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Mechanical Properties Test and Enhancement Mechanism of Lime Soil Modified by High Content Soda Residue for Road Use

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Abstract: In order to solve the problem of solid waste soda residue (SR) environmental pollution and resourceful utilization, lime soil modified by high content soda residue (LSMHCSR) is prepared by solid waste SR, lime and soil. In this paper, the basic characteristics of SR and the mechanical properties of LSMHCSR were tested, and the enhancement mechanism of LSMHCSR was analyzed. The test results showed that: (1) SR is mainly composed of $CaCO_3$, $Ca(OH)_2$ and $CaCl_2$, with high natural moisture content, which is not recommended as a separate engineering filler; (2) As the SR content gradually increased, the optimum moisture content of LSMHCSR gradually increased, with the maximum dry density first increasing and then decreasing; (3) With SR content in the range of 10% to 30%, both 7d and 28d UCS of LSMHCSR increased first and then decreased, reaching the maximum under 15% SR, with the increase as high as 36.9% and 37.2%, respectively. The optimal material mix ratio was SR:lime:soil = 15%:6%:85%; (4) An appropriate amount of SR could effectively promote the physical filling, cementation, crystallization and carbonization, and pozzolanic reactions of the material, and the resulting cementing substances, such as $CaCO_3$ crystals, C-H-S and N-A-S-H, could improve the material strength. However, under excessive SR amounts, the excess SR did not react, with the material strength reduced. Based on the engineering benefit analysis of the test section, lime soil modified by high content SR can effectively alleviate the road material supply shortage, soil erosion and solid waste pollution problems, demonstrating remarkable technical, economic and social benefits and enjoying a good prospect of application and promotion.

Keywords: soda residue; high content; lime soil; unconfined compressive strength; enhancement mechanism

Citation: Zhu, S.; Tang, Y.; Xu, Q.; Zhang, K.; Li, H.; Zhu, Z.; Yin, W. Mechanical Properties Test and Enhancement Mechanism of Lime Soil Modified by High Content Soda Residue for Road Use. *Coatings* **2022**, *12*, 1539. https://doi.org/10.3390/coatings12101539

Academic Editor: Claudio Lantieri

Received: 27 August 2022
Accepted: 5 October 2022
Published: 13 October 2022

1. Introduction

Soda Residue (SR) refers to the solid waste residue discharged in the process of industrial soda production and treatment, mainly including calcium carbonate, calcium sulfate, calcium chloride, etc., and a small amount of sulfur dioxide [1]. Soda production in China is mainly based on the ammonia–alkali method. According to statistics, every ton of sodium carbonate produced by a soda plant incurs discharge of about 300–600 kg of solid waste SR [2]. There are more than 50 soda producers in the country, with SR discharge of 7.8–10 million kg every year [3]. Due to the high moisture content and high chloride ion of the SR [4], it is very difficult to treat solid waste SR, and the utilization rate is less than 15% [5].

The treatment of SR mainly relies on surface accumulation, occupying a large amount of land resources, polluting soil and groundwater, and endangering the ecological environment [6,7]. Solid waste SR has high retention, low diffusion and a long incubation period. How to safely dispose of solid waste SR seriously concerns the sustainable development of enterprises, and it is imminent a resource-based, large-scale and high-value new SR utilization method [8,9] will be developed.

Scholars have long studied the recycling and utilization of SR. Hou Guihua [10] used SR as the main raw material to sinter a new type of white cement. The product has high strength in the early stage and sets fast, but its strength increases little in the later stage. Xu Chengwen [11] prepared all-solid-waste marine concrete by coupling iron and steel metallurgical slag, desulfurized gypsum and iron tailings. Yang Yibo [12] dechlorinated, dried and pulverized the SR to prepare the soda residue internal curing agent and studied its effect on the self-shrinkage and early crack resistance of concrete. Ma Jiaxiao [13] used SR and fly ash as raw materials to prepare soda residue soil for filling in the liquid phase. Yan Shuwang [14] mixed SR and calcium-enhancing ash in a certain proportion to form soda residue soil and backfilled the site. Huang Lanfen and Wang Hui et al. [15,16] studied the improvement effect of SR on acidic soil through experiments. Liu Ming [17] proved through investigation that straw compost with SR combined with chemical fertilizers could not only improve soil fertility and biological function, but also promoted high yield and high quality of crops. Canakci H [18] used SR particles with a large specific surface area as adsorbents. The above method utilizes some SR to a certain extent, but the SR has low strength, great compressive deformation and high chloride content, so it is difficult to meet the engineering requirements for bearing capacity, environmental protection and scale at the same time.

Since soil alone is used in road engineering, with poor gradation and cohesion of a small, high permeability coefficient, the repeated deformation results in uneven deformation of the subgrade. Scholars have attached great importance to the study of improved soil. Hang Huan [19] studied the improvement effect of weak expansive soil with different dosages of silty soil and concluded that the reasonable dosage of silty soil is 30%. An Fenglei [20] built on the expansive soil improved by using cement + fly ash; basalt fiber or natural sand are further added to the improved expansive soil. When the content of basalt fiber is 0. 6% or the content of natural sand is 8%, the dynamic mechanical properties of the improved expansive soil are the best. Zhang Shasha [21] carried out lime and lime + volcanic ash to improve sulfate soil. The results show that adding lime or lime + volcanic ash can reduce salt expansion and the sensitive temperature range effectively. Zhu Kaijian [22] replaced lime with calcium carbide slag and fly ash to improve the road performance of soil. Zhang Guirong [23] used cement and fly ash to improve fine sand, and the results showed that the combination of the two could improve the mechanical properties of soil and reduce the permeability coefficient of soil at the same time. Witnessing the gradual expanding scale of road construction and maintenance and road construction, imposes growing demand for building materials such as cement and lime. Pavement base and subgrade layers without steel bar pavement faces no potential threat of Cl^- [24,25]. As China attaches great importance to the ecological environment, some regions have begun to explicitly restrict the production of raw materials such as lime and cement. Studies have shown that SR contains a large amount of minerals, such as $CaCO_3$ and $Ca(OH)_2$, which can produce cementation between soil particles [26] and can replace traditional materials, such as lime and cement, to solidify natural soil. SR is believed to enjoy a huge application potential in the road engineering field. Yang Zhaoxu and Chen Yonghui et al. [27] carried out a series of studies on the application of SR as modifiers or modified materials in road engineering. At present, only low-content SR is used to replace the lime components in the lime soil [28], and the soda residue lime soil is prepared. The influence of SR on the strength of the lime soil was studied; the study showed that the 7d UCS of the material with 3% SR content was as high as 2.76 MPa. The SR can effectively improve the strength of the material. However, the content of SR to replace lime is small, and the basic large-scale utilization of solid waste SR is required to study the replacement of soil components in lime soil with SR, so as to increase the content of SR and prepare lime soil modified by high content soda residue (LSMHCSR). Based on the idea of large-scale treatment, the study proposed to replace the soil components in lime soil with low dosages of SR, so as to increase the dosage of SR, and prepare lime soil modified by high content SR for road use. In order to achieve large-scale utilization of SR, this paper studies the mechanical properties of lime soil modified by high content SR through laboratory experiments and explores the material strength enhancement mechanism to provide a reference for the large-scale utilization of solid waste SR in road engineering.

2. Basic Characteristics of Materials

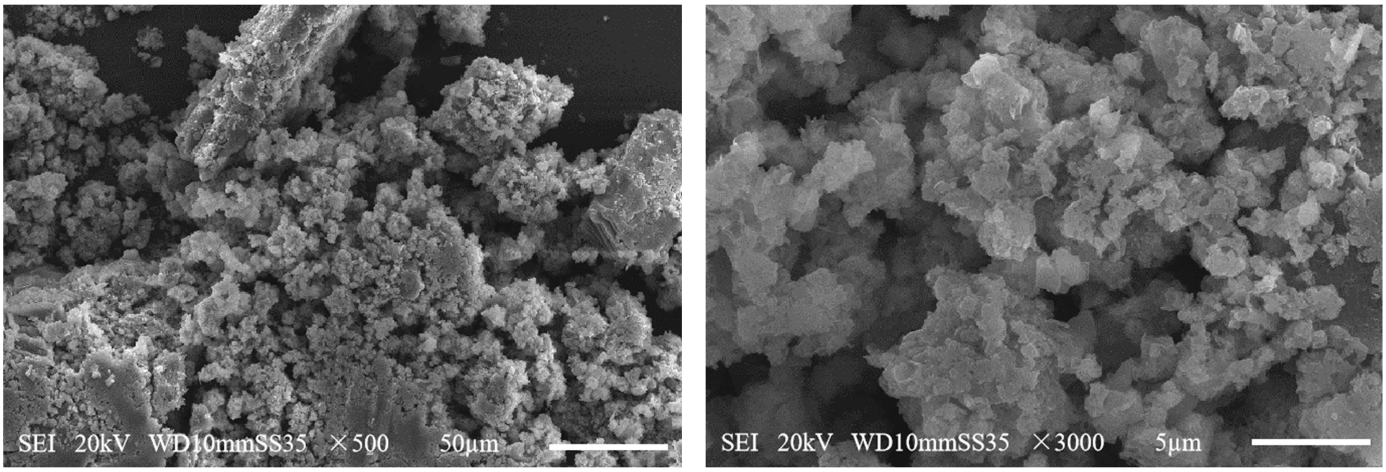
The test SR was taken from Huai'an Alkali Factory. The fresh SR from the factory was gray-white viscous paste with a pungent odor. The moisture content of slag was as high as 98.5%–105%. Natural air-dried SR has the moisture content of about 43.6%, the pH value of 9.2 and the dry density of 1.65 g/cm^3. The unconfined compressive strength (UCS) was at a low level of only 0.20 MPa, with a great compressive deformation. The chemical composition of the air-dried SR was tested by XRD (Bruker, Billeria MA, USA) experiment, with the main chemical composition of the SR shown in Table 1.

Table 1. Main chemical composition of SR.

Number	Compositions	Content/%	Number	Compositions	Content
1	$CaCO_3$	42.53	6	NaCl	2.51
2	$Ca(OH)_2$	11.04	7	$Mg(OH)_2$	8.21
3	$CaCl_2$	10.54	8	Al_2O_3	2.31
4	$CaSO_4$	2.84	9	Fe_2O_3	1.05
5	CaO	7.32	10	SiO_2	2.36

Analysis shows that the SR is mainly composed of $CaCO_3$, $Ca(OH)_2$ and $CaCl_2$, with a small amount of $CaSO_4$ and NaCl. Its rich $CaCO_3$ and $Ca(OH)_2$ generate cements in the later stage, which can improve the soil particle performance [29] and potentially replace inorganic binders such as lime in road engineering.

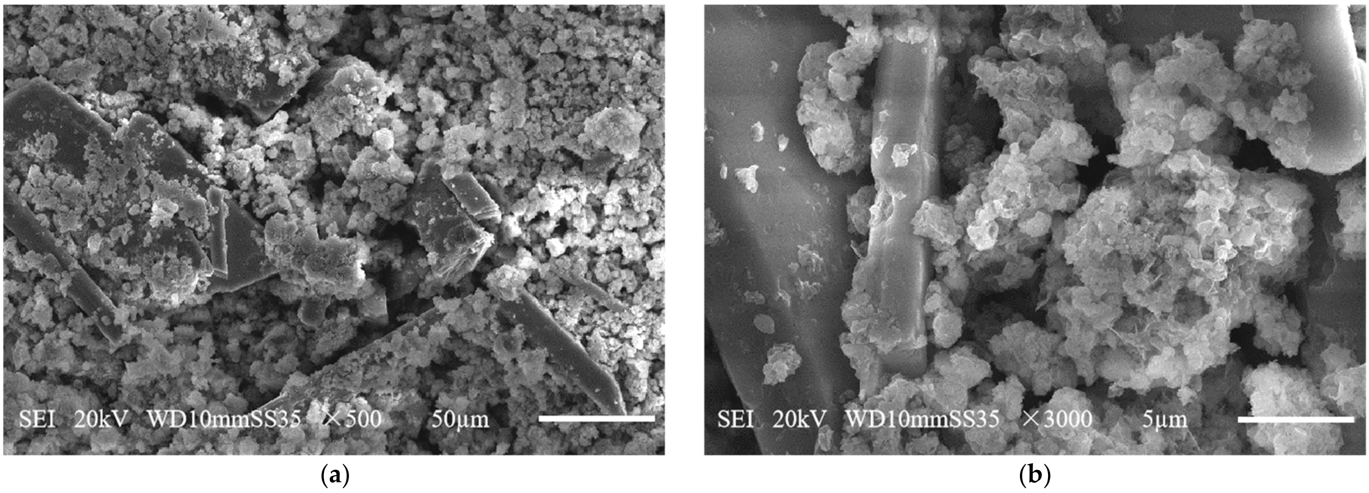
SEM scanning electron microscope (JSM 7800F, JEOL, Tokyo, Japan) was used to scan the internal structure of fresh SR and air-dried SR at different magnifications, as shown in Figures 1 and 2.



(**a**) (**b**)

Figure 1. SEM micrographs of fresh SR. (**a**) 500×; (**b**) 3000×.

From the figure analysis, it can be seen that fresh and air-dried SR have similar porous aggregate structures. It is inferred that the SR forms its material skeleton mainly by $CaCO_3$. A single particle has a particle size of about 2–5 μm, and the particles are cemented with each other to form agglomerates. Particles are dominated by point contact, with weak cementation effect. The agglomerate structure has a relatively rough surface, with pores of different sizes on the surface and inside of the particles, and the pores are abundant and connected with each other, so moisture content is high in the natural state, with great compression deformation under load.



(**a**) (**b**)

Figure 2. SEM micrographs of natural air-dried SR. (**a**) 500×; (**b**) 3000×.

The soil is from the test section of Jinhu 247 project in Huai'an City. The tested soil has a liquid limit of 39.1%, a plastic limit of 19.0% and a plasticity index of 20.1, which is a low liquid limit clay. The total expansion and shrinkage rate is 2.66%. The natural moisture content of the back soil is 1.85%, and the crushed soil passes through a 2.36 mm sieve.

3. Methods and Scheme

This paper designs a single factor experiment to study the impact of SR content on the mechanical properties of lime soil. The material mix ratio was optimized. The concrete design idea was to use SR to replace the soil in the lime soil of the control group and then prepare lime soil modified by high content soda residue (LSHCSR for short). The test took the secondary highway construction section in the Huai'an area as the engineering background. The original pavement sub-base was paved with 12% lime soil, that is, lime:soil equals 12:100 (dry weight). "Technical Guidelines for Construction of Highway Roadbases" (JTG/T F20-2015) requires that each group of proportioning materials be made of UCS specimens under the optimal moisture content state. The test first refers to the "Test Methods of Materials Stabilized with Inorganic Binders for Highway Engineering" (JTG E51-2009) and adopts a light compaction test. Refer to the 7d UCS of material required in the (JTG/T F20-2015) to determine whether the standards are met. The study takes 7 day UCS as the LSHCSR strength index. The mixing ratio design process of LSHCSR is shown in Figure 3.

In order to investigate the influence characteristics of different SR contents have on the mechanical properties of lime soil, a total of five groups of experiments from A1 to A5 were designed, of which A0 was the control group without SR. The specific test matching scheme is shown in Table 2.

Table 2. Test matching scheme.

Group Number	A0	A1	A2	A3	A4	A5
SR/(%)	0	10	15	20	25	30
Lime/(%)	12	12	12	12	12	12
Soil/(%)	100	90	85	80	75	70

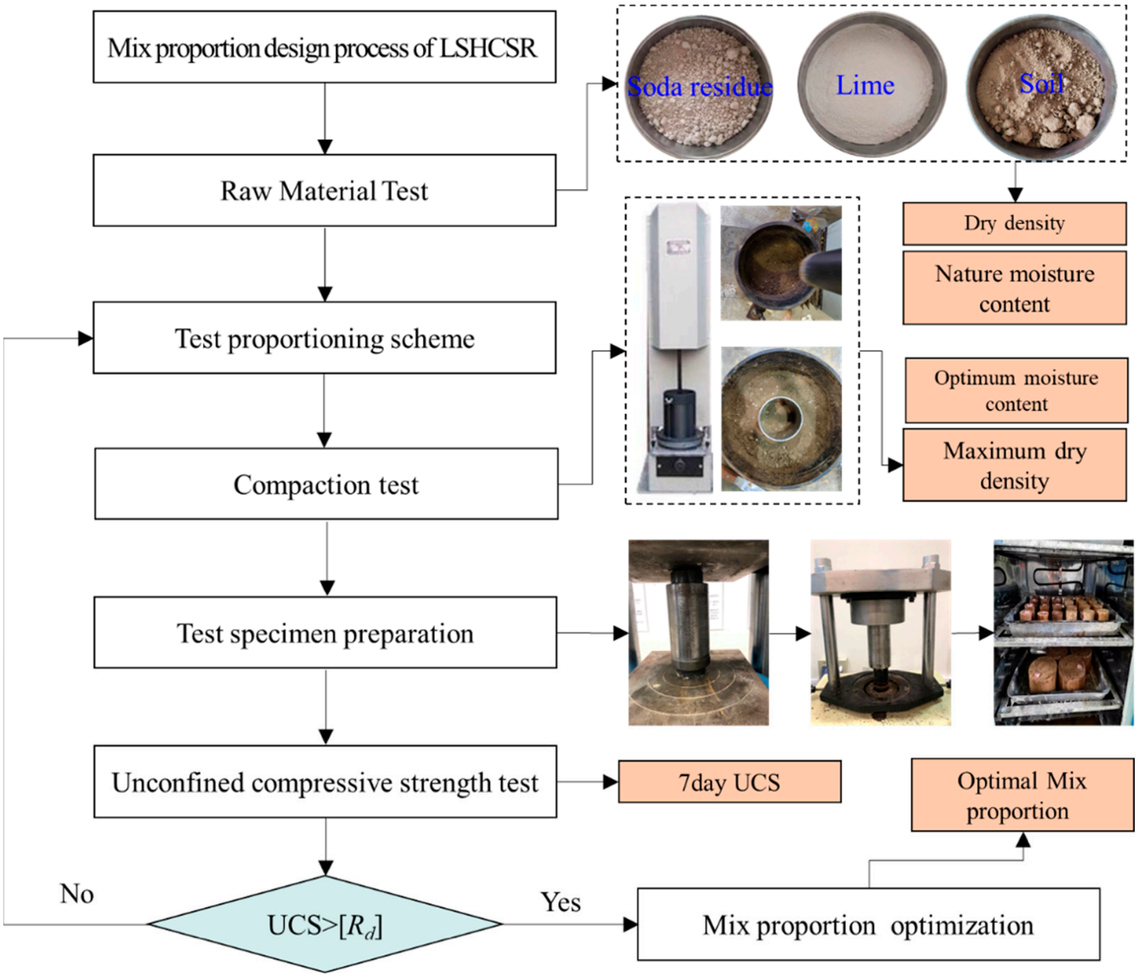


Figure 3. The mixing ratio design process.

4. Results and Discussion

4.1. Compaction Test

4.1.1. Target Moisture Content

When making UCS specimens, the first step is to determine the optimum moisture content and maximum dry density of materials A1–A5. With reference to the optimal moisture content of 18.8% in the control group, A1–A5 groups were designed with 5 target moisture contents of 17%, 19%, 21%, 23% and 25%, in turn. The amount of water required to be added in each group of specimens to reach the target moisture content was calculated according to Formula (1). The formula comes from „Test Methods of Materials Stabilized with Inorganic Binders for Highway Engineering" (JTG E51-2009). The specific compaction test plan and mass ratio are shown in Table 3.

$$m_w = \left(\frac{m_n}{1+0.01w_n} + \frac{m_c}{1+0.01w_c} + \frac{m_k}{1+0.01w_k}\right) \times 0.01w - \frac{m_n}{1+0.01w_n} \times 0.01w_n - \frac{m_c}{1+0.01w_c} \times 0.01w_c - \frac{m_k}{1+0.01w_k} \times 0.01w_k \quad (1)$$

where m_w: the amount of water to be added in LSHCSR/g; w: Target moisture content of LSHCSR/%; m_n: Mass of soil/g; w_n: Natural moisture content of soil/%; m_c: Mass of lime/g; w_c: Natural moisture content of lime/%; m_k: Mass of SR/g; w_k: Natural moisture content of SR/%.

Table 3. Compaction test scheme and mass ratio.

Group Number	Content/%			Target Moisture Content w/%	Quality/g			
	SR	Lime	Soil		SR	Lime	Soil	Water
A1–1	10	12	90	17	178.57	214.29	1607.14	239.55
A1–2				19	178.57	214.29	1607.14	277.83
A1–3				21	178.57	214.29	1607.14	316.12
A1–4				23	178.57	214.29	1607.14	354.40
A1–5				25	178.57	214.29	1607.14	392.68
A2–1	15	12	85	17	267.86	214.29	1517.86	230.57
A2–2				19	267.86	214.29	1517.86	268.69
A2–3				21	267.86	214.29	1517.86	306.82
A2–4				23	267.86	214.29	1517.86	344.95
A2–5				25	267.86	214.29	1517.86	383.08
A3–1	20	12	80	17	357.14	214.29	1428.57	221.58
A3–2				19	357.14	214.29	1428.57	259.55
A3–3				21	357.14	214.29	1428.57	297.53
A3–4				23	357.14	214.29	1428.57	335.51
A3–5				25	357.14	214.29	1428.57	373.48
A4–1	25	12	75	17	446.43	214.29	1339.29	212.59
A4–2				19	446.43	214.29	1339.29	250.42
A4–3				21	446.43	214.29	1339.29	288.24
A4–4				23	446.43	214.29	1339.29	326.06
A4–5				25	446.43	214.29	1339.29	363.88
A5–1	30	12	70	17	535.71	214.29	1250.00	203.61
A5–2				19	535.71	214.29	1250.00	241.28
A5–3				21	535.71	214.29	1250.00	278.95
A5–4				23	535.71	214.29	1250.00	316.61
A5–5				25	535.71	214.29	1250.00	354.28

4.1.2. Optimum Moisture Content and Maximum Dry Density

The experimental soil was screened through a 2.36 mm standard sieve, and the light compaction test was performed to calculate the dry density values of each group of specimens under different target moisture contents. The results are shown in Figure 4.

Analysis in Figure 4 shows that under the same SR content, with the increase in the target moisture content, the dry density of LSMHCSR in different groups first increases and then decreases. For this reason, after the moisture content in LSMHCSR exceeds the optimal moisture content, the excess water no longer reacts and exists in the form of free water. The free water prevents the material densification at the time of compaction, resulting in decreased dry material per unit volume and small relative density of water, so the dry density of LSMHCSR becomes smaller.

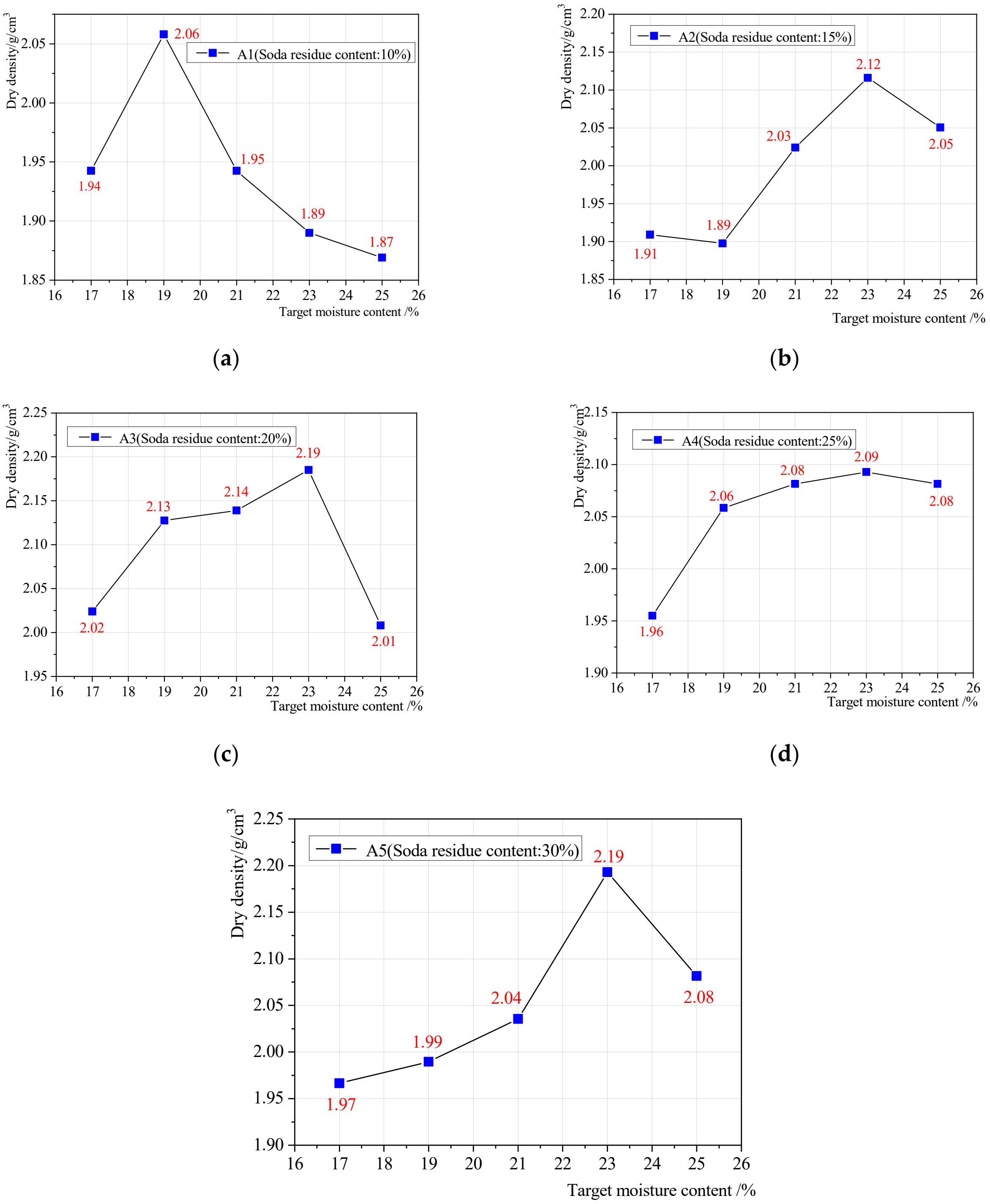
The moisture content–dry density data of each group of samples were fitted to establish the moisture content–dry density fitting equation of each group. The results are shown in Table 4. The optimal moisture content and maximum dry density of each group were deduced, and the relationship curve between the SR content and the optimal moisture content and maximum dry density was plotted, as shown in Figure 5.

According to the analysis in Figure 5:

(1) As the SR content increased from 10% to 30%, the optimal moisture content of A1–A5 groups were 17.93%, 19.33%, 20.11%, 21.36% and 21.82%, respectively. The optimal moisture content of LSMHCSR presented a gradual rising trend. The reason is that SR has high moisture content; with the increase in the SR content, the optimum moisture content of LSMHCSR also gradually increases.

(2) The maximum dry density of LSMHCSR in groups A1–A5 increased first and then decreased. For this reason, an appropriate amount of SR participated in the lime–soil reaction, generating relatively dense cements, with material density increased. However,

the excess SR no longer participated in the reaction. Due to the high moisture content and relatively small density of SR, material density decreased.

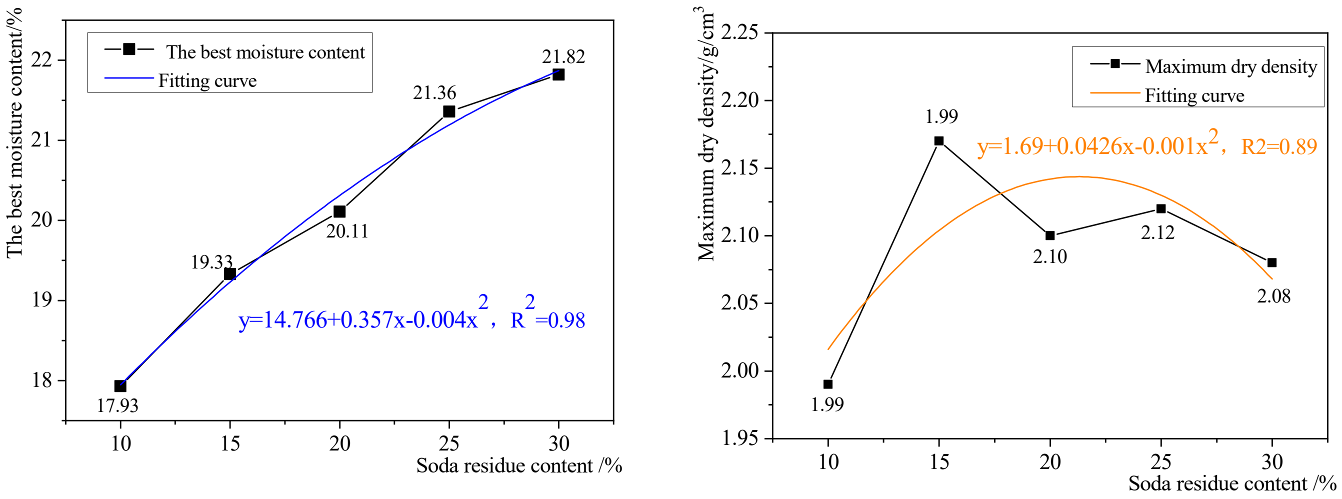


(**a**) (**b**) (**c**) (**d**) (**e**)

Figure 4. Moisture content–dry density curve. (**a**) SR content: 10%; (**b**) SR content: 15%; (**c**) SR content: 20%; (**d**) SR content: 25%; (**e**) SR content: 30%.

Table 4. Fitting results of moisture content–dry density.

Group	Water Content–Density Fitting Curve	The Best Moisture Content	Maximum Dry Density
A1	$Y = -2.846 + 0.538x - 0.015x^2$	17.93%	1.99
A2	$Y = -11.452 + 1.431x - 0.037x^2$	19.33%	2.17
A3	$Y = -4.685 + 0.684x - 0.017x^2$	20.11%	2.10
A4	$Y = -2.809 + 0.470x - 0.011x^2$	21.36%	2.12
A5	$Y = -2.607 + 0.4364x - 0.01x^2$	21.82%	2.08



(**a**) (**b**)

Figure 5. Optimum moisture content and maximum dry density. (**a**) Optimum moisture content; (**b**) Maximum dry density.

4.2. UCS Test

4.2.1. Specimen Preparation

Based on the compaction test results, the UCS specimen mixture was formulated according to the optimum moisture content and maximum dry density. The test lime was anhydrous lime produced by Huihui Industry, with content of calcium and magnesium over 90%. The test soil was taken from the test section. The soil was low liquid limit clay, with a plastic index of 20.1. Raw material SR and soil were naturally air–dried and screened through a 2.36 mm standard sieve. The lime was ground quicklime powder.

To study the influence of SR content on strength, multiple specimens were prepared for groups A1–A5. The curing age was 7 days and 28 days. The average value of the 3 specimens in each group was taken as the final UCS. The standard specimen was a cylinder with a diameter of 50 mm and a height of 50 mm; the standard curing was carried out on the specimen, under curing temperature 20 ± 1 °C and humidity 95%. On the last day of the curing period, the specimen was soaked in water at a depth exceeding the specimen top surface by about 2.5 cm. Displacement control was adopted as the loading method, with the loading rate set at 1 mm/min. The steps of specimen preparation and testing mainly included: breaking of material, screening, moulding, demoulding, curing, soaking and UCS test; the actual shot of the process is shown in Figure 6.

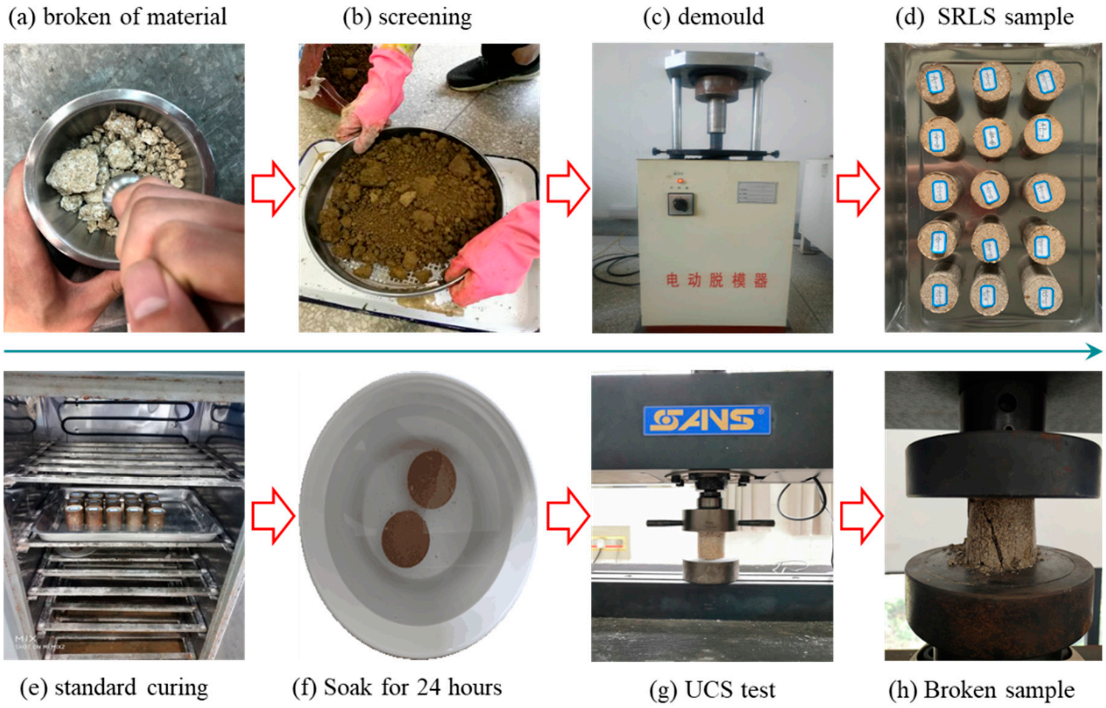


Figure 6. Specimen preparation and test processes.

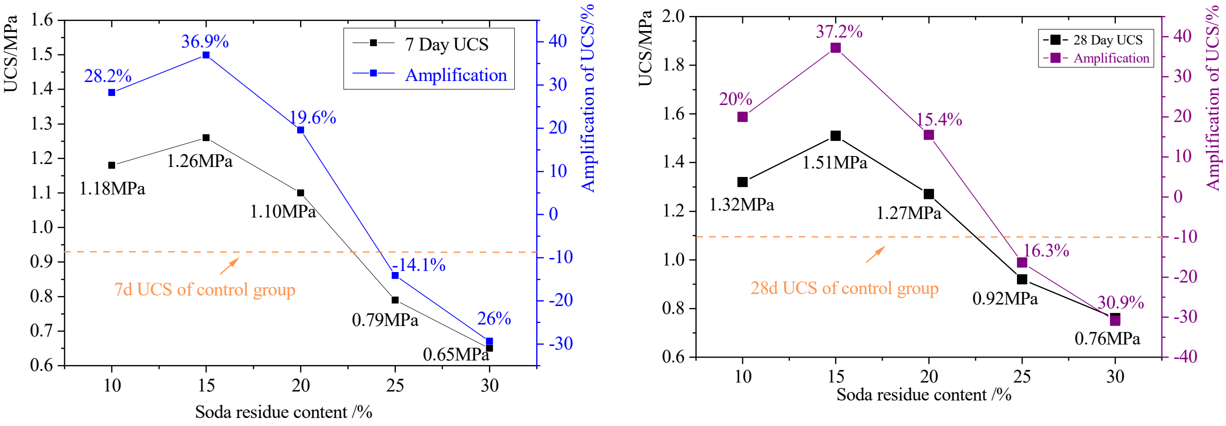
4.2.2. UCS of LSHCSR

Table 5 shows the test results of specimens with different curing ages in groups A1–A5, where A0 is the lime soil control group without SR.

Table 5. UCS test result.

Group	SR Content	7d UCS/MPa	28d UCS/MPa
A0	0	0.92	1.11
A1	10%	1.18	1.32
A2	15%	1.26	1.51
A3	20%	1.10	1.27
A4	25%	0.79	0.92
A5	30%	0.65	0.76

In order to further analyze the effect of SR content on the specimen UCS, the data was plotted, as shown in Figure 7.



(**a**) (**b**)

Figure 7. SR content–UCS curve. (**a**) 7–day maintenance period; (**b**) 28–day maintenance period.

Analysis of Figure 7 shows that when the SR content is in the range of 10–30%:

1. The 7 d UCS of the LSHCSR specimen increases first and then decreases. Under 15% SR content, UCS reaches a maximum value of 1.18 MPa and an increase of 36.9% compared with the control group LSHCSR.
2. The 28 d UCS of the LSHCSR specimen also first increases and then decreases. Under 15% SR content, the 28d UCS of the LSHCSR material reaches the maximum, with an increase up to 37.2%.
3. The test results show that adding an appropriate amount of SR into lime soil can effectively improve the material UCS, but when the SR content exceeds a certain proportion, the material strength will be reduced, so the SR amount should be strictly controlled in practical application. The experimental results show that an appropriate amount of SR can significantly improve the material strength. Based on the SR properties and the strength formation mechanism of the lime soil, it is believed that the mechanism by which SR enhances the lime soil strength mainly includes:
    (1) Physical filling effect: Studies have pointed out that cement–lime soil has a filling enhancement effect [30,31]. LSHCSR is mainly composed of soil. In the experiment, part of the soil was replaced by SR. SEM showed that SR had much smaller particle size than soil. The SR underwent chemical reaction with the soil to form a cementitious material, thus playing the role of “micro–aggregate filling” and “skeleton support”, forming a good dense gradation system under the action of compaction. The filling action belongs to a physical effect, which enhances the strength by changing the particle gradation of the mixture.
    (2) Cementation: The SR contains a large amount of $CaCO_3$, and the cementation of $CaCO_3$ can increase the cohesion between soil particles. SR contains more $CaCO_3$ than the replacement soil, so the $CaCO_3$ content of LSHCSR increases. Combing $CaCO_3$ generated in the reaction between lime soil and pozzolan, $CaCO_3$ in the SR cements the soil particles into a whole, which improves the soil integrity and increases the material strength [32].
    (3) Crystallization and carbonization: SR contains a certain amount of $Ca(OH)_2$. Replacement with SR increases the $Ca(OH)_2$ in the mixture, and the partially saturated $Ca(OH)_2$ in LSHCSR crystallizes by itself. This reaction is similar to generation of a slaked lime crystalline grid in lime–water reaction [33]. The specific reaction is shown in Formula (2).

$$Ca(OH)_2 + nH_2O \rightarrow Ca(OH)_2 \bullet nH_2O \tag{2}$$

In addition to crystallization of $Ca(OH)_2$ in SR and lime, part of CaO and $Ca(OH)_2$ in SR will react with CO_2 in the air to cause carbonization [34,35]. The specific reaction is shown in the Formulas (3) and (4). The resulting hard $CaCO_3$ crystals and other generated complex salts cement the soil particles, providing soil strength and integrity. There is low CO_2 content in the air, so the reaction is relatively slow, with intensity gradually increased.

$$CaO + H_2O \rightarrow Ca(OH)_2 \tag{3}$$

$$Ca(OH)_2 + CO_2 \rightarrow CaCO_3 + H_2O \tag{4}$$

(4) Pozzolanic effect: The addition of SR increases the concentration of $Ca(OH)_2$ in the mixture system. By reaction with the active SiO_2 and Al_2O_3 in the soil, a series of cementitious substances were produced, such as water–containing calcium silicate hydrate (C–H–S) and calcium aluminate hydrate (N–A–S–H) [36,37]. The reactions are shown in Formulas (5) and (6).

$$mCa(OH)_2 + SiO_2 + (n-1)H_2O \rightarrow mCaO \bullet SiO_2 \bullet nH_2O \tag{5}$$

$$mCa(OH)_2 + Al_2O_3 + (n-1)H_2O \rightarrow mCaO \bullet Al_2O_3 \bullet nH_2O \tag{6}$$

In order to further analyze the internal structure of LSHCSR, the specimens of groups A2 and A5 were partially scanned by electron microscopy, with the results shown in Figure 8. The XRD spectra of A2 are shown in Figure 9.

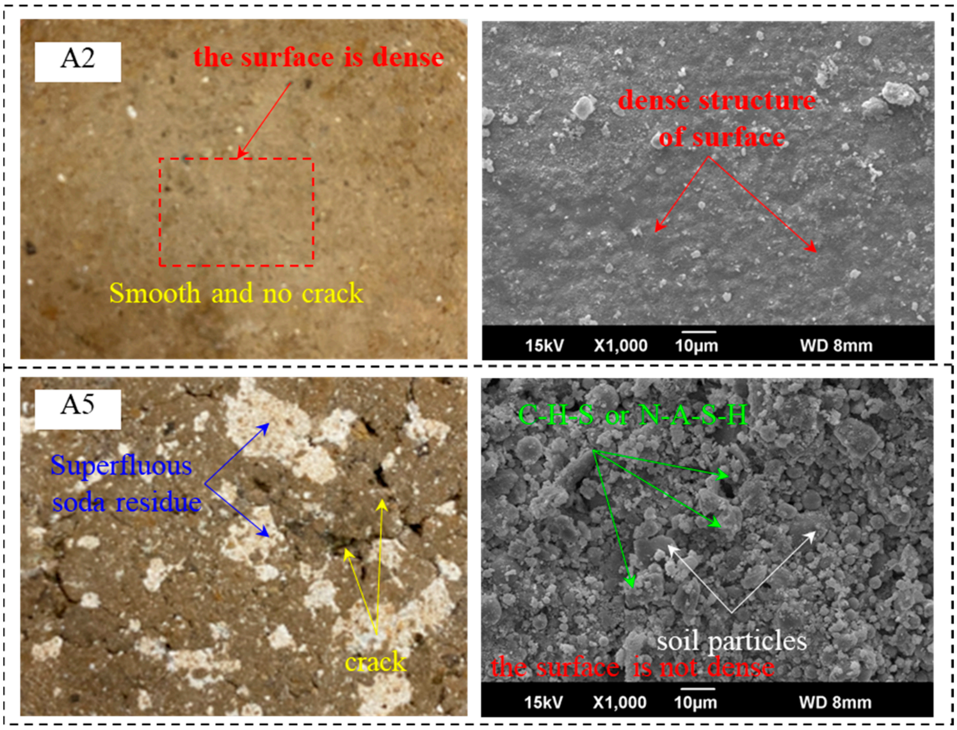


Figure 8. Partial live shot and electron microscope scanning of specimens of groups A2 and A5.

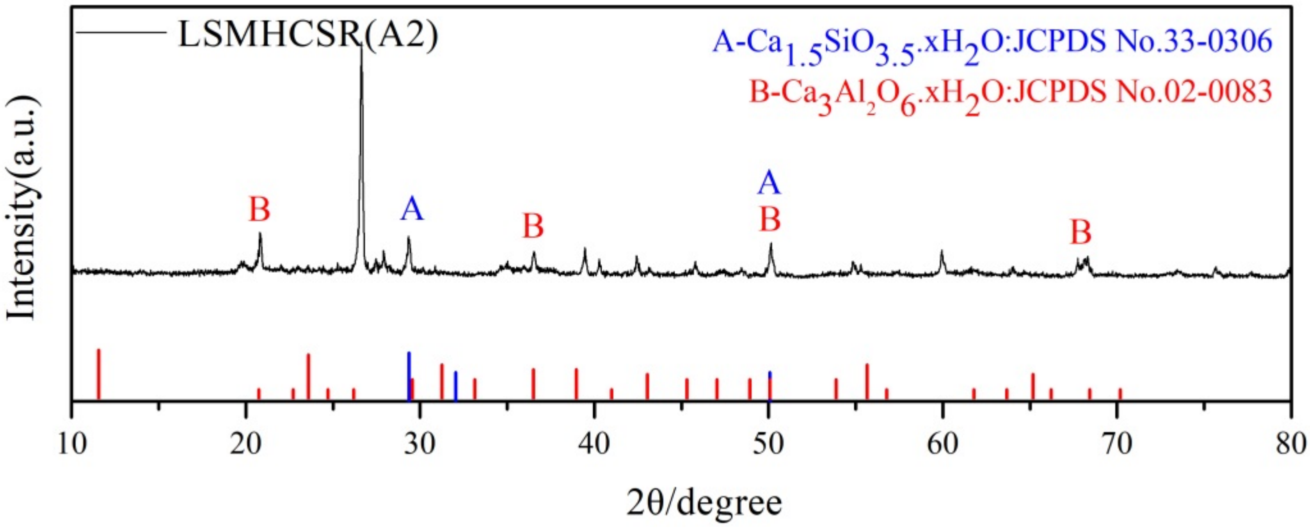


Figure 9. XRD spectra of A2.

Figures 8 and 9 show that an appropriate amount of SR can promote the formation and growth of C–H–S and N–A–S–H, as well as the mutual contact and adhesion of crystals, which strengthens the connection between stabilized soil particles and increases the solidification cohesion between soil particles. However, under excessive content of SR (specimen A5), the excess SR does not participate in the reaction. SR with large pores and low strength will reduce the material strength when it is simply used as a carrier, making the strength of soda LSHCSR decrease with the further increase in SR content.

In addition to the above reactions, the SR also contains a certain amount of calcium sulfate, which can react with the hydration product to form hydrated calcium sulfate [38]. Such material also contributes to the LSHCSR strength, but SR has low calcium sulfate content with weak effect, so the contribution to the strength is low.

5. Benefit Analysis

The test section is located at the intersection of Huaijin Line of Provincial Highway 247 in Huai'an City, Jiangsu Province, China, and the test section is a secondary road. The scheme was designed as lime soil modified by low content SR, with SR:lime:soil = 6%:6%:100%. The sub–base of the test section was laid in June 2020, and the engineering application effect was fine. In order to analyze the LSHCSR engineering benefits, simulation analysis was carried out for benefit calculation in the background of the test section, where the strength of A1–A3 group materials was greater than 0.8 MPa, and the prepared LSHCSR technically met the technical requirements of the standard [24]. The technical, economic and social benefits were analyzed for A1–A3 group materials and the control group, according to the engineering background of the experimental section, with the results shown in Table 6.

Table 6. Benefit Analysis.

Group	SR Content	Technical Benefits	Economic Benefit	Social Benefit		
		Increase Amplitude of 7 Day UCS	Cost Savings per KM	Material Shortage	Soil Erosion Caused by Borrow Soil	Ecological Pollution Caused by Discharge of SR
A0	0	–	–	Yes	Yes	Yes
A1	10	22.03%	¥7916	No	No	No
A2	15	26.99%	¥11,874	No	No	No
A3	20	16.36%	¥15,831	No	No	No

Analysis of Table 6 shows that lime soil modified by high content SR demonstrates significant technical, economic and social benefits in engineering application. The experimental groups A1, A2 and A3 all have potential application value, of which group A2 has optimal technical benefit, while group A3 has optimal economic benefit. For the test section with good engineering geology, the mix proportion scheme of group A3 is preferentially recommended, which maximizes the SR utilization under the premise of guaranteeing the strength. Compared with the A0 control group without SR, the UCS of the A3 group materials increased by 16.36%. The test section was calculated based on the hypothesis that only the roadway sub–base was paved (width 15 m, thickness 0.2 m, the average soil transportation distance 10 km). CNY 3653 worth of soil materials was saved per kilometer, and CNY 12,178 of production costs were reduced per kilometer due to SR consumption. At the same time, it can effectively alleviate the shortage of bulk road material supply, soil erosion and solid waste pollution, demonstrating significant social benefits with good promotion and application value.

6. Conclusions and Discussion

The influencing characteristics of SR content on LSMHCSR strength, mix ratio of LSMHCSR and the strengthening mechanism of LSMHCSR were studied in this research. The following conclusions are made based on the results:

(1) The SR is mainly composed of $CaCO_3$, $Ca(OH)_2$ and $CaCl_2$ and contains a small amount of $CaSO_4$ and NaCl. With high natural moisture content, low strength and slight alkalinity, it is not suitable for separately loading as an engineering material.

(2) The LSMHCSR dry density increased and then decreased with the increase in moisture content. As the SR content increased from 10% to 30%, the optimum moisture content of LSMHCSR gradually increased, and the maximum dry density first increased and then decreased. For this reason, SR has high moisture content and small density, and the excess of SR will not participate in the material reaction.

(3) As the SR content increased from 10% to 30%, both the 7 d and 28D UCS of the LSMHCSR specimen increased first and then decreased. The LSHCSR strength reached the maximum at 15% SR dosage, with the 7 d and 28 D UCS increased by 36.9% and 37.2%, respectively. The recommended optimal mix ratio of materials is to set SR:lime:soil as 15%:6%:85%.

(4) An appropriate amount of SR can effectively promote the physical filling, cementation, crystallization, carbonization and pozzolanic reaction of the material. The resulting $CaCO_3$ crystals and cementitious substances, such as C–H–S and N–A–S–H, can cement the soil particles to improve the material strength and integrity, but when excessive SR was added, the excess SR would not react, with the material strength reduced.

(5) Benefit analysis shows that the strength of the A3 group with the highest dosage has an increase up to 16.36%, and economic benefit of about CNY 15,831 is created per kilometer of road, which can alleviate the shortage of bulk road material supply, soil erosion and solid waste pollution, demonstrating significant social benefits with good market promotion and application value.

At present, LSMHCSR is in the stage of laboratory theoretical research. It has been proved that the soil composition of lime soil replaced by high–content SR can meet the requirements of material engineering performance, but the standards and specifications have not been formed yet, and it is not able to be widely applied. The research can provide theoretical reference for the design of the experimental section. If the technology can be successfully implemented, it will provide an effective technical path for the large–scale and resource utilization of SR.

Author Contributions: Conceptualization, S.Z. and W.Y.; methodology, S.Z. and W.Y.; software, K.Z.; formal analysis, H.L., K.Z. and Q.X.; investigation, Q.X.; resources, S.Z.; data curation, Z.Z., Y.T.; writing—original draft preparation, Y.T.; writing—review and editing, Y.T. and W.Y.; project administration, S.Z.; funding acquisition, W.Y. All authors have read and agreed to the published version of the manuscript.

Funding: This work is funded by National Natural Science Foundation of China (Grant No.: 51904110) and Natural Science Foundation of the Higher Education Institutions of Jiangsu Province, China (20KJB560006).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The original contributions presented in the study are included in the article; further inquiries can be directed to the corresponding author.

Conflicts of Interest: The authors declare no conflict of interests.

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