World Journal of Engineering Research
Print ISSN: 2959-9865
Online ISSN: 2959-9873
DOI: https://doi.org/10.61784/wjer3102

THE PERFORMANCE OF COAL GANGUE SUBGRADE FILLER MODIFIED BY CEMENT-FLY ASH SYNERGY

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Abstract: To address the problems of performance discreteness, low strength, and insufficient water stability encountered in the resource utilization of coal gangue for road embankment filling, this study selected coal gangue samples from Meihuajing and Yangchangwan Mines in Lingwu City, Yinchuan, Ningxia. The coal gangue was compounded with typical fine-grained soil (Group C filler) at different proportions, and additives such as cement, fly ash, and lime were incorporated to systematically investigate the engineering properties of the mixtures. Through a series of laboratory tests, including particle size analysis, heavy compaction test, California Bearing Ratio (CBR) test, expansion ratio test, and resilient modulus test, the gradation characteristics, compaction behavior, strength, water stability, and deformation performance of the mixtures were comprehensively evaluated. The results show that blending coal gangue with Group C filler can significantly optimize the gradation, with the coefficient of uniformity (C_u) being greatly improved. The mixture with 3% cement and 8% fly ash exhibits the optimal performance: its maximum dry density reaches 2.16 g/cm³, the peak CBR value is 171.49%, and the resilient modulus exceeds 60 MPa. All these indices are far higher than the requirements specified in current specifications for subgrade filler used in the lower embankment of high-grade highways. In addition, the incorporation of cement and lime effectively inhibits the expansibility of the mixtures. This study verifies the feasibility of using coal gangue mixtures as subgrade filler and provides a theoretical basis and data support for the optimization of its engineering mix ratio.
Keywords: Coal gangue; Cement; Fly ash; Subgrade filler; Solid waste utilization

1 INTRODUCTION

During coal mining, substantial amounts of coal gangue are generated. Its stockpiling not only occupies land but also easily leads to environmental issues such as dust emissions, air pollution, and groundwater contamination. Meanwhile, with the continuous development of transportation infrastructure construction in China, the demand for high-quality roadbed fill materials is increasing, while natural sand and gravel resources are becoming increasingly scarce. Utilizing coal gangue as an alternative filler material not only alleviates the pressure of its disposal but also reduces dependence on natural materials, which holds significant importance for promoting green and sustainable development in civil engineering [1-2].

However, raw coal gangue exhibits complex composition, high variability in mechanical properties, and susceptibility to weathering and disintegration. Its direct use as roadbed filler often faces challenges such as compaction difficulty, insufficient strength, and poor long-term stability. Researchers worldwide have conducted relevant studies, such as determining the optimal moisture content of coal gangue through compaction tests or enhancing its strength using cement-based modification alone. However, existing research has predominantly focused on single-source coal gangue or simple cementitious material modification. There remains a notable lack of systematic investigation into the synergistic combination of coal gangue from different origins with fine-grained soils, as well as the comprehensive road performance (including strength, deformation, and water stability) of mixtures modified with composite additives such as cement and fly ash [3-4].

Based on the “Shang Gou Wan Logistics Park Coal Gangue Filling Project,” this study takes coal gangue from the Ningxia Meihuajing and Yangchangwan mines as the research object. The gangue is combined with Group C filler in various proportions and mixed with additives such as cement, fly ash, and lime. Through systematic indoor geotechnical tests, the physical and mechanical properties of the composite materials are analyzed, and the synergistic modification mechanisms are elucidated. The aim is to propose optimized mix proportion schemes suitable for different subgrade structural layers.

2 MATERIALS AND EXPERIMENTAL PROCEDURES

2.1 Experimental Materials

Figure 1 Coal Gangue Samples

(1) Coal gangue: Collected from the Meihuajing Coal Mine and Yangchangwan Coal Mine, presenting a dark grey color and being primarily composed of broken sandstone and shale fragments (as shown in Figure 1).
(2) Group C fill material: The fine-grained soil used in this project (as shown in Figure 2) is primarily composed of silt and clay particles, with particles smaller than 0.075 mm accounting for 85.22% of the total composition.

Figure 2 Dried Group C filler

(3) Additives: P.O 42.5 Ordinary Portland Cement, Grade II Fly Ash, and Quicklime Powder.
(4) Mix Design: Using the ratio of coal gangue to Group C filler (3:1, 4:1) and the type and content of additives (3% cement, 3% cement + 8% fly ash, 3% cement + 15% fly ash, 5% lime, 5% lime + 15% fly ash) as the main variables, multiple mix proportion schemes for the composite material are designed [5-6].

2.2 Experimental Method

All tests were conducted in accordance with the "Test Methods of Soils for Highway Engineering" (JTG 3430-2020).
(1) Particle Analysis Test: The sieving method is employed to determine the particle composition of the material, plot the particle size distribution curve, calculate the coefficient of uniformity (Cu) and coefficient of curvature (Cc), and evaluate the gradation quality.
(2) Heavy Compaction Test: Conducted using the heavy compaction standard to determine the optimum moisture content and maximum dry density of the mixture, providing a control benchmark for field compaction.
(3) California Bearing Ratio (CBR) and expansion rate Test: After curing the specimen under immersion under specified conditions (as shown in Figure 3), the expansion rate is measured. Subsequently, a penetration test is conducted at a standard penetration rate to calculate the CBR value, thereby evaluating the bearing capacity and water stability of the fill material.

Figure 3 CBR Test under Loading

(4) Resilient Modulus Test (as shown in Figure 4): A stepwise loading and unloading method (50, 100, 150, 200 kPa) is

employed to measure the corresponding resilient deformation. The resilient modulus is then calculated to evaluate the elastic deformation characteristics of the fill material under dynamic loading [7].

Figure 4 Resilient Modulus Test in Progress

3 RESULTS AND DISCUSSION

3.1 Particle Size Distribution Characteristics

The particle analysis results in Figure 5 indicate that both types of raw coal gangue are coarse-grained soils but have generally poor gradation (Meihuajing Cu=13.75, Yangchangwan Cu=7.57). The Group C filler, on the other hand, is a fine-grained soil. After mixing the coal gangue with the Group C filler at a 3:1 ratio, the coefficient of uniformity Cu of the mixtures increases sharply (Meihuajing mixture Cu=95.12, Yangchangwan mixture Cu=134.15), and the coefficient of curvature Cc also falls within the range indicative of well-graded soils. This demonstrates that the mixed mode of "coarse coal gangue skeleton + fine Group C filler filling" effectively optimizes the overall particle gradation, forming a more compact particle structure, which lays the foundation for the mixed soil material to achieve higher compaction density and mechanical strength.

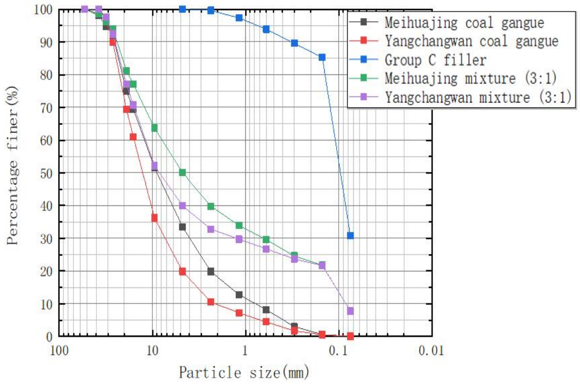

Figure 5 Grading Curves of Each Filler Particle

3.2 Compaction Characteristics

According to the data presented in Figure 6, the maximum dry density of pure coal gangue ranges from 2.02 to 2.05 g/cm³, with an optimum moisture content between 7.6 % and 8.2 %, indicating characteristics of low moisture content and easy compaction. For the blended materials, the maximum dry density generally falls within 2.085–2.15 g/cm³, and the optimum moisture content lies between 7.9 % and 8.9 %. The overall trend shows that as the proportion of Group C filler increases, the optimum moisture content of the mixture rises, while the maximum dry density first increases and then decreases.

Regarding the effect of additives, the incorporation of cement and fly ash exhibits complex patterns in terms of their influence on optimum moisture content and maximum dry density; however, they generally enhance the strength of the blended mixtures [8].

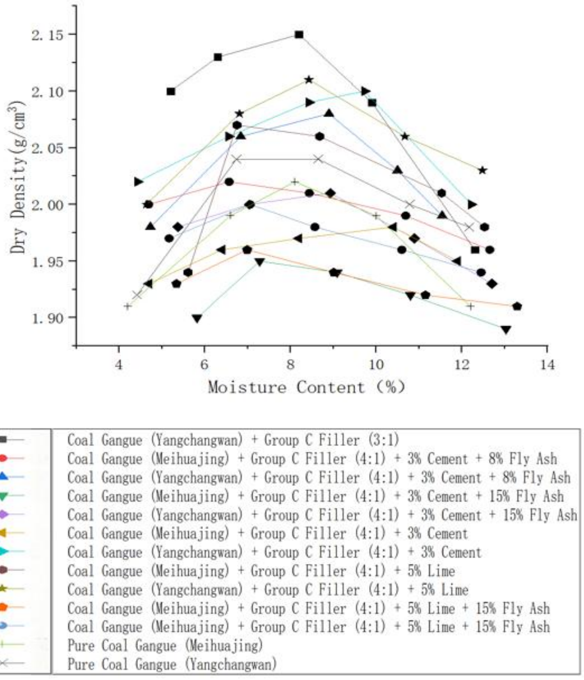

Figure 6 Compaction Test Curves of Mixtures with Different Components

3.3 CBR and Swelling Characteristics

The unimproved coal gangue-Group C filler mixture exhibits a relatively low California Bearing Ratio (CBR) value (6%–11%), which can only meet the requirements for low-grade roads. After incorporating 3% cement and 8% fly ash, the CBR value of the mixture increases dramatically, reaching a maximum of 171.49%, far exceeding the specifications for high-grade highway subgrades. Comparative analysis indicates that the improvement effect of the “3% cement + 8% fly ash” formulation is superior to that achieved by using cement alone or the “cement + 15% fly ash” formulation. This suggests the existence of an optimal proportion between cementitious materials and active admixtures. The CBR test data for each filler mixture are presented in Table 1 [9-10].

Table 1 Summary of CBR Test Data for Various Fillers

Filler Ratio	Sample	CBR Value (2.5)	CBR Value (5.0)	Coefficient of Variation (2.5)	Coefficient of Variation (5.0)
Pure coal gangue	0.92	20.51%	23.11%	29.54%	32.36%
	0.95	34.26%	42.03%		
	0.97	37.73%	45.03%		
Coal gangue + Group C filler (3:1) filler (compaction degree 0.95)	Sample1	8.56%	10.14%	13.74%	13.76%
	Sample2	8.39%	13.23%		
	Sample3	10.66%	12.71%		
Coal gangue + Group C filler (4:1) (compaction degree 0.95)	Sample1	12.49%	14.92%	36.09%	38.09%
	Sample2	21.26%	25.69%		
	Sample3	27.00%	33.73%		
Coal gangue + Group C filler (4:1) + 3% cement (compaction degree 0.95)	Sample1	179.11%	156.02%	10.02%	5.73%
	Sample2	147.51%	174.89%		
	Sample3	157.40%	164.38%		
Coal gangue + Group C filler (4:1) + 5% lime filler (compaction degree 0.95)	Sample1	6.11%	8.24%	37.90%	29.22%
	Sample2	12.97%	14.58%		
	Sample3	8.49%	10.34%		

Coal gangue + Group C filler (4:1) + 3% cement + 8% fly ash (compaction degree 0.95)	Sample1	171.49 %	160.54 %	16.73%	6.66%
	Sample2	122.46 %	144.03 %		
	Sample3	156.37 %	163.19 %		
Coal gangue + Group C filler (4:1) + 3% cement + 15% fly ash (compaction degree 0.95)	Sample1	148.64 %	169.73 %	25.13%	25.66%
	Sample2	249.83 %	287.18 %		
	Sample3	212.84 %	229.75 %		

Expansion rate tests indicate that the incorporation of cement and lime significantly suppresses the expansion of the mixture. The expansion rate of the unmodified mixture ranges from 0.3% to 0.9%, while that of the modified mixture is generally reduced to below 0.3%, with most values falling under 0.1%, demonstrating excellent water stability. Details are provided in Table 2.

Table 2 Summary of Expansion Rates for Each Filler

Filler Ratio	Sample	Before Soaking (mm)	After Soaking (mm)	Height Difference (mm)	Sample Height (mm)	Expansion Rate (%)
Pure coal gangue	0.92	3.955	4.165	0.210	116	0.180
	0.95	9.146	9.527	0.381	116	0.330
	0.97	8.385	8.578	0.193	116	0.170
Coal gangue + Group C filler (3:1) filler (compaction degree 0.95)	Sample1	0.101	0.659	0.558	116	0.480
	Sample2	2.639	2.981	0.342	116	0.290
	Sample3	1.929	2.447	0.518	116	0.450
Coal gangue + Group C filler (4:1) (compaction degree 0.95)	Sample1	1.662	2.024	0.362	116	0.310
	Sample2	4.209	4.362	0.153	116	0.130
	Sample3	4.271	4.604	0.333	116	0.290
Coal gangue + Group C filler (4:1) + 3% cement (compaction degree 0.95)	Sample1	9.219	9.225	0.006	116	0.005
	Sample2	6.240	6.248	0.008	116	0.007
	Sample3	6.671	6.678	0.007	116	0.006
Coal gangue + Group C filler (4:1) + 5% lime filler (compaction degree 0.95)	Sample1	4.196	4.335	0.139	116	0.120
	Sample2	3.597	3.949	0.352	116	0.303
	Sample3	2.502	3.168	0.666	116	0.574
Coal gangue + Group C filler (4:1) + 3% cement + 8% fly ash (compaction degree 0.95)	Sample1	1.691	1.749	0.058	116	0.050
	Sample2	7.411	7.438	0.027	116	0.023
	Sample3	1.708	1.758	0.050	116	0.043
Coal gangue + Group C filler (4:1) + 3% cement + 15% fly ash (compaction degree 0.95)	Sample1	5.784	5.831	0.047	116	0.041
	Sample2	3.001	3.048	0.047	116	0.041
	Sample3	2.550	2.601	0.051	116	0.044

3.4 Resilient Modulus Characteristics

Resilient modulus is a key parameter in pavement design. The modified mixture exhibits a significant improvement in resilient modulus. For instance, under a 200 kPa load, the resilient modulus of the mixture with "3% cement + 8% fly ash" generally ranges from 45 to 66 MPa (as shown in Figure 7).

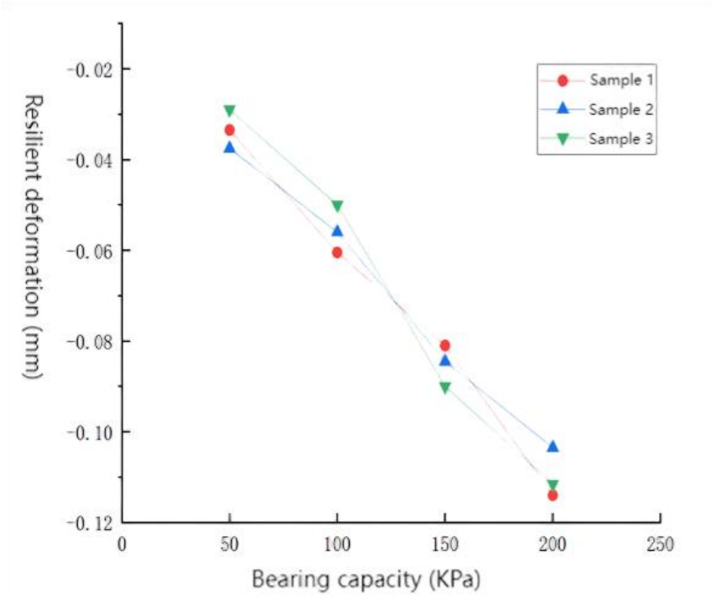

Figure 7 Coal GANGUE GROUP C Filler (4:1) 3% Cement 8% Fly Ash (Compaction 0.95) Compression Load Rebound Curve

4 THE MECHANISM OF SYNERGISTIC EFFECTS

Optimization of Physical Skeleton and Pore Structure: Coarse coal gangue particles constitute the primary load-bearing skeleton. Group C fine materials fill the large pores within this skeleton, initially enhancing compactness. Fly ash microspheres further fill the secondary pores, achieving a “micro-filling” effect. This optimizes the pore structure, reduces permeability, and forms a low-permeability environment conducive to cementation reactions [11-12].

Formation and Reinforcement of the Chemical Cementation Network: The hydration of cement rapidly produces cementitious products such as C-S-H, which provide early-stage strength. Under alkaline conditions, fly ash undergoes a pozzolanic reaction, forming a dense C-S-H gel that continuously fills pores and enhances cementation, contributing to long-term strength development. The synergistic interaction between cement and fly ash effectively integrates the physical densification system with the chemical cementation system, fundamentally improving the strength and water stability of coal gangue mixtures [13-15].

5 CONCLUSION

(1) The combination of coal gangue and Group C filler can effectively improve the particle gradation, resulting in a continuous and well-graded curve, which lays a solid foundation for achieving high density and strength.

(2) The incorporation of appropriate amounts of cement and fly ash (e.g., 3% cement + 8% fly ash) can significantly enhance the mechanical properties of the mixed material, achieving a CBR value > 120% and a resilient modulus > 60 MPa, which fully meets the requirements for high-grade highway subgrade construction.

(3) The incorporation of cement and lime significantly reduces the expansion rate of the mixture (mostly <0.1%) through cementation and pozzolanic reactions, thereby imparting excellent water stability and durability.

(4) The mix ratio of coal gangue to Group C filler at 4:1, with an addition of 3% cement and 8% fly ash, is recommended as the optimized proportion. This mixture exhibits superior engineering properties, complies with the industry standards for high-grade highways, and demonstrates strong potential for broad application. It enables large-scale, resource-recovery utilization of coal gangue, offering significant environmental and economic benefits. With its competitive edge in green infrastructure, this optimized mixture holds substantial promise for widespread engineering applications.

COMPETING INTERESTS

The authors have no relevant financial or non-financial interests to disclose.

REFERENCES

[1] Jia P. Application of coal gangue mixture in road subbase construction. Development Guide to Building Materials, 2025, 23(17): 58-60. DOI: 10.16673/j.cnki.jcfzdx.2025.0742.

[2] Cui X R, Huo X P, Zhou B J, et al. Spatial distribution characteristics and graded quality utilization pathways of coal gangue in China. Environmental Science, 2025, 46(4): 2281-2291. DOI: 10.13227/j.hjkx.202401269.

[3] Chen Y Y. Research on the application of cement-stabilized washed coal gangue in pavement base. Auto Time, 2025(19): 168-170.

[4] Xie X H. Pavement performance and dynamic response of coal gangue powder modified rubber asphalt mixture. Guangdong Highway Communications, 2025, 51(5): 7-12. DOI: 10.19776/j.gdgljt.2025-05-0007-06.

[5] Wang D C, Wei J W, Hu L, et al. Experimental study on mixing method and durability of coal gangue in pavement base mixture. Materials Reports, 2025, 39(11): 171-180.

[6] Xue X Y, Zhao M Z, Zhang J, et al. Effect of composite curing agent on pavement performance of fly ash-coal gangue mixture. Hebei Journal of Industrial Science and Technology, 2025, 42(1): 62-69.

[7] Song Q, Yang Y, Xu S, et al. Mechanical properties, durability, and carbon emissions of concrete with coal gangue coarse aggregate, fine aggregate and mineral admixtures in coal mining environment. Case Studies in Construction Materials, 2025, 23: e05187. DOI: 10.1016/J.CSCM.2025.E05187.

[8] Liu Y K, Luo Q, Jin F L, et al. Experimental study on influence of fines content on compaction characteristics of fine sandy soil. Railway Engineering, 2018, 58(12): 87-91.

[9] Mei H H. Experiment on permanent deformation characteristics of silt under cyclic-intermittent loading. Journal of Civil Engineering and Management, 2021, 38(2): 160-167. DOI: 10.13579/j.cnki.2095-0985.2021.02.023.

[10] Xie C H, Liu Y. Exploration on rapid determination method of CBR index for expansive soil filler. Chinese & Overseas Architecture, 2018(8): 249-251. DOI: 10.19940/j.cnki.1008-0422.2018.08.077.

[11] Liang C X. Experimental study on engineering characteristics of limestone rock mixture and gravel mixture. Chengdu University of Technology, 2018. DOI: 10.26986/d.cnki.gcdlc.2018.000058.

[12] Chen Y Y, Gao L. Laboratory model test study on reinforced fly ash embankment. Fly Ash Comprehensive Utilization, 2017(4): 40-42.

[13] Zhang T L. Analysis of pavement performance of cement stabilized coal gangue mixture. Western China Communications Science & Technology, 2023(11): 27-29. DOI: 10.13282/j.cnki.wccst.2023.11.009.

[14] Han J, Wang L H, Ma L, et al. Influence of cement and lime content on shear strength of improved expansive soil. Yellow River, 2025, 37(4): 137-139.

[15] Bai Y P, Xia Y, Ma L, et al. Performance study on fly ash-based geopolymer stabilized loess. Fly Ash Comprehensive Utilization, 2025, 39(5): 8-13. DOI: 10.19860/j.cnki.issn1005-8249.2025.05.002.