Research Article

Strength and Road Performance of Superabsorbent Polymer Combined with Cement for Reinforcement of Excavated Soil

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The process of road construction is often accompanied by a large number of excavation work, and most of the excavated soil has poor engineering performance and needs to be transported away. It has the significance of environmental protection and cost saving to treat the excavated soil as pavement materials. The aim of this study is to present laboratory experiments into the mechanical properties, engineering properties, and microstructure of excavated soil stabilized by ordinary Portland cement (OPC) and superabsorbent polymer (SAP). Laboratory experiments were performed to determine unconfined compressive strength (UCS), compactness, durability after wetting and drying cycles, drying shrinkage, and California bearing ratio (CBR). Apart from these, X-ray diffraction (XRD) and scanning electron microscopy (SEM) were used for the microstructure analysis to understand the impact of SAP on cemented excavated soil. It shows that SAP can effectively improve the strength and the compaction of cemented excavated soil with good durability. Although SAP will reduce the CBR value of cemented excavated soil, it still meets the requirements of engineering acceptance. Microscopic analysis shows that SAP absorbs water in the cemented excavated soil and plays a filling role.

1. Introduction

Excavation works are often encountered in road construction, such as tunnels and pipe gallery excavation. A considerable part of the excavated soil is soft soil such as silt and silty clay. These types of soils often have the characteristics of the high water content and compressibility, low strength and permeability, and poor engineering properties, making it difficult to reuse directly. The common treatment method is to replace it after being discarded, but it is a problem that the discarded earthwork will take up land resources. In recent years, in the context of sustainable development and ecological environmental protection in China, harmless use of excavated soil has become an engineering problem that needs to be solved urgently.

Due to this background, the reuse of the excavated soil as pavement materials, such as subgrade and roadbed, is considered and encouraged. However, most of the excavated soils are soft soils and classified as finely divided materials. The characteristics of these materials often take the form of high void ratio and compressibility, weak strength, and bearing capacity. Hence, untreated excavated soft soil cannot be directly reused as pavement materials. In order to solve this problem, the commonly used reinforcement methods include dewatering, sintering, geotextile tube, and stabilization treatment. Dewatering and geotextile tube are mainly applied to the ultrahigh water content (generally greater than 100%) of the initial process dredged silt, so it is not suitable for treating excavated soft soils [1]. The method of sintering is used by melting and sintering the soft soil into ceramicsite or fired bricks and tiles, but this method is often with high energy consumption and limited processing capacity. The stabilization treatment is adding a hardener to the soil. The hardener generates a gelling substance and then cements the soil particles and fills the pores of the soil, thereby improving and enhancing the engineering
characteristics of the soil [2, 3]. One of the traditional technologies is the use of ordinary Portland cement for stabilization, which can effectively improve the unconfined compressive strength of soft soil and reduce its compressibility [4–8].

The addition of traditional hardeners, such as cement, will cause hydration reaction in the soil. The degree of hydration reaction determines the strength of cemented soil. Some researchers through experimental studies believe that, with the increase of water content in soil or the decrease of cement content, the porosity of soil will increase, and it will make the soil particles and the cemented structure in the soil relatively loose, leading to the decrease in strength. So, it is generally believed that the degree of hydration reaction is closely related to the content of cement and water content of soil [4, 9, 10]. Consequently, in order to meet the construction requirements, the excavated soil with high water content needs to consume a large amount of cement materials or other traditional cemented materials to improve its mechanical properties. In addition, some researchers find that the durability of cemented soil, especially under the condition of the dry-wet cycle, is not very ideal [8, 11]. For the otherwise, cement material has drying shrinkage, which can have a negative impact on durability. In order to optimize the durability of cemented soil, other materials need to be added into the cemented soils.

The additional material needs to be water-absorbing. Studies have shown that organic polymers have good water absorption properties and are used as water-retaining agents in agriculture. So the researchers focused on organic polymer materials. Specifically, the main role of organic polymers as soil stabilizers is to improve the loose structure of raw materials through filling or cementation, so as to improve the strength characteristics of raw materials [12]. It was found that polyacrylamide (PAM) can significantly increase the strength and stability of the soil at low usage situation, and anionic polyacrylamide (APAM) can not only improve the strength and stability of the soil but also improve the permeability of the soil [13]; Polyacrylic acid copolymer (PAA) can generate electrostatic attraction between the amide and carboxylic acid groups in the polymer chain and the soil particles after ionization, thereby improving the strength and stability of the soil [14, 15]. Polyvinyl alcohol (PVA) can improve the corrosion resistance and water stability of soils and is more prominent in soils with higher clay content [16–18]. Above several polymer materials, they have good performance in improving the soil strength and stability, but did not achieve the expected amount of water absorption. As a result, the superabsorbent polymer (SAP), which is often used as a water-saving agent in agriculture, has received widespread attention [19]. SAP is a kind of polyacrylate polymer material, which is a kind of material with good water absorption. SAP can absorb dozens of times or even nearly a thousand times of water, compared to its own size. In terms of engineering, it has been used as a water storage agent to improve the self-drying of concrete [20–23]. To reduce the cost of using cement to improve the strength of dredged silt soil, the researchers introduced SAP as a water-reducing agent. The experimental studies have shown that SAP has a positive impact on the improvement of the strength performance of dredged silt soils with significantly higher water content. The UCS of cemented soils increases with the increase of SAP content, and the compressibility of cemented soils decreases with the increase of SAP content [9, 10, 24, 25].

It can be known from the existing research results that SAP can absorb a large amount of water in the soil and improve the strength of the soil, but the road performance has not been systematically studied, especially about the durability. This article aims to use SAP and cement to quickly treat the excavated soil with high water content, so that the excavated soil after the treatment can not only meet the requirements in strength and terms of compaction but also has good durability, so as to achieve the purpose of resource utilization.

2. Materials and Methods

2.1. Sample Preparation. Samples of excavate soil was collected from the experimental section of the road construction along the lower reaches of the Yangtze River in Jiangsu Province, China. The basic physical properties of the excavated soil are provided in Table 1. According to the Unified Soil Classification System, the excavated soil is classified as organic silt (OL) [26].

In this study, two different inorganic additives were used as stabilizing binders: quick lime and ordinary Portland cement. The chemical compositions of ordinary Portland cement and quick lime are given in Table 2. The SAP used in this study belongs to water-absorbing resin of polyacrylates. In the dry state, the diameter of the SAP particles is about 100–150 μm. According to the tea bag method [27], the water absorption per gram of SAP is about 60 g.

This study uses the remodeling method to prepare samples. Firstly, the air-dried excavated soil is broken up, and then a predetermined amount of water and the excavated soil are mixed to obtain an excavated soil with a water content of 38.53% (the original water content). Then SAP particles are added to the excavated soil to absorb water. Subsequently cement and lime are added to the soil in the form of powder and mixed for 5–10 min to meet the requirements of uniformity. The test scheme and corresponding additive content are shown in Table 3. The whole mixing process should be controlled within 10 min to avoid hardening of the soil due to hydration reaction of the cement. The soil samples are prepared for use in various test methods.

2.2. Unconfined Compression Strength (UCS) Test. The UCS tests were performed according to the guidelines provided in ASTM D2166. The samples were prepared with the mixed soil which was mentioned before. The sample is a 5 cm × 5 cm cylindrical sample, which is formed by static pressure using a reaction force frame and a hydraulic Jack. After the sample is made, put it into a standard curing box at 20°C ± 2°C and 95% humidity for curing and measure its
unconfined compressive strength at 3d, 7d, 14d, and 28d. The unconfined compressive strength of the test scheme is obtained by averaging the test results of the two samples, denoted as $q_{uc}$. Unconfined compression testing machine with maximum stress of 50 kN was used in the test. The load was carried out at a rate of 1 mm/min until the stress reached the maximum. The $q_{uc}$ was taken to be the maximum load attained per unit area.

2.3. Compaction Test. Compaction degree refers to the ratio of the actual dry density of construction site to the maximum dry density obtained in the standard indoor compaction test, which is one of the most important internal indexes for the quality management of road engineering construction. According to ASTM D698, the compaction test was carried out by using the compaction instrument. The soil samples were put into the compaction cylinder in three layers, and each layer was dropped from the height of 305 mm with a 2.5 kg heavy hammer for 56 times. By changing the water content of soil samples through the plastic limit of different schemes, the maximum dry density of different schemes is finally obtained. Through the same compaction test on the soil sample of different schemes, the actual dry density is obtained, and the final compaction degree is determined by the ratio of the actual dry density and the maximum dry density.

2.4. Durability Test. In order to test the impact of SAP material loss and repeated water absorption on the durability of cemented soil, simulate the water-loss process of the roadbed of construction site and refer to the method of ASTM D559 for the drying and wetting cycle test and drying shrinkage test.

For the drying and wetting cycle test, the unconfined compressive samples with different proportions were cured in a curing box with a standard curing condition for 28 days. The sample is immersed in water at room temperature ($20 \pm 2^\circ$C) for 5 h, then dried in drying oven at 45$^\circ$C for 24 h,

### Table 1: Basic physical properties of excavated soil.

| Natural water content (%) | Void ratio | Optimum water content (%) | Liquid limit (%) | Plastic limit (%) | Plastic index (%) | Organic matter content (%) |
|--------------------------|------------|----------------------------|------------------|-------------------|-------------------|---------------------------|
| 38.53                    | 1.31       | 16.58                      | 18.73            | 38.60             | 19.87             | 1.35                      |

### Table 2: Composition of Portland cement and lime used in this study (%).

| Binders  | CaO   | SiO$_2$ | Al$_2$O$_3$ | Fe$_2$O$_3$ | MgO  | SO$_3$  | Others |
|----------|-------|---------|-------------|-------------|------|---------|--------|
| Cement   | 58.95 | 23.4    | 6.3         | 3.98        | 4.85 | 1.5     | 1.02   |
| Lime     | 94.7  | —       | —           | —           | 3.42 | —       | 1.88   |

### Table 3: Test program.

| Symbol | Lime (%) | Cement (%) | SAP (%) | UCT      | XRD    | SEM |
|--------|----------|------------|---------|----------|--------|-----|
| C2     | —        | 2          | —       | 3d, 7d, 14d, 28d |        |     |
| C4     | —        | 4          | —       | 3d, 7d, 14d, 28d | 7d, 28d| 7d, 28d|
| C6     | —        | 6          | —       | 3d, 7d, 14d, 28d |        |     |
| L2C2   | 2        | 2          | —       | 3d, 7d, 14d, 28d |        |     |
| L2C4   | 2        | 4          | —       | 3d, 7d, 14d, 28d |        |     |
| L2C6   | 2        | 6          | —       | 3d, 7d, 14d, 28d |        |     |
| C2S15  | —        | 2          | 0.15    | 3d, 7d, 14d, 28d |        |     |
| C2S30  | —        | 2          | 0.3     | 3d, 7d, 14d, 28d |        |     |
| C2S45  | —        | 2          | 0.45    | 3d, 7d, 14d, 28d |        |     |
| C4S15  | —        | 4          | 0.15    | 3d, 7d, 14d, 28d |        |     |
| C4S30  | —        | 4          | 0.3     | 3d, 7d, 14d, 28d |        |     |
| C4S45  | —        | 4          | 0.45    | 3d, 7d, 14d, 28d |        |     |
| G6S15  | —        | 6          | 0.15    | 3d, 7d, 14d, 28d |        |     |
| G6S30  | —        | 6          | 0.3     | 3d, 7d, 14d, 28d |        |     |
| G6S45  | —        | 6          | 0.45    | 3d, 7d, 14d, 28d |        |     |
| L2C2S15| 2        | 2          | 0.15    | 3d, 7d, 14d, 28d |        |     |
| L2C2S30| 2        | 2          | 0.3     | 3d, 7d, 14d, 28d |        |     |
| L2C2S45| 2        | 2          | 0.45    | 3d, 7d, 14d, 28d |        |     |
| L2C4S15| 2        | 4          | 0.15    | 3d, 7d, 14d, 28d |        |     |
| L2C4S30| 2        | 4          | 0.3     | 3d, 7d, 14d, 28d |        |     |
| L2C4S45| 2        | 4          | 0.45    | 3d, 7d, 14d, 28d |        |     |
| L2C6S15| 2        | 6          | 0.15    | 3d, 7d, 14d, 28d |        |     |
| L2C6S30| 2        | 6          | 0.3     | 3d, 7d, 14d, 28d |        |     |
| L2C6S45| 2        | 6          | 0.45    | 3d, 7d, 14d, 28d |        |     |

The percentage of admixtures in the table is based on the quality of undisturbed soil.
and cooled at room temperature for at least two hours. This is a dry-wet cycle. After reaching the target number of dry-wet cycles, soak the sample in deionized water at 25 ± 2°C for 1 h. Subsequently, unconfined compressive strength tests were performed on samples that had undergone 3, 5, and 10 dry-wet cycles.

The sample size of the dry shrinkage test is 50 × 50 × 200 mm. After curing under standard curing conditions for 7 d, the sample is saturated with water, and the initial length of the sample is measured before moving to the dry shrinkage box (temperature is 20 ± 1°C, relative humidity is 60 ± 5%), and then, the dial meter reading is recorded as required.

2.5. California Bearing Ratio (CBR) Test. The CBR value is an important index of road performance. In addition, the underground water level in Nanjing is high and the rainfall period is concentrated. The CBR test can well simulate the adverse effects of extreme weather conditions of long-term rainfall and long-term vehicle. According to ASTM D1883, tests were carried out on the samples that met the requirements of compactness. The samples with standard curing for 7 d were soaked in water for 4 d to determine their load ratio.

2.6. Microstructure Test. The microstructure characteristics of the representative samples were studied by X-ray diffraction (XRD) and scanning electron microscopy (SEM), and the freeze-dried samples were prepared for the scanning electron microscopy (SEM) test. First, cut the soil sample into small squares (1 cm × 1 cm × 1 cm). The cubes are then immersed in liquid nitrogen and vacuum cooled to about −210°C. Finally, the frozen sample is placed in a vacuum chamber of a freeze-dryer and sublimated for about 24 hours. Studies have shown that this process minimizes the disturbance to soil microstructure [28–30]. The freeze-dried samples prepared by the above method were coated with gold to induce electrical conductivity for scanning electron microscopy analysis. The samples were analyzed by scanning electron microscopy (SEM) and X-ray diffractometer with copper cathode. The freeze-dried samples were ground into fine powder with scanning speed of 2°/min, scanning range of 5°–90°, and scanning step size of 0.02°. Then, the JADE 5.0 software was used for semi-qualitative analysis of the results.

3. Results and Discussion

3.1. Unconfined Compressive Strength. Figure 1 depicts the typical relationship between the SAP content and unconfined compressive strength ($q_u$) of excavation soil treated with lime and cement at an initial water content of 38.53%. Under certain lime content and curing time, unconfined compressive strength ($q_u$) was significantly increased with the increase of the SAP content. Specifically, when 0.15% of the SAP content was added to the excavated soil treated with lime and cement, the $q_u$ average increased 0.48 times compared with those without SAP. In the case of SAP 0.3% and 0.45%, the increase of $q_u$ reached about 0.51 and 0.57 times compared with that without SAP, respectively. As can be seen from Figure 2, a similar conclusion can be obtained for excavated soil after cement treatment. With SAP at 0.15%, 0.3%, and 0.45%, the curves increased by about 0.75, 0.90, and 1.01 times, respectively, compared with the absence of SAP. The significant increase in unconfined compressive strength indicates that SAP has a positive effect on the strength of the cement slurry at a high moisture content and significantly improves the effectiveness of the slurry mixing method in specific situations. Specifically, by comparing 3 d and 7 d, it was not difficult to find that the speed of increase in $q_u$ of the samples increased with the increase of the SAP content, which shows that SAP has a positive impact on improving the strength of cement excavated soil in a short time.

The main reason is that in the curing process, the degree of hydration reaction of all samples is almost the same. Although SAP particles absorb part of the free water, it is generally believed that the hydration degree of cement is at the same level under the condition of higher water content [31]. So the improvement of strength is inseparable from the role SAP plays in it. SAP water absorption and expansion can effectively improve the pore structure in the cement excavated soil and can provide the surrounding cement particles with free water necessary for hydration reaction, thus having a higher relative humidity compared with the cement excavated soil without SAP. Therefore, both the external water supply and the internal water supply provided by SAP were involved in the structural improvement under wet curing conditions. However, considering that the water supply of SAP is related to its content, the higher the SAP content, the greater the strength of the sample increases.

Figure 3 shows the strength development of the excavated soil cemented with SAP over curing time. The results show that the strength of the samples containing SAP is higher than that without SAP at a certain amount of lime and cement. This showed that SAP had a positive effect on the strength increase throughout the curing period (3–28 days). By observing the trend of strength slope, it is not difficult to find that the strength growth rate of the samples containing SAP in the early stage (3 and 7 days) is higher than that of the samples without SAP. This is because the strength increase of the cemented excavated soil is due to the hydration process of the cement, during which water is consumed. As curing time, SAP particles are around basic hydration of cement particles; due to the consumption of water, the sample has a new pore, which may lead to the decrease in the strength of the sample, but due to other parts of the cement hydration still going on, in the later period, the integrated intensity of the sample is characterized by increase, but the increased rate significantly reduced. Therefore, the strength increase range of the sample containing SAP is close to that of the sample without SAP.

3.2. Degree of Compaction. Compaction degrees for representative symbols at 3 and 7 days are given in Table 4. Since the excavated soil will be used in Nanjing area, China, according to JTGD30-25 of China, the minimum pressure
compactness of the subgrade filling material is required to be 94%. It is not difficult to see from the table that SAP can effectively improve the optimal water content of soil samples. Compared with the soil samples without SAP, the optimal water content increased by 1.889% on average. This makes the water content of the soil sample with SAP closer to the optimal water content, that is, higher compactness under the same water content condition. According to the test results, it can be seen that the compactness of soil samples containing SAP can already meet the requirements in 3 d and has been further improved in 7 d. It can be considered that SAP can make the cemented soil meet the requirements of construction compaction in a short period of time, thus reducing the construction cycle.

Furthermore, as shown in Figure 4, the optimum water content and the maximum dry density of the soil samples were both higher than that of the plain soil after the addition of cement. This is because after cement is added, water is consumed during cement hydration. As the generation of hydration products increases, the structural resistance of cemented soil and the cohesion between soil particles and the amount of water required to lubricate the resistance between soil particles increases, and the optimal water content increases slightly after cement is added. This also indicates that the soil structure is denser after adding cement, so the maximum dry density is also increased. After mixed with lime, it further improves the optimal water content of the soil; this is because after adding lime, there is a large amount of consumption of soil water in the body, while there is subsequent generation of hydration products, but because of the generation of hydration products is limited, the compact structure of the degree of impact due to the ascension of the optimum water content cannot offset the maximum dry density of the lower.

After the incorporation of SAP, the optimal water content of soil samples was significantly increased compared with the plain soil, cemented soil, and cement-limed soil, while the maximum dry density was decreased compared with the plain soil, cemented soil, and cement-limed soil. Due to the super water-absorbing performance of SAP, in order to reach a relatively saturated state in the soil body, a large amount of water absorption is needed. SAP particles after water absorption mainly fill the pores in the soil body, forming large aggregates between soil particles to improve the compactness of the soil body. Therefore, the optimal water content of the soil sample after SAP incorporation is
increased. Due to the filling effect of relatively saturated SAP particles, the pores in the soil body are actually filled with water. This filling effect makes the soil structure more refined, and the maximum dry density of the native soil body decreases. After the incorporation of SAP, the compaction curve of the solidified soil tends to be flat, which means that the compaction requirement stipulated in the construction can be reached within a wide range of water content, and the improvement of the optimal water content is conducive to the control of water content in the construction process.

3.3. California Bearing Ratio. In order to further clarify the impact of SAP on cemented excavated soil, CBR tests of representative schemes are analyzed here. Table 5 presents the requirements of CBR values in JTGD30–25 of China for reasonable construction. CBR tests were carried out on cement excavated soil with and without SAP, and the results are given in Table 6. The CBR value of the unstabilized excavated soil is 3.5 at 7 d and 3.8 at 28 d, both of which are difficult to meet the requirements of subgrade filling. After curing for 7 days, the CBR values of C2, C4, and C6 were 7.2, 12, and 15.2, respectively, which increased by 2.1 times, 3.4 times, and 4.3 times compared with the unstabilized excavated soil. After curing for 28 days, the CBR values of C2, C4, and C6 were 10.1, 19.2, and 35.7, respectively, which increased by 2.7 times, 5.1 times, and 9.4 times compared with the unstabilized excavated soil. This trend is consistent with the trend of cement hydration. After curing for 7 d, the CBR value of the cement sample with SAP added decreases with the increase of the content of SAP, and C2S15, C2S30, and C2S45 cannot reach the standard of subgrade filling. Although the CBR value of the other programs is reduced, they can still reach the standard of subgrade filling. This reduction in the CBR value may be due to the long soaking time in the sample, so SAP particles in the sample can fully absorb water and expand to fill the pores between soil particles. Long-term immersion environment makes the expansion of SAP particles far greater than that under normal curing conditions, which may prevent cement hydration products from forming a cementation structure with soil particles and cause damage to the pore structure in soil body. This possibility will be examined in detail in the microscopic analysis. After curing for 28 d, the CBR value of the cement sample added with SAP has similar conclusions, but the difference is that all schemes can reach the standard of subgrade filling.
Therefore, C4S15 is the minimum material use scheme to improve the CBR value of unstabilized excavated soil.

In this study, it was found that the correlation between the CBR value and the curvature value of excavated soil stabilized by OPC is shown in Figure 5. The linear equation was used to fit, and it was found that the CBR value was about 0.0546 qu. Similar findings have been made by other researchers looking at various types of stable soils. When using OPC and fly ash to stabilize expansive soil, Vootti-pruex and Jansawang found that the CBR value was about 0.0179 qu [32]. Jiang et al. used calcium carbide slag as a stabilizer to improve the soft soil highway material and found that the CBR value was about 0.042 qu [33]. Amadi found that the CBR value was about 0.0617 qu when OPC was used to improve the strength and durability of subgrade filling materials [34]. It is generally believed that the

| Symbol        | Optimal water content (%) | $\rho_{d,max}$ (g/cm³) | $\rho_{d.3d}$ (g/cm³) | Compactness of 3 d (%) | $\rho_{d.7d}$ (g/cm³) | Compactness of 7 d (%) |
|---------------|---------------------------|------------------------|-----------------------|------------------------|------------------------|------------------------|
| Undisturbed soil | 16.576                    | 1.840                  | —                     | —                      | 1.736                  | 92.74                  |
| C4            | 16.902                    | 1.872                  | 1.717                 | 91.72                  | 1.736                  | 92.74                  |
| L2C4          | 17.359                    | 1.737                  | 1.609                 | 92.63                  | 1.627                  | 93.67                  |
| C4S30         | 18.906                    | 1.814                  | 1.712                 | 94.38                  | 1.732                  | 95.48                  |
| L2C4S30       | 19.132                    | 1.763                  | 1.661                 | 94.21                  | 1.679                  | 95.24                  |

Figure 3: Strength development with curing times.
correlation between \( q_u \) and CBR values of stabilized soils is only applicable to cemented material stabilized soils. Therefore, the fitting equations of CBR and \( q_u \) of SAP samples are added in Figure 5, and the coefficient of variation (\( R^2 \)) was only 0.6634. Therefore, this formula cannot well fit the relationship between the CBR value and \( q_u \) of the sample with SAP material added. This indicates that the method of SAP stabilizing cement excavated is probably not based on cementation, but more likely to play a role as a filling material. Further analysis will also be carried out in the microscopic analysis.

### 3.4. Analysis of Durability

The dry-wetting cycle is one of the main factors affecting the durability of soil. Durability is an important parameter to evaluate whether waste materials can be used in engineering, and it is also one of the main requirements for subgrade filling materials to be used in practical engineering. More durable subgrade materials reduce maintenance costs and environmental impact, thus promoting waste utilization. The influence of actual environment on the strength and durability of cement and polymer-stabilized excavated soil was studied by means of the dry-wetting cycle effect.

Figure 6 shows the strength development of representative samples with curing ages of 7 days and 28 days and drying and wetting cycles of 3, 5, and 10. In the samples without the wetting and drying cycle, the \( q_u \) of the samples increased with the increase of SAP dosage and curing time. Compared with the samples in the wetting and drying cycle test, the unconfined strength of the samples at 7 and 28 days increased with the increase of the amount of polymer. It is concluded that the polymer reinforced cement excavated has better durability in both the early and late curing stages. Furthermore, the samples cured for 28 days can be regarded as the parallel samples cured for 7 days and subjected to a dry-wetting cycle for 10 weeks (about 27 days). Although the strength development of the samples undergoing the drying and wetting cycles is not as good as that of the samples under standard curing conditions, the difference between the two is not large, and this gap gradually shrinks with the increase of high molecular weight. This is due to the condition of dry-wet circulation on the structure of cement excavated soil damage. The moist environment will make the soil particles of cemented soil filled with water, showing the state of expansion. The dry environment will lead to the loss of water between soil particles, which will lead to the reduction of pore volume, showing a shrinkage state. This results in surface crack and tension of the sample [35, 36]. The quality loss increases as the number of cycles increases (Figure 7). For SAP cement soil excavated, unconfined strength of sample increased with the increase of cycling times that may be due to the existence of SAP for the structure of the sample has a certain protective effect; under the condition of the dry cycle, SAP will be slow to release the internal storage of water and keep the water content of the sample inside at a given relative humidity; under the condition of the wet cycle, SAP, compared with the soil, the water absorption rate is faster and the soil structure is protected. In addition, SAP can effectively promote cement hydration [21]. That is, under the condition of the dry-wetting cycle, SAP can keep the water content inside the sample in a relatively balanced state, promote cement hydration, and increase the strength of cement excavated soil.

The addition of SAP enhanced the hydration reaction of cement under the condition of the wetting and drying cycle, thus promoting the strength development of the sample and improving the durability of the sample. This mainly determines the relationship between durability and strength. Figure 8 shows the relationship between the durability (\( q_{u WD} \)) of a representative sample and the unconfined compressive strength (\( q_u \)). The results show that the \( q_{u WD} \) at any number of cycles is directly related to \( q_u \). The relationship between the normalized intensity and the number of cycles is shown in Figure 8(c), and the relationship equation is given as

\[
\frac{q_{u WD}}{q_u} = 0.0284C + 0.9423.
\] (1)

In the formula, \( C \) is the number of cycles. Considering the reliability of the fitting formula, the value range of \( C \) is suggested to be a natural number from 1 to 10. The \( C \) value can be changed according to actual engineering requirements. Since previous studies focused on the water retention of SAP [37, 38], there was a lack of research on the durability strength of the solidified soil. Figure 8(c) only shows the fitting formula of the solidified dredged sediment durability of cement and fly ash studied by previous studies [8, 35], which is compared with this study. It is not difficult to find that the strength of cement and fly ash solidified soil decreases with the increase of the number of cycles, which further indicates that SAP can effectively improve the durability of cement solidified soil and has had a significant effect in the early stage. Therefore, equation (1) can be used to quickly estimate the dry and wet cycle strength of treated excavated soil in subgrade filling materials.

According to Figure 9(a), with the increase of time, the drying shrinkage strain of representative samples all...
increased with the increase of time. The drying shrinkage strain of C4 after 7 days has reached 89.1% of the maximum strain, and the drying shrinkage strain of C4S30 after 7 days is 93.8% of the maximum strain. However, the maximum strain of C4S30 is only 67.4% of the maximum strain of C4.

In other words, the drying shrinkage strain of C4 will be significantly reduced and the time to reach a steady state will be shortened after the SAP material is added. Similar results are obtained for L2C4 and L2C4S30.

According to Figure 9(b), with the growth of time, the shrinkage coefficient rises rapidly at first, reaches the maximum and then decreases, and gradually becomes stable over time. The drying shrinkage coefficient of C4 reached the maximum value in 3d, and the C4S30 reached the maximum value in 4d. The drying shrinkage coefficient of L2C4 reached the maximum value in 3d, and the drying shrinkage coefficient of L2C4S30 also reached the maximum value in 3d. There was no obvious change in the time when the drying shrinkage coefficient of representative samples reached the maximum value. By comparing the value of the drying shrinkage coefficient when the drying shrinkage coefficient reaches a steady state, it can be found that the drying shrinkage coefficient of C4 and L2C4 is significantly higher than that of C4S30 and L2C4S30. In addition, there is little difference between the drying shrinkage coefficient of representative samples.

By comprehensive comparison of the variation rules of drying shrinkage strain and drying shrinkage coefficient, it can be seen that the peak strength of CSH, CAH, and Aft in cemented soils is related to the hydration products. Some researchers have also found these hydrate products in cemented soils. By comparing the XRD results of C4 and C4S30, it can be seen that the peak strength of CSH, CAH, and Aft in cemented soils is related to the hydration products. Some researchers have also found these hydrate products in cemented soils.

Through the study of the drying and wetting cycle and drying shrinkage, it can be considered that the cemented soil treated by SAP has better durability. This is probably because the water absorbed by SAP can be released slowly in the later stage, making the sample in a relatively humid environment. Therefore, the strength of the sample can continue to increase, and the mechanism of this will be further revealed in the microscopic analysis.

3.5. Microscopic Analysis

3.5.1. Results of XRD Tests. The X-ray diffraction patterns of representative schemes and excavated soil at 28 days are shown in Figure 10. The results show that the main minerals in the excavated soil are quartz and clay minerals such as illite, chlorite, kaolinite, and calcite, which are consistent with the results of clay mineral composition studied by other scholars [39, 40].

When cement is added to the excavated soil, it is found that the new reactions corresponding to the composition of hydration products are calcium silicate hydrate (CSH), calcium aluminate hydrate (CAH), and ettringite (Aft). Some researchers have also found these hydrate products in cemented soils [41, 42].

By comparing the XRD results of C4 and C4S30, it can be seen that the peak strength of CSH, CAH, and Aft in cemented soils is related to the hydration products. Some researchers have also found these hydrate products in cemented soils.

Table 5: Minimum bearing ratio requirement of roadbed filling.

| Subgrade area | Below the surface of the road depth (m) | Minimum CBR value of packing (%) |
|---------------|----------------------------------------|----------------------------------|
| The road bed  | 0–0.3                                  | Expressways and first class roads |
| Under the road bed | Light, medium 0.3–0.8                      | The secondary roads              |
|               | Heavy traffic 0.3–1.2                   | Third and fourth level roads     |
|               |                                        | 8                                |
|               |                                        | 6                                |
|               |                                        | 5                                |
|               |                                        | 4                                |
|               |                                        | 3                                |
|               |                                        | 5                                |
|               |                                        | 4                                |
|               |                                        | —                                |

Table 6: CBR values of representative samples.

| Symbol     | 7 d CBR (%) | 28 d CBR (%) |
|------------|-------------|--------------|
| Unstabilized | 3.5         | 3.8          |
| C2         | 7.2         | 10.1         |
| C4         | 12.0        | 19.2         |
| C6         | 15.2        | 35.7         |
| C2S15      | 6.8         | 9.4          |
| C2S30      | 6.1         | 8.6          |
| C2S45      | 5.5         | 8.1          |
| C4S15      | 11.2        | 18.1         |
| C4S30      | 9.8         | 17.3         |
| C4S45      | 8.7         | 15.8         |
| C6S15      | 13.9        | 32.8         |
| C6S30      | 12.3        | 30.1         |
| C6S45      | 10.7        | 27.7         |

Through the study of the drying and wetting cycle and drying shrinkage, it can be considered that the cemented soil treated by SAP has better durability. This is probably because the water absorbed by SAP can be released slowly in the later stage, making the sample in a relatively humid environment. Therefore, the strength of the sample can continue to increase, and the mechanism of this will be further revealed in the microscopic analysis.

3.5.2. Analysis of SEM Result. Figure 11 shows the microstructure of the soil samples after curing for 7 d and 28 d when the SAP content is 0% and 0.3% (C4, C4S30). From the figure, the flake-shaped soil particles and needle-shaped cement hydration products can be clearly identified. This needle-like hydration product is a typical gelling substance. They cover the surface of the aggregates, occupy the large pores between the aggregates, and form a well-developed flocculation structure among the soil particles. The
formation of this flocculating structure eventually leads to the increase of soil strength.

Regarding the impact of SAP on the microstructure of soil, without SAP, although hydration products are cemented between soil particles to form agglomerates, there are many pores between and within the agglomerates. Due to the existence of these pore spaces, the soil structure is relatively loose. As shown in Figure 11(b), SAP covers the surface of the aggregates in the form of filaments and can fill the pores between the aggregates well. Since the sample is freeze-dried, the water is directly sublimated. Comparing Figure 11(a), it can be seen that when the water is not sublimated, the SAP particles should fill the pore space in a full form. It can be considered that the function of SAP is to absorb the water in the soil and form expansive particles to achieve the effect of water fixation. This process fills the pores in the soil matrix and results in a denser microstructure, which leads to an increase in strength.

Figure 12 shows the microstructure of lime soil samples (L2C4 and L2C4S30). With the addition of lime, the hydration products increase significantly, and the cementing ability of these newly added hydration products is obviously not as good as that of cement hydration products, and the cemented aggregates are obviously looser. However, it fills the original pore space to a certain extent and has a positive effect on strength development. It can be seen from Figure 12(b) that the addition of SAP can effectively improve this loose agglomerate. SAP fills the internal pore space of loose agglomerates in the form of filaments, making the soil microstructure more compact, resulting in an increase in strength. Therefore, under the same amount of cement and lime, the formation of soil structure plays a significant role in the improvement of strength. It means that the higher strength is due to lower pore volume and denser microstructure.
Figure 7: Change curve of quality loss of sample with the number of cycles.

Figure 8: Relationship between the W-D cycle strengths and $q_{u}$. (a) 7 days. (b) 28 days. (c) Relationship between the normalized strength and number of cycles.
Figure 9: Relationship between the time and drying shrinkage strain/coefficient.

Figure 10: XRD diffractograms of cemented soil with different symbols.
Figure 11: Scanning electron microscope images of the symbol without lime. (a) SEM images of C4. (b) SEM images of C4S30.

Figure 12: Scanning electron microscope images of the symbol with lime. (a) SEM images of L2C4. (b) SEM images of L2C4S30.
The effect of curing time on the microstructure can be analyzed according to Figures 11 and 12. It is generally believed that hydration products increase with time. With the increase of hydration products, the cementation between soil aggregates and cement clusters tends to increase, and the volume of greater pore is further reduced. The filling effect of SAP will fill the remaining pores, making the soil denser. This is similar to the effect of curing time on the strength of cement soil [4].

It is proved that the improvement of strength of cemented clay by SAP is directly related to the change of microstructure. The effect of SAP on strength increase can be explained as follows: when SAP particles are added to the excavated soil, they rapidly absorb water and expand, and the corresponding solid mass (soil particles and expanded SAP particles) increases with the decrease of pore water. In other words, due to the strong water absorption capacity, the presence of SAP causes the pore volume to decrease significantly as the size of the expanded SAP particles increases. When cement and lime are added and mixed and stirred, the hydration product wraps the soil aggregates and expanded SAP particles, filling the large pores. Therefore, the pores between the aggregates are significantly reduced, thereby forming a dense flocculation structure in the soil matrix (as shown in Figures 11 and 12). When there is no SAP, large pores will be formed between the agglomerates, resulting in a relatively loose structure. This also corresponds to SAP’s ability to improve soil compaction. In terms of durability, as the wet and dry conditions change, some water may separate from the SAP. The separated water will promote the cementation between the agglomerates, that is, promote the cement hydration reaction. The strengthening of cementation is often the increase of hydration products, and the newly added hydration products will fill the pores created by the loss of water from the SAP particles. Therefore, compared with soil samples without SAP, soil samples containing SAP have better durability. And because of the presence of SAP particles, the compactness of the structure is not attenuated, which can also explain the increasing trend of the strength of SAP-containing soil samples after the dry-wet cycle. In terms of bearing ratio, due to prolonged immersion in water, the excessive expansion of SAP particles will reduce the compactness of the soil. Therefore, the CBR value of SAP-containing soil samples is slightly lower than that of SAP-free soil samples. In summary, the increase in strength of the excavated soil due to SAP is mainly attributed to the improvement of soil structure, mainly due to the strong water absorption capacity of SAP and the lower water-loss rate.

4. Conclusions

This article introduces the experimental research on the physical and mechanical properties and microstructure of the excavated soil quickly treated with SAP, cement, and lime. Through the unconfined compressive strength test, dry-wet cycle test, and CBR test, the road performance changes of cement soil and cement-lime soil after mixing with SAP are obtained. By analyzing the results of XRD and SEM, the microscopic mechanism of these changes is explained. According to this research, the following conclusions can be drawn:

1. Under the same content of cement and lime, the unconfined compressive strength of the sample increases with the increase of SAP content (0∼0.45%), and the increase rate is similar. The strength of the cement sample containing SAP is 0.75∼1.01 times higher than that of the cement sample. The increase in intensity is also related to the curing time. As the curing time goes on, the rate of increase in intensity slows down.

2. Adding SAP can increase the optimal water content of cement soil and cement-lime soil, and the maximum dry density of soil samples will be slightly reduced, thereby improving the compaction performance of the soil.

3. Adding SAP will reduce the CBR value of cement soil and cement-lime soil, but it can meet the acceptance requirements. It is known from empirical formula analysis that SAP does not mainly play a role in cementing the soil.

4. Incorporating SAP can effectively improve the dry-wet cycle strength and drying shrinkage of cemented soil. In the dry-wet cycle test, the strength of all soils during the curing time depends on the unconfined compressive strength. The correlation between the normalized strength and the number of wet and dry cycles can be used to quickly estimate the strength under different numbers of wet and dry cycles with the equation of $(q_{u-WD}/q_u) = 0.0284C + 0.9423$, so as to quickly determine the service life of the treated excavated soil for subgrade filling materials.

5. XRD analysis was carried out on soil samples containing SAP and soil samples without SAP, which confirmed that the formation of CSH and SAP performs a physical reaction, and no new substances are produced. And through the analysis of SEM results, it is further explained that SAP mainly plays a filling role in the soil, making the soil structure more compact.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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