Research Article

Study on Strength Test and Application of Lime Soil in Pavement Base Modified by Soda Residue

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To solve the difficult problems of large-scale utilization of solid waste soda residue (SR) as a resource and reduce the cost of road building materials, the technical idea of using SR instead of part of lime to prepare lime soil of pavement base was put forward. Through laboratory tests, the basic characteristics of SR and the optimum moisture content and maximum dry density of soda residue lime soil (SRLS) under different proportioning conditions were tested. The test results showed that (1) with the change of SR content in the range of 0%–12%, the optimum moisture content of SRLS showed the change law of first increasing and then decreasing, but the change range was small; (2) the UCS of SRLS gradually increased with the extension of curing age, with the strength increasing faster in the early stage and slower in the later stage. The UCS of SRLS with SR content in the range of 0%–12% shows the law of first increasing and then decreasing, and the UCS value was the highest when the content of SR is 3%. Compared to the control group, the increase in the amplitude of UCS is as high as 34.6%; (3) appropriate content of SR will increase the gelation of C-S-H and N-A-S-H, and at the same time generated hydrated calcium sulfate and other cementitious materials, enhancing the cementation and strength of SRLS. However, when the content of SR is too much, the excess SR will not participate in hydration reaction even reduce the strength of lime soil. The cost of road materials per kilometer in the test section of SRLS base can be saved by 164,000 yuan, and the treatment cost per ton of SR in alkali factory can be reduced by about 80 yuan. The research results have remarkable economic, technical, and social benefits, which can provide technical reference for large-scale recycling of solid waste SR.

1. Introduction

Sodium carbonate, known as the “mother of chemical industry,” is widely used as a raw material in construction, chemical industry, textile and other industries [1]. China’s sodium carbonate production ranks first in the world. According to statistics, about 0.3–0.6 ton of solid waste soda residue (SR) is discharged per ton of sodium carbonate produced by ammonia-alkali process [2]. Because of SR’s high alkalinity and high chloride ion content [3], the traditional direct ground drainage treatment method not only occupies a large amount of land resources but also causes harmful components penetrating underground with rainwater, polluting soil and groundwater [4, 5] and ecological environment [6]. Therefore, from the perspective of environmental protection and land resource utilization, scientific treatment of solid waste SR has become a challenge faced by salt chemical enterprises.

In recent years, scholars at home and abroad have been devoted to the research on the resource utilization of solid waste SR [7, 8]. SR and fly ash can be mixed into engineering soil for reclamation and road construction [9]. The strength properties of solidified sludge were investigated under dry-wet cycle with SR as a curing agent [10]. SR and calcium-enriched ash were mixed in a certain proportion to form SR for backfilling [12]. SR and fly ash were mixed to produce embankment materials [13]. Fly ash
can significantly improve the mechanical properties of SR [14]. SR has a significant effect on the expansion of expansive soil [15]. SR can be used as a modifier to stimulate the properties of gangue-cemented filling materials [16]. SR was used as an admixture to partially replace fly ash to prepare building mortar materials [2]. The abovementioned SR utilization methods consume SR to a certain extent. However, due to the low strength of the alkali slag itself and the rich Cl−, the phenomenon of overspreading alkali and corrosion of reinforcement appears in the project, which makes it difficult for the conventional SR treatment methods to meet the requirements of the projects on bearing capacity, environmental protection, and other aspects at the same time. Therefore, how to solve the difficult problem of large-scale utilization of solid waste SR is imminent.

By 2020, the total mileage of roads in China reached 5 million KM, with the mileage of annual newly added roads exceeding 150,000 KM, which indicates huge demand for road construction materials [17]. At present, inorganic binders such as lime and cement are often used to treat engineering soil to improve the integrity and bearing capacity of soil materials [12, 18]. Inorganic binder base stabilizing materials such as lime and cement have been widely used because of high strength, good stability, and strong frost resistance, but this kind of base consumes a lot of industrial materials such as lime and cement. According to statistics, one ton of quicklime production consumes 1786 kg of limestone and 408 kg of raw coal [19–22]. The exploitation of raw materials such as limestone and coal consume a lot of energy and emits a lot of greenhouse gases such as CO2 [23] causing great burden to the environment [24]. It is found that the pH of SR is alkaline. SR contains a large amount of mineral components such as CaCO3 and Ca(OH)2, which can produce cementation between soil particles [25]. Considering its gelling property, it can effectively improve the strength of soil when used together with lime and other materials. Considering that there is no reinforcement and chloride ion corrosion in the pavement base [26, 27], the technical idea of preparing lime soil with SR in pavement base is put forward. Through laboratory tests, the basic characteristics and microstructure of SR were analyzed. The optimum moisture content of soda residue lime soil (SRLS) with different SR contents was analyzed. The law of influence of SR content and curing age on the strength of SRLS and the strength formation mechanism were explored. Moreover, industrial tests were carried out, which provided technical reference for large-scale recycling of solid waste SR.

2. Basic Characteristics of SR

The test SR is a gray sticky paste with pungent smell when it is in fresh state. After air-drying the SR naturally, the moisture content is measured by drying method; the liquid-plastic limit of SR was tested by photoelectric liquid limit tester, and the composition of SR was analyzed by XRF test. The test results of basic physical parameters and chemical composition of SR are shown in Table 1.

The analysis showed that the SR in fresh state had high moisture content with pH value of 9.2 and plasticity index of 29.53. After natural air-drying, the strength and bearing capacity were decreased, with unconfined compressive strength (UCS) of only 0.2 MPa; therefore, the SR is not suitable for direct use as an engineering material alone.

The internal structure of air-dried SR was scanned by SEM. The internal structure of SR at different magnifications is shown in Figure 1.

According to the analysis, the SR has a porous aggregate structure. Combining with chemical composition, it can be concluded that the material skeleton of SR is mainly composed of CaCO3 [28]. The single particle has a size of about 2 μm to 5 μm. The particles agglomerate with each other in point contact, with weak cementation. The surface of aggregate structure is rough, and there are many pores of different sizes on the surface and inside of the particles. The pores are connected with each other, resulting in high moisture content and large bearing deformation of the SR in its natural state.

3. Test Scheme and Method

3.1. Test Scheme. This study discussed the improvement effect of solid waste SR on the strength of lime soil of pavement base, studied the law of influence of different SR contents and curing age on the strength of SRLS, and optimized the mix ratio of SRLS materials. The specific technical idea is to use SR as a substitute for some lime components in lime soil materials of pavement base with SR, so as to achieve the goal of disposing SR and reducing lime consumption. In addition to the strength parameters, it is necessary to consider the cost factors in the mix ratio design of SRLS materials, increase the content of SR on the premise of meeting the material strength requirements, and give consideration to the technical and economic benefits. The mix ratio design process of SRLS materials in road base is shown in Figure 2.

The original design scheme of pavement base in Jinhu No.247 reconstruction and expansion section was taken as the control group, and the control group was 12% lime soil (lime: soil = 12%;100%). A–E 5 group experiments were designed, in which group A was the field control group. The specific test proportioning scheme is shown in Table 2.

3.2. Specimen Preparation. As described in “Technical Guidelines for Construction of Highway Road bases” (JTG/T F20-2015), UCS specimens are required to be made by each group of proportioning materials in the optimum moisture content, so it is necessary to first test the optimum moisture content and the maximum dry density of SRLS in groups A–E through compaction test. The soil used in the test is a fine-grained soil. After the SR is crushed, it passes through a 2.36 mm standard sieve. With reference to the Test Method for Compaction of Inorganic Binder Stabilized Road Base Materials (JTG/T F20-2015), the laboratory test was carried out, and the specimens were prepared following the method in Table 2.
Materials, a light compaction test is adopted. The site reference optimum moisture content of the control group is 18.8%, and five target moisture contents are designed for Groups A–E, respectively. The specific compaction test scheme and mass ratio are shown in Table 3. According to formula (1), the content of water to be added for each group of specimens to reach the target moisture content is calculated, where the test water is deionized water.

\[
m_{w} = \left( \frac{m_{n}}{1 + 0.01w_{n}} + \frac{m_{c}}{1 + 0.01w_{c}} + \frac{m_{k}}{1 + 0.01w_{k}} \right) \times 0.01w - \left( \frac{m_{n}}{1 + 0.01w_{n}} \times 0.01w_{n} \right) - \left( \frac{m_{c}}{1 + 0.01w_{c}} \times 0.01w_{c} \right) - \left( \frac{m_{k}}{1 + 0.01w_{k}} \times 0.01w_{k} \right),
\]

where \( m_{w} \) is the amount of water to be added in SRLS, \( w \) is target moisture content of SRLS, \( m_{n} \) is mass of soil, \( w_{n} \) is natural moisture content of soil, \( m_{c} \) is mass of lime, \( w_{c} \) is natural moisture content of lime, \( m_{k} \) is mass of SR, and \( w_{k} \) is natural moisture content of SR.

The test lime was an anhydrous lime powder of Huihui Industry, with a content of calcium and magnesium over 95%. The test soil was collected from the test section of Huai’an Jinhu No.247 provincial highway reconstruction and extension project. The soil is low liquid limit clay, with a liquid limit of 9.1%, a plastic limit of 19.0%, and a plastic index of 20.1. To study the influence of SR content and curing age on UCS of SRLS, UCS of groups A – E at curing age of 7 d, 14 d, and 28 d were selected as indicators. The standard specimen was a cylinder with a diameter of 50 mm and a height of 50 mm; the standard curing of specimen was carried out under curing temperature of 20 ± 1°C and humidity of 95%. On the last day of the curing, the specimen was soaked in water of which the depth exceeded the top surface of the specimen by about 2.5 cm. SANS-300 hydraulic press was selected as the loading system. Displacement control was adopted as the loading method, with the loading rate of 1 mm/min. The raw materials and actual test process are shown in Figure 3.

### 4. Test Results and Analysis

#### 4.1. Optimum Moisture Content and Maximum Dry Density

The dry density values of each group of specimens under different target moisture contents were obtained by light compaction test. The data of moisture content-dry density in each group of tests were fitted by Origin software, and the best moisture content-dry density curves of A–E groups of specimens are shown in Figure 4.

The fitting equation of moisture content-dry density fitting curve of SRLS for groups A–E is shown in Table 4. Let \((y)' = 0\), solve optimum moisture contents of groups A–E, respectively, and draw the optimum moisture content curves of SRLS under different SR contents, as shown in Figure 5.

From the analysis of Figure 5, we can see the following:

1. When the content of SR is 0, 3, 6, 9, and 12%, the optimum moisture content of SRLS is 18.23, 19.59, 20.47, 19.34, and 18.03%, respectively. The optimum moisture content of SRLS changes slightly with the content of SR.

2. The optimum moisture content of SRLS increases gradually when the content of SR is in the range of 0–6% and decreases gradually in the range of 6–12%, showing the change law of first increasing and then decreasing.

#### 4.2. Bearing Deformation Characteristics

In the test, it was observed that the specimens of Group E at 7 d and 14 d collapsed when immersed in water. This was due to fact that the specimens did not contain lime, the cementing...
performance of pure SR was not as good as lime, and its water stability was poor. Therefore, specimens in group E were not considered in the test of load-bearing deformation characteristics. SRLS specimens of groups A–D at 7 d were selected, and the loading stress and strain characteristic curves were drawn, as shown in Figure 6.

From the analysis of Figure 6, we can see the following:

1. The strength curves of SRLS specimens with different contents of SR under uniaxial compression show obvious three-stage characteristics, namely, prepeak bearing area (area I), postpeak attenuation area (area II), and residue bearing area (area II).

2. The strength of the specimen in area I increases linearly, which belongs to the strain hardening stage; in area II, with the continuous loading of the specimen, the strength of the specimen decays rapidly; the cracks of the specimens in area II continue to develop and penetrate, and the bearing capacity gradually decreases. But the specimens do not completely lose the bearing capacity, which indicates that the specimens still have a certain bearing capacity after failure. Areas II and III belong to the strain softening stage.

3. The peak strain of specimens in groups A–D are 0.012, 0.022, 0.016, and 0.014, respectively. The peak strain of specimens gradually increases in the range of 0–3% and decreases in the range of 3–12%. The
peak strain in group B is the largest, and the peak load-bearing deformation ability is the strongest.

4.3. Unconfined Compressive Strength. To analyze the strength of specimens of groups A–E, the average UCS value \( R \) of three specimens in each group is taken as the indicators. The UCS test results of SRLS under different curing ages and SR contents are shown in Table 5.

According to the requirements of formula (2), the \( R \) value of indoor average compressive strength is checked, and the results show that it meets the specified requirements: \( R \geq R_d \left/ \left( 1 - Z_a C_v \right) \right. \) (2)

where \( R_d \) is design strength, which is 0.8 MPa; \( C_v \) is deviation coefficient of test results; and \( Z_a \) is a confidence-dependent coefficient in a standard normal distribution table, nonheavy traffic road, \( Z_a = 1.282 \).

4.3.1. Curing Age. Specimen in Group E disintegrated after soaking in water on the 7th day of curing, so they were excluded from the analysis. The UCS curves of groups A–D at 7 d, 14 d, and 28 d were drawn as shown in Figure 7.

From the analysis of Figure 7, we can see the following:

(1) With the extension of curing age, the strength of SRLS specimens in groups A–D all showed a gradual increasing trend, and the UCS values of the specimens in groups A–D at 28 d were 1.30, 1.39, 1.42, and 1.28 time of that at 7 d, respectively. Under different SR content conditions, the later strength of the specimens increased by 1.3–1.4 times, with a small change range, indicating that the content of SR had a small influence on different specimens.

(2) With the prolongation of curing age, the strength growth rate of each group of specimens increased rapidly at first and then slowed down. Taking the specimen in Group B with the highest strength as an example, the UCS values of specimens at 7 d, 14 d, and 28 d increased by 2.76, 3.61, and 3.86 MPa, respectively. The UCS values of specimens at 14 d increased by 30.7% compared with those at 7 d, and the UCS values of specimens at 28 increased by 7% compared with those at 14 d. The strength growth rate of specimens gradually slowed down, and the strength tended to be stable.

4.3.2. The Content of SR. The UCS curves of SRLS of A–D groups under different contents of SR were drawn, as shown in Figure 8.

From the analysis of Figure 8, we can see the following:

(1) The UCS values of lime soil with SR at different curing ages showed the law of first increasing and then decreasing when the content of the SR was in the range of 0–12%. The UCS value of SRLS gradually increased in the range of 0–3% content, and decreased in the range of 3–12%.
Taking the specimen at the curing age of 7 d as an example, the UCS value of 3% SR content (Group B) was 2.76 MPa, which was 34.6% higher than that of the control group in Group A. But, the UCS value of 9% SR content (Group D) was only 1.1 MPa, which was 46.3% lower than that of the control group, indicating that the appropriate content of SR could improve the strength of lime soil, but too much content of SR content could not.

5. Strength Formation Mechanism

5.1. Microstructure. The experiment showed that adding appropriate content of SR could improve the strength of lime soil. To explain the reason why SR can improve UCS of lime soil, the cured specimen was broken, and a small cuboid specimen with a bottom area of 10 × 10 mm and a height of 2–10 mm was cut from the inside of the specimen. After that, it was glued to the base with conductive glue and sprayed with gold to improve the conductivity. Finally, the specimen was observed under an electron microscope. The fabrication process of the specimen and the actual image in the experiment are shown in Figure 9. The internal structure of the SRLS specimen with different SR contents and the magnification of 3000x was scanned, as shown in Figure 10.

5.2. Mechanism of Strength Enhancement

(1) The internal structures of lime soil specimens with different SR contents are quite different. As shown in Figure 10(a), the interior of group A of calcareous soil specimens without SR is relatively dense. Referring to formulas (3)–(5), lime reacts with water to produce a series of gelled substances, such as hydrated lime crystal grid [29], hydrated calcium silicate (C–H–S), and hydrated calcium aluminate (N–A–S–H) [30,31]. The above gelled soil particles are cemented together to form larger soil particle clusters. A stable protective film is formed around the soil particle clusters, which fills the particle gaps and improves the compactness of the soil.
(1) The reaction can be expressed as:

$$\text{Ca(OH)}_2 + n\text{H}_2\text{O} \rightarrow \text{mCa(OH)}_2 \cdot n\text{H}_2\text{O}, \quad (3)$$

$$\text{mCa(OH)}_2 + \text{SiO}_2 + (n-1)\text{H}_2\text{O} \rightarrow \text{mCaO} \cdot \text{SiO}_2 \cdot n\text{H}_2\text{O}, \quad (4)$$

$$\text{mCa(OH)}_2 + \text{Al}_2\text{O}_3 + (n-1)\text{H}_2\text{O} \rightarrow \text{mCaO} \cdot \text{Al}_2\text{O}_3 \cdot n\text{H}_2\text{O}. \quad (5)$$

(2) UCS test data show that the increase in the rate of UCS of B group of SRLS specimens at 7 d is as high as 34.6%. Combined with the analysis of internal structure scanning image of specimens in Figure 10(b), it can be seen that the structure of SRLS is denser, indicating that pores and holes are reduced [32]. The reason is that SR changes the pH value of the mixture system, and alkaline environment is conducive to the pozzolanic reaction between lime and silicates.
and soil. The amount of C-S-H gelation and N-A-S-H gelation in the SRLS system increases [33, 34], and the SR is rich in CaO and Ca(OH)$_2$, which greatly increases the contents of hydrated lime crystal grid [35] and later calcium carbonate (see formula (6) for reaction) in the mixture system. Moreover, the SR contains a certain amount of calcium sulfate, which can be mixed with hydration products [36, 37] (see formula (7) for reaction). All the abovementioned cementing substances can enhance the cementation strain (ε).

<table>
<thead>
<tr>
<th>Group number</th>
<th>UCS(MPa)</th>
<th>7 d</th>
<th>14 d</th>
<th>28 d</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>2.05</td>
<td>2.46</td>
<td>2.67</td>
<td></td>
</tr>
<tr>
<td>B</td>
<td>2.76</td>
<td>3.61</td>
<td>3.86</td>
<td></td>
</tr>
<tr>
<td>C</td>
<td>2.16</td>
<td>2.87</td>
<td>3.07</td>
<td></td>
</tr>
<tr>
<td>D</td>
<td>1.1</td>
<td>1.21</td>
<td>1.41</td>
<td></td>
</tr>
<tr>
<td>E</td>
<td>—</td>
<td>—</td>
<td>1.13</td>
<td></td>
</tr>
</tbody>
</table>

Table 5: UCS of SRLS.

![Figure 6: Stress-strain curve of SRLS. (a) A-1 group (0% content of SR). (b) B-1 group (3% content of SR). (c) C-1 group (6% content of SR). (d) D-1 group (9% content of SR).](image)

![Figure 7: Curing age-UCS curve.](image)
of SRLS, reduce the connectivity of pores, and greatly improve the strength of materials [38, 39]. As shown in Figure 11, (a), (b), (c), the SRLS has good surface density.

\[
\text{Ca(OH)}_2 + \text{CO}_2 + \text{CaCO}_3 + \text{H}_2\text{O}, \quad (6)
\]

\[
m\text{CaO} \cdot \text{Al}_2\text{O}_3 \cdot n\text{H}_2\text{O} + \text{CaSO}_4 \cdot 2\text{H}_2\text{O} \cdot m\text{CaO} \cdot \text{Al}_2\text{O}_3
\]

\[
\bullet \text{CaSO}_4 \cdot (n + 2)\text{H}_2\text{O}. \quad (7)
\]

(3) The test results show that the UCS of 12% SR content (Group D) 28 d is only 1.13 MPa, which is 57.6% lower than that of the control group. Seen from Figure 10(c), as the internal pores and holes of SRLS are large, the cementation of the material becomes worse, and the scale of soil particles becomes smaller. Combined with Figure 11(d), the reason for the strength reduction is that the material does not contain lime soil, and the cementation performance of SR is not as good as that of lime. Moreover, when

Figure 8: SR content-UCS curve.

Figure 9: Fabrication of a specimen for electron microscope scanning and actual image in the experiment.

Figure 10: Scanning of internal structure of SRLS.
the content of SR used is too much, the excess SR does not take part in the reaction. The SR itself has large pores and low strength, so it as a carrier will reduce the strength of SRLS. The strength of SRLS decreases with the increase of SR content.

6. Engineering Application

6.1. Project Overview. The test section of SRLS pavement base is located at the intersection of Jinma Expressway in Huai’an City, Jiangsu Province and Huaijin Line of No.247 Provincial Highway, and the test section is a secondary highway pavement. The total pavement thickness is 62 cm. The upper layer is 4 cm thick fine-grained SBS modified asphalt concrete (SMA-13), and the lower layer is 6 cm thick medium-grained asphalt concrete (SUP-20). The upper base course is 32 cm thick cement stabilized macadam pavement, and the original design scheme of the subbase course is 20 cm thick 12% lime soil. In this test section, SR was used as a substitute for a part of lime in the lime soil of the pavement base. To give consideration to the technical and economic benefits, the utilization rate of SR in group C was high and the strength of SR met the standard specification. Therefore, the material mix proportion of Group C was selected as the material mix proportion of the test section, that is, SR: lime: soil = 6%: 6%: 100%. Considering that the laying temperature on-site was slightly higher than the laboratory environment, the actual moisture content on-site was 20.5%. The geographical location of the test section and the live shot of site construction are shown in Figure 12.

6.2. Economic and Benefit Analysis. The pavement base of the test section was laid in June 2020, and the cutting-ring method was used for field sampling. The test showed that the pavement base had good integrity and flatness, solid road surface, and its compaction degree was up to 95.5%. The whole road was completed and accepted in March 2021. To comprehensively compare the economic, technical, and social benefits of the SRLS base in the test section, the benefit analysis of the test section and the control group was conducted, as shown in Figure 13. Compared with the control group, the increase of UCS values of the SRLS base material in the test section at 7 d, 14
d, and 28 d was up to 5.4, 14.7, and 15.0%, respectively, indicating remarkable technical benefit. According to the market price, the lime is about 350 yuan/ton, and the cost of transporting SR to the test section is about 16 yuan/ton. For each ton of SR used in the test section, the road material cost can be reduced by 334 yuan, that is, the material cost can be saved by about 164,000 yuan per kilometer. In addition, the original cost of treatment of per ton solid waste SR by the alkali factory is about 80.74 yuan. If it can be planned and popularized, the annual cost of SR treatment can be saved as much as 10 million yuan. The preparation of road base material with SR causes no pollution to the environment. The research results have remarkable economic, technical, and social benefits, and can provide technical reference for large-scale recycling of solid waste SR.
7. Conclusion

(1) Fresh SR has high moisture content and high pH value. SR is a porous loose structure composed of aggregate particles, and the cementation between particles is weak. SR itself has low strength and poor bearing capacity, so it is not suitable to be used as engineering packing material alone.

(2) The optimum moisture content and maximum dry density of SRLS were obtained by light compaction test. Within 0–12% SR content, the optimum moisture content of SRLS first increased and then decreased.

(3) From the load-bearing deformation characteristics analysis, the SRLS has obvious three-stage bearing deformation characteristics: prepeak bearing area, postpeak attenuation area, and residue bearing area. The damaged SRLS does not completely lose its bearing strength, but its bearing capacity is weak.

(4) UCS of SRLS gradually increases with the increase of curing age, with the growth rate being faster in the early stage and slower in the later stage. When the content of SR is in the range of 0–12%, the UCS of SRLS shows a trend of first increasing and then decreasing. The optimum content of SR is 3%, which is 34.6% higher than that of the control group.

(5) Appropriate content of SR is conducive to the pozzolanic reaction between lime and soil. The increase of the cementitious amount of C-S-H and N-A-S-H can promote the generation of cementitious materials such as hydrated calcium sulfate and enhance the cementation and strength of SRLS. However, when the content of SR is too much, the excess SR will not participate in the reaction, resulting in decreased amounts of the C-S-H and N-A-S-H cementitious materials in the mixture. In contrast, SR itself has large pores and low strength, which leads to the decrease of UCS of the SRLS.

Data Availability

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 that there are no conflicts of interest.

Authors’ Contributions

All authors contributed equally to this work.

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