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# Experimental Study on the Enhancement of Physical Properties of Expansive Soil Utilizing Calcium Carbide Slag-Zeolite Powder Composite

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***Abstract:*** *To mitigate engineering challenges caused by the expansion and contraction properties of expansive soils while achieving resource utilization of industrial solid waste calcium carbide slag, this study employed a composite improvement mixture of calcium carbide slag and zeolite powder to modify expansive soils. Comprehensive tests were conducted on the modified soils, including compaction tests, free swelling ratio, unloading expansion rate, and unconfined compressive strength, to investigate the variation patterns of expansion/contraction behavior and unconfined compressive strength under different curing periods and additive dosages of calcium carbide slag-zeolite powder (C-ZP) mixture. The results demonstrated that increasing the total dosage of calcium carbide slag and zeolite powder progressively elevated the optimal moisture content of the modified soil while reducing its maximum dry density; both free swelling ratio and unloading expansion rate decreased with higher dosages, with the composite modification exhibiting superior performance compared to single additive applications. The use of C-ZP significantly enhanced the early-stage strength of expansive soils, with the highest unconfined compressive strength and optimal material utilization achieved at dosages of 8% calcium carbide slag and 9% zeolite powder.*

***Keywords:*** *Expansive Soil, Calcium Carbide Slag, Zeolite Powder, Physical Properties, Swelling and Shrinkage Behavior, Unconfined Compressive Strength*

## 1. Introduction

Expansive soil is a highly plastic clay rich in hydrophilic clay minerals (such as montmorillonite and illite), exhibiting distinct expansion and contraction characteristics upon water contact—expanding when wet and contracting when dehydrated [1]. During construction projects such as highways, railways, and water conservancy works in expansive soil areas, failure to apply proper treatment often leads to severe engineering issues including subgrade cracking, slope instability, and uneven settlement of structures [2]. Therefore, soil improvement is essential for ensuring structural stability in these regions. Current methods of expansive soil improvement primarily include physical, chemical, and biological approaches. Physical improvement involves mechanical treatments without chemical reactions, such as adding fibers, waste rock powder, weathered sand [3][4][5], or performing replacement filling and dynamic compaction to achieve desired engineering conditions. Chemical improvement entails adding additives like cement, fly ash, or lime [6][7][8], which modify the soil's properties through chemical reactions to reduce expansiveness and enhance strength. Biological improvement utilizes microorganisms or enzymes to induce calcium carbonate precipitation, thereby improving soil performance [9][10]. Among these methods, chemical modification is the most widely used due to its significant effectiveness and ease of application. However, common modifiers (such as cement and lime) not only consume substantial energy during production but also generate harmful gases and waste residues, causing irreversible damage to the ecological environment. Therefore, developing an economical, environmentally friendly, and efficient modification material remains a key focus of current research. In recent years, with the ongoing advancement of sustainable development concepts, utilizing industrial solid waste materials to modify expansive soil has increasingly become a research hotspot.

Calcium carbide slag is an industrial waste residue generated during the production of acetylene via the calcium carbide method, primarily composed of $Ca(OH)_2$ with strong alkalinity and high calcium

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content [11]. China emits over 20 million tons of calcium carbide slag annually; its large-scale storage not only occupies land but also causes soil alkalization and water pollution [12]. Studies have demonstrated that calcium carbide slag can be utilized to improve expansive soil [13][14], operating through mechanisms similar to those of lime: $Ca^{2+}$ ions undergo ion exchange with clay minerals, reducing the double-layer thickness while the alkaline environment triggers pozzolanic reactions to form cementitious products. Zeolite powder, a natural aluminosilicate mineral, possesses a three-dimensional framework structure, high specific surface area, and excellent cation exchange capacity. Under alkaline conditions, its active $SiO_2$ and $Al_2O_3$ components dissolve and react with $Ca^{2+}$ to form C-S-H and C-A-H gels [15]. Applying calcium carbide slag combined with zeolite powder for enhancing Nanyang expansive soil aligns with green building material development trends, reduces environmental pollution, and promises fundamental optimization of the material's engineering properties.

In summary, this study focuses on Nanyang expansive soil, employing calcium carbide slag and zeolite powder as composite improvement materials to investigate the evolution of its physical properties under varying dosage levels and to explore the synergistic effects of the composite modification, aiming to provide experimental evidence for both engineering applications of expansive soil and the resource utilization of calcium carbide slag.

## 2. Experiment

### *2.1 Testing Materials*

The expansive soil used in the test was sampled at a depth of 2–3 m in Shigang Town, Neixiang County, Nanyang City, and presented a yellowish-brown appearance. Its fundamental physical properties were determined according to the "Standard for Geotechnical Testing Methods" (GB/T 50123-2019), as shown in Table 1. This study also refers to the "Technical Code for Construction in Expansive Soil Regions". According to the classification of expansion potential in GB 50112-2013, this expansive soil exhibits a free swelling ratio of 63%, indicating a weak expansion tendency.

*Table 1: Basic Parameters of Expansive Soils.*

| Natural moisture content(%) | Liquid limit(%) | Plastic limit(%) | Optimum moisture content(%) | Maximum dry density(g/cm$^3$) | Free swelling ratio(%) |
|---|---|---|---|---|---|
| 22.6 | 49.7 | 26.1 | 18.7 | 1.74 | 63 |

The calcium carbide slag used in the experiment appears gray, powdery, and possesses an irritating odor; its main component is CaO, accounting for up to 67.36% by mass. Zeolite powder is a white powder ground to 200 mesh and contains significant amounts of $SiO_2$ and $Al_2O_3$. The primary chemical compositions of calcium carbide slag and zeolite powder are listed in Table 2.

*Table 2: Main Chemical Components of Calcium Carbide Slag and Zeolite Powder.*

| Ingredient | $SiO_2$ | $Fe_2O_3$ | $Al_2O_3$ | CaO | MgO | $SO_3$ |
|---|---|---|---|---|---|---|
| Carbide slag | 1.54% | 0.47% | 1.94% | 67.36% | - | 0.32% |
| Zeolite powder | 62.87% | 1.33% | 13.46% | 2.42% | 2.37% | - |

### *2.2 Test Scheme*

The expansive soil, calcium carbide slag, and zeolite powder were dried in an oven at 105 °C to constant weight, crushed, and then passed through standard sieves with mesh sizes of 2 mm and 0.5 mm, respectively. Based on preliminary experiments, the calcium carbide slag dosage was set at 8% (by mass), while the five types of zeolite powder dosages were 0%, 3%, 6%, 9%, and 12%. After manual mixing, the mixture was watered with predetermined amounts of water (for the compaction test, water was added according to the target moisture content; for other tests, water was added according to the optimal moisture content). The mixture was mixed uniformly again, sealed and left undisturbed for 24 hours before sample preparation. Both the calcium carbide slag and zeolite powder dosages were expressed as ratios to the mass of dry soil.

### *2.3 Experimental Methods*

The compaction test was conducted using an LQ-DJ-II electric compactor for light compaction tests. For each mix proportion, five specimens with varying moisture contents were prepared from modified expansive soils at moisture content gradients of 2%–3%. The uniformly mixed soil was layered and placed into the compaction cylinder for sequential compaction. After completion, the wet density and moisture content of the specimens were measured, and the dry density was calculated. A compaction curve was plotted with moisture content on the x-axis and dry density on the y-axis to determine the optimal moisture content and maximum dry density for each mix proportion. Each proportion was tested twice independently, and the average value was recorded.

The free swelling ratio is a crucial indicator for evaluating the swelling characteristics of expansive soils, effectively reflecting their swelling potential. Soil samples from unconfined compressive strength tests were crushed through a 0.5 mm sieve. Using a graduated cylinder, 10 mL of sieved soil powder was measured and slowly poured into a 50 mL graduated cylinder containing 30 mL of distilled water. A 5 mL solution of sodium chloride at 5% concentration (by mass) was added, followed by thorough stirring with a glass rod. The stirring rod and cylinder walls were then rinsed with distilled water until the suspension volume reached 50 mL. After allowing the mixture to stand for 24 hours, the final volume of the sample after stable water absorption and swelling was recorded.

The unloading expansion rate test was conducted using a WZ-2 type expansion tester. A modified expansive soil sample (Φ61.8 mm × 20 mm) cured to the specified age was placed in the tester's chamber, with a percentage gauge installed and zeroed. Pure water was slowly injected into the chamber until the water level exceeded the sample's top surface and remained constant. The percentage gauge readings were recorded periodically until the deformation did not exceed 0.01 mm over two consecutive hours; at this point, the system was considered stable.

The unconfined compressive strength test was conducted using a micro-controlled electronic universal testing machine, with the loading rate of the pressure plate maintained at 1 mm/min, and stress-strain data automatically recorded. The test was terminated when strain reached 5%, and the maximum failure pressure was recorded.

## 3. Test Results and Analysis

### *3.1 Compaction Test*

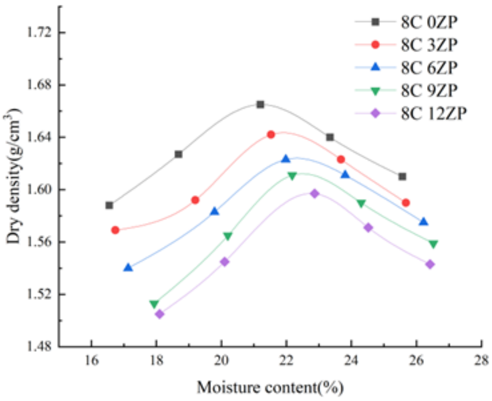


*Figure 1: Compaction curve of the specimen.*

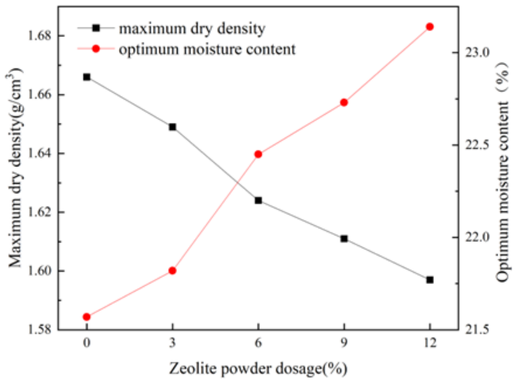


*Figure 2: Optimal moisture content and maximum dry density of modified expansive soil.*

Figures 1 and 2 show, respectively, the compaction curves, maximum dry density curves, and optimal moisture content curves of the modified expansive soil. Comparison of the compaction curves for different mix proportions in Figure 1 reveals that as the total zeolite powder content increases, the peak point of the compaction curve shifts to the lower right; this indicates a gradual increase in the optimal moisture content and a gradual decrease in the maximum dry density. As shown in Figure 2, the maximum dry density of the modified expansive soil ranges from 1.597 to 1.666 g/cm³, which is lower than that of the unmodified soil (1.74 g/cm³); the optimal moisture content ranges from 21.57% to 23.14%, both higher than the optimal moisture content of 18.7% for the unmodified soil. Taking the addition of 8% calcium carbide slag and 9% zeolite powder as an example, the optimal moisture content rises to 22.73% while the maximum dry density decreases to 1.611 g/cm$^3$. This phenomenon is mainly attributed to the addition of calcium carbide slag and zeolite powder.

Upon contact with zeolite powder, the calcareous residue immediately undergoes ion exchange and agglomeration, which makes fine soil particles agglomerate into large particles and form a granular structure. This alters the particle size distribution of the expansive soil, thereby affecting its compaction behavior under consolidation conditions. Additionally, zeolite powder possesses a porous structure with strong water absorption capacity; when water molecules enter its micropores, they form bound water. Some components in calcium carbide slag (CaO, MgO) will react with water, consuming a portion of the moisture and thereby increasing the optimal moisture content for solidifying the expansive soil.

### *3.2 Free Swelling Ratio Test*

When the calcium carbide slag content is fixed at 8%, the relationship between the free swelling ratio of expansive soil modified with calcium carbide slag and zeolite powder, as well as the zeolite powder dosage and curing duration, is illustrated in Figure 3. The figure demonstrates that the addition of calcium carbide slag and zeolite powder effectively reduces the free swelling ratio of expansive soil, with lower rates observed at longer curing durations. As zeolite powder dosage increases, the free swelling ratio decreases progressively, showing significant changes within the range of 0%–9%; beyond this range, the variation diminishes. This indicates limited further reduction effects from additional dosage increases, while extended curing periods still yield some improvement but with diminishing efficacy. At excessively low zeolite powder dosages, calcium carbide slag undergoes a pozzolanic reaction with zeolite powder, producing gel products such as hydrated calcium silicate that densely fill interstitial pores, significantly reducing the free swelling ratio. When zeolite powder dosage exceeds 9%, some particles function solely as inert fillers, weakening their expansion-suppressing capacity. Compared to unmodified expansive soil (free swelling ratio: 63%), the mixture of 8% calcium carbide slag and 9% zeolite powder exhibited a 73.8% reduction in free swelling ratio after 28 days of curing, demonstrating substantial improvement. Balancing cost-effectiveness and modification efficiency, a dosage of 9% is recommended as optimal.

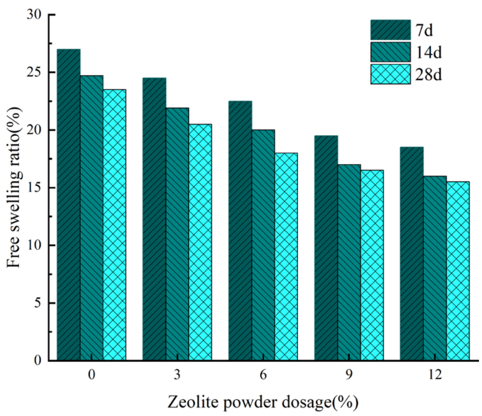


*Figure 3: Relationship between free swelling ratio and dosage.*

### *3.3 Unloaded Expansion Rate Test*

The unloading expansion rates of the modified soil at different curing ages were measured, with results shown in Figure 4. As curing time increased from 7 to 28 days, the unloading expansion rate decreased from 3.8% to 0.28%. The expansion rate at day 7 was 3.8%, indicating that $Ca^{2+}$ released from calcium carbide slag had undergone ion exchange with clay minerals, compressing the double electric layer, while zeolite powder initially activated volcanic ash activity in an alkaline environment, forming small amounts of calcium silicate-hydrate (C-S-H) gel, thereby effectively suppressing most expansion deformation. By day 14, the unloading expansion rate dropped sharply to 0.98%, indicating that the period from day 7 to day 14 represented the rapid development stage of pozzolanic reaction: substantial C-S-H and calcium aluminate hydrate (C-A-H) gels filled interstitial pores between soil particles and cemented them, making the soil structure more compact. By day 28, the expansion rate further declined to 0.28%, close to the level of non-expansive soil, indicating full structural stabilization. Compared with the unloading expansion rate of 10.69% in untreated

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expanding soil, the significantly reduced value after modification demonstrates a pronounced synergistic effect of the calcium carbide slag-zeolite composite treatment, enabling the expanding soil to achieve a non-expanding state by day 28.

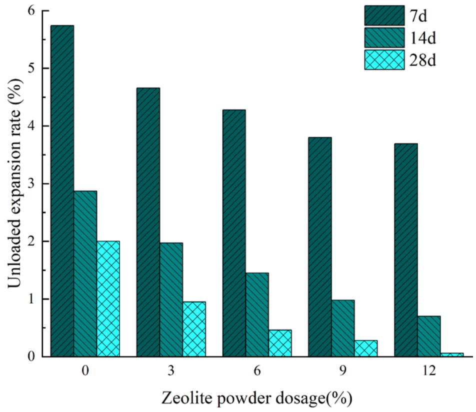
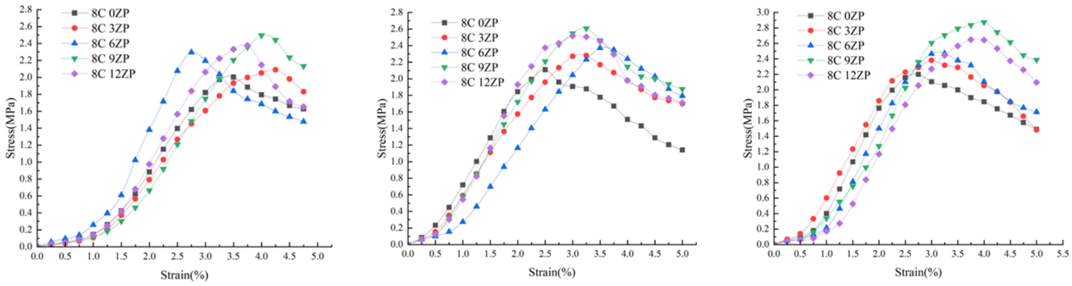



*Figure 4: Relationship between unloading expansion rate and dosage.*

### *3.4 Unconfined Compressive Strength Test*

The stress-strain curves of C-ZP-modified expansive soil specimens at different curing ages are shown in Figure 5. As illustrated, the stress-strain relationship can be divided into four distinct phases: 1) The compaction phase: The curve exhibits a slight concavity with increasing slope, indicating particle compression under axial pressure, reduced intergranular pores, and enhanced stiffness; 2) The elastic phase: The stress-strain relationship follows an approximate linear pattern where stress increases linearly with strain, demonstrating material hardening; 3) The plastic phase: The curve becomes nonlinear with decreasing slope, reaching a peak stress value known as the unconfined compressive strength before further increase; 4) The post-failure phase: After peak stress is reached, the curve declines significantly, exhibiting characteristic brittle failure behavior. Higher zeolite powder content intensifies strain softening and brittle failure characteristics, as hydration products formed between calcium carbide slag, zeolite powder, and soil particles create a high-strength brittle matrix that contributes to elevated mechanical properties and brittleness.




(a)7d (b)14d (c)28d

*Figure 5: Stress-strain curve of improved expansive soil.*

The relationship between the unconfined compressive strength of calcium carbide slag-zeolite powder modified expansive soil specimens and zeolite powder dosage is shown in Figure 6. The figure indicates that at a zeolite powder dosage of 9% and a curing age of 28 days, the unconfined compressive strength reaches its maximum value of 2.874 MPa—1.31 times that of the group without zeolite powder under identical curing conditions, and 1.15 times higher than that achieved after 7 days of curing with the same dosage. At constant curing ages, the highest unconfined compressive strength is attained at a 9% zeolite dosage; further increases in dosage lead to gradual decreases, demonstrating that appropriate zeolite incorporation significantly enhances the material's strength properties. When curing time extends from 7 to 28 days, the unconfined compressive strength continues to rise, indicating thorough completion of the pozzolanic reaction between calcium carbide slag and zeolite powder, with generated calcium silicate hydrate (C-S-H) and calcium aluminate hydrate (C-A-H) gels progressively filling pores and binding soil particles, thereby maintaining sustained strength improvement. The resulting modified expansive soil exhibits strength far exceeding the requirements specified for subgrade soils in engineering standards.

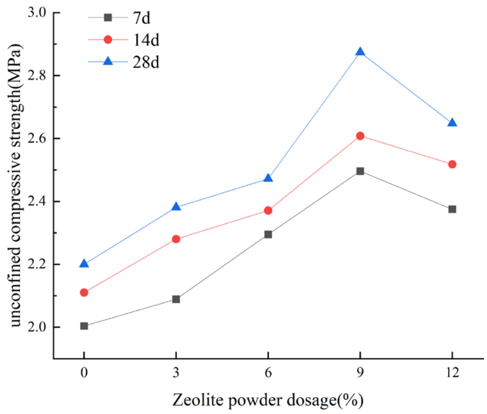



*Figure 6: Effect curve of zeolite powder dosage on unconfined compressive strength.*

## 4. Conclusions

Under specific moisture content and dry density conditions, the expansion characteristics and mechanical properties of expansive soil modified with calcium carbide slag–zeolite powder composite were investigated, yielding the following conclusions.

(1) The composite modification using calcium carbide slag and zeolite powder increases the optimal moisture content of expansive soil while reducing its maximum dry density. The free swelling ratio decreases with increasing zeolite powder dosage, showing a significant decline within the range of 0%–9%, followed by a gradual decrease beyond 9%. The unloading expansion rate drops sharply with extended curing duration, reaching 0.28% at 28 days—close to that of non-expansive soil.

(2) The addition of calcium carbide slag and zeolite powder effectively enhances the unconfined compressive strength of expansive soil. When the zeolite powder content is 9% and the curing period is 28 days, the strength reaches a maximum value of 2.874 MPa, which is 1.31 times that obtained with 0% zeolite powder at the same curing period.

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