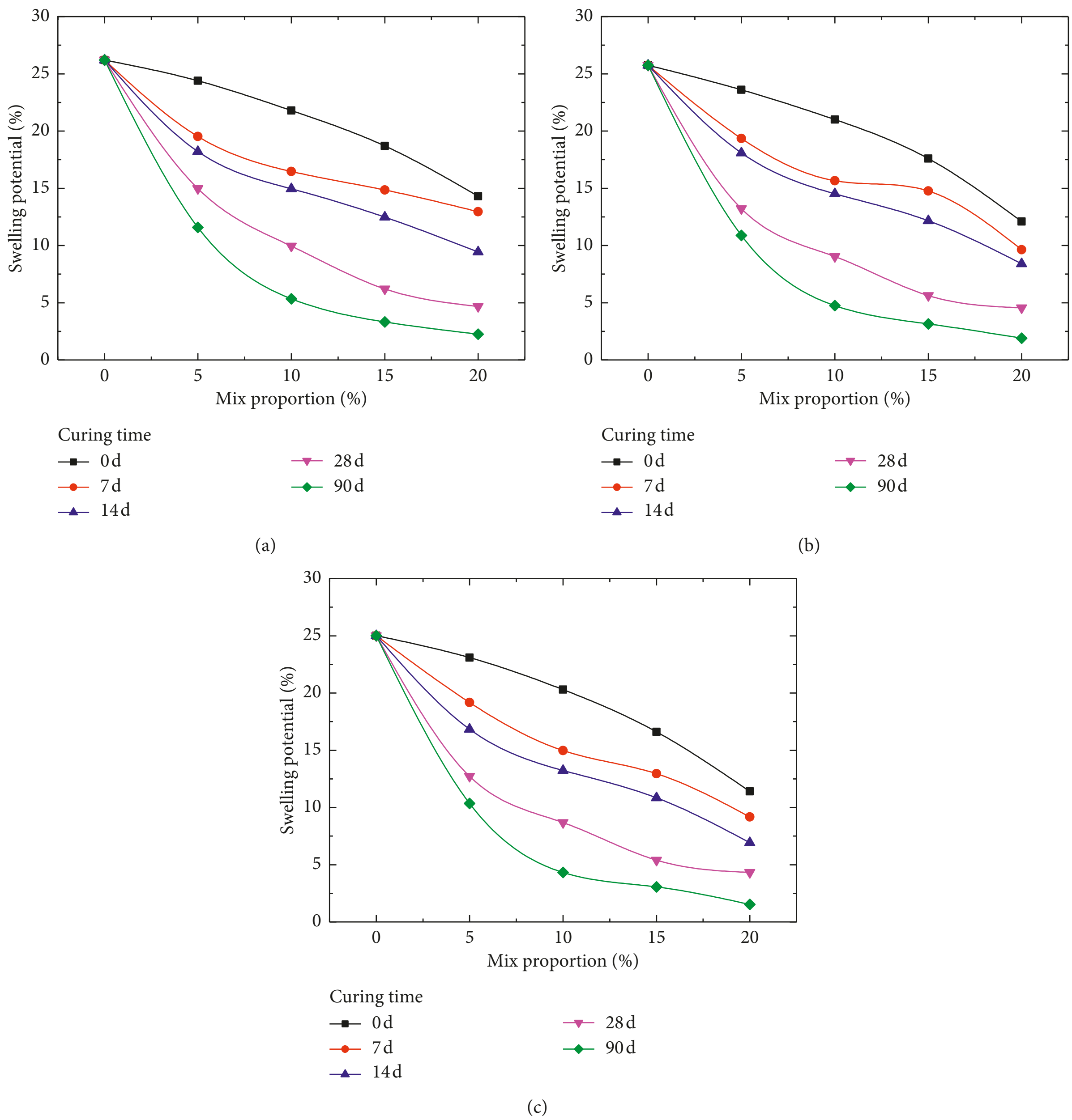


Figure 13: Swelling potential of expansive soil stabilized by RHA-lime. (a) $w = \text{OMC}$, (b) $w = 1.2\text{OMC}$, and (c) $w = 1.4\text{OMC}$.

materials (rice husk ash and lime) and absorbent material (rice husk ash). Thus, physical properties of original expansive soil were changed.

(2) As curing time increases, swelling potential and swelling pressure of stabilized soil decrease accordingly. Giving an example with mix proportion of 15%, when curing time increases from 0 to 90 days, swelling potential decreases from 17.60% to 3.15% in Figure 13(b), and swelling pressure drops from 171.4 kPa to 45.5 kPa in Figure 14(b). It should be noted that daily reduction rate of swelling potential is 0.27% in the range of 0–28 days and 0.04% in the range of 28–90 days. This shows that in the early stage of curing period, the decrease is very fast, and in the late stage, it is relatively slow. At the same time, swelling pressure is also reflecting this trend.

The reduction in swelling potential and swelling pressure values with curing time is due to interaction between expansive soil and RHA-lime. The active silica reacts with calcium and forms calcium silicate hydrate (C–S–H) gel. So samples of stabilized expansive soil became stronger and more brittle than natural expansive soil. The longer the curing time, the more complete the reaction. Consequently, swelling potential and swelling pressure of stabilized expansive soil decreased with increase of curing time.

(3) The initial water content (w) of stabilized soil has a large effect on swelling performance. Figures 13 and

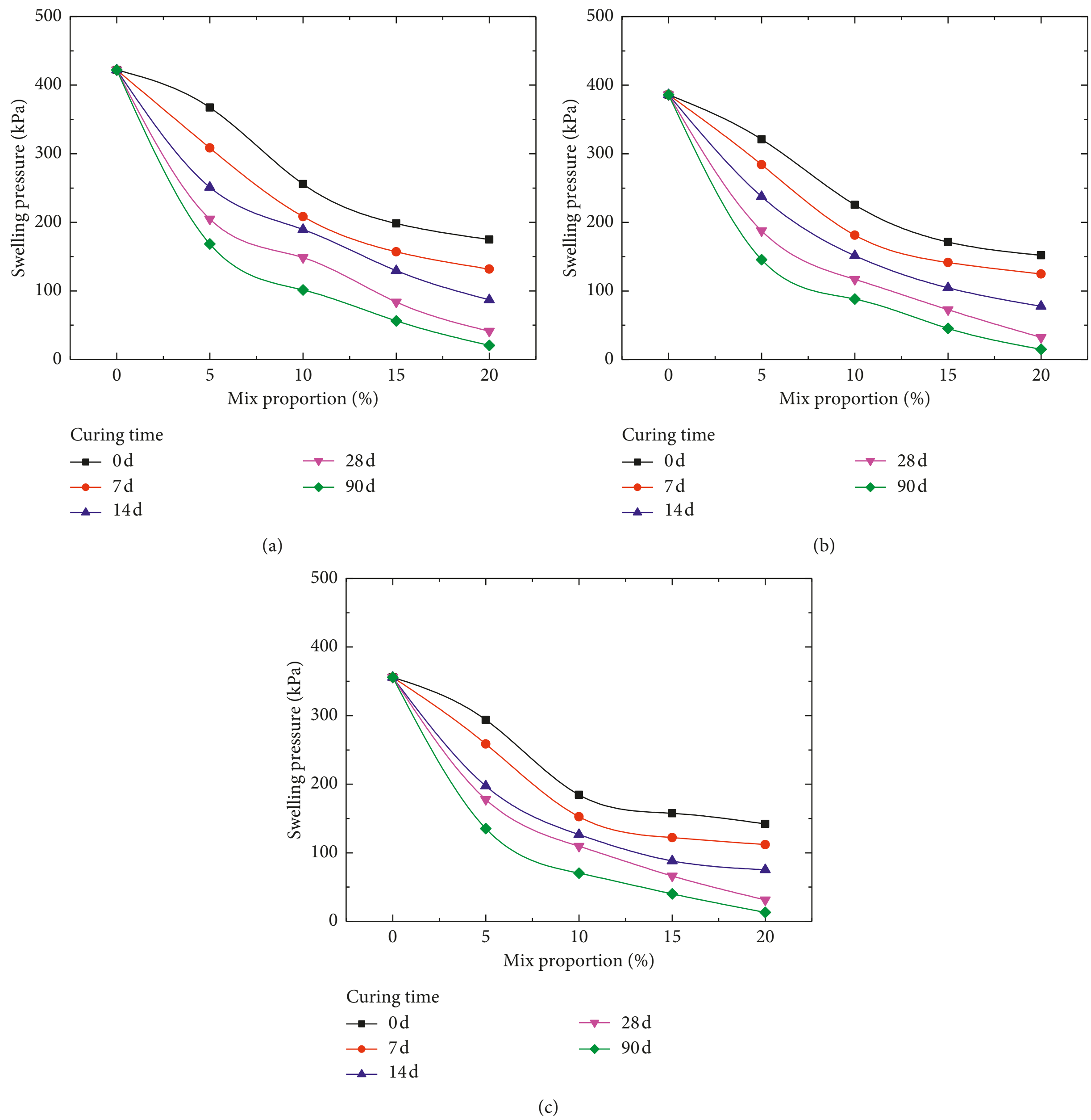


Figure 14: Swelling pressure of expansive soil stabilized by RHA-lime. (a) $w = \text{OMC}$, (b) $w = 1.2\text{OMC}$, and (c) $w = 1.4\text{OMC}$.

14 display three different water contents 1.0OMC, 1.2OMC, and 1.4OMC, respectively. It can be seen that as the initial water content increases, both swelling potential and swelling pressure decrease. This phenomenon exists in both expansive soils that are treated or not. However, compared to untreated expansive soil, the decrease amount of swelling potential and swelling pressure due to increase in water content is smaller for treated expansive soil.

3.4. Compression Index of Expansive Soil Stabilized by RHA-Lime. Compression index was obtained from the e–$\log P$ curves of consolidation test. Figure 15 shows variation of compression index of stabilized expansive soil with different mix proportion of RHA-lime and curing time. Clearly, compression index is dropped owing to addition of cementitious material. The compression index of expansive soil decreases from 0.244 to 0.118 when 20% RHA-lime is blended. The reduction rate in compression index varies from 14.8% to 51.7% at different percentage of RHA-lime as compared to the untreated soil. Increase in curing time also decreases compression index. The compression index is dropped to 0.067 at 28 days and 0.045 at 90 days of curing as mix proportion is 20%. This phenomenon is caused by chemical reaction and filling of RHA-lime with soil.

3.5. Unconfined Compression Strength of Expansive Soil Stabilized by RHA-Lime

(1) The unconfined compressive strength (UCS) versus mix proportion of RHA-lime is described in

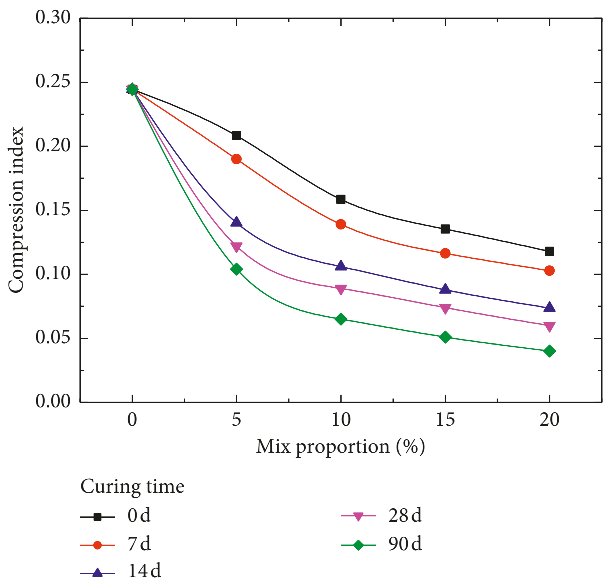


Figure 15: Compression index of expansive soil stabilized by RHA-lime.

Figure 16 for curing times of 0, 7, 14, 28, and 90 days. As can be seen from the figures, unconfined compressive strength increases with increasing amount of RHA-lime. For uncured expansive soils, the admixture plays a good filling role because of their fine particles. The addition of RHA-lime changes structure of particles and reduces their plasticity. Therefore, uncured expansive soil has an increased strength as RHA-lime content increases. For example, in Figure 16(b), as amount of RHA-lime increases, unconfined compressive strength increases from 0.88 to 1.61 MPa. The max increase rate of unconfined compressive strength is up to 82.9% as compared to natural soil. Meanwhile, Figure 16 shows that obvious change is strength of expansive soil after curing. Evidently, as curing time increases, unconfined compressive strength increases accordingly. About the sample with 20% RHA-lime content and 28th day curing period, maximum strength is about 4.0 times that of the uncured soil. The detailed variation of unconfined compressive strength with curing time is shown in Figure 17. For all cases, rate of increased strength is high at the early stage (within 28 days), but reduces at the later stage. It is worth noting that there is no inflection point in UCS between 0% and 20% of mix proportion for all cases.

(2) The initial water content (w) of stabilized soil has a remarkable effect on unconfined compressive strength. Figures 16 and 17 display unconfined compressive strength of stabilized soil with three different water contents, 1.0OMC, 1.2OMC, and 1.4OMC, respectively. In Figure 18(a), it can be seen that when mix proportion is between 0 and 10%, the larger the initial water content, the lower the strength. However, when mixing proportion exceeds 10%, this law changes, and UCS of 1.2 times OMC reaches maximum value. Figure 18(b) verifies this phenomenon. Regardless of whether curing time is long or short, UCS of 1.2 times OMC is largest. The reason is that the porous system of RHA which has strong water absorption effect reduces water content of expansive soil.

3.6. Shear Strength of Expansive Soil Stabilized by RHA-Lime. The shear strength parameter such as cohesion and internal friction angle was obtained from direct shear test. The effect of mix proportion on cohesion is shown in Figure 19. The addition of RHA-lime tends to increase cohesion of soil. For uncured soil, cohesion increases from 51.5 kPa to 70.1 kPa when mix proportion increases from 0.0 to 20.0%. After curing, cohesion is significantly improved. For instance, cohesion of 20% RHA-lime content after curing 28 days is 2.70 times that of uncured soil.

The effect of mix proportion on internal friction angle is provided in Figure 20. With increase of mix proportion, internal friction angle of stabilized expansive soil increase from 7° to 16.7°. As same as cohesion, internal friction angle is significantly improved after cured. For instance, internal friction angle of 20% RHA-lime content after curing 90 days is 2.26 times that of the uncured soil.

To sum up, addition of RHA-lime has obviously upgraded shear properties of expansive soil, which is beneficial to bearing properties of soil.

3.7. Crack Development of Expansive Soil Stabilized by RHA-Lime. Cracking is one of the main characteristics of expansive soil. Shrinkage and overconsolidation stress release processes of expansive soils can lead to cracks. The occurrence and expansion of initial fissure not only destroys soil integrity, but also provides a channel for seepage of water, which aggravates expansion, contraction, and development of fissures. After drying at 100°C for 24 hours, cracks of expansive soil sample with 14 days of curing are illustrated in Table 4. In general, the more the RHA-lime content, the less and the finer the crack, and the better integrity of the sample. When RHA-lime content exceeds 10%, coarse cracks are substantially eliminated. As a result, RHA-lime is beneficial to inhibiting cracking of expansive soil.

3.8. Stabilized Efficiency of RHA-Lime. In order to analyze stabilized efficiency of RHA-lime on expansive soil, three parameters were defined:

(1) Mix proportion α: RHA-lime content as mentioned above, it is 0, 5%, 10%, 15%, and 20%

(2) Improvement rate β: $\beta : \beta = (|Y_0 - Y_i|)/(Y_0) \times 100\%$, where Y_i expresses the value of various indexes of stabilized soil and Y_0 expresses the value of various indexes of nature expansive soil

(3) Improved efficiency coefficient $\gamma : \gamma = \beta/\alpha$

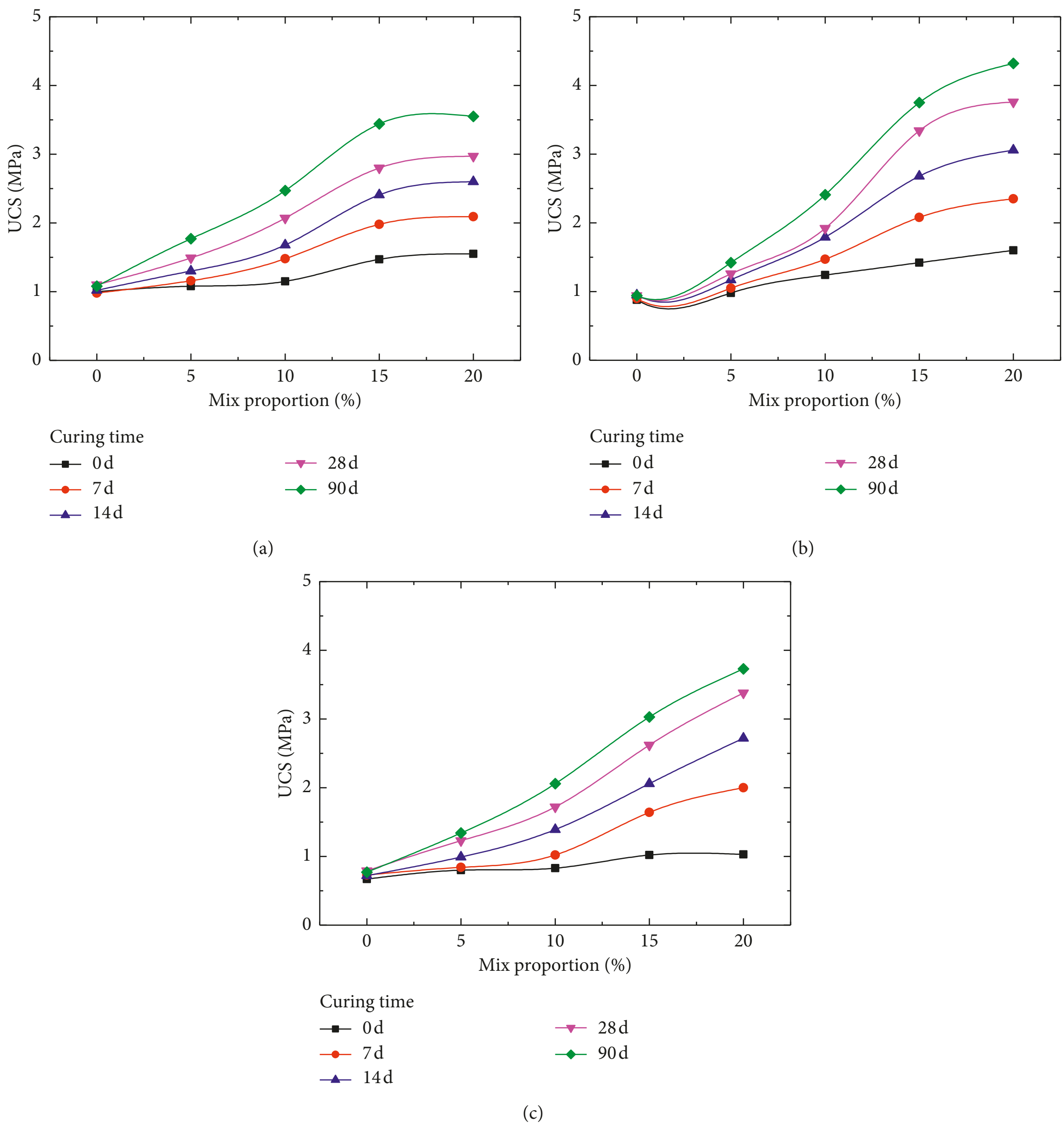


FIGURE 16: Unconfined compression strength of expansive soil stabilized by RHA-lime. (a) w = OMC, (b) w = 1.2OMC, and (c) w = 1.4OMC.

The strength and deformation indexes of stabilized expansive soil after 28 days with different mix proportion are summarized in Table 5. Improvement rate and improved efficiency coefficient are shown in Tables 6 and 7, respectively. Compared with improvement rate of all samples, 20% is better than other mix proportion. But considering the improved economy, 5% is best. Combined with value of engineer index, improvement effect, and improvement cost, the mix proportion of 15% is most suitable for expansive soil in this paper.

For other expansive soils, the optimum mix proportion of RHA-lime needs to be determined experimentally. However, this paper fully proves feasibility and scientificity of this stabilizing method. Although RHA was obtained from biomass power plants, it could still be effective in improving properties of expansive soil. In China, this type of rice husk ash is abundant and considered as waste material. Utilization of RHA in construction of foundation, roads, railways, and other geotechnical works is intensely attractive. This will generally lead to low construction costs, alleviate disposal costs, and reduce environmental pollution.

4. Discussion

4.1. Stabilized Mechanism of RHA-Lime. After the addition of RHA-lime, granular structure of expansive soil changes. As the curing time progresses, RHA, lime, and soil begin to react with each other. Then, the gelling material is formed to cement and aggregate soil particles; therefore, the mechanical and deformation properties of soil get great change.

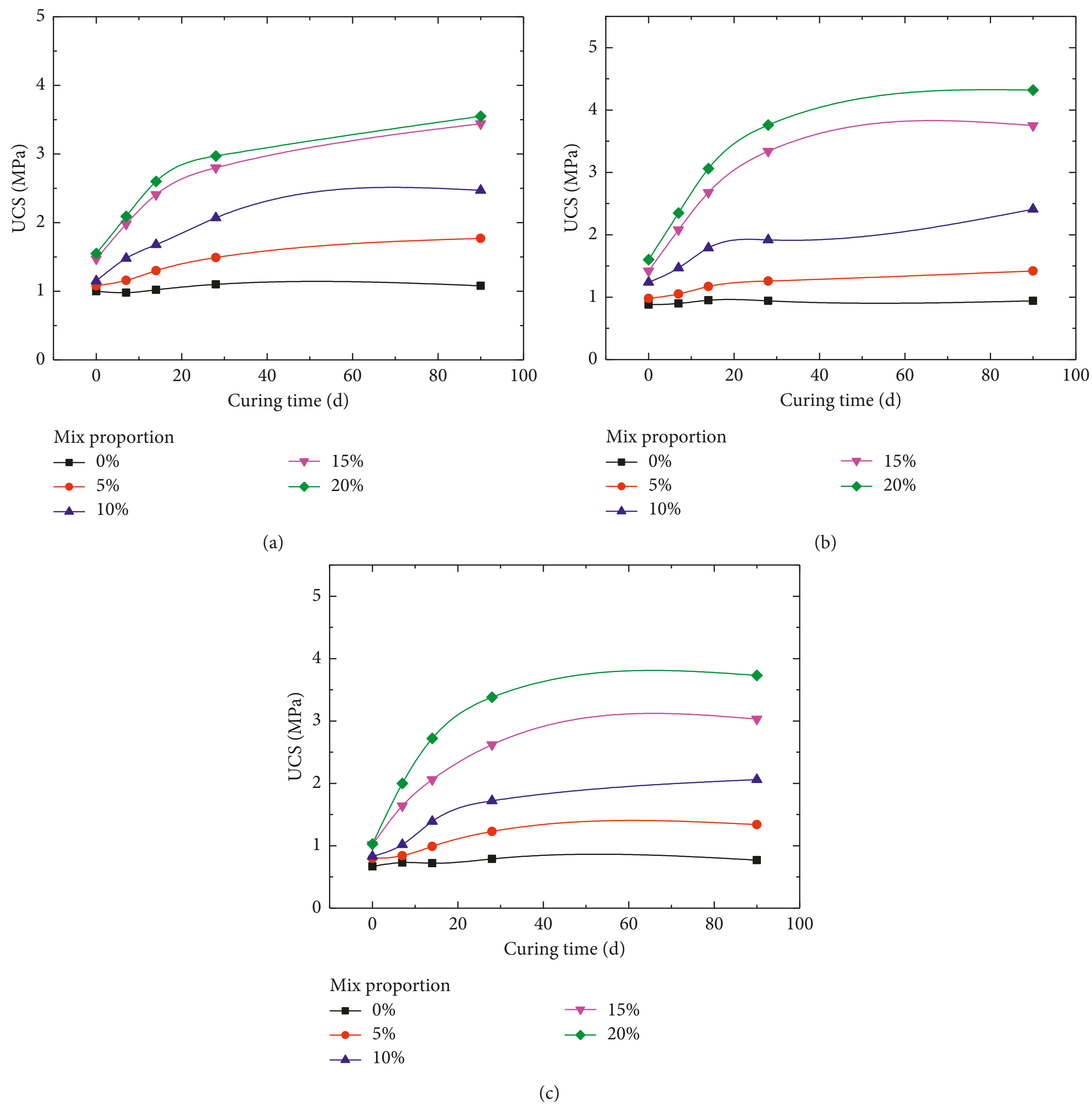


FIGURE 17: Unconfined compression strength of expansive soil stabilized by RHA-lime in different curing time. (a) w = OMC, (b) w = 1.2OMC, and (c) w = 1.4OMC.

Ingles and Metcalf have conducted an in-depth analysis of mechanism of lime-solidified soil [57]. Referring to their theory, mechanism of stabilized by RHA-lime is as follows.

4.1.1. Replacement. Added to expansive soil, rice husk ash and lime play a certain degree of replacement effect. On the one hand, due to the low plasticity, nonexpansion, and water absorption, physical properties of expansive soil will change, especially, plasticity index and swelling potential. On the other hand, because particles of lime are very fine, they can also have a good filling effect on the soil particles. As a result, replacement efficiency is more and more obvious with increase of RHA-lime content.

4.1.2. Coagulation Reaction. Since rice husk ash contains a large amount of active silica, it is an ideal pozzolanic material. It is well known that lime reacts with pozzolanic component to form calcium-silicate cement. In this paper, hydrated calcium silicate (CaO·SiO2·nH2O) and hydrated calcium aluminate ($CaO{\cdot}Al_2O_3{\cdot}mH_2O$) can be generated with $Ca(OH)_2$ from lime and SiO_2, Al_2O_3 from RHA and expansive soil under the water environment. The chemical product is ideal cementitious material and water insoluble. The silicate gel proceeds immediately to coat and bind clay lumps in the soil and to block off the soil voids. Along with these cementitious materials gradually transforming from gel state to crystalline state, the particles of expansive soil are joined together and consolidated. In time, this gel gradually

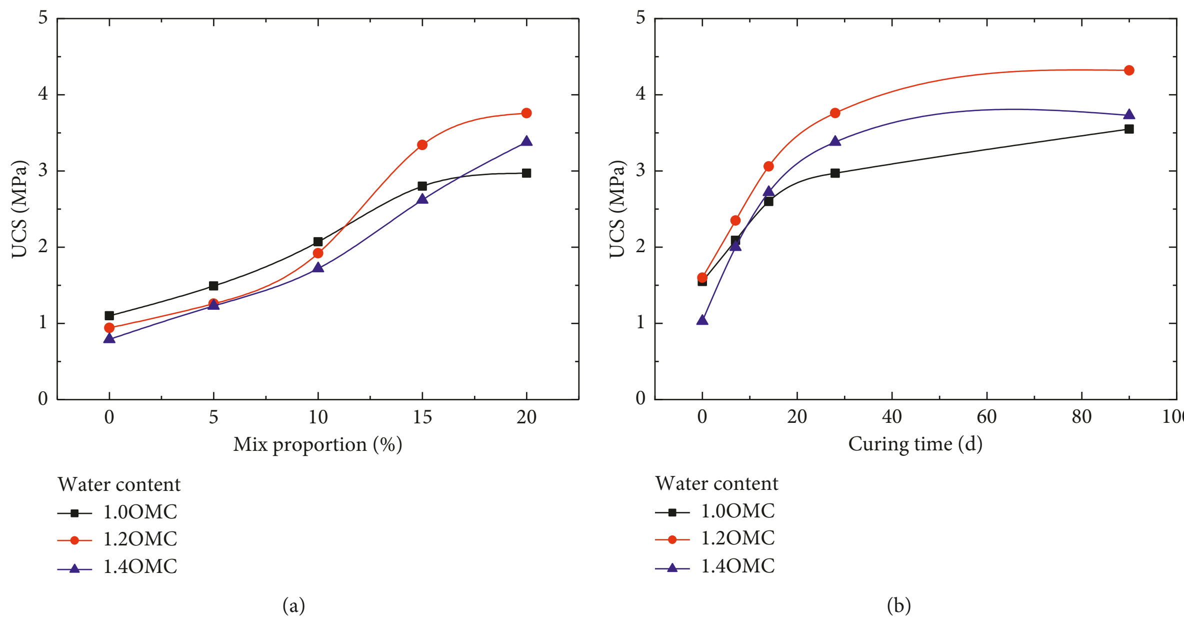


Figure 18: Unconfined compression strength of expansive soil stabilized by RHA-lime in different water content. (a) Effect of mix proportion; (b) effect of curing time.

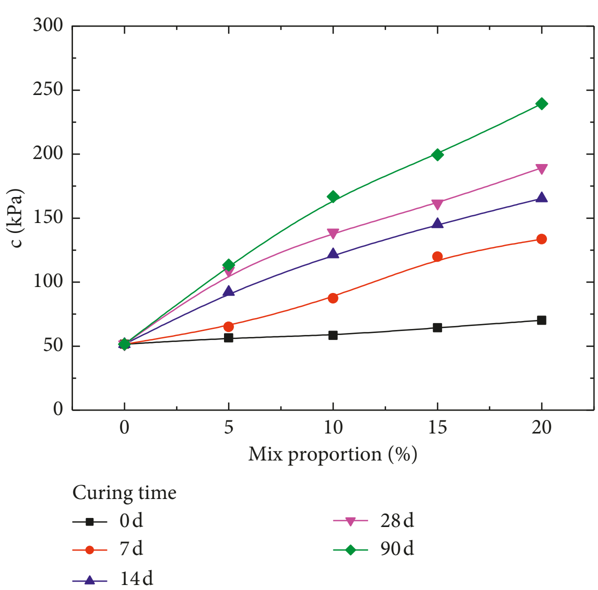


Figure 19: Cohesion of expansive soil stabilized by RHA-lime.

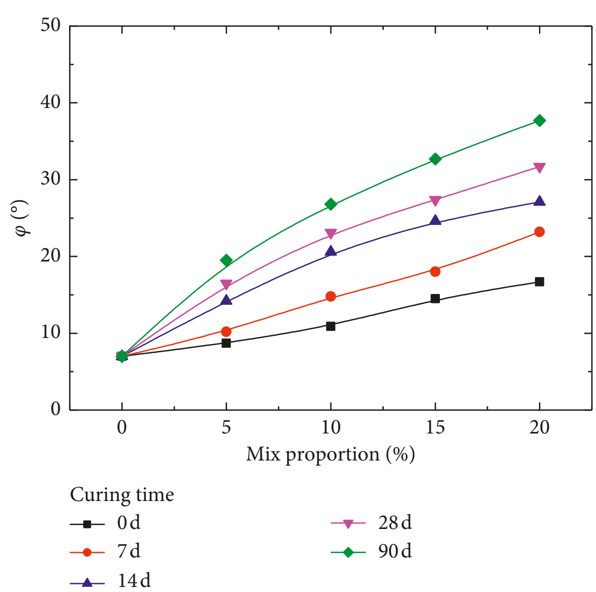


Figure 20: Internal friction angle of expansive soil stabilized by RHA-lime.

crystallizes into well-defined calcium silicate hydrates such as tobermorite and hillebrandite. The microcrystals can also mechanically interlock. As a result, the strength and rigidity increase and the swelling performance decrease when the soil is cured for some time.

4.1.3. Ion Exchange. Expansion and shrinkage of expansive soil is mainly due to water absorption of expansive mineral in soil. After absorbing water, the thickness of water film will change. The thinner the thickness, the greater the cohesive force between the particles, the higher the shear strength of the soil, and the smaller the swell-shrinking property. After added to the expansive soil and assisted by water, lime is dissociated into Ca^{2+} and OH^- ions. Ca^{2+} is replaced by Na^+ and K^+ in the clay particles by ion exchange, so that the colloidal adsorption layer is thinned. As a result, the thickness of water film becomes thinner and the swelling potential of the soil reduces. In addition, alkaline environment accelerates ion exchange. As lime is one kind of alkali, the pH value of expansive soil increases with the addition of lime. Generally speaking, the more the lime is, the more the ion exchanged will be.

Table 4: Crack morphology of expansive soil with different RHA-lime content.

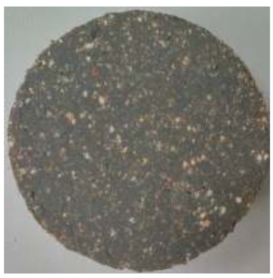
Mix proportion (%)	Before drying	After drying	Crack description
0			There are more than 30 obvious cracks and most of cracks are very wide
5			There are more than 20 obvious cracks and half of cracks are wide
10			There are about 15 obvious cracks and little of cracks are wide
15			There are more than 20 visible cracks and most of cracks are thin
20			There are less than 10 visible cracks and most of cracks are thin

Table 5: The strength and deformation index of stabilized expansive soil.

α (%)	Swelling potential (v)	Swelling pressure (kPa)	Compression index	UCS (MPa)	Cohesion (kPa)	Internal friction angle (°)
0.0	25.8	386.0	0.244	0.94	51.5	7.0
5.0	13.2	187.8	0.102	1.26	109.0	16.5
10.0	9.0	126.8	0.089	1.92	138.9	23.1
15.0	5.6	72.5	0.074	3.34	161.5	27.4
20.0	4.6	32.1	0.067	3.76	189.3	31.7

Table 6: The improvement rate of stabilized expansive soil.

α (%)	Swelling potential (%)	Swelling pressure (%)	Compression index (%)	UCS (%)	Cohesion (%)	Internal friction angle (%)
5.0	48.80	51.35	58.20	34.04	111.65	135.71
10.0	64.96	67.15	63.52	104.26	169.71	230.00
15.0	78.22	81.22	69.67	255.32	213.59	291.43
20.0	82.33	91.68	72.54	300.00	267.57	352.86

Table 7: The improvement efficiency coefficient of stabilized expansive soil.

α (%)	Swelling potential	Swelling pressure	Compression index	UCS	Cohesion	Internal friction angle
5.0	9.76	10.27	11.64	6.81	22.33	27.14
10.0	6.50	6.72	6.35	10.43	16.97	23.00
15.0	5.21	5.41	4.64	17.02	14.24	19.43
20.0	4.12	4.58	3.63	15.00	13.38	17.64

4.2. Result Comparison of Other Research Studies. As mentioned above, there have been some findings on the stabilization of expansive soil or clay soils using RHA-lime. To this end, the material sources (RHA source, silica content, and soil properties) and the engineering properties of stabilized soil were compared, as shown in Table 8. Because the source of test materials is different and the parameters tested are not uniform, the values of each specific index are not compared, only to judge their general trend.

After comparison in Table 8, the biggest difference between this paper and other papers is that RHA is derived from biomass power plants, while other RHA are generally obtained through self-manufacturing or processing. In order to ensure the balance of power production, rice husk is usually not fully incinerated during biomass power generation, resulting in a significantly lower silica content of rice husk ash in this paper than other self-made methods.

Meanwhile, the commonalities of these papers are as follows: under the cementation of RHA-lime, swelling potential, swelling pressure, and compression index of stabilized expansive soil would decrease obviously, and at the same time, UCS, CBR, cohesion, and internal friction angle would increase drastically. This implies that the rice husk ash produced by biomass power plant can also achieve a good curing effect compared with other RHA.

Due to large yield, simple acquisition, and low price of rice husk ash in biomass power plants, it can be applied on a large scale in the lime stabilization of expansive soil. The application of this method not only solves the environmental pollution problem of waste, but also reduces the construction cost in areas of expansive soil.

5. Conclusions

Based on above experimental investigations and result analysis, the following conclusions can be drawn:

(1) Rice husk ash, which is obtained from biomass power plants, in combination with lime can form a new cementitious material. The compressive strength of RHA-lime mortar is about half of that of P.O 32.5 cement mortar, and flexural strength of RHA-lime mortar is more than half of that of cement mortar. Comparing different blending ratios of RHA/lime, 4 : 1 can obtain the best performance in strength. Therefore, this blending ratio is adopted to stabilize expansive soil with very high swelling potential.

(2) After mixed with RHA-lime, the fine particles of expansive soil are reduced, and the coarse particles are correspondingly increased. As the amount of RHA-lime becomes larger, specific surface area of the mixture is remarkably lowered, and at the same time, medium particle size is increased.

(3) Swelling potential and swelling pressure of stabilized soil decrease with increase in mix proportion of RHA-lime, curing time, and initial water content, indicating RHA is very useful for inhibiting soil expansion.

(4) RHA-lime not only inhibits expansion but also suppresses compression. Addition of RHA-lime material dropped compression index. At the same time, increase in curing time leads to a reduction in compression index.

Table 8: Result comparison with existing literature.

	[46]	[47]	[49]	[50]	[51]	[52]	This paper
RHA source	Self-made	Open-field burnt	Made in controlled temperature	Burnt in incinerator	Not stated	Processed RHA from a plant	Biomass power plant
SiO_2 in RHA	89.08%	90.73%	90.80%	86.71%	Not stated	91.60%	72.34%
Soil	Clayey soil	Residual granite soil	Black cotton soil	Expansive soil	Black cotton soil	Expansive soil	Expansive soil
Particle size distribution	√						√
Compaction		√	√	√	√	√	
Swelling potential	√	√		√			√
Swelling pressure				√		√	√
Compression index	√					√	√
Cracking index							√
Unconfined compressive strength	√	√	√		√	√	√
CBR	√		√	√		√	
Cohesion	√					√	√
Internal friction angle	√					√	√
Optimum mix proportion	6–10% RHA, 6–10% lime	6–12% RHA, 9% lime	5% RHA, 2% lime	6% RHA, 6% lime	20% RHA, 3% lime	10% RHA, 15% lime	15% (RHA: lime = 4 : 1)

(5) Unconfined compressive strength of expansive soil increases rapidly when soil is treated with the admixture of lime and RHA. As curing time increases, the strength of the treated soil increases accordingly. About sample with 20% RHA-lime content and 28th day curing period, the maximum strength is about 4.0 times that of uncured soil. The initial water content of stabilized soil has an important effect on unconfined compressive strength. Regardless of whether the curing time is long or short, the UCS at water content of 1.2OMC is largest.

(6) Cohesion and internal friction angle of stabilized soil promote greatly when the mix proportion and curing time increase. Obviously, addition of RHA-lime has promoted shear properties of expansive soil, which is beneficial to bearing properties of the soil.

(7) The more the RHA-lime content, the less and the finer the crack, the better the integrity of the sample. When mix proportion exceeds 10%, coarse cracks are substantially eliminated. RHA-lime is very beneficial to overcome cracking weakness of expansive soil.

(8) Expansive soil stabilization using RHA-lime is achieved through replacement efficiency of RHA-lime, coagulation reaction, and ion exchange.

(9) Finally, experiment results add another dimension to use of waste material (RHA) in soil stabilization. RHA-lime in construction of cushions, roads, airfields, and other earthworks is particularly attractive because of lowered construction and disposal costs, reduced environmental damage, and conservation of high-grade construction materials. Considering performance and cost, a mix proportion of 15% and an initial water content of 1.2OMC is recommended for the treatment engineering for expansive soil.

Data Availability

The numerical data used to support the findings of this study are included within the article. All the lab test data and calculation results data used to support the findings of this study are also available.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

Acknowledgments

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