

Experimental Study on Engineering Properties of Expansive Soil Improved by Coal Gangue with Different Particle Sizes

Zhonghang Zhang, Pinghui Liu, Yiyuan Sun, Kaijia Xue, Xixi Qin, Honghao Han

School of Geosciences and Engineering, North China University of Water Resources and Electric Power, Zhengzhou 450046, China

Abstract: In order to investigate the effects of coal gangue particle size and content on the properties of expansive soil, a series of laboratory tests including compaction test, swelling test, direct shear test, and unconfined compressive strength test were carried out. Three particle size groups of coal gangue (0–2 mm, 2–5 mm, and 5–10 mm) and six content levels (0%, 5%, 10%, 15%, 20%, and 25%) were selected. The results show that, for the same particle size, the maximum dry density of the mixture increases with increasing coal gangue content, while the optimum moisture content decreases. All particle sizes of coal gangue can effectively inhibit the swelling behavior of expansive soil, and the inhibition effect becomes more significant with increasing content, particularly at 15%. Under the same content, larger particle sizes exhibit better swelling suppression effects. For shear strength, the internal friction angle and cohesion fluctuate significantly when small (<2 mm) or large (>5 mm) particles are added, while the optimal improvement is achieved at a particle size of 2–5 mm and a content of 15%–20%. The unconfined compressive strength increases first and then decreases with increasing content, reaching a peak at 15%. Meanwhile, under the same content, the strength decreases with increasing particle size, and the optimal combination for compressive strength is 0–2 mm particle size with 15% content.

Keywords: Expansive soil, Coal gangue, Swelling ratio, Strength characteristics, Optimal proportion.

1. Introduction

Expansive soil is a type of high-plasticity clay mainly composed of strongly hydrophilic clay minerals such as montmorillonite and illite. It is characterized by significant swelling-shrinkage behavior, well-developed fissures, and strength degradation, and is typically classified as unsaturated soil. Due to its pronounced volume change behavior, it is also referred to as swelling-shrinkage soil or fissured soil [1]. Its main chemical components include SiO_2 , Al_2O_3 , and Fe_2O_3 , accounting for approximately 81%–86% of the total composition.

Expansive soil is widely distributed and poses significant hazards to engineering construction due to its strong swelling-shrinkage properties and fissured structure, making it difficult to treat. Current improvement methods mainly include physical, chemical, and biological approaches. Physical methods involve replacement, compaction, and reinforcement, or mixing with other materials to modify particle gradation. Chemical methods rely on reactions between additives and soil particles to fundamentally improve soil properties, with common stabilizers including lime and cement. However, these methods may lead to soil alkalization and environmental issues. Biological methods involve microbial-induced bonding, which enhances soil strength but has limitations such as complex procedures and long treatment time [2].

Coal gangue, a common industrial solid waste generated during coal mining, accounts for approximately 10%–20% of

raw coal production. In China, the accumulated amount has exceeded 1 billion tons, with an annual increase of about 100 million tons. Improper disposal not only wastes land resources but also causes environmental pollution. Therefore, its resource utilization has attracted increasing attention.

Previous studies have shown that adding coal gangue can effectively improve the compaction characteristics, swelling behavior, and strength properties of expansive soil [3–10]. However, most existing studies focus on a single particle size (typically <2 mm) and only consider the effect of content, lacking systematic investigation on the combined influence of particle size and content.

Therefore, this study considers both particle size (0–2 mm, 2–5 mm, 5–10 mm) and content (0%–25%) as variables, and conducts a series of laboratory tests to analyze their coupled effects on the engineering properties of expansive soil, aiming to determine the optimal combination and provide a reference for practical engineering applications.

2. Materials and Experimental Scheme

2.1. Materials

The expansive soil used in this study was obtained from a construction site in Handan City, Hebei Province, China. The excavated soil had been exposed for a long time and became hard, thus requiring crushing before testing. The physical properties were determined according to the Standard for Geotechnical Testing Method (GB/T 50123-2019), as shown in Table 1.

Table 1. Basic Physical Parameters of Expansive Soil

Liquid limit $w_l/\%$	Plastic limit $w_p/\%$	Plasticity index I_p	Free swelling ratio/ $\%$	Max dry density $/(g\cdot cm^{-3})$	Optimum moisture content $W_{op}/\%$	Specific gravity G_s
44.2	22.2	22.1	59	1.84	15.1	2.7

Coal gangue was collected from a coal mine in Xingyang, Henan Province, and crushed into three particle size groups:

CG-1 (5–10 mm), CG-2 (2–5 mm), and CG-3 (0–2 mm). The physical properties are listed in Table 2.

Table 2. Basic Physical Indexes of Coal Gangue Particles

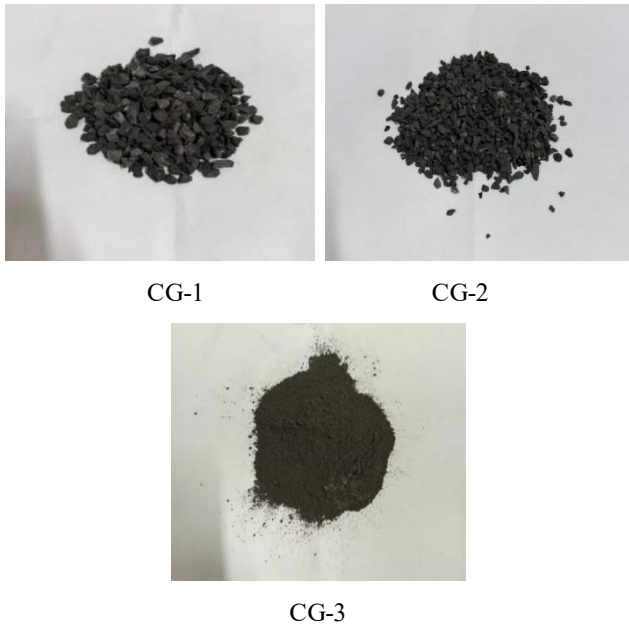
Coal gangue particle numbering	Relative density G_s	Air-dried moisture content /%	Water absorption rate /%	Particle size /mm
CG-1	2.6	0.4	1.9	[5, 10)
CG-2	2.58	0.5	2	[2, 5)
CG-3	2.57	0.7	2.1	[0, 2)

2.2. Experimental Scheme

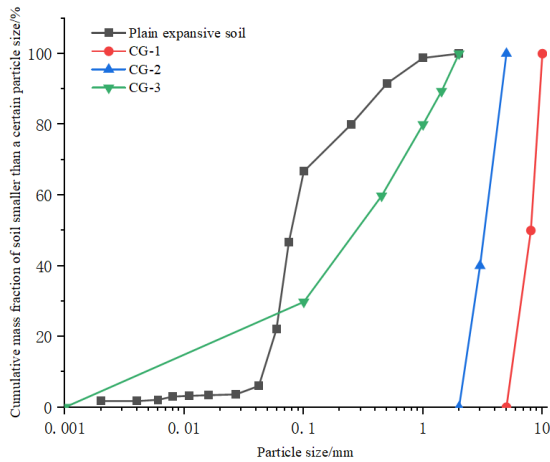
The coal gangue–expansive soil mixture is defined by the mass percentage of coal gangue in the total mixture:

$$x = \frac{m_o}{m_o + m_s} \times 100\% \quad (1)$$

Where: m_o is the mass of coal gangue particles (air-dried); m_s is the mass of dry expansive soil.



(a) Photos of Coal Gangue Particles



(b) CG particle size distribution curve

Figure 1. Gradation Curves of Expansive Soil and CG Particles

A certain amount of expansive soil was dried in an oven at 105°C for 24 hours, then crushed and passed through a 2 mm sieve to remove redundant impurities. According to the estimated optimum moisture content, an appropriate mass of the sieved dry expansive soil was weighed and mixed with

coal gangue of three particle size groups (CG-1, CG-2, CG-3) to prepare coal gangue-expansive soil mixtures with coal gangue contents of 0%, 5%, 10%, 15%, 20%, and 25%. These mixtures were labeled as CT0, CT5, CT10, CT15, CT20, and CT25 respectively, where CT denotes compaction test.

In accordance with the Standard for Geotechnical Testing Method (GB/T 50123-2019), five different moisture contents were prepared for each group of samples. After being sealed and stored in a moisture chamber for 24 hours, heavy compaction tests were carried out. The maximum dry density and optimum moisture content of coal gangue-expansive soil mixtures with different contents and particle size groups were obtained from the relationship curves between moisture content and dry density.

Subsequently, under the control of the optimum moisture content, samples with different particle size groups and coal gangue contents were prepared for expansion ratio tests, mainly including 100 kPa confined swelling ratio test and free swelling ratio test.

Table 3. Design of Test Scheme for Direct Shear and Unconfined Compressive Strength Tests

Serial number	Direct shear specimen		Compressive specimen	
	Group number	Number	Group number	Number
CT0	0	$\tau_{0,50-150}$	16	q _{16,1-3}
CT5	1	$\tau_{1,50-150}$	17	q _{17,1-3}
	2	$\tau_{2,50-150}$	18	q _{18,1-3}
	3	$\tau_{3,50-150}$	19	q _{19,1-3}
CT10	4	$\tau_{4,50-150}$	20	q _{20,1-3}
	5	$\tau_{5,50-150}$	21	q _{21,1-3}
	6	$\tau_{6,50-150}$	22	q _{22,1-3}
CT15	7	$\tau_{7,50-150}$	23	q _{23,1-3}
	8	$\tau_{8,50-150}$	24	q _{24,1-3}
	9	$\tau_{9,50-150}$	25	q _{25,1-3}
CT20	10	$\tau_{10,50-150}$	26	q _{26,1-3}
	11	$\tau_{11,50-150}$	27	q _{27,1-3}
	12	$\tau_{12,50-150}$	28	q _{28,1-3}
CT25	13	$\tau_{13,50-150}$	29	q _{29,1-3}
	14	$\tau_{14,50-150}$	30	q _{30,1-3}
	15	$\tau_{15,50-150}$	31	q _{31,1-3}

Note: 50-150 is used to distinguish the vertical pressure, and 1-3 is used to distinguish parallel specimens.

Unconfined compressive strength tests and direct shear tests were also carried out on coal gangue-expansive soil mixtures under the condition of maximum compaction degree. For the unconfined compressive strength test, six coal gangue contents (0%, 5%, 10%, 15%, 20%, 25%) and three particle sizes (CG-1, CG-2, CG-3) were adopted, and the tests were

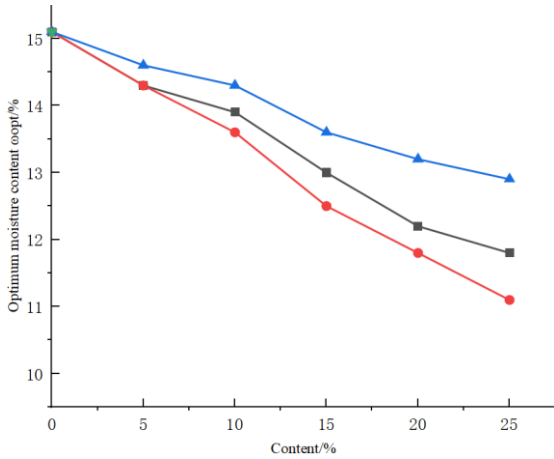
divided into 16 groups with three parallel specimens for each group.

Similarly, for the direct shear test, the tests were also divided into 16 groups according to different coal gangue contents and particle sizes, with three specimens per group, tested under vertical pressures of 50, 100, and 150 kPa, respectively.

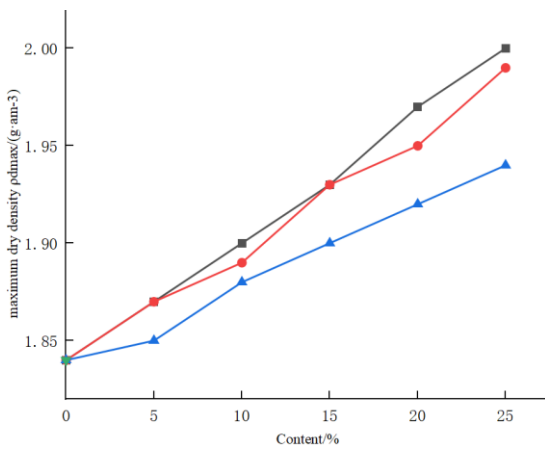
3. Results and Analysis

3.1. Compaction Test

The variation curves of optimum moisture content and maximum dry density of coal gangue–expansive soil mixtures with different particle sizes and contents are shown in Fig. 2.



(a) Relationship between optimum moisture content and CG content



(b) Relationship between maximum dry density and CG content

■ CG-1 ● CG-2 ▲ CG-3 ▼ Plain expansive soil

Figure 2. Variation curves of optimum moisture content and maximum dry density with CG content

It can be observed that, for a given particle size of coal gangue, the optimum moisture content decreases monotonically with increasing coal gangue content, while the maximum dry density increases correspondingly. Compared with the natural expansive soil (optimum moisture content of 15.1% and maximum dry density of 1.84 g/cm³), the addition of coal gangue significantly improves the compaction characteristics.

This phenomenon can be explained by the physical

properties of coal gangue. Coal gangue particles are hard and angular, and their incorporation into the soil matrix can fill the voids between fine soil particles, reducing capillary water absorption and facilitating the expulsion of air and water during compaction. As a result, a denser structure can be achieved at lower moisture content, leading to an increase in maximum dry density.

Meanwhile, expansive soil contains a large amount of clay minerals with strong hydrophilicity and large specific surface area, requiring higher water content for optimal compaction. In contrast, coal gangue has relatively stable mineral composition and low water absorption capacity, which dilutes the hydrophilic minerals in expansive soil and reduces the overall water demand, resulting in a decrease in optimum moisture content.

3.2. Swelling Test

The results of loaded (100 kPa) and unloaded swelling ratio tests for different coal gangue contents and particle sizes are shown in Fig. 3.

It can be seen that, under the same particle size condition, both loaded and unloaded swelling ratios decrease first and then increase with increasing coal gangue content. Compared with the natural expansive soil, which has an unloaded swelling ratio of 17.7% and a loaded swelling ratio of 5.55%, the swelling ratios decrease significantly after adding coal gangue, reaching minimum values at approximately 15% content.

This indicates that coal gangue has a significant inhibitory effect on the swelling potential of expansive soil. However, when the content exceeds 10%, the decreasing trend of swelling ratio gradually slows down, and the curves become flatter. This suggests that although coal gangue effectively reduces swelling, the improvement effect becomes less pronounced at higher contents. Therefore, the optimal content should be determined in combination with strength properties.

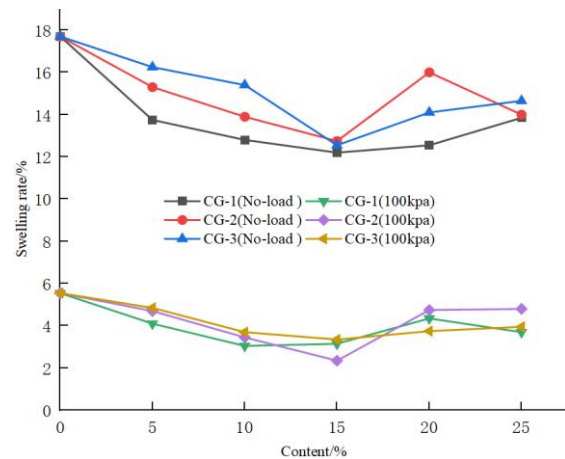


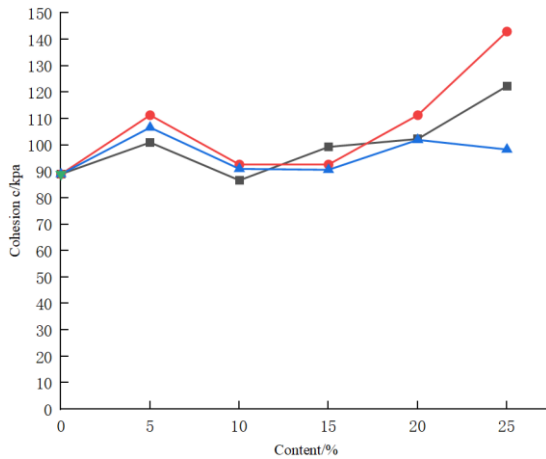
Figure 3. Relationship Between Loaded(100kPa) and Unloaded Swell Ratio with CG Content and Particle Size

3.3. Direct Shear Test

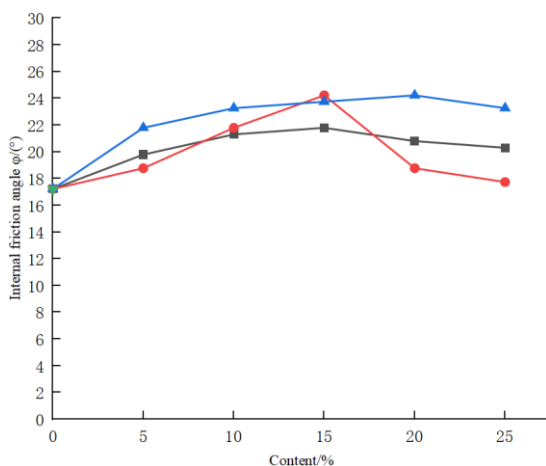
The direct shear test results of coal gangue–expansive soil mixtures under different conditions are summarized in Table 4, and the variation of cohesion and internal friction angle with coal gangue content is shown in Fig. 4.

Table 4. Shear Strength of Coal Gangue-Expansive Soil Mixtures with Different Contents and Particle Sizes

Serial number	Direct shear group number	Particle size number	Shear strength under different loads/kpa			Linear fitting formula	Correlation coefficient
			50kpa	100kpa	150kpa		
CT0	0	0	105	119	136	$y=0.31x+89$	0.9984
CT5	1	CG-1	120	135	156	$y=0.36x+101$	0.9908
	2	CG-2	129	144	163	$y=0.34x+111.33$	0.9954
	3	CG-3	126	148	166	$y=0.4x+106.67$	0.9967
CT10	4	CG-1	103	132	142	$y=0.39x+86.667$	0.9267
	5	CG-2	112	134	152	$y=0.4x+92.667$	0.9967
	6	CG-3	113	133	156	$y=0.43x+91$	0.9984
CT15	7	CG-1	120	138	160	$y=0.4x+99.333$	0.9967
	8	CG-2	115	138	160	$y=0.45x+92.667$	0.9998
	9	CG-3	113	134	157	$y=0.44x+90.667$	0.9993
CT20	10	CG-1	120	143	158	$y=0.38x+102.33$	0.9826
	11	CG-2	129	144	163	$y=0.34x+111.33$	0.9954
	12	CG-3	125	146	170	$y=0.45x+102$	0.9985
CT25	13	CG-1	140	161	177	$y=0.37x+122.33$	0.9939
	14	CG-2	159	175	191	$y=0.32x+143$	1
	15	CG-3	121	139	164	$y=0.43x+98.333$	0.9912



(a) Relationship between cohesion and CG content



(b) Relationship between internal friction angle and CG content

■ CG-1 ● CG-2 ▲ CG-3 ▼ Plain expansive soil

Figure 4. Relationship curves between cohesion c , internal friction angle ϕ and CG content

The results show that the shear strength of all mixtures follows the Mohr–Coulomb criterion well, exhibiting a linear increase with increasing normal stress (50, 100, and 150 kPa). Compared with natural expansive soil, the addition of coal

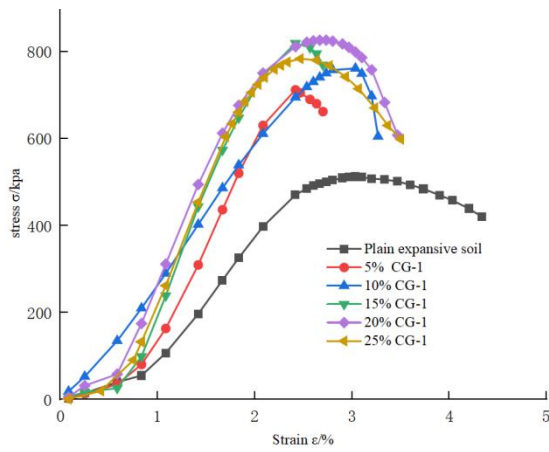
gange significantly improves shear strength.

For cohesion, CG-1 (5–10 mm) shows an overall increasing trend with a slight fluctuation, CG-2 (2–5 mm) exhibits the most significant increase, while CG-3 (0–2 mm) shows a trend of first increasing and then decreasing. For the internal friction angle, CG-1 and CG-2 show a peak at around 15% content, whereas CG-3 increases steadily with increasing content.

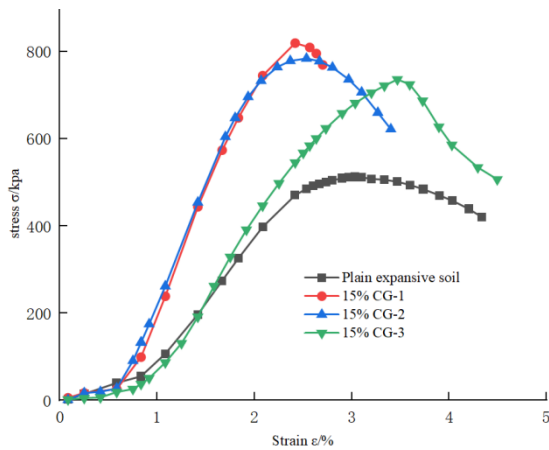
Overall, the influence of coal gangue on cohesion is more fluctuating, while its effect on internal friction angle becomes more pronounced with increasing content. The optimal improvement in shear strength is achieved at a particle size of 2–5 mm and a content of 15%–20%.

3.4. Unconfined Compressive Strength

The stress–strain curves of selected specimens and the variation of unconfined compressive strength with coal gangue content are shown in Fig. 5 and Fig. 6.



(a) Same particle size, different content



(b) Same content, different particle size

Figure 5. Stress-Strain Relationship of Rubber-Expansive Soil Mixtures with Same Particle Size and Different Contents, and Same Content and Different Particle Sizes

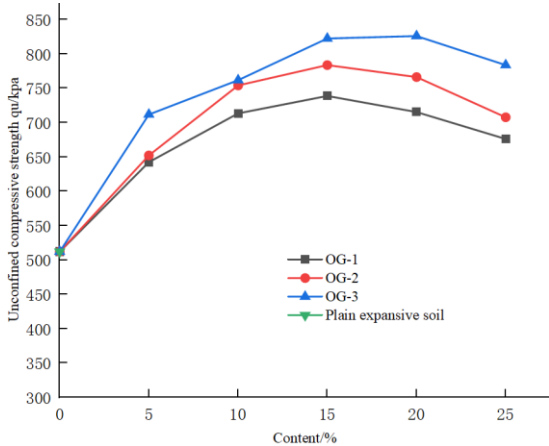


Figure 6. Relationship between unconfined compressive strength of coal gangue-expansive soil mixtures and CG content for various particle sizes

The results indicate that the unconfined compressive strength of all mixtures is higher than that of natural expansive soil (512.1 kPa), demonstrating the strengthening effect of coal gangue. This improvement is mainly attributed to the formation of a “soil–stone” skeleton structure, which enhances soil compactness and load-bearing capacity.

For the same particle size, the compressive strength increases first and then decreases with increasing coal gangue content, with the peak value occurring at 15%. For the same content, the compressive strength decreases with increasing

particle size.

Therefore, the optimal combination for compressive strength is a particle size of 0–2 mm with a content of 15%. Additionally, the influence of particle size becomes less significant at higher contents, indicating the existence of a critical content (approximately 15%) where particle size has the greatest impact.

3.5. Mechanism Analysis of Coal Gangue–Expansive Soil Interaction

After the incorporation of coal gangue (CG) particles into expansive soil, the improvement in its engineering properties is mainly attributed to the skeleton support effect, pore-filling effect, and mineral composition dilution effect. Coal gangue possesses relatively high strength and angular particle shapes, which enable the formation of a stable soil–stone composite skeleton structure within the soil mass. This significantly enhances interparticle interlocking and friction, thereby improving the shear strength and overall structural stability of the soil. Meanwhile, coal gangue particles can effectively fill the internal pores of expansive soil, optimize the gradation of the mixture, increase its compactness, and reduce the optimum moisture content. From a physical structural perspective, these effects jointly contribute to the suppression of swelling–shrinkage deformation of expansive soil.

The experimental results indicate that the improvement mechanisms and effects of coal gangue with different particle sizes on expansive soil vary significantly. When the particle size is 2–5 mm and the content is 15%–20%, the shear strength of the soil is most significantly enhanced; this combination is suitable for engineering applications such as highway subgrades and embankment fills, where high shear stability is required. In contrast, when the particle size is 0–2 mm with a content of approximately 15%, the unconfined compressive strength reaches its peak, making it more suitable for applications such as foundation treatment and base reinforcement, where higher vertical bearing capacity is needed.

In practical engineering, the particle size and content of coal gangue should be selected based on the type of project, stress characteristics, and performance requirements, so as to achieve both optimal improvement of expansive soil and efficient utilization of solid waste resources.

4. Conclusion

Based on a series of laboratory tests on coal gangue–expansive soil mixtures with different particle sizes and contents, the following conclusions can be drawn:

(1) The maximum dry density increases with increasing coal gangue content, while the optimum moisture content decreases.

(2) Coal gangue effectively inhibits the swelling potential of expansive soil, with the best performance at 15% content. Larger particle sizes exhibit stronger inhibition under the same content.

(3) The shear strength of the mixtures is significantly improved, with the optimal condition being a particle size of 2–5 mm and a content of 15%–20%.

(4) The unconfined compressive strength increases first and then decreases with increasing content, reaching a maximum at 15%. For the same content, it decreases with increasing particle size, and the optimal condition is 0–2 mm particle size with 15% content.

(5) The influence of particle size on soil properties depends on the content. When the content exceeds 15%, the effect of particle size gradually weakens.

References

- [1] Liu Guonan, Wu Xiaoming. Study on suction characteristics of expansive soil [C]//China Civil Engineering Society. Proceedings of the 7th National Conference on Soil Mechanics and Foundation Engineering. Railway Science Research Institute, Ministry of Railways, 1994: 272–275.
- [2] Bao Jie, Shen Chunni, Fang Xiangwei, et al. Research progress on improvement methods of expansive soil foundation [J]. Comprehensive Utilization of Fly Ash, 2019(05): 98–104.
- [3] Li Weisheng, Zhang Yan, Guo Liyong, et al. Study on the mechanism of compaction characteristics of expansive soil improved by coal gangue [J]. Journal of Inner Mongolia Agricultural University (Natural Science Edition), 2014, 35(04): 107–110 DOI:10.16853/j.cnki.1009-3575.2014.04.021.
- [4] Guo Liyong, Zhang Yan, Zhou Tianping, et al. Experimental study on coal gangue powder modified expansive soil [J]. Journal of Inner Mongolia Agricultural University (Natural Science Edition), 2013, 34(04): 127–130. DOI:10.16853/j.cnki.1009-3575.2013.04.025.
- [5] Zhang Yan, Zhu Hongxing, Yin Xiaoxiao. Microscopic evaluation of expansive soil improved by coal gangue under different moisture contents and pressures [J]. China Sciencepaper, 2021, 16(12): 1354–1360.
- [6] Yang Xiaoyun, Zhang Yan. Mechanism analysis of shear strength of expansive soil improved by coal gangue powder [J]. Coal Engineering, 2014, 46(09): 123–125.
- [7] Zhang Yan, Zhang Yu, Guo Liyong, et al. Study on properties of unsaturated compacted expansive soil mixed with coal gangue [J]. Chinese Journal of Environmental Engineering, 2016, 10(09): 5115–5120.
- [8] Liu Tong, Zhang Yan, Feng Xiaobo, et al. Study on shrinkage characteristics of expansive soil improved by coal gangue powder [J]. China Sciencepaper, 2018, 13(12): 1434–1439.
- [9] Zhang Yan, Wang Minglei, Yin Xiaoxiao, et al. Effect of dry–wet cycles on the behavior of coal gangue stabilized expansive soil [J]. Bulletin of the Chinese Ceramic Society, 2018, 37(11): 3604–3610. DOI:10.16552/j.cnki.issn1001-1625.2018.11.040.
- [10] Wu Libo, Liu Huiyang, Yang Jiawei, et al. Experimental study on freeze–thaw characteristics of loess fill improved by coal gangue in seasonal frozen regions [J]. Journal of Natural Disasters, 2025, 34(04): 128–139. DOI:10.13577/j.jnd.2025.0411.