

## Review Article

# Expansive Soil Embankment Filling and Cutting Treatment Technology: A Systematic Review

Zhen Huang <sup>1,2</sup>, Hang Shi <sup>1</sup>, Wei Zhang <sup>1</sup>, Shaokun Ma <sup>1,2</sup>, Feng Gao <sup>1</sup>,  
and Min Ma <sup>1</sup>

<sup>1</sup>School of Civil Engineering and Architecture, Guangxi University, Nanning 530004, China

<sup>2</sup>Key Laboratory of Disaster Prevention and Structural Safety, Guangxi University, Nanning 530004, China

Correspondence should be addressed to Wei Zhang; [zw971126la\\_lune@163.com](mailto:zw971126la_lune@163.com)

Received 21 July 2022; Revised 17 September 2022; Accepted 27 September 2022; Published 25 October 2022

Academic Editor: Abhinay Kumar

Copyright © 2022 Zhen Huang et al. This is an open access article distributed under the Creative Commons Attribution License, which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.

The characteristics of expansive soil, including over consolidation, swelling-shrinkage, fissures, and strength attenuation, can cause potential hazards in road construction, which are mainly manifested as subgrade swelling-shrinkage deformation and slope collapse. Effective treatment can not only ensure long-term subgrade stability but also reduce investment costs and environmental impact. In this review, the current development status of embankment filling and cutting slope treatment technology in expansive soil areas were summarized, and the classification standards of expansive soil filler, moisture retention, and antiseepage technology were described. Then, the utility of chemical, physical, biological, and solid waste modification materials in improving the engineering characteristics of core-filled expansive soil was discussed, and the cost and technical characteristics of these modification technologies were compared and analysed. Next, the application of rigid and flexible support technology in the treatment of cutting slope collapse was analysed, and the advantages and disadvantages of rigid and flexible supports were summarized. Finally, the development direction of expansive soil subgrade treatment technology was discussed. This review includes a summary of the treatment methods of highway subgrade in expansive soil areas and can provide a technical reference for treatment methods of expansive soil subgrade.

## 1. Introduction

Expansive soil (rock) is widely distributed in the world; among countries with expansive soil, China possesses the widest distribution and largest area of expansive soil, with a total distribution area larger than 100000 km<sup>2</sup>. Expansive soil yields a unique structural effect under alternating dry-wet climatic conditions, so expansive soil is very sensitive to changes in water migration and exhibits the engineering characteristics of wet swelling and dry shrinkage. Highway subgrades in expansive soil areas often exhibit high compression, low strength, and random expansion due to water entry. Additionally, the characteristics of wet swelling and dry shrinkage easily result in cracking of cutting slopes, resulting in sliding failure along the crack development direction [1]. Therefore, it is disadvantageous to directly use expansive soil as a subgrade filling material. The

“Specification for the Design of Highway Subgrades of China” states that nonexpansive materials should generally be used to replace expansive soil. However, the method of soil replacement may lead to water and soil loss and even geological disasters such as debris flows and landslides under the joint action of natural conditions such as heavy rainfall [2]. In addition, for areas where expansive soil is widely distributed, the cost of discarding soil for filling is high, which is not conducive to engineering economics. Therefore, it is necessary to adopt reasonable technology to address the subgrades of expansive soil. Due to the different expansive properties and engineering properties of expansive soil, the treatment methods that need to be adopted are also different. For example, in areas with low expansibility, expansive soil can still be directly used as a subgrade filling material. Researchers have proposed many classification standards and evaluation indices [3, 4], and based on the particularity

of expansive soil, the conventional evaluation index has been improved [5, 6].

The risk of natural disasters and traffic accidents due to expansive soil subgrades is higher than that due to ordinary soil subgrades [7, 8]. Many projects have been shelved due to improper treatment of expansive soil. Figure 1 shows the phenomenon of exposed cracking of expansive soil cutting slopes. Regarding the treatment of expansive soil subgrades, existing research mainly focuses on both embankment and cutting. In regard to embankment filling material modification, for moderate or highly expansive soils that cannot be directly used as filler, the soil physical properties (unconfined compressive strength, cohesion, internal friction angle, shear stress, expansive force, etc.) [9–12] and road properties [13] can be improved by adding modified materials. The goal of expansive soil modification is to discover new modification materials with high environmental performance and low treatment costs. Among the various modification methods, chemical modification technology has been greatly developed, and abundant research results have been obtained. Considering environmental problems, biological improvement technology and solid waste improvement technology have been applied.

The failure process of expansive soil cutting slopes exhibits complex characteristics, such as a gradual nature, randomness, repeatability, and hysteresis [14]. In research on the stability of expansive soil cutting slopes, many researchers have found that the occurrence and development of cracks notably impact slope stability [15, 16]. Considering the complexity of the failure process of expansive soil slopes, it is difficult to summarize the appropriate treatment of all slopes with a single method. Reinforcement measures for expansive soil cutting slopes can be divided into two types: slope foot support and slope protection measures. Slope foot support structures mainly include rigid retaining structures such as pile-plank retaining walls, interpile retaining walls, gravity retaining walls, and antislide piles. Slope protection measures generally involve irrigation and grass slope protection, water cut-off framework slope protection, anchor frame beam slope protection and support seepage ditches [17]. In recent decades, treatment technology for expansive soil cutting slopes has been developed to a certain degree. Because rigid support technology impedes soil deformation and is costly, researchers have focused on flexible support technology with suitable economic and environmental protection, and support performance features. Flexible support technology is based on geogrid reinforcement technology, which is constantly being improved (Figures 2(a) and 2(b)). However, even if cutting slope support technology is optimized, due to imperfect quality control and evaluation methods in the construction process, slopes with supports may still experience problems such as cracking, as shown in Figures 2(d) and 2(c).

The existing review papers on expansive soil mainly focus on methods of improving the poor properties of expansive soil [18, 19], and there are few comprehensive discussion papers on engineering technology in expansive soil areas. At present, expansive soil is widely distributed in the world, and engineering problems in expansive soil areas

often threaten engineering safety and increase engineering costs. Solving engineering problems in expansive soil areas is an important part of creating a resource-saving society. The research status of treatment technologies available for expansive soil embankments and cutting slopes was determined in this literature review. Aiming at embankment treatment projects, classification and filling standards of weak, moderately strong, and strong expansive soil were examined, treatment methods based on the moisture retention and seepage prevention principle were presented, and existing physical, chemical, biological, and solid waste improvement technologies for expansive soil were summarized. Regarding cutting slope engineering, the prevention principles and existing achievements of rigid and flexible support technology and ecological soil bag slope protection were summarized, and the advantages and disadvantages of these support measures were analysed. At the end of this paper, the shortcomings of each treatment scheme in an embankment and cutting engineering were described, and a new development direction of expansive soil treatment technology was proposed, including a new idea for follow-up research.

## 2. Treatment Technology for Expansive Soil Embankments

*2.1. Filler Selection Methods and Standards.* Expansive soil is a unique soil. Due to the influences of its wet swelling, dry shrinkage, and overconsolidation characteristics on engineering quality, the use of untreated expansive soil as a filler material of an embankment poses engineering risks. The successful experience of the research group focusing on the design, reinforcement, and construction technology of expansive soil subgrade at the Ministry of Communications of China shows that by adopting reasonable classification standards for grade screening, it is possible to directly use expansive soils with reasonable expansion and contraction grades as fillers in different regions. To promote the popularization of this new treatment technology and ensure the strength and stability of subgrades, it is necessary to establish a corresponding filling classification index system [20].

Filler materials of compacted expansive soil filling embankments can be classified according to their strength, deformation, and construction manoeuvrability characteristics [4]. For instance, the improved California bearing ratio (CBR) value (which is tested by preparing samples under a heavy compaction standard and with an optimum moisture content in light of the wet compaction test, changing the water soaking method from upper immersion to lateral immersion while increasing the load on the samples during the soaking period), CBR expansion capacity, and natural consistency can be adopted as classification indices. Notably, through the classification of expansive soil subgrade filler materials, as summarized in Table 1, we can determine whether expansive soil can be used as a subgrade filling material in various areas. This classification system can suitably analyse the essential and engineering characteristics of expansive soil, and the acquisition process of index parameter values is simple and fast, which can greatly broaden



FIGURE 1: Cracking and collapse of expansive soil slopes.

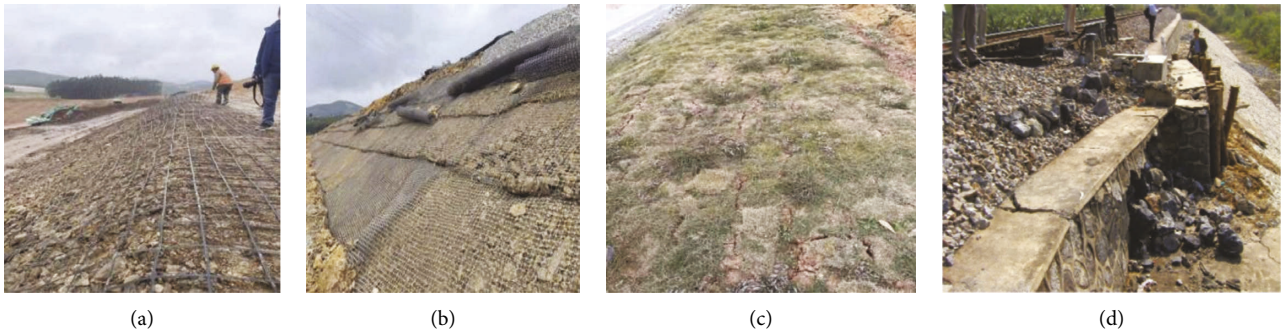


FIGURE 2: Flexible support of expansive soil and problems after support application. (a) Geogrid. (b) Waterproof material. (c) Cracking after flexible support. (d) Rigid support failure.

TABLE 1: Classification of expansive soil filler materials (if  $w_c > 1.30$ , preferably they are not adopted).

Filler grade	CBR value/%	CBR expansion/%	Natural consistency of expansive soil $w_c$	Treatment method
Grade I	>6.5	<2.6		
Grade II	5.2~6.5	2.6~3.6	$1.00 \leq w_c \leq 1.30$	Direct filling
Grade III	3.9~5.2	3.6~5.1		
Grade IV	<3.9	>5.1	$w_c < 1.00$	Modified to adopt or discarded

the application range of schemes directly using expansive soil as filler [20] and can reduce engineering costs.

In fact, supplementation and improvement of the traditional CBR test method are important steps to accurately obtaining the bearing capacity of expansive soil [5]. The improved CBR value is one of the important indices used to measure the bearing capacity of a subgrade filled with expansive soil [6]. In addition, there exists a good linear relationship between the expansion ratio and the amount of CBR expansion of expansive soil under 50 kPa pressure [3]. Therefore, the amount of CBR expansion can replace the total rate of swelling and shrinkage to evaluate the deformation characteristics of filler materials [20]. According to the research conclusion about expansive soil by the Ministry of Communications of China, to evaluate the road properties of expansive soil,

the three indices listed in Table 1 must meet certain requirements.

According to the Specification for the Design of Highway Subgrades (JTGD30-2015) [21], when expansive soil is used as subgrade filler, the total swelling-shrinkage rate of compacted expansive soil should be adopted as a classification index, and expansive soil should be classified according to Table 2.

There are many indices reflecting the degree of expansion of expansive soil. For example, according to the evaluation indices of the plasticity index, shrinkage limit (SL), swelling volume strain, expansion degree, and colloidal particle content, the American Reclamation Bureau [22] divides expansive soil into four grades: extremely strong, strong, moderately strong, and weak expansive soil. This classification method provides a reference for determining

TABLE 2: Classification of the expansion potential of expansive soil.

Filler grade	Total swelling-shrinkage rate of compacted expansive soil %	Scope of use
Nonexpansive soil	$e_{ps} < 0.7$	Directly applicable
Weak expansive soil	$0.7 \leq e_{ps} < 2.5$	After applying physical treatment measures such as edge wrapping, reinforcement, and cushion setting, this soil type can be used as embankment filler, and this soil type can be used as roadbed filler after treatment with an inorganic binder
Moderately strong expansive soil	$2.5 \leq e_{ps} < 5.0$	This soil type can be used as subgrade filler after treatment with an inorganic binder
Strong expansive soil	$e_{ps} \geq 5.0$	This soil type cannot be used as subgrade filler

TABLE 3: American standard for expansion and shrinkage grades of expansive soil.

Expansion degree	Content of colloidal particles with particle size <0.001 mm (%)	Indices		
		Plasticity index $I_p$ (%)	Shrinkage limit $\omega_s$ (%)	Swelling volume strain $\delta_p$ (%)
Extremely strong	>28	>35	<11	>30
Strong	20~21	25~41	7~12	20~30
Moderately strong	13~23	15~28	10~16	10~20
Weak	<15	<18	>15	<10

whether expansive soil can be directly used as subgrade filler. The corresponding classification criteria are listed in Table 3.

Professor Ke [23] recommended that the expansion and shrinkage grades of expansive soil be divided into four grades, namely, extremely strong, strong, moderately strong and weak, by using direct indices, i.e., the maximum linear shrinkage rate, the maximum volumetric shrinkage rate, and the maximum expansion rate, as indicated in Table 4.

Through comprehensive consideration of the various standards to reasonably determine the expansive strength of expansive soil, we can more accurately identify expansive soil that can be directly used as roadbed filler to reduce the filling time of expansive soil subgrades and lower the cost of special soil treatments in projects.

## 2.2. Moisture Retention and Seepage Prevention Technology.

Rainwater is one of the important sources of soil moisture. At the same time, rainwater infiltration is the main cause of slope landslides in expansive soil embankments. Khan et al. studied the influence of rainfall on the safety factor of filling slopes in Yazoo, where shallow landslides occur year round, and verified that regardless of the rainfall intensity and duration, the total rainfall amount directly affects the slope safety factor, resulting in slope instability [24]. You et al. found that the stability of expansive soil embankment slopes is mainly affected by humidity. To avoid a decrease in expansive soil slope safety after rainwater soaking, a reasonable slope ratio and embankment slope protection and drainage measures are very important [25]. Therefore, waterproofing technology plays an important role in the filling quality of expansive soil embankments.

Water content is an important factor affecting the strength and stability of expansive soil slopes. Research shows that if the expansive soil meets the condition of

insufficient water, especially when the moisture content of the soil is low, the strength is high. Therefore, implementing effective measures such as closure cover to control the variation range of the water content in embankment soil can meet the strength requirements of expansive soil as filler and this idea of physical treatment can avoid the problem of soil and water loss caused by the borrow-and-spoil phenomenon. This method can also reduce the project's cost [26].

At present, waterproofing of expansive soil subgrades mainly depends on the use of geosynthetic materials, including geomembranes and geosynthetic clay liners (GCLs) suitable for underwater slopes [8]. GCLs are impermeable materials made by adding expansive soil powder (or expansive soil particles) between two layers of nonwoven geotextiles. The antiseepage mechanism is that the expansive soil powder will expand when encountering water and fill the gaps of the geotextile to stop the entry of water. This kind of geosynthetic is not affected by drying-wetting and freezing-thawing cycles and has strong self-healing properties, good durability, convenient lapping, and simple installation. Thus, it has practical significance.

The core covering method is an effective closure cover measure based on the basic principles of moisturization and antiseepage. This method can effectively stop the infiltration of external water, maintain the working state of core-filled expansive soil, and meet the requirements of filler materials and forces, enhancing the strength and stability of subgrades. Yang et al. proposed the design idea of the appropriate wrapping width of an expansive soil embankment via the cover method; namely, the atmospheric influence depth of local expansive soil is first obtained, and the wrapping width is then calculated according to the proposed slope rate [27]. In follow-up engineering research, researchers put forward the scheme of a nonexpansive soil-wrapped edge and expansive soil core filling (Figure 3(a)), which is the

TABLE 4: Expansion and shrinkage grade standards of expansive soil.

Filler grade	Indices		
	Maximum linear shrinkage rate (%)	Maximum volume shrinkage rate (%)	Maximum expansion rate (%)
Extremely strong expansive soil	>11	>30	>10
Strongly expansive soil	8~11	23~30	7~10
Moderately strong expansive soil	5~8	16~23	4~7
Weak expansive soil	2~5	8~16	2~4

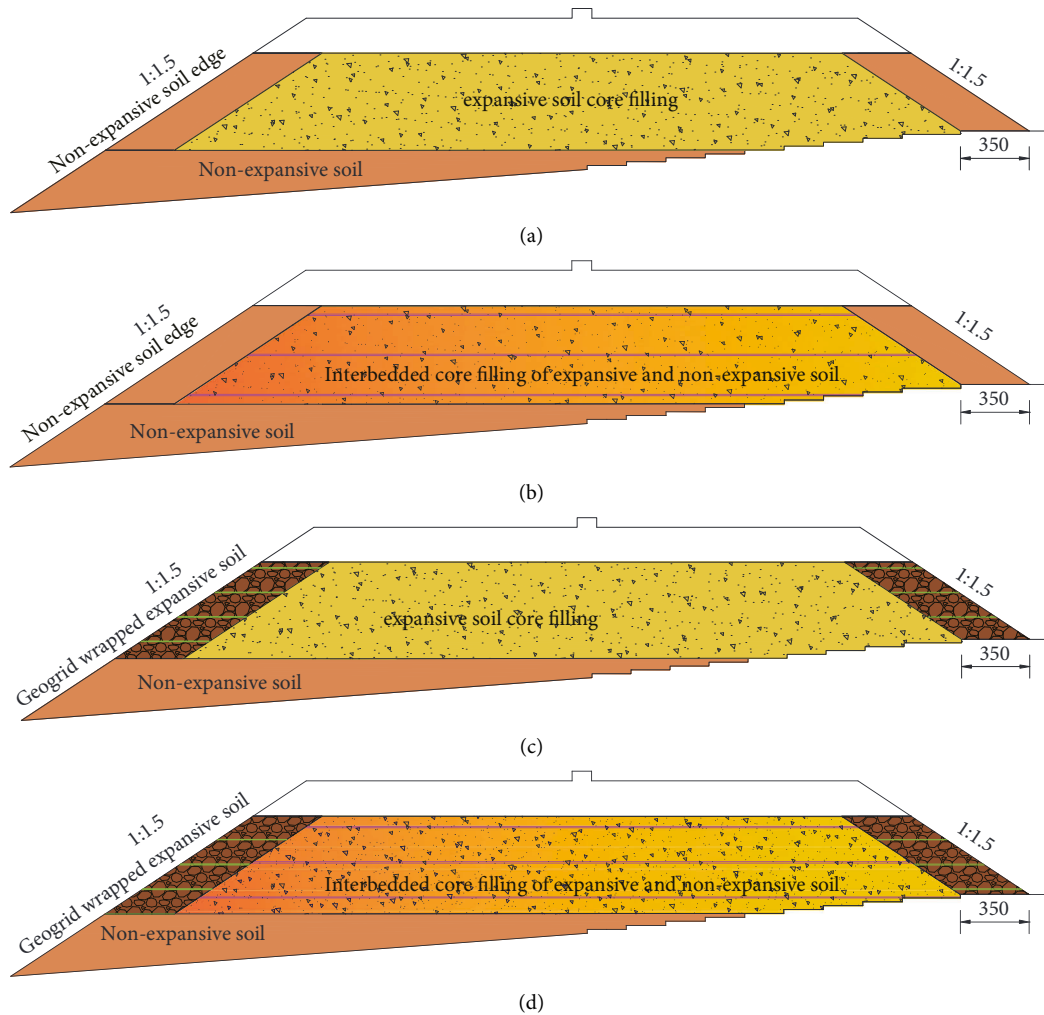


FIGURE 3: Treatment scheme under the cladding method.

most convenient and economical scheme in projects at present. When the filling or compaction effect is not satisfactory, the core filling strength of expansive soil is low. A scheme involving nonexpansive soil-wrapped edges and expansive soil interbedded with nonexpansive soil filler material in the core (Figure 3(b)) can be used as a remedial measure. Considering the lack of nonexpansive soil filler material and the economic cost of borrowing soil in expansive soil areas, researchers also proposed the filling scheme of geogrid-reinforced expansive soil-wrapped edges (Figure 3(c)) and supplemented this approach with the

filling scheme of nonexpansive interbedding with expansive soil (Figure 3(d)) [28].

2.3. *Improvement Technology.* Moderately strong and strong expansive soil cannot be directly used as embankment filling and must be improved. Improvement methods mainly involve chemical, physical, biological, and industrial waste improvement methods. The common chemical improvement method entails mixing lime [29], cement [30], fly ash [31, 32] and other materials into expansive soil [33]. Illite

and montmorillonite in expansive soil undergo a series of physicochemical reactions with modified materials, which can alter the soil structure and mechanical properties, such as reducing hydrophilicity and enhancing self-stability, to meet the requirements of embankment filling [34]. Physical improvement mainly enhances the structure and strength of soil by adding materials such as sandy soil and silty soil to expansive soil. Biological improvement is a recently developed soil modification method that mainly uses biological metabolic activities to change the original soil environment and uses dead bacteria to fill the soil particle cementation or intergranular pores. Hence, the engineering properties of expansive soil can be improved [35]. In addition, with regard to environmental problems, certain industrial solid waste materials, such as polymers, rubber powder, and tailings residues, can be used to improve the properties of expansive soil.

**2.3.1. Physical Improvement Technology.** The physical improvement mainly involves mixing gravel and other materials with expansive soil to prepare soil mixtures to achieve improved performance. The research focus includes the selection and content of materials [36]. Sandy particles exhibit a certain hardness and particle size, and the difficulty of mixing sandy particles into the soil is obviously lower than that of mixing fine materials such as lime, cement and fly ash. Adding weathered sand can effectively improve the shear strength of expansive soil. Moreover, soil cohesion gradually decreases with increasing sand proportion, and the internal friction angle first increases and then decreases with increasing sand ratio [37]. From the perspective of economy and applicability, the improvement effect of weathered sand is suitable, and weathered sand has been applied in highway subgrades [38]. Mixing expansive soil with an appropriate amount of fine silica sand can also be used as a physical improvement method. Relevant experimental results indicate that the expansive soil characteristics increasingly deteriorate with increasing mixed silica sand content [39]. However, the effect of improving expansive soil only by using a mixed composite soil is not significant, and on the basis of adding sandy soil to improve expansive soil, marble waste can be added as a potential stabilizer to further enhance the volume and strength characteristics of expansive soil [40], which supports the idea of using solid waste for not only improving expansive soil but also reasonably realizing solid waste disposal. It has even been noted that the use of sand and expanded polystyrene (EPS) geotechnical foam can effectively stabilize expansive soil [41]. Disintegrated sandy soft rock can also be used as an improvement admixture, and this material exhibits the characteristics of easy crushing, nonexpansion, and a low natural moisture content, which provides suitable conditions for use as a weak expansive soil modification material. The internal friction angle and cohesion of improved soils can differ with the amount of disintegrating sandy soft rock (Figure 4(a)), and the change in shear strength with the amount of disintegrating sandy soft rock is shown in Figure 4(b), which indicates that the mixing amount is crucial to control the improvement effect. In addition, the improvement effect of hydrated sandstone is

better than that of machine-crushed sandstone, indicating a potential solution for resource utilization of river excavation debris in river diversion projects [42].

As a new type of temperature-control material, phase change materials can also be used to improve the freeze-thaw properties of expansive soils. In the phase change process, phase change materials can store and release a large amount of energy to regulate the internal temperature field of soil in response to the freeze-thaw environment of expansive soils. Studies have demonstrated that typical phase change materials (Figure 5), such as paraffin-based liquid phase change material (pPCM) and paraffin-based microcapsule phase change material (mPCM) can effectively improve soil performance. pPCM is very effective in improving soil thermal stability, while mPCM provides a clear advantage in resisting the impact of repeated freeze-thaw cycles. Therefore, energy-efficient and low-cost phase change materials are the best choices in seasonal permafrost regions [43].

**2.3.2. Chemical Improvement Technology.** Physical improvement methods are slow and inefficient. Therefore, chemical improvement methods that mainly use materials such as lime, cement, fly ash, and alkali slag have been further developed [38]. Researchers have performed a considerable amount of research on this topic. For example, to evaluate and enhance the tensile and compressive strengths of expansive soil subgrades, Frank et al. proposed an improvement scheme entailing the addition of a mixture of activated fly ash ( $\alpha$ -FA) and sisal fibres into expansive soil [44]. The American Coal Ash Association states that slaked lime and fly ash can be used as chemical stabilizers, namely, slaked lime can be used to alter the granular structure of soil, and the bulk expansion potential of expansive soil can be reduced with fly ash [45]. Researchers analysed changes in the engineering properties of soil samples when lime and fly ash were used to improve expansive soil in the Esenboga area experimentally, where lime effectively constrained the changes in the liquid limit (LL) and plasticity index (PL) within the range of 4–5% (Figure 6(a)), while fly ash was not effective in improving the swelling properties (LL, PL, SL) of highly plastic clay soils at reasonable contents of 20–25% (Figure 6(b)). Figures 7 and 8 show the variations in clay activity and methylene blue values with the lime content in the above region, respectively [46]. Sharma and Sivapullaiah studied the influence of an admixture consisting of fly ash and ground granulated blast furnace slag (GGBS) and lime on the variation in the volume of expansive soil and concluded that lime plays a main role in determining stability [47]. Masrur Mahedi et al. stated that cement can effectively stabilize expansive soil, but when sulfate is present in soil, it is difficult to achieve the desired effect of cement treatment because the presence of sulfate salts impairs the performance of cement, leading to a higher stabilizer requirement. If the slag was added into the type I/II Portland cement to make a stabilizer, as the CaO (41%) content of slag was low, the sulfate-induced heaving [48] would be reduced, and the effect of stabilizing sulfate expansive soil can be effectively achieved [30].

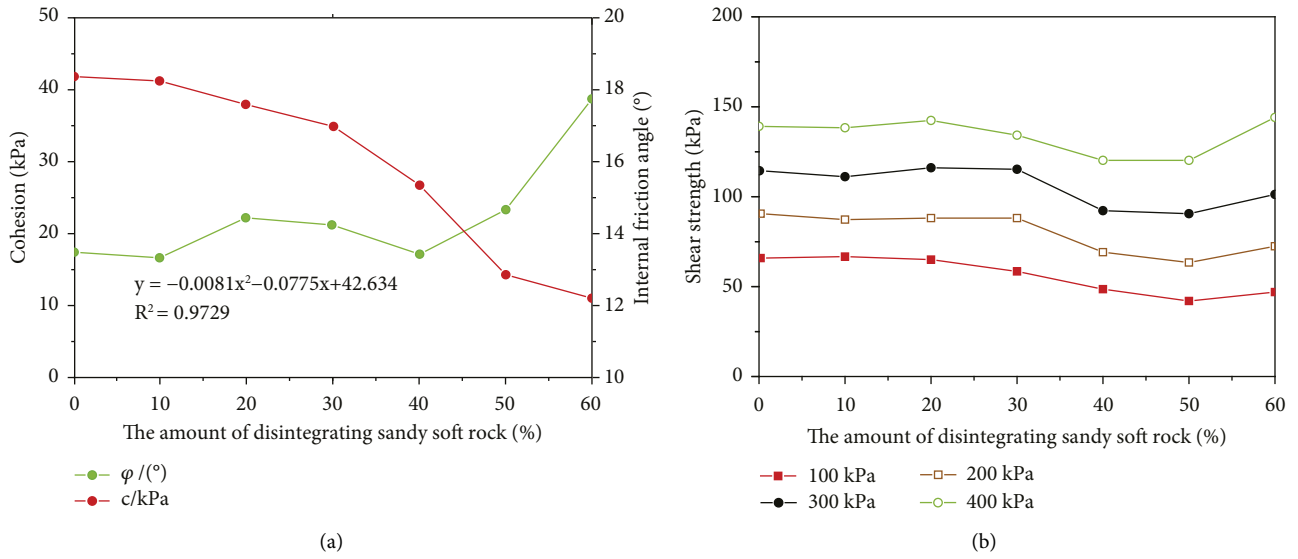


FIGURE 4: Relationship between the dosage and shear strength. (a) Shear strength parameters; (b) shear strength.

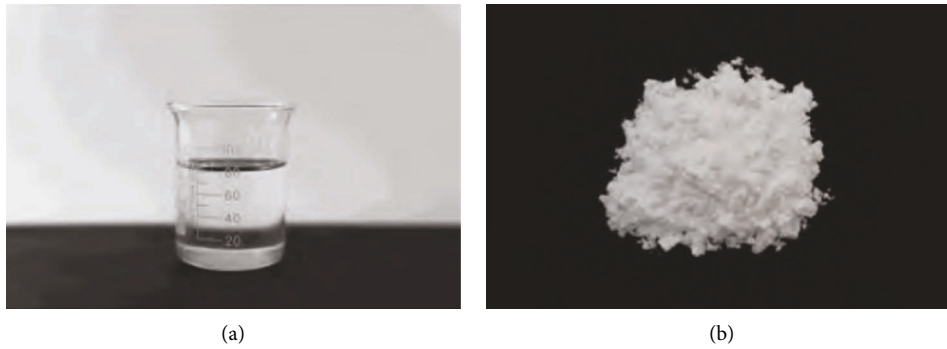


FIGURE 5: Phase change materials. (a) pPCM. (b) mPCM.

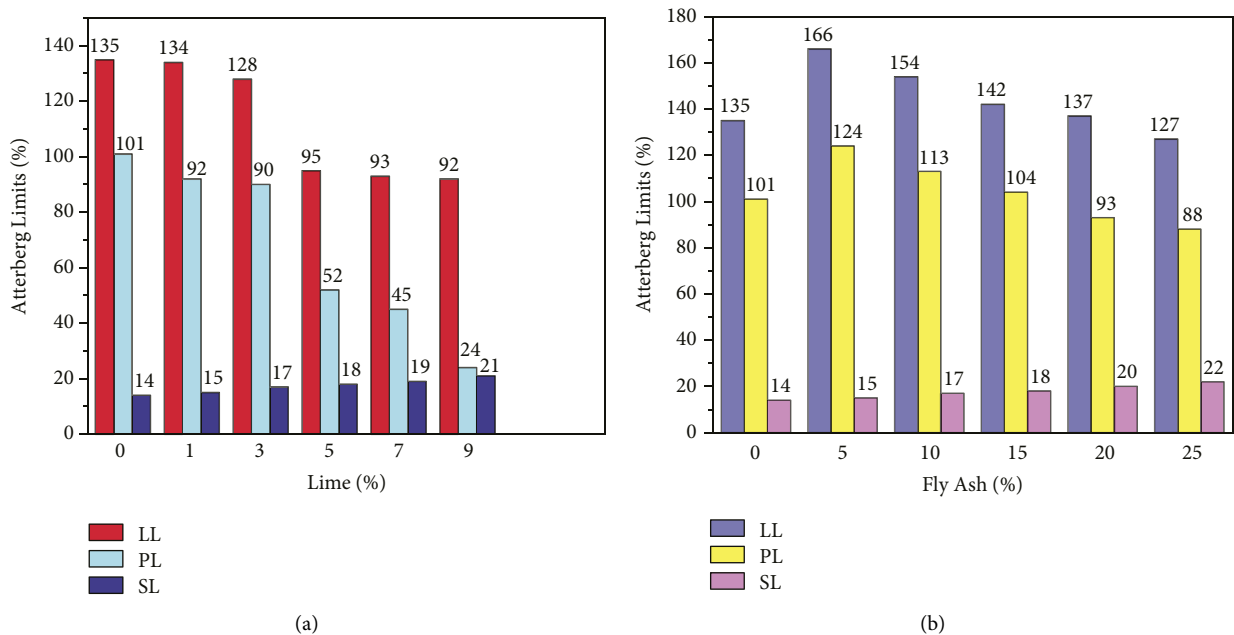


FIGURE 6: Variation in the Atterberg limits, i.e., LL (liquid limit), PI (plasticity index), and SL (shrinkage limit), with increasing lime and fly ash contents. (a) lime; (b) fly ash.

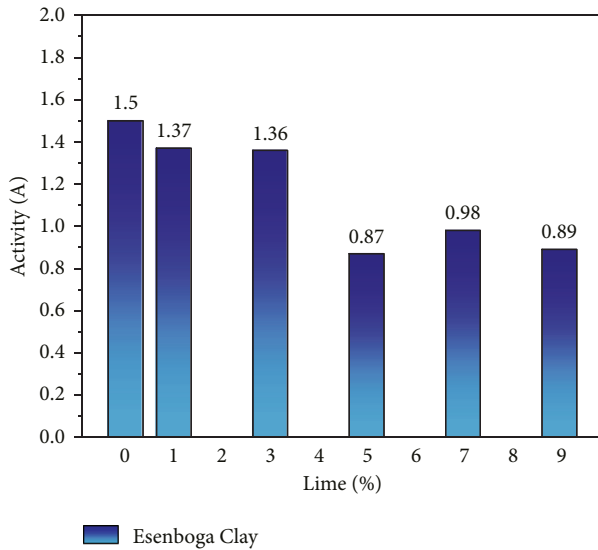


FIGURE 7: Variation in A (activity) with the lime content for Esenboga clay.

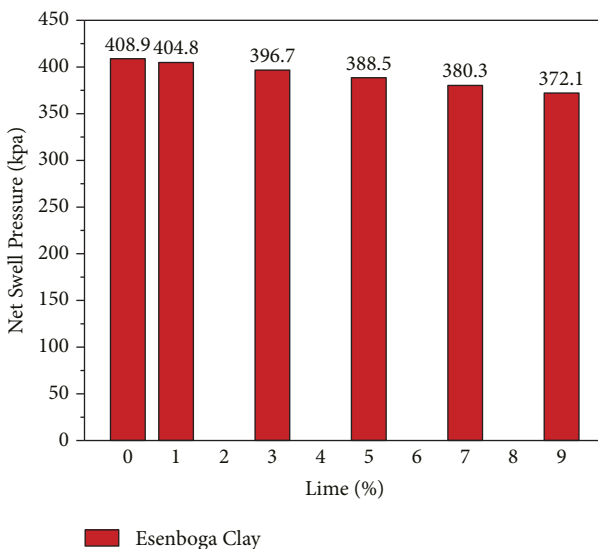


FIGURE 8: Variation in the net swelling pressure with the lime content.

It can be observed that lime and cement are good stabilizers. However, lime and cement are resource materials, and the cost of these materials as stabilizing materials is relatively higher than that of industrial wastes such as fly ash and alkali slag [49]. The characteristics of expansive soils are extremely complex, and the addition of mixed admixture can effectively improve the soil properties and reduce the cost of chemical treatment. Therefore, mixing multiple stabilizers constitutes a current research area of heightened interest for expansive soil improvement [50]. In addition, the improvement in soil properties via chemical reagents should be considered; for example, NaCl solutions can significantly reduce soil swelling within a short period, and the improvement effect is significantly different under various solution concentrations [51]. Cationic modifiers can

reduce the free swelling rate of expansive soil and improve particle size gradation, strength characteristics, and hydrological properties [52].

Expansive soil subgrades are greatly affected by the climate and the environment, so it is necessary to consider various environmental factors, such as dry-wet cycling and freeze-thaw cycling [53]. This could facilitate the study of expansive soil improvement under these environmental conditions. Many scholars have conducted valuable research on this important topic.

Anca et al. compared the mechanical properties of high-plasticity bentonite and low-plasticity kaolinite stabilized by lime under freeze-thaw cycles and concluded that freeze-thaw cycles could affect the durability of improved soils [54]. Tan et al. investigated the evolution trend of the long-term performance of expansive soil subgrades improved with cement under dry-wet/freezing-thaw cycling through field investigations and related experiments [55]. Lu et al. concluded that cement and freeze-thaw cycles achieve the two effects of improvement and aggravation, respectively, and their study conclusions can serve as a guide for the use of cement to improve the frost resistance of expansive soils [56]. The effectiveness of lime and cement in improving expansive soils has been widely verified, but as resource materials, lime and cement are costly, and the properties of improved soils could be greatly affected by freeze-thaw cycling. Based on the above, admixtures consisting of expansive soil, cement, steel slag powder, and NaOH (ES-SSP-C-N) were included in the improvement scheme. The addition of steel slag powder and cement yielded an improving effect on expansive soil, and steel slag powder is an industrial waste material with a low selection cost. NaOH could accelerate the hydration reaction of steel slag powder and cement, stabilize expansive soil, and effectively inhibit the reduction in soil strength and other properties during freeze-thaw cycling [57]. In addition, the improvement effect of this scheme under dry-wet cycling is satisfactory. The specific performance indicates that the strength of the soil samples remained relatively unchanged, and the unconfined compressive strength was higher than that of both the cement-improved expansive soil (ES-C) and steel slag-cement-improved expansive soil (ES-SSP-C) (Figure 9). Adopting ES-SSP-C-N admixtures is an effective improvement method for expansive soils in environments with cyclic dry-wet and freeze-thaw conditions [58].

**2.3.3. Biological Improvement Technology.** Microorganisms are very small organisms with a simple structure that are invisible to the naked eye. The cementation effect of organic mucilage substances and polymers secreted by microorganisms with notable stickiness can produce clusters of powdery, clayey soil particles. Therefore, biological metabolic activities can promote soil particle cementation, and microbial carcasses can function as interparticle filler materials. Theoretically, the use of microorganisms to improve expansive soils is a verified approach, but this option remains at the stage of theoretical analysis and experimental research [35].



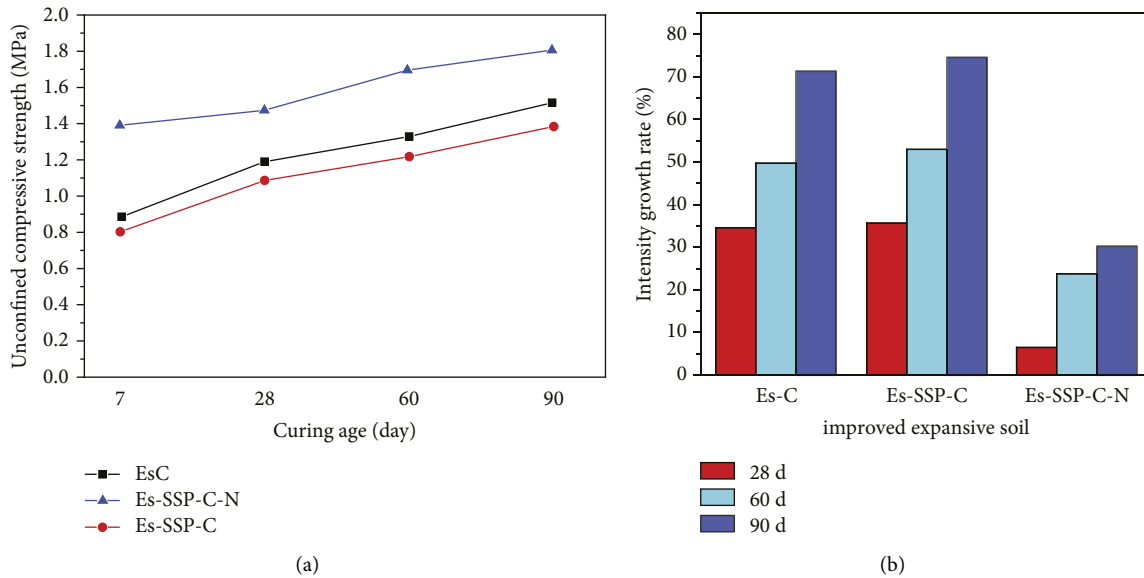


FIGURE 9: Variation in the unconfined compressive strength and rate of improvement with the curing age for various solidified soil specimens. (a) Unconfined compressive strength; (b) rate of improvement in unconfined compressive strength.

Yang et al. first proposed the idea of microbiological technology to improve expansive soil from the perspectives of microbiological chemistry, physics, and engineering geology and considered that the application of micro-technology in expansive soil improvement was theoretically feasible [59]. Subsequently, scholars carried out notable research on this topic. Du et al. obtained specific bacteria with a good improvement effect on the swelling-shrinkage characteristics of expansive soil through screening tests [60]. Ma et al. isolated bacteria that could inhibit the free expansion rate of expansive soil and screened and determined the most effective bacteria for further mitigation of swelling and shrinkage [61]. Based on the Lade-Duncan model, the elastoplastic stress-strain relationship of expansive soil modified by biological enzymes was analysed, and it was considered that biological enzymes could significantly improve the shear and compression resistance of expansive soil [62]. Guar gum biopolymer can possibly control the swelling-shrinkage behaviour of expansive clay, so this biopolymer can be used as a stable geological material. Raju et al. carried out laboratory research on expansive soil treatment with guar gum and verified its superior improvement effect [63].

In conclusion, the microbial improvement method for expansive soil is feasible. The sustainable environmental benefits attributed to the improvement achieved with biopolymers far exceed those of traditional stabilizers [63]. Biological improvement methods achieve more persistent effects than those achieved with physical and chemical improvement methods; these methods also exhibit ecological, safe and economical characteristics, but microbial improvement of expansive soils requires systematic and complex projects. Biological improvement for application in soil improvement programs needs to be further studied.

**2.3.4. Solid Waste Improvement Technology.** In recent years, environmental problems have become increasingly prominent, and solid waste production has increased. Many scholars have focused on the resource utilization of solid waste and have attempted to use solid waste as an improvement material for expansive soil. Phosphorus tailings are solid waste resulting from phosphate ore after beneficiation. When the content of phosphorus tailings is 7%, the dynamic strength of phosphorus tailings-improved expansive soil can be increased by approximately 40 kPa at most, and the increase rate reaches approximately 30% of that of pure expansive soil (Figures 10 and 11, respectively) [64]. Iron tailing sand is an industrial fine-grained waste material generated after beneficiation. This method represents a successful “treat waste with waste” case that uses iron tailings sand as a material to improve expansive soil, and experiments have demonstrated that the optimal rate of iron tailings sand is 30% (Figure 12) [49]. Rational treatment of waste rubber tyres is a current environmental problem. Research has indicated that the addition of ground rubber powder (Figure 13) can effectively reduce the expansion potential and that ground rubber powder can play a major role in expansive soil improvement [65]. In addition, fibrous materials obtained from plastics and glass, such as glass fibres combined with epoxy resin [66] and polypropylene fibres [67], have yielded significant results in improving the properties of fissures and the strength of expansive soils.

The particle morphology and microscopic images of some solid waste materials mentioned above are shown in Figure 13. Quarry dust, which causes environmental pollution and serious health hazards, can also be used as an expansive clay stabilizer. Sudhakar et al. mixed different proportions of quarry dust into expansive clay and determined that the optimal amount of quarry dust was 15%, confirming that the use of expansive clay improved by

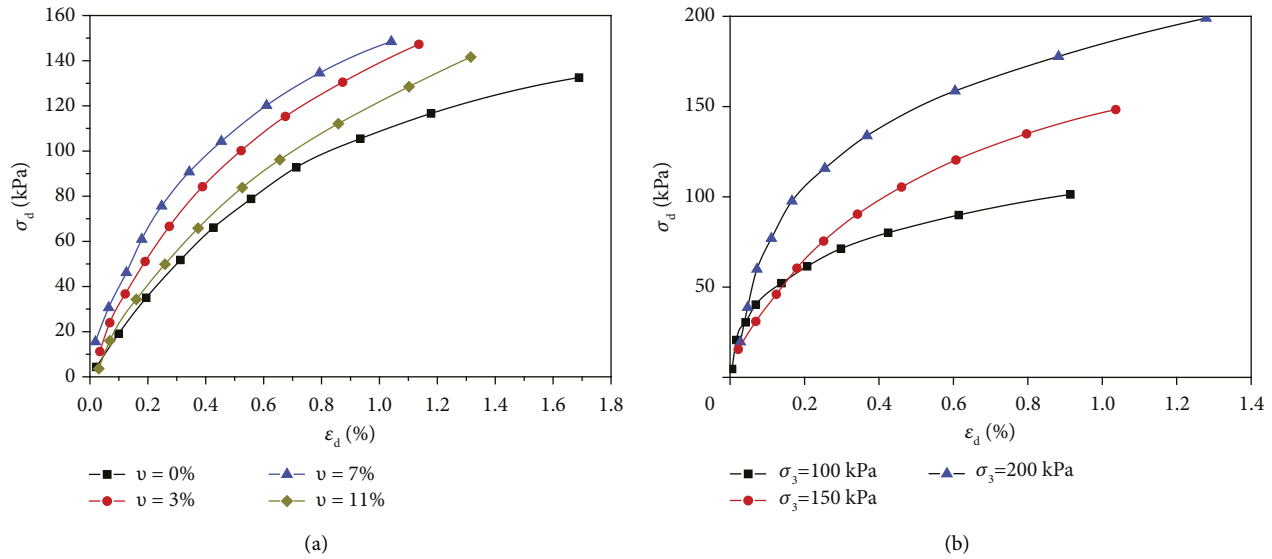


FIGURE 10: Dynamic stress-strain curve. (a)  $\sigma_3 = 150$  kPa; (b)  $v = 7\%$ .

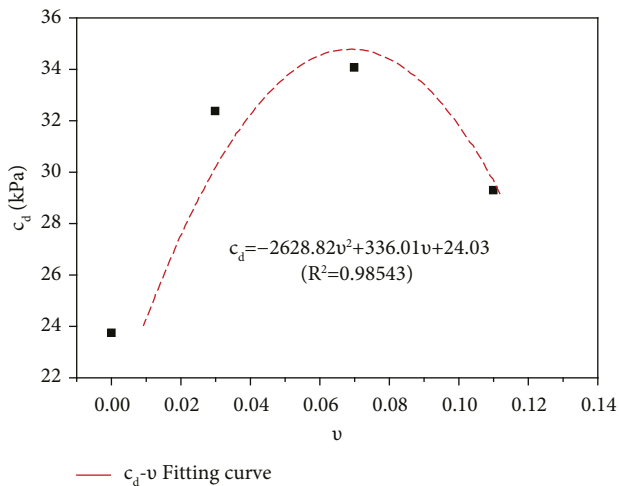


FIGURE 11: Relationship between dynamic strength parameters and iron tailings sand content.

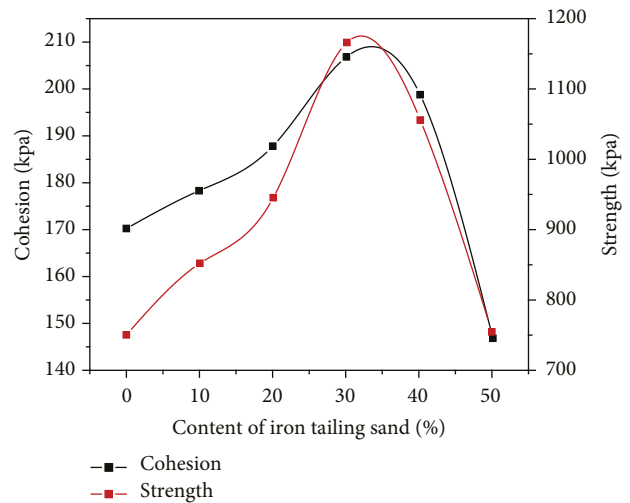


FIGURE 12: Variation in the strength and cohesion of the improved expansive soil with the iron tailings sand content.

quarry dust instead of pure expansive clay as a subgrade could greatly reduce the construction cost of flexible pavement [68]. Cement bypass dust (CBPD) is comparable to cement and better than lime in terms of reducing the plasticity index and swelling potential of expansive soils and thus can be used as an expansive soil stabilizer, and it has been experimentally demonstrated that the optimum content of CBPD is 15% [69].

Calcium lignosulfonate (CLS), a byproduct of the paper industry and a biopolymer, exhibits potential applications as a stabilizer to improve the swelling properties of expansive soils. This stabilizer can not only effectively improve the physical properties of soil, such as the specific surface area and Atterberg limits, but also significantly reduce the cation exchange capacity [70]. Sand-grade recycled glass (RG) can be used as an aggregate to improve the performance of expansive subgrades, and it was found that the use of 30%

RG to treat expanded clay subgrades resulted in a reduction in pavement strain and an improvement in the fatigue and rutting life values [71]. The successful application of the above industrial byproducts in expansive soil subgrades has encouraged the construction industry to consider the use of environmentally clean recycled aggregates (such as RG and CLS) to improve problematic expansive soil subgrades and promote the development of sustainable construction materials and application methods.

Resource utilization of industrial solid waste materials in various industries is a new approach for the improvement and acquisition of expansive soil subgrade filler. The use of these industrial solid waste materials as soil stabilizers not only improves the soil properties but also eliminates the economic and environmental costs of their disposal. However, there remains a need to further improve the solid waste recycling system, such as optimizing the processes,

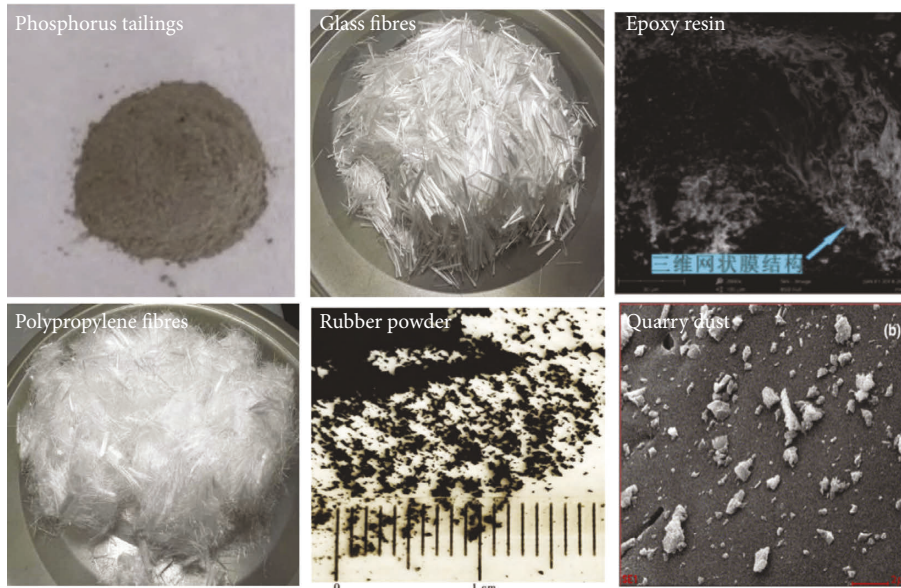


FIGURE 13: Solid waste materials.

machinery, and equipment. Table 5 summarizes the effect and cost analysis of the different improvement methods discussed above. To identify the lowest cost and most efficient treatment of expansive soil improvement, many related topics should still be examined.

### 3. Treatment Technology for Expansive Soil Cutting Slopes

Slope protection or reinforcement methods for expansive soil cutting slopes can be divided into two categories: flexible and rigid support measures. Rigid support mainly relies on the self-weight of the support structure to compensate for the force imbalance in the slope due to excavation and to offset the effect of the expansion force of expansive soil, not allowing soil deformation. In regard to moderately strong and weak expansive soil slopes, frame anchor bolts or flexible retaining walls should be used to mitigate shallow instability. Retaining walls or antislip piles should be used to support deep instability, and plants and lattice structures should be used to protect the slope surface [72]. Flexible support uses synthetic materials such as geotextiles for comprehensive treatment and involves reasonable slope protection measures. This support method allows wall deformation, and the cost is relatively low. In fact, in addition to reasonable support scheme selection, slope surface protection cannot be ignored. The presence of vegetation can improve the soil permeability and greatly reduce the erosion effect of rainwater on slopes [73].

**3.1. Rigid Support.** Common rigid support structures include self-weighted retaining walls, antislip piles, or cantilevered and buttress retaining walls. These structures are usually subject to shear fracture or crush damage due to expansion deformation after wetting of the expansive soil body [74]. Scholars have carried out many studies on this

subject, aiming to establish effective support methods. Liu et al. investigated a highway expansive soil cutting slope and concluded that the foot of the slope was poorly managed by traditional reinforcement methods such as retaining walls and antislip piles [75]. Liu pointed out that the use of fibre-reinforced polymer (FRP) anchor bolts could effectively replace traditional steel anchor bolts for the stable support of expansive soil slopes, and the durability with FRP anchor bolts was higher than with traditional supports [76]. Notably, strong support structures such as pile-slab walls and pile-to-pile retaining walls can restrict the foot instability of expansive soil cutting slopes, but almost all remaining rigid support measures face problems such as structural damage due to lateral expansion pressure and expansion deformation [77]. To counteract the earth pressure and lateral expansion force of expansive soil behind such a wall, engineers have considered emplacing an EPS energy dissipation layer at the back of the retaining wall, which mainly consists of polystyrene foam. Energy dissipation technology for rigid support of expansive soil cutting slopes is an important direction of current development research, and many valuable research data should still be obtained.

**3.2. Flexible Support.** Compared to rigid support, flexible support provides more advantages in terms of engineering cost and does not restrict soil deformation and drainage [78]. The geogrid-reinforced flexible support scheme and the supporting seepage trench + slope foot antislip retaining wall scheme are representative flexible support schemes proposed by Professor Zheng of Changsha University of Science and Technology. Choosing the closure cover and combination of rigidity and flexibility as technical bases, comprehensively considering the problems of waterproofing and drainage, soil slope stability, and slope protection, these schemes can solve the technical problem of slippage under

TABLE 5: Summary of the effect and cost analysis of different improvement methods.

Improvement method	Modifier	Cost analysis	Effect analysis
Physical	1. Weathered sand 2. Fine silica sand 3. Sandy soil and marble waste 4. Sand and expanded polystyrene (EPS)	The cost of physical improvement is lower than that of chemical improvement.	Sand particles have certain hardness and particle size, and the mixing difficulty of sand in expansive soil is obviously less than that of lime, cement, fly ash, and other fine materials in expansive soil. Mixing sand with expansive soil can effectively improve the shear strength of expansive soil, reduce the cohesion of soil, increase the internal friction angle, and reduce soil swelling characteristics; however, physical improvement is slow and inefficient compared to chemical improvement.
	5. Disintegrated sandy soft rock		
Chemical	1. A mixture of activated fly ash ( $\alpha$ -FA) and sisal fibres into expansive soil 2. Slaked lime and fly ash 3. Admixture consisting of fly ash and ground granulated blast furnace slag and lime 4. Slag added into the type I/II Portland cement 5. NaCl solutions 6. Admixtures consisting of expansive soil, cement, steel slag powder, and NaOH (ES-SSP-C-N) 7. Paraffin-based liquid phase change material (pPCM) and paraffin-based microcapsule phase change material (mPCM)	Lime and cement are resource materials, and the cost of these materials as stabilizing materials is higher than that of industrial waste such as fly ash and alkali slag; the cost of some admixtures is relatively low, such as ES-SSP-C-N. In all of the improvement methods, the chemical improvement technology is the most costly, but its treatment effect is the best.	The greatest advantage of chemical improvement is that it can improve the bad engineering properties of expansive soil in essence, and theoretically eliminate the expansion and contraction of expansive soil. It is a hot field in the engineering treatment technology of expansive soil at home and abroad and is widely used.
	1. Put bacteria into the vegetable garden soil, and put moulds and actinomycetes into the organic matter to make solid bacteria, respectively 2. Biological enzymes 3. Guar gum biopolymer  4. Oyster powder		
Biological	1. Put bacteria into the vegetable garden soil, and put moulds and actinomycetes into the organic matter to make solid bacteria, respectively 2. Biological enzymes 3. Guar gum biopolymer	The sustainable environmental benefits attributed to the improvement achieved with biopolymers far exceed those of traditional stabilizers. These methods also exhibit ecological, safe, and economical characteristics. However, this technology is not mature enough for practical application.	Biological metabolic activities can promote the cementation of soil particles, and microbial corpses can also be used as inter particle fillers. Theoretically, it is one of the effective methods to improve expansive soil by microorganism, but microbial improvement of expansive soils requires systematic and complex projects; this approach is still at the stage of theoretical analysis and experimental research.
	4. Oyster powder		
Solid waste	1. Phosphorus tailings 2. Iron tailings sand 3. Waste rubber tires 4. Glass fibres combined with epoxy 5. Resin, polypropylene fibres 6. Quarry dust, cement bypass dust (CBPD) 7. Calcium lignosulfonate (CLS)	The treatment cost of solid waste is reduced, and the cost of expansive soil treatment is low. However, the improvement effect is also poor.	A successful case of “treating waste with waste” that reduces the pollution of solid waste to the environment and achieves resource utilization of solid waste. The modification effect of expansive soil is good, which can effectively improve the fissure property and strength of expansive soil, reduce the expansion potential and plasticity index, and improve the road performance of expansive soil subgrade.
	8. Sand-grade recycled glass (RG)		

every cut in expansive soil areas [74, 79]. Moreover, these schemes have been applied in highways, with good reinforcement effects. A typical design drawing of the geogrid-

reinforced flexible support structure and the treatment engineering effect of the cutting slope in a section of the Nanning outer ring road are shown in Figure 14.

The geogrid-reinforced flexible support method relies on a complete support system, drainage prevention system, and slope vegetation system, which can achieve long-term stability of expansive soil cutting slopes [2]. Moreover, in the construction process of the flexible support structure, expansive soil is backfilled and then compacted in layers and reinforced with a geogrid backpack, which can produce a flexible reinforced support body of a sufficient thickness. This flexible support technology can not only support but also achieve moisturization and impermeability of expansive soil in slopes. Simultaneously, by varying the geogrid reinforcement spacing and length, expansive soil cutting slopes can be optimally designed [80]. The layer-by-layer reverse wrapping structure functions as a frame hoop for the filling soil, which can wrap the cutting slope into a flexible whole body and effectively inhibit slope traction failure [81]. It is important to note that the geogrid reinforcement spacing exerts a notable influence on the stability of expansive soil slopes. The smaller the reinforcement spacing is, the higher the slope stability [82].

**3.3. Ecological Straw Bag Slope Protection.** The use of a soil bag for slope protection is also an effective method to prevent expansive soil slope damage and landslides. The placement of soil bags on the slope surface can counteract the increasing horizontal stress and prevent the sliding of expansive soil slopes [83–85]. Liu et al. conducted field tests of soil bag reinforcement in a 60 m section of an expansive soil/rocky river slope in the South-North Water Transfer Project and concluded that soil bags could significantly and effectively prevent water migration, limiting the swelling potential and improving slope stability. Figure 15 shows a schematic diagram of a slope treated with soil bags [86]. In addition, Deng et al. studied the shallow damage mechanism of channel expansive soil slopes via centrifugal tests based on measured data of a field destabilization section of an expansive soil channel and formulated construction suggestions, such as the adoption of plastic film cover and soil bag pressing slope measures, for slope protection to reduce shallow soil cracking due to moisture dissipation after slope repair completion; in an area with a high degree of fissure development, additional antislip support measures should be appropriately installed [87].

Synthesizing previous studies, Xu et al. proposed a new method for the design of expansive soil slopes based on the balance between the active Earth pressure caused by the friction of soil bags and the expansion pressure of expansive soils, thereby using the balance principle to calculate the height and width of the soil bags to be filled, solving the inaccuracy of empirical determination, proposing soil bag accumulation units for expansive soil slopes of different heights, and reducing the amount of soil bag construction operations [1]. Due to the lack of a soil reinforcement mechanism and poor durability under climate change, soil bag reinforcement has not been widely used in permanent structures in the past [88]. However, with the optimization and improvement of the soil bag reinforcement method, it can be applied in permanent slope protection projects [89].

#### **4. Research Analysis and Development Trend of Expansive Soil Subgrade Treatment Technology**

- (1) During the filling of expansive soil subgrade, the method of soil replacement can cause water and soil erosion and environmental damage, which can lead to engineering geological disasters such as mudslides and landslides. Moreover, this construction method is costly. Soil improvement has always remained a research focus. In recent years, many new improvement materials have been proposed, and the improvement effect has been validated against laboratory soil samples. The use of different materials (such as cement, lime, fly ash, slag, sand, chemical solutions, biological enzymes, fibre, and rubber) to improve the mechanical properties of expansive soil has been proven to be a better method for subgrade construction in expansive soil areas than the method of soil replacement. It reduces not only costs but also environmental pollution. However, to construct an expansive soil subgrade with better quality, the application of soil improvement in subgrade engineering should still be further improved in terms of the required machinery and quality control. Among many new improved materials, the cost of physical improvement technology is low, but the improvement effect is poor. The improvement effect of chemical improvement technology is good, but the cost is relatively high. Biological improvement technology, which exhibits ecological, safe and economical properties, is one of the research directions in recent years. However, due to the complexity of research on biological improvement technology, the improvement effect needs to be further studied and tested, and few in-depth studies have been conducted regarding this improvement scheme, the sustainability benefits of this approach have been consistently ignored. Solid waste improvement of expansive soils is also an environmentally friendly and low-cost method of soil improvement. We have conducted some studies on this method, such as the use of oyster shell powder with high durability and low-cost nature to effectively improve the swelling and strength properties of expansive soil (Figure 16 shows the current research results). Actually, many interesting studies have been derived from various existing soil improvement schemes, and further excavation and research will be performed.

With the increasing maturity of various testing technologies and new materials, the study of new improvement methods that are efficient, low-cost, and environmentally friendly and can solve mechanical problems is one future direction of expansive soil improvement. Moreover, it is necessary to consider the actual replacement conditions when developing new improvement materials for environmental protection and energy savings, based on

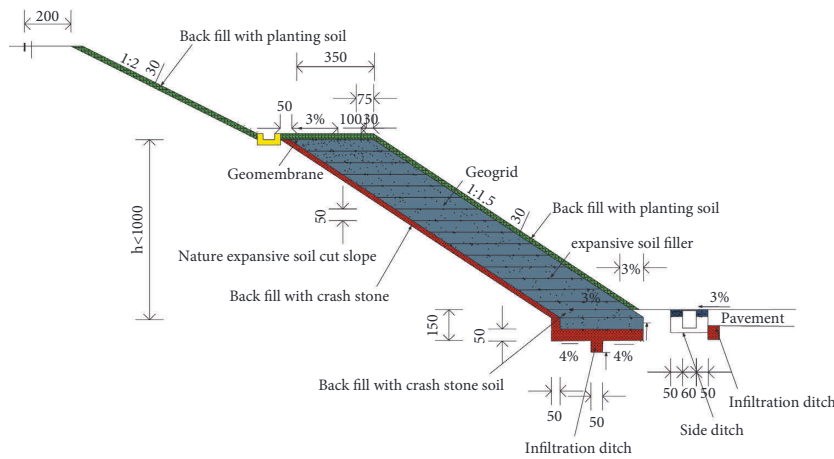


FIGURE 14: Design drawing of the flexible support structure and treatment effect.

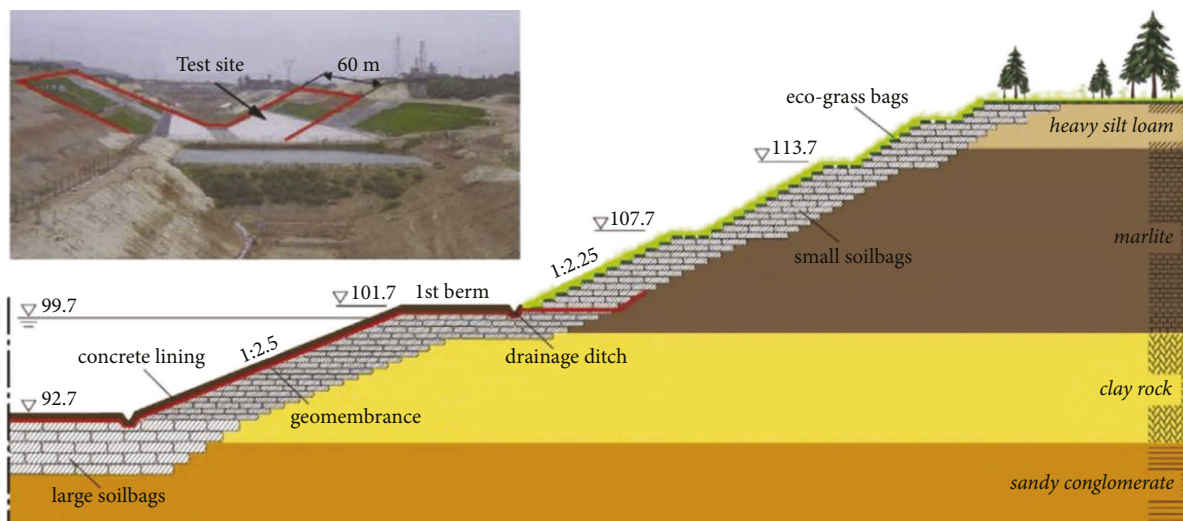


FIGURE 15: Treatment of expansive soil/rock channel slopes with soil bags.

which it is necessary to establish a test section to analyse the road performance after improvement.

- (2) At present, the development of treatment technology for expansive soil embankments and cutting slopes is mature, and the treatment effect of each treatment plan is satisfactory in the short term. Embankment treatment problems have been examined in detail, and many practical solutions have been proposed by researchers. Regarding the problems faced in cutting slope treatment, the traditional rigid support structure achieves a poor ability to resist deformation, and a retaining wall is susceptible to damage due to the high expansion force of the soil behind the structure. Although flexible support technology attains better support performance than rigid support technology, the construction process is complicated. In regard to the problem of rigid support, an EPS

energy dissipation layer can be emplaced at the back of the retaining wall to reduce the lateral pressure of the soil behind the wall and the lateral expansion force of water absorption and expansion, as shown in Figure 17. Polystyrene foam material is often used in the energy dissipation layer, and more suitable energy dissipation materials should be identified. In addition, the above scheme lacks effective field data to enrich the corresponding theoretical protection system.

In current research, rigid and flexible support technologies have been recognized by engineers, and the protection methods for cutting slopes are still being improved. Among these methods, the ecological protection method is one of the current hot research directions, and new ecological slope protection methods are beginning to emerge. As shown



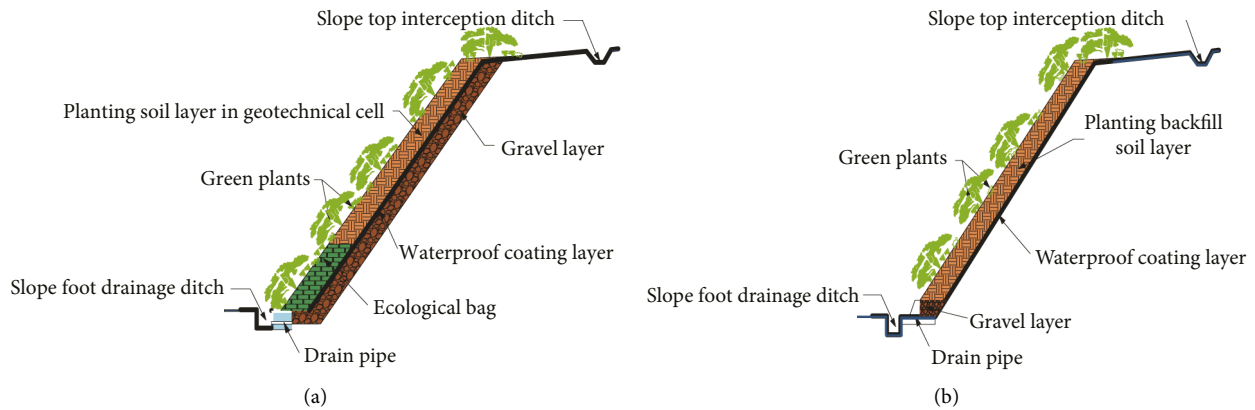


FIGURE 18: New research schemes. (a) Scheme I; (b) Scheme II.

amount of gravel could be solved in this scheme, and the costs could be reduced while meeting protection requirements. The scheme is shown in Figure 18(b).

Figure 19 shows the main construction process of the new ecological slope protection scheme I. This new ecological slope protection scheme combines the respective advantages of rigid and flexible support technologies and overcomes their disadvantages (such as a high cost and difficult construction process). This scheme represents a meaningful development direction of expansive soil cutting slope treatment technology.

- (3) The emergence of artificial intelligence and robot technology provides new solutions in the treatment and evaluation of expansive soils. In the future, machine vision systems can be used to monitor the displacement and deformation of slope surfaces from different angles. An intelligent slope monitoring system with all-weather, high-precision, and full-coverage features can be introduced to collect information at monitoring points in real time, quickly feed the obtained monitoring results back into an analysis, and realize early warning of slope disasters. The combination of measuring robots and low-stress strain gauges to monitor deformation and record and analyse the bearing capacity of slopes can provide a data basis for future slope protection. The introduction of new technology can accelerate construction progress, shorten the construction period, reduce rework and capital investments, and minimize maintenance costs to the greatest extent in the future. Therefore, maximizing the advantages of the combination of artificial intelligence and expansive soil subgrade engineering is a very meaningful research direction.

## 5. Conclusion

- (1) In embankment protection engineering in expansive soil areas, the principles of water separation, moisture preservation, and seepage prevention are the

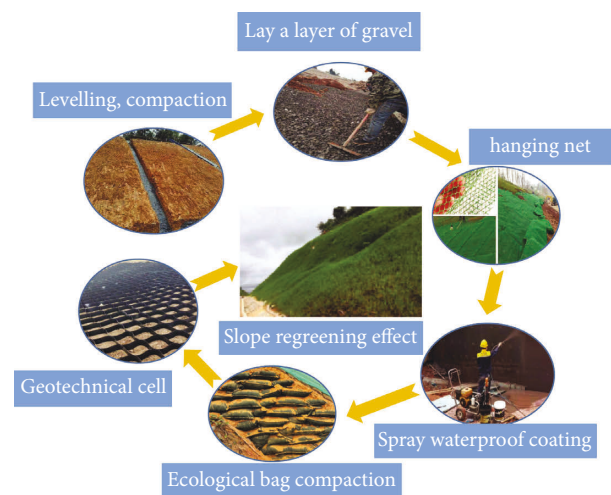


FIGURE 19: Implementation process of the new scheme.

focus of research. Most treatment schemes focus on preventing rainwater infiltration and impeding water migration in multifissure soil. In fact, under the condition of ensuring that the soil strength is not affected by water, improvement in the properties of core-filled expansive soil is the focus of embankment protection engineering.

- (2) After reasonable classification of the expansive soil properties, a certain level of weak expansive soil can be directly used as subgrade filler, while for moderately strong and strong expansive soil, appropriate materials can be used for modification of the soil. The improved expansive soil can then be used as a subgrade filler, which can not only solve the problem of water and soil loss due to waste but also reduce the cost of borrowing soil.
- (3) Expansive soil improvement is no longer limited to traditional ash mixing improvement technology. New improvement materials, such as phase change materials, solid waste materials, chemical reagents, and biological enzymes, can be applied, which could ensure the improvement effect and save costs. The purpose of using solid waste as an improvement



admixture is to better utilize resources and reduce engineering costs. The sustainable benefits of biological improvement are high, and the long-term ecological, safety, and economic effects of biological improvement cannot be ignored. However, there are few research results and many research limitations, and the effect of biological improvement technology needs to be verified by performing more experiments and applications.

- (4) Rigid support structures of an expansive soil cutting slope exhibit the disadvantages of high cost, susceptibility to damage, unsatisfactory support effect, and inability to allow deformation. In contrast, flexible support technology can allow slope deformation and is less costly, but the construction process is complex. New ecological bag protection schemes and EPS energy dissipation technology to overcome the disadvantages of rigid supports that do not allow deformation are a focus of research.
- (5) The treatment of expansive soil subgrades entails projects that require time and capital to assess. At present, there are few studies on the engineering life and actual road properties of flexible and rigid support technologies, and there are few discussions on engineering maintenance schemes. It is necessary to focus on these aspects in the future. In addition, artificial intelligence and robot technology can yield new solutions to treatment technology and the evaluation of expansive soils.

### Data Availability

The data used in this review are obtained from the corresponding articles, and we cited these articles in the references.

### Conflicts of Interest

The authors declare that they have no conflicts of interest or personal relationships that could have appeared to influence the work reported in this paper.

### Authors' Contributions

Z. Huang investigated the study, developed methodology, reviewed and edited the manuscript, and acquired funding. H. Shi investigated the study, wrote the original draft, and analysed the data. W. Zhang investigated the study, reviewed and edited the manuscript, and acquired funding. S.K. Ma investigated the study and analysed the data. F. Gao investigated the study and analysed the data. M. Ma also investigated the study.

### Acknowledgments

This work was supported by the Guangxi Science and Technology Base and Talent Special Project (No. AD21220039), Guangxi Natural Science Foundation (No.

2021JJB160110), and Guangxi Postgraduate Education Innovation Programme (No. YCSW2022071).

### References

- [1] Y. F. Xu and H. R. Zhang, "Design of soilbag-protected slopes in expansive soils," *Geotextiles and Geomembranes*, vol. 49, no. 4, pp. 1036–1045, 2021.
- [2] H. P. Yang, Y. Y. Li, and J. Xiao, "Soil erosion caused by highway construction in swelling soil area and its effective treatment technology," in *Proceedings of the 2011 Conference on Applied Information Technology (AASRI-AIT 2011)*, pp. 126–129, Noida, India, December 2011.
- [3] L. Fang, B. H. Tang, M. J. Xu, and F. Jiang, "Discrimination and classification of the expansibility of the highway subgrade filler," *Journal of Highway and Transportation Research and Development*, vol. 22, pp. 31–34, 2005.
- [4] Y. C. Li, "Study on comprehensive popularization and application of new treatment technology of expansive soil subgrade in nanning outer ring road," *Transportation Planning, Survey, Design and Research Institute of Guangxi Zhuang Autonomous Region*, Nanning, China, 2015.
- [5] B. Zheng and G. L. Yang, *Preliminary Discussion on Bearing Ratio Test of Expansive Soil*, pp. 42–43, Exploration Engineering, West-China, 2005.
- [6] H. P. Yang, P. C. Zhao, and J. L. Zheng, "Suggestion and verification on modified CBR test method for expansive soils fill," *Chinese Journal of Geotechnical Engineering*, vol. 29, pp. 1751–1757, 2007.
- [7] C. Tong and H. P. Yang, "The swelling behavior of expansive soil is evaluated by its internal specific surface and pore size distribution," *Journal of China and Foreign Highway*, vol. 37, no. 1, pp. 209–215, 2017.
- [8] W. L. Zou, J. G. Lin, and Z. Han, "Progress on strengthening techniques for expansive soil slopes," *Journal of Central South University*, vol. 53, no. 1, pp. 126–139, 2022.
- [9] C. Mao and Y. J. Qiu, "Testing study on dynamic properties of expansive soil and improved expansive soil," *Chinese Journal of Rock Mechanics and Engineering*, vol. 24, pp. 1783–1788, 2005.
- [10] X. P. Yu, H. B. Xiao, Z. Y. Li, J. Qian, S. Luo, and H. Su, "Experimental study on microstructure of unsaturated expansive soil improved by MICP method," *Applied Sciences*, vol. 12, no. 1, p. 342, 2021.
- [11] S. Y. Lei and H. Q. Hui, "Dynamostatic analysis of properties of expansive soil and improved soil," *Chinese Journal of Rock Mechanics and Engineering*, vol. 23, pp. 3003–3008, 2004.
- [12] Z. J. Wang and J. B. Liang, "Engineering characteristics of expansive soil and its improved research development," *Advanced Materials Research*, vol. 884–885, pp. 657–661, 2014.
- [13] M. W. Wang, K. Ge, and D. R. Zhu, "Experimental study of engineering behaviors on improved expansive soils in the Xinqiao airport runway of Hefei," *Advanced Materials Research*, vol. 261–263, pp. 1329–1335, 2011.
- [14] C. Yan, Y. Liu, and Z. W. Huang, "Comprehensive application of root pile + CMA mixed solution in the treatment of expansive soil cutting slope," *Journal of Chongqing Jianzhu University*, vol. 25, pp. 69–73, 2006.
- [15] R. Q. Huang and L. Z. Wu, "Stability analysis of unsaturated expansive soil slope," *Earth Science Frontiers*, vol. 14, no. 6, pp. 129–133, 2007.
- [16] R. Yang, P. W. Xiao, and S. C. Qi, "Analysis of slope stability in unsaturated expansive soil: a case study," *Frontiers of Earth Science*, vol. 7, 2019.

- [17] K. Teng, G. L. Yang, and Y. L. Yi, "Global stability analysis method of flexible cutting slope protection," *Journal of Central South University*, vol. 46, pp. 3907–3913, 2015.
- [18] F. E. Jalal, Y. F. Xu, B. Jamhiri, and S. A. Memon, "On the recent trends in expansive soil stabilization using calcium-based stabilizer materials (CSMs): a comprehensive review," *Advances in Materials Science and Engineering*, vol. 2020, Article ID 1510969, 23 pages, 2020.
- [19] C. C. Ikegwuani and D. C. Nwonu, "Emerging trends in expansive soil stabilisation: a review," *Journal of Rock Mechanics and Geotechnical Engineering*, vol. 11, no. 2, pp. 423–440, 2019.
- [20] H. P. Yang, P. C. Zhao, and J. L. Zheng, "Classification of expansive soils used as embankment fills," *Chinese Journal of Geotechnical Engineering*, vol. 31, pp. 194–202, 2009.
- [21] C. Standard, *Specifications for Design of Highway Subgrades*, Ministry of Transport of the People's Republic of China, Beijing, China, JTG D. 30-2015, 2015.
- [22] D. G. Fredlund and H. Rahardjo, *Soil Mechanics for Unsaturated Soils*, Wiley-Interscience, Hoboken, NJ, USA, 1997.
- [23] Z. H. Qing, *Field Experimental Study on Swelling and Strength Characteristics of Expansive Soil in Yunnan-Guangxi Railway*, pp. 1–113, Central South University, Changsha, China, 2013.
- [24] M. S. Khan, M. Nobahar, J. Ivoke, and F. Amini, *Rainfall Induced Shallow Slope Failure over Yazoo clay in mississippi*, Geotechnical Special Publication, no. 302, pp. 153–162, Dallas, TX, 2018.
- [25] Q. Y. You, "Numerical simulation of the stability of added lime expansive soils embankment," *Advanced Materials Research*, vol. 838–841, pp. 821–824, 2013.
- [26] H. P. Yang, G. F. Zhang, J. L. Zheng, P. C. Zhao, and Y. X. He, "Physical treating techniques of highway embankments filled with expansive soils," *Chinese Journal of Geotechnical Engineering*, vol. 31, pp. 491–500, 2009.
- [27] H. P. Yang and G. F. Zhang, "Appropriate wrapping width of expansive soil embankment built by enveloping method," *Journal of Highway and Transportation Research and Development*, vol. 25, pp. 37–42, 2008.
- [28] J. L. Zheng, *Study on Complete Set Technology of Highway Construction in Expansive Soil Area*, Changsha University of Technology (Hunan Province), Changsha, China, 2007.
- [29] A. J. Chen, J. S. Zhang, L. Y. Peng, and Z. H. Ren, "Indoor experimental research on the unconfined compressive strength of lime improving expansive clay," *Advanced Materials Research*, vol. 250–253, pp. 2296–2301, 2011.
- [30] M. Mahedi, B. Cetin, and D. J. White, "Performance evaluation of cement and slag stabilized expansive soils," *Transportation Research Record*, vol. 2672, no. 52, pp. 164–173, 2018.
- [31] B. A. Mir and A. Sridharan, "Mechanical behaviour of fly-ash-treated expansive soil," *Proceedings of The Institution of Civil Engineers-Ground Improvement*, vol. 172, no. 1, pp. 12–24, 2019.
- [32] B. R. P. Kumar and R. S. Sharma, "Effect of fly ash on engineering properties of expansive soils," *Journal of Geotechnical and Geoenvironmental Engineering*, vol. 130, pp. 764–767, 2004.
- [33] M. Mahedi, B. Cetin, and D. J. White, "Cement, lime, and fly ashes in stabilizing expansive soils: performance evaluation and comparison," *Journal of Materials in Civil Engineering*, vol. 32, no. 7, 2020.
- [34] S. N. Wang, *Study on Treatment Effect of Expansive Soil Filler for Subgrade of First-Class Highway*, Transpword, New Zealand, Oceania, pp. 103–104, 2021.
- [35] X. J. Hu and Y. Z. Wu, "Summarizing on improvement technology research of expansive soil," *Journal of Hefei University(Natural Sciences)*, vol. 24, pp. 80–85, 2014.
- [36] J. Yang, L. Tong, G. D. Zhang, Y. W. Tang, and H. P. Chen, "Effect of initial moisture content and improved material amount on shear strength of expansive soil," *Advances in Science and Technology of Water Resources*, vol. 34, pp. 39–43, 2014.
- [37] M. Y. Huang, J. L. Xiong, J. B. Tang, and C. Long, "Experimental study on shear strength of expansive soil improved by lime-weathered sand," *Applied Mechanics and Materials*, vol. 446–447, pp. 1441–1447, 2013.
- [38] J. Yang, J. L. Wang, G. D. Zhang, Y. W. Tang, and Z. G. Xie, "Comparative experiment research on different material improvement to the influence of expansive soil expandability," *Advanced Materials Research*, vol. 598, pp. 574–579, 2012.
- [39] N. Hudyma and B. B. Avar, "Changes in swell behavior of expansive clay soils from dilution with sand," *Environmental and Engineering Geoscience*, vol. 12, no. 2, pp. 137–145, 2006.
- [40] S. Oncu and H. Bilsel, "Utilization of waste marble to enhance volume change and strength characteristics of sand-stabilized expansive soil," *Environmental Earth Sciences*, vol. 77, no. 12, p. 461, 2018.
- [41] S. B. Ikizler, M. Aytakin, and M. Vekli, "Reductions in swelling pressure of expansive soil stabilized using EPS geofabric and sand," *Geosynthetics International*, vol. 16, no. 3, pp. 216–221, 2009.
- [42] G. W. Li, Q. Q. Gong, T. Li, J. T. Wu, W. Chen, and X. S. Cao, "Experimental study on properties of weak expansive soil improved by disintegrated sandstone," *Journal of Engineering Geology*, vol. 29, pp. 34–43, 2021.
- [43] Y. H. Huang, Y. Chen, X. Zhu et al., "Experimental study and micro-mechanism analysis of freezing-thawing performance of expansive soil improved by phase change materials," *Chinese Journal of Geotechnical Engineering*, vol. 43, pp. 1994–2002, 2021.
- [44] F. I. Aneke, M. M. H. Mostafa, and W. El Kamash, "Pre-compression and capillarity effect of treated expansive subgrade subjected to compressive and tensile loadings," *Case Studies in Construction Materials*, vol. 15, Article ID e00575, 2021.
- [45] American Coal Ash Association, "Fly ash facts for highway engineers," FHWA Report Washington D.C. No: FHWA-IF-03-019, American Coal Ash Association, Farmington Hills, MI, USA, 2003.
- [46] İ. Süt Ünver, M. A. Lav, and E. Cokca, "Improvement of an extremely highly plastic expansive clay with hydrated lime and fly ash," *Geotechnical & Geological Engineering*, vol. 39, no. 7, pp. 4917–4932, 2021.
- [47] A. K. Sharma and P. V. Sivapullaiah, "Swelling behaviour of expansive soil treated with fly ash-GGBS based binder," *Geomechanics and Geoengineering*, vol. 12, no. 3, pp. 191–200, 2017.
- [48] E. U. Eyo, S. J. Abbey, S. Ngambi, E. Ganjian, and E. Coakley, "Incorporation of a nanotechnology-based product in cementitious binders for sustainable mitigation of sulphate-induced heaving of stabilised soils," *Engineering Science and Technology, an International Journal*, vol. 24, no. 2, pp. 436–448, 2021.
- [49] H. Zhao, C. F. Chu, K. L. Guo, and H. Ye, "Experimental analysis of the basic engineering properties of expansive soils improved tailings sand," *Journal of Civil, Architectural & Environmental Engineering*, vol. 39, pp. 98–104, 2017.

- [50] B. H. Ma, K. Cai, X. Zeng et al., "Experimental study on physical-mechanical properties of expansive soil improved by multiple admixtures," *Advances in Civil Engineering*, vol. 2021, Article ID 5567753, 15 pages, 2021.
- [51] G. M. H. Makeen, S. A. Awad, and H. Dilawar, "Amelioration of soil expansion using sodium chloride with long-term monitoring of microstructural and mineralogical alterations," *Arabian Journal for Science and Engineering*, vol. 46, no. 5, pp. 4461–4476, 2021.
- [52] Z. Q. Li, L. Fu, F. Xie, R. J. Tan, Y. P. Wang, and D. Zhong, "Experimental study on expansive soil improved with cation modifier," *Advanced Materials Research*, vol. 197–198, pp. 1005–1009, 2011.
- [53] Z. T. Zeng, H. B. Lu, and Y. L. Zhao, "Wetting-drying effect of expansive soils and its influence on slope stability," *Applied Mechanics and Materials*, vol. 170–173, pp. 889–893, 2012.
- [54] A. Hotineanu, M. Bouasker, A. Aldaood, and M. Al-Mukhtar, "Effect of freeze-thaw cycling on the mechanical properties of lime-stabilized expansive clays," *Cold Regions Science and Technology*, vol. 119, pp. 151–157, 2015.
- [55] W. Tan, G. K. Liu, and S. Q. Wang, "Study on long-term property evolution law of subgrade cement improved expansive soil," *Highway Engineer*, vol. 46, pp. 149–155, 2021.
- [56] Y. Lu, S. H. Liu, Y. G. Zhang, Z. Li, and L. Xu, "Freeze-thaw performance of a cement-treated expansive soil," *Cold Regions Science and Technology*, vol. 170, Article ID 102926, 2020.
- [57] Y. K. Wu, X. L. Qiao, X. B. Yu, J. L. Yu, and Y. F. Deng, "Study on properties of expansive soil improved by steel slag powder and cement under freeze-thaw cycles," *KSCE Journal of Civil Engineering*, vol. 25, no. 2, pp. 417–428, 2020.
- [58] Y. K. Wu, K. J. Shi, Y. Han, T. Han, J. L. Yu, and D. D. Li, "Experimental study on strength characteristics of expansive soil improved by steel slag powder and cement under dry-wet cycles," *Iranian Journal of Science and Technology-Transactions of Civil Engineering*, vol. 45, no. 2, pp. 941–952, 2020.
- [59] H. P. Yang, Y. X. He, and W. W. Jiang, "Present situation of microbial influence on geotechnical engineering and thoughts on improving expansive soil with microbial technology," *Journal of China and Foreign Highway*, vol. 27, pp. 228–231, 2007.
- [60] J. Du and D. Zhou, "Experimental study on improvement of expansive soil with microbe," *Water Resources and Hydro-power Engineering*, vol. 43, pp. 103–105, 2012.
- [61] G. T. Ma, J. L. Xu, D. Zhou, and J. Du, "Isolation and screening of improved expansive soil strains and their characteristics," *Journal of Guangxi University (Science and Technology)*, vol. 32, pp. 70–74, 2007.
- [62] C. P. Wen, "Study on elasto-plastic constitutive relation of bioenzyme-treated expansive soil based on LADE-DUNCAN model," *Journal of Central South University*, vol. 52, pp. 4190–4200, 2021.
- [63] R. Acharya, A. Pedarla, T. V. Bheemasetti, and A. J. Puppala, "Assessment of guar gum biopolymer treatment toward mitigation of desiccation cracking on slopes built with expansive soils," *Transportation Research Record Journal of the Transportation Research Board*, vol. 2657, no. 1, pp. 78–88, 2017.
- [64] X. S. Zhuang, T. Zhuang, G. L. Tao, H. W. Zhao, and W. X. Li, "Experimental study on dynamic deformation and dynamic strength of expansive soil modified by phosphorus tailings," *Chinese Journal of Rock Mechanics and Engineering*, vol. 39, pp. 3032–3038, 2020.
- [65] A. Soltani, A. Deng, A. Taheri, and M. Mirzababaei, "Rubber powder-polymer combined stabilization of south australian expansive soils," *Geosynthetics International*, vol. 25, no. 3, pp. 304–321, 2018.
- [66] C. Yuan, Z. Zhou, J. M. Zhang, S. F. Wang, and K. Xu, "Experimental study on strengthening mechanism of adding epoxy resin and glass fiber to cement modified expansive soil," *Engineering Journal of Wuhan University*, vol. 54, pp. 709–716, 2021.
- [67] X. G. Wang, B. Hu, Y. L. Liu, and H. M. Tang, "Test of expansive soil roadbed improving with fiber materials and numerical simulation analysis," *Advanced Materials Research*, vol. 163–167, pp. 734–739, 2010.
- [68] S. Sudhakar, E. Duraisekaran, G. Dilli Vignesh, and G. D. Kanna, "Performance evaluation of quarry dust treated expansive clay for road foundations," *Iranian Journal of Science and Technology-Transactions of Civil Engineering*, vol. 45, no. 4, pp. 2637–2649, 2021.
- [69] Y. Mohamedzein, H. Hassan, and K. Al-Hashmi, "Effect of cement-by-pass dust stabilized-expansive soil subgrade on pavement rutting," *Innovative Infrastructure solutions*, vol. 7, no. 1, p. 63, 2022.
- [70] M. T. Fernandez, S. Orlandi, M. Codevilla, T. M. Pique, and D. Manzanal, "Performance of calcium lignosulfonate as a stabiliser of highly expansive clay," *Transportation Geotechnics*, vol. 27, Article ID 100469, 2021.
- [71] E. Yaghoubi, M. Yaghoubi, M. Guerrieri, and N. Sudarsanan, "Improving expansive clay subgrades using recycled glass: resilient modulus characteristics and pavement performance," *Construction and Building Materials*, vol. 302, Article ID 124384, 2021.
- [72] Z. Z. Ding, Y. R. Zheng, J. L. Wang, and L. S. Li, "Comprehensive treatment technique of a cut slope in expansive soils area," *Industrial Construction*, vol. 37, no. 60–65, p. 85, 2007.
- [73] X. W. Li, L. W. Kong, and A. G. Guo, "Effects and correlation analysis of infiltration velocity of expansive soil cut slope," *Rock and Soil Mechanics*, vol. 30, pp. 1291–1296, 2009.
- [74] J. Xiao, H. P. Yang, J. H. Zhang, and X. Y. Tang, "Surficial failure of expansive soil cutting slope and its flexible support treatment technology," *Advances in Civil Engineering*, vol. 2018, Article ID 1609608, 13 pages, 2018.
- [75] L. W. Liu, J. L. Zheng, and W. Liao, "Researches on characteristics of swell and shrinking active zone of expansive soil and failure mechanism of landslides," *Chinese Journal of Geotechnical Engineering*, vol. 30, pp. 28–33, 2008.
- [76] X. J. Liu, "Comparative study on expansive soil steep slope FRP materials bolt support," *Applied Mechanics and Materials*, vol. 454, pp. 250–254, 2013.
- [77] R. Zhang, Z. N. Liu, J. L. Zheng, and J. H. Zhang, "Experimental evaluation of lateral swelling pressure of expansive soil fill behind a retaining wall," *Journal of Materials in Civil Engineering*, vol. 32, no. 2, 2020.
- [78] H. P. Yang, L. P. Lin, and Y. X. He, "Soil erosion caused by highway construction in expansive soils districts and its prevention measures," *Geotechnical Engineering for Disaster Mitigation and Rehabilitation*, Springer, Berlin, Heidelberg, 2008.
- [79] J. L. Zheng, *Study on Design and Construction Technology of Expansive Soil Cutting Slope of Expressway*, Henan Nanyang Expressway Co., Ltd, Nanyang, China, 2007.
- [80] R. Zhang, M. X. Long, T. Lan, J. L. Zheng, and C. Geoff, "Stability analysis method of geogrid reinforced expansive soil slopes and its engineering application," *Journal of Central South University*, vol. 27, pp. 1965–1980, 2020.

- [81] B. Cheng, *Numerical Simulation Analysis of Reinforced Expansive Soil Slope Stability Considering Grid Reverse Envelope*, pp. 1–84, Changsha University of Science and Technology, Changsha, China, 2012.
- [82] G. Y. Chen, P. He, G. Wang, S. Q. Sun, and J. Xiao, “Shallow layer destruction law of expansive soil slope under rainfall and the application of geogrid reinforcement,” *Geofluids*, vol. 2021, Article ID 6636894, 14 pages, 2021.
- [83] S. H. Liu, F. Q. Bai, Y. S. Wang, S. Wang, and Z. Li, “Treatment for expansive soil channel slope with soilbags,” *Journal of Aerospace Engineering*, vol. 26, no. 4, pp. 657–666, 2013.
- [84] L. J. Wang, S. H. Liu, and B. Zhou, “Experimental study on the inclusion of soilbags in retaining walls constructed in expansive soils,” *Geotextiles and Geomembranes*, vol. 43, no. 1, pp. 89–96, 2015.
- [85] Y. F. Xu and J. Huang, “Case study on earth reinforcement using soilbags,” *Geosynthetics in civil and environmental engineering*, Springer, Berlin, Heidelberg, pp. 597–602, 2008.
- [86] S. H. Liu, Y. Lu, L. P. Weng, and F. Q. Bai, “Field study of treatment for expansive soil/rock channel slope with soilbags,” *Geotextiles and Geomembranes*, vol. 43, no. 4, pp. 283–292, 2015.
- [87] M. J. Deng, Z. Y. Cai, X. Zhu, and C. Zhang, “Failure mechanism and reinforcement measures of shallow slopes of expansive soils in Northern Xinjiang,” *Chinese Journal of Geotechnical Engineering*, vol. 42, pp. 50–55, 2020.
- [88] Y. Q. Wang, K. Liu, X. Li et al., “Experimental and upper-bound study of the influence of soilbag tail length on the reinforcement effect in soil slopes,” *Geotextiles and Geomembranes*, vol. 47, no. 5, pp. 610–617, 2019.
- [89] Y. F. Xu, J. Huang, Y. J. Du, and D. A. Sun, “Earth reinforcement using soilbags,” *Geotextiles and Geomembranes*, vol. 26, no. 3, pp. 279–289, 2008.