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Experimental Study on the Mechanical Properties of Loess Improved by a Carbide Slag–Fly Ash Composite

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Abstract: To investigate the effects of carbide slag and fly ash on the mechanical properties of loess, laboratory tests were conducted using three treatment approaches: single incorporation of carbide slag, single incorporation of fly ash, and composite incorporation of both materials. Compaction tests were performed to analyze the variations in maximum dry density and optimum moisture content under different dosage conditions, and specimens were subsequently prepared at their respective optimum moisture contents for unconfined compressive strength tests to evaluate the load-bearing capacity of the treated loess. The results indicate that the incorporation of carbide slag and fly ash significantly modifies the compaction performance and strength characteristics of loess, and an appropriate dosage interval exists for composite treatment. With increasing carbide slag content, the strength of the treated loess continuously increases, whereas the influence of fly ash content exhibits an increasing–then–decreasing trend. Overall, the combination of fly ash with carbide slag yields superior improvement compared with single-additive treatments. These findings provide experimental evidence for the use of industrial solid wastes in loess improvement and offer reference value for both waste resource utilization and engineering applications involving loess foundations.

Keywords: Loess; Carbide slag; Fly ash; Compaction test; Unconfined compressive strength (UCS); Composite treatment

I. INTRODUCTION

Loess is a typical Quaternary aeolian sediment [1] and the most widely distributed unsaturated soil in Northwest China [2], mainly occurring north of the Qinling Mountains, south of the Yinshan Mountains, and along the eastern margin of the Tibetan Plateau, forming the largest and thickest loess plateau in the world. This type of soil is characterized by large pores, vertical joints, and strong water sensitivity [3]: it maintains relatively high structural strength under dry conditions, but once wetted its pore structure collapses rapidly, leading to a significant strength reduction and frequent loess slope failures [4–6].

Traditional stabilizers such as cement and lime can improve the engineering properties of loess; however, these materials suffer from drawbacks including high carbon emissions, high cost, increased brittleness after treatment, and unstable long-term performance [7], which do not meet current green and low-carbon development requirements. In contrast, the resource utilization of industrial solid waste provides a promising alternative for loess improvement. Carbide slag, a by-product of acetylene production [8], and fly ash, a typical solid waste from coal-fired power plants [9], are produced in large quantities and contain active chemical components capable of participating in pozzolanic reactions to enhance the strength and durability of soils. Carbide slag supplies $Ca(OH)_2$ to create an alkaline environment, while fly ash provides SiO_2 and Al_2O_3 that participate in pozzolanic reactions, resulting in potential synergistic strengthening effects. This approach not only improves soil engineering performance but also achieves solid waste utilization, yielding significant environmental and economic benefits.

Based on the above background, this study conducted laboratory tests to systematically investigate the engineering properties of loess improved by carbide slag and fly ash. First, single-incorporation tests of carbide slag and fly ash were carried out to analyze the physical and strength properties under different dosage conditions through compaction tests and unconfined compressive strength tests. Composite improvement tests were then performed to explore the synergistic effects of carbide slag and fly ash and their influence on the mechanical properties of loess. Finally, the improvement efficiency and strength enhancement characteristics of single and composite modifications were compared to determine suitable material ratios. The findings of this study aim to provide feasible mix design schemes and experimental evidence for the application of industrial solid waste in loess stabilization, with practical significance for promoting solid waste resource utilization and enhancing the mechanical performance of loess

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foundations.

II. Materials and Methods

2.1 Soil specimens

The soil used in this study was a typical loess collected from the Pingliang area of Gansu Province. This type of loess is widely distributed in Northwest China and is characterized by loose structure, well-developed pores, and pronounced water sensitivity. The loess appears yellowish-brown or light yellow, and after drying at 110 °C its color becomes slightly lighter while retaining its silty structure, exhibiting the typical characteristics of Quaternary aeolian loess, as shown in Fig. 1. The basic physical properties of the loess were determined in accordance with the Standard for Soil Test Method (GB/T 50123-2019), and the results are presented in Table 2.1.

Fig. 1 Field photograph of loess

Table 1 Basic physical properties of loess

Water content	Natural density	Dry density	Liquid limit	Plastic limit	Specific gravity	Maximum dry density	Optimum moisture content
9.83 %	1.64g/cm^3	1.50g/cm^3	32.04 %	18.11 %	2.6985	1.75 g/cm^3	14.92 %

2.2 Stabilizing materials

Carbide slag is a by-product of acetylene production, appearing as a grayish-white powder, and is mainly composed of $Ca(OH)_2$ with certain alkaline reactivity. Fly ash is a gray fine powder generated from coal combustion and contains active components such as SiO_2 and Al_2O_3, which can improve the structural characteristics of loess. Photographs of the materials are shown in Figs. 2 and 3.

Fig. 2 Carbide slag used in the test

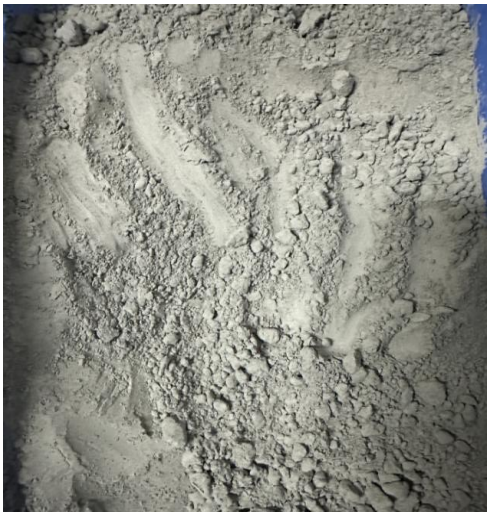

Fig. 3 Fly ash used in the test

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2.3 Mix Design

Based on the different modification mechanisms of carbide slag and fly ash, two experimental approaches, namely "single incorporation" and "composite incorporation", were adopted in this study. First, single-incorporation tests of carbide slag and fly ash were conducted, in which the dosage of carbide slag was set to 2%, 3%, 4%, and 5%, and that of fly ash was set to 5%, 10%, 15%, 20%, and 25% by dry weight of soil. Untreated loess was used as the control group to analyze the effects of individual stabilizing materials on the mechanical properties of loess. Based on the results of the single-incorporation tests, composite incorporation tests of carbide slag and fly ash were further carried out within the selected effective dosage range. Different combinations were compared to evaluate the strength enhancement and reinforcement performance of the composite treatment. The detailed mix design scheme is presented in Table 2.

Table 2 Dosage design of carbide slag and fly ash

Specimen ID	Carbide slag content (%) (D)	Fly ash content (%) (F)	Notation
1	2	5	2D5F
2		10	2D10F
3		15	2D15F
4		20	2D20F
5		25	2D25F
6	3	5	3D5F
7		10	3D10F
8		15	3D15F
9		20	3D20F
10		25	3D25F
11	4	5	4D5F
12		10	4D10F
13		15	4D15F
14		20	4D20F
15		25	4D25F
16	5	5	5D5F
17		10	5D10F
18		15	5D15F
19		20	5D20F
20		25	5D25F
21	2	0	2D0F
22	3	0	3D0F
23	4	0	4D0F
24	5	0	5D0F

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25	0	5	0D5F
26	0	10	0D10F
27	0	15	0D15F
28	0	20	0D20F
29	0	25	0D25F
30	0	0	0

2.4 Test Methods

Compaction tests were carried out in accordance with the *Specifications for Highway Soil Testing* (JTG 3430-2020), using the Light Compaction Method I. The compaction mold had an inner diameter of 10 cm and a volume of 997 cm³. The specimens were prepared using the wet preparation method, in which the water content was adjusted based on the natural water content. Prior to specimen preparation, the loess was air-dried and passed through a 2 mm sieve, and water was added gradually to reach the target water content. The mixed soil was then sealed and left to equilibrate to allow uniform moisture distribution.

Before compaction, the inner walls of the mold and collar were coated with vaseline. The soil was compacted in three layers, with each layer being tamped 27 times, and the surface was scarified between layers. After compaction, the collar was removed, the soil surface was trimmed flush with the mold top, and the mass of the mold and wet soil was measured. The compacted specimen was then extruded using an electric extruder. Approximately 400 g of soil was taken from the center of the specimen to determine its water content. The dry density of each specimen after compaction was calculated using Equation (1).

$$\rho_d = \frac{\rho}{1+0.01w} \quad (1)$$

where ρ_d is the dry density (g/cm³), ρ_w is the wet density (g/cm³), and ω is the water content (%).

On this basis, compaction tests were conducted on loess treated with single incorporation of carbide slag, single incorporation of fly ash, and composite incorporation of carbide slag and fly ash. The compaction curves for each mix proportion were obtained using the same testing procedure, and the maximum dry density and optimum moisture content corresponding to different mix conditions were determined, providing preparation parameters for subsequent unconfined compressive strength tests. In the subsequent strength tests, all specimens were prepared at their respective optimum moisture contents and compacted to approximately 95% relative compaction to ensure comparability among different mix proportions. The dry density and water content of each specimen were used to plot compaction curves, in which the peak point corresponds to the optimum moisture content (horizontal axis) and the maximum dry density (vertical axis).

Unconfined compressive strength (UCS) tests were performed in accordance with the *Specifications for Highway Soil Testing* (JTG 3430-2020), using a YAW-300 kN computer-controlled electronic pressure testing machine manufactured by Shenzhen Wance Co., Ltd., with a loading rate of 1 mm/min.

Prior to specimen preparation, loess, carbide slag, and fly ash were mixed uniformly according to the specified mix proportions, and water was added based on the optimum moisture content obtained from the compaction tests. The mixture was then allowed to stand to ensure uniform moisture distribution. Cylindrical specimens with a diameter of 39.1 mm and a height of 80 mm were prepared using a static compaction method, and the relative compaction was controlled at approximately 95%. For each mix proportion, three parallel specimens were prepared, and the average value was taken as the UCS of that group. During testing, the peak stress obtained from the stress–strain curve was recorded as the unconfined compressive strength, which was used to evaluate the influence of different dosages and modification approaches on the strength characteristics of the loess.

III. Test Results and Analysis

3.1 Compaction Test

To investigate the compaction characteristics of loess treated with single incorporation of carbide slag, single incorporation of fly ash, and composite incorporation of both materials, compaction tests were conducted on specimens with different mix proportions, and the corresponding water content–dry density curves were plotted. The figures present the compaction curves of natural loess, loess modified with carbide slag, loess modified with fly ash, and

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loess composite-modified under various dosage combinations, providing an intuitive comparison of the effects of different stabilizing materials and dosages on the dry density and optimum moisture content of loess. The relevant test results are shown in Figs. 4–15.

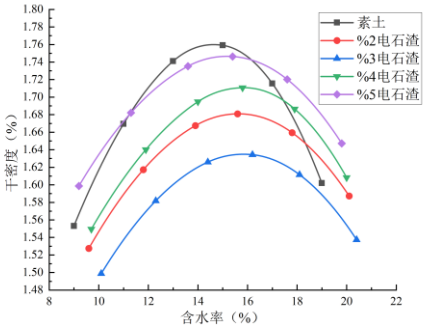

Fig. 4 Compaction curves of loess modified with carbide slag

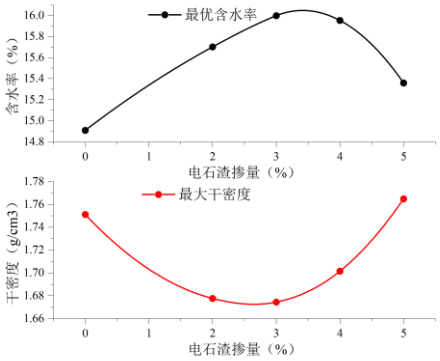

Fig. 5 Variation of MDD and OMC for carbide slag–modified loess

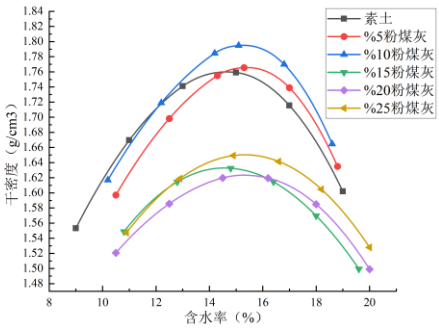

Fig. 6 Compaction curves of loess modified with fly ash

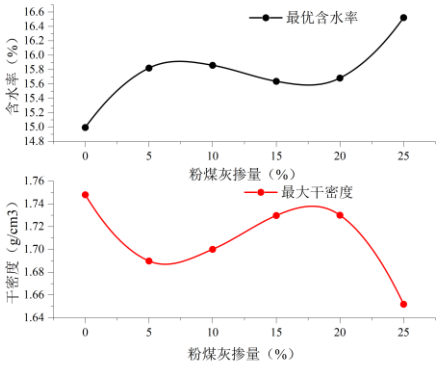

Fig. 7 Variation of MDD and OMC for fly ash–modified loess

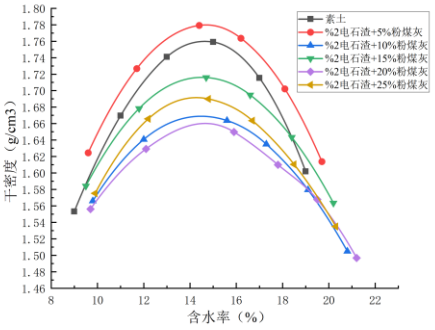

Fig. 8 Compaction curves

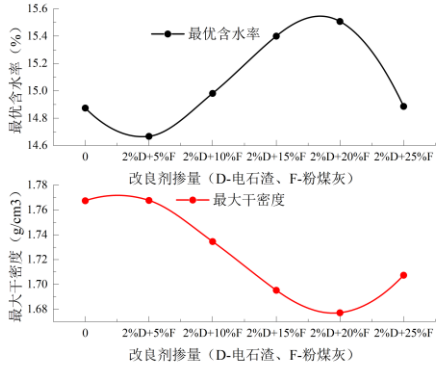

Fig. 9 Maximum dry density and optimum moisture content

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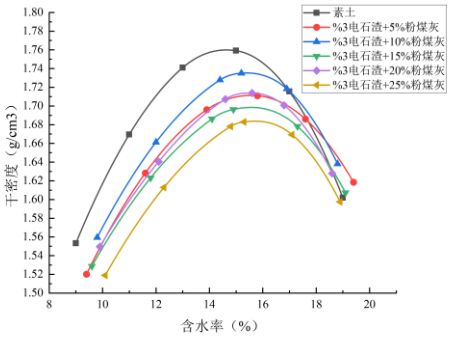

Fig. 8 Compaction curves

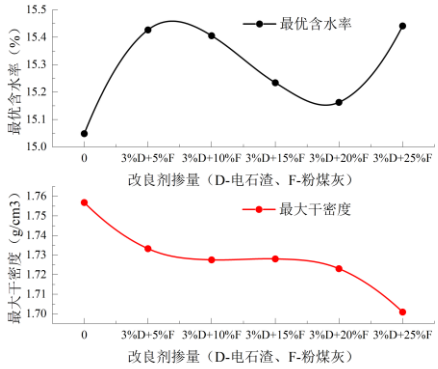

Fig. 9 Maximum dry density and optimum moisture content

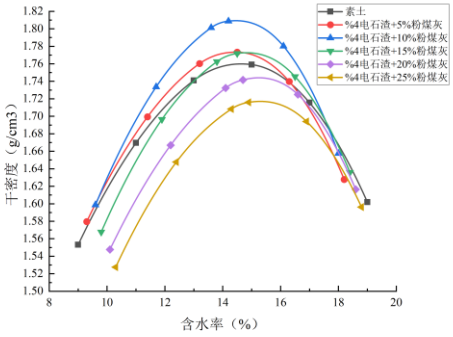

Fig. 8 Compaction curves

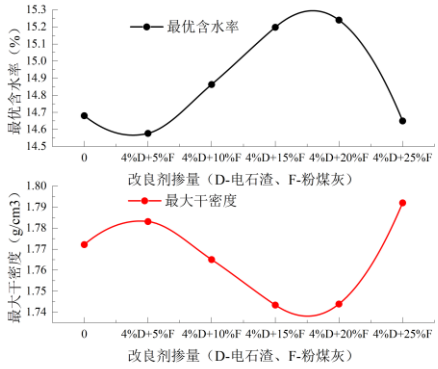

Fig. 9 Maximum dry density and optimum moisture content

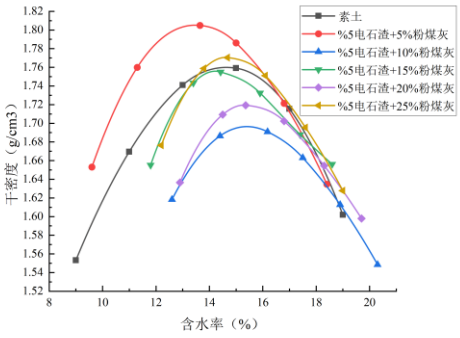

Fig. 8 Compaction curves

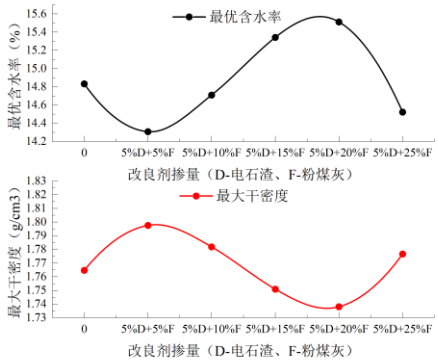

Fig. 9 Maximum dry density and optimum moisture content

The incorporation of carbide slag alters the compaction characteristics of loess, and the dry density and water content exhibit fluctuating variations with increasing slag content, indicating the existence of an appropriate dosage range. The fly ash content also has a significant influence on the compaction behavior of loess, with the maximum dry density and optimum moisture content showing staged fluctuation patterns as the dosage increases. The compaction curves of fly ash–modified loess under different carbide slag contents further demonstrate that fly ash substantially affects both the maximum dry density and optimum moisture content of the modified soil. As the fly ash content increases, both parameters exhibit trends of increasing followed by decreasing, or vice versa, depending on the carbide slag content, suggesting that an appropriate amount of fly ash can improve particle gradation and soil structure, thereby enhancing compaction performance, whereas excessive addition weakens the improvement effect.

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3.2 Unconfined Compressive Strength

The unconfined compressive strength (UCS) test is an effective method for evaluating the compressive bearing capacity of loess under unconfined conditions, and serves as an important indicator for assessing the improvement effect and mechanical performance enhancement. In this study, UCS tests were conducted on loess treated with single incorporation of carbide slag, single incorporation of fly ash, and composite incorporation of both materials. The test results are presented in Figs. 16–21.

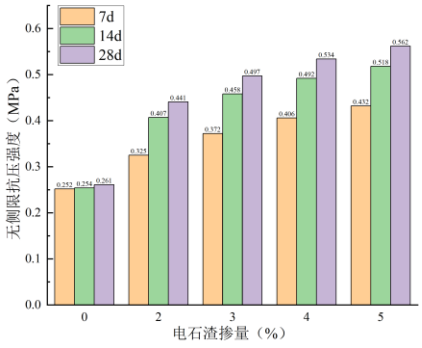

Fig. 16 Unconfined compressive strength of loess modified with carbide slag under different dosages

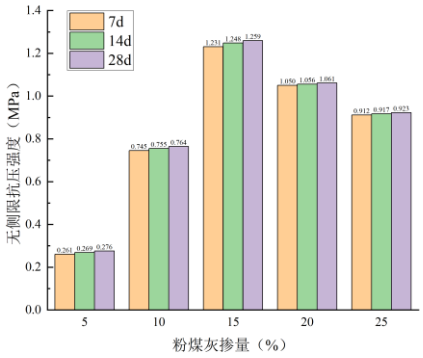

Fig. 17 Unconfined compressive strength of loess modified with fly ash under different dosages

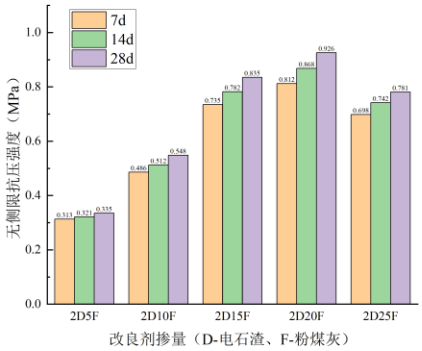

Fig. 18 Unconfined compressive strength of loess modified with 2% carbide slag and fly ash

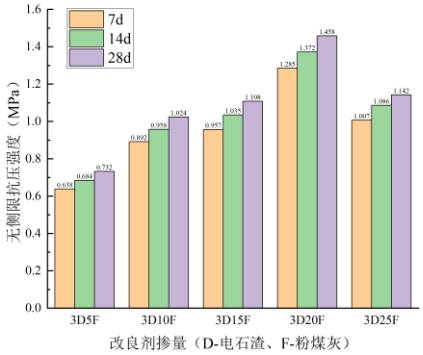

Fig. 18 Unconfined compressive strength of loess modified with 3% carbide slag and fly ash

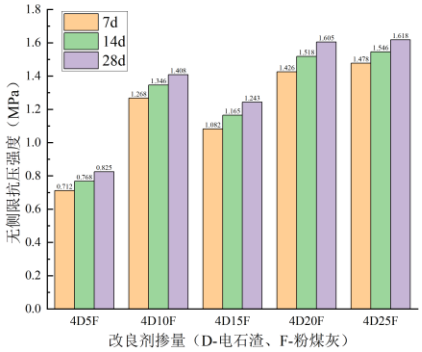

Fig. 18 Unconfined compressive strength of loess modified with 4% carbide slag and fly ash

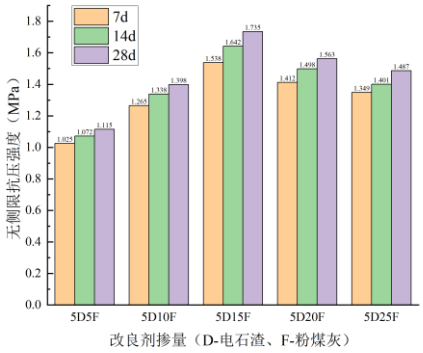

Fig. 18 Unconfined compressive strength of loess modified with 5% carbide slag and fly ash

The unconfined compressive strength (UCS) of loess modified with different carbide slag–fly ash combinations increased with curing age, with the most notable improvement observed at 28 days. As the fly ash content increased, the strength of the modified soil first increased and then decreased. Under a low carbide slag content of 2%, the UCS increased continuously with increasing fly ash dosage, reaching a peak value of 0.926 MPa at 2D20F, while a slight decrease to 0.781 MPa was observed at 2D25F. When the carbide slag content was 3%, the UCS reached its maximum value of 1.458 MPa at 3D20F and decreased to 1.142 MPa at 25% fly ash. When the carbide slag content increased to 4% and 5%, the strength peak appeared at a lower fly ash dosage; for example, 4D20F yielded 1.605 MPa, and 5D15F reached 1.735 MPa, while further increases in fly ash content resulted in limited improvement or slight reduction in strength.

These results indicate that an appropriate amount of fly ash can significantly enhance the strength of loess at a given carbide slag dosage, whereas excessive fly ash does not contribute to further strength improvement. Overall, combinations of 3%–5% carbide slag with 15%–20% fly ash produced relatively high strength levels, demonstrating that lower carbide slag dosages combined with suitable fly ash dosages can achieve improvement effects comparable to or even better than those obtained at higher carbide slag contents. In practical engineering applications, such combinations not only improve the mechanical performance of modified loess, but also reduce material costs and promote the utilization of industrial byproducts, achieving dual benefits in terms of economic efficiency and environmental sustainability.

IV. Conclusions

(1) Based on the compaction tests, the effects of carbide slag, fly ash, and their composite incorporation on the compaction characteristics of loess were analyzed. The results showed that the maximum dry density and optimum moisture content exhibited notable variations under different dosage conditions. Composite incorporation could enhance the compaction performance of loess within a certain dosage range, indicating the existence of an optimal mix proportion. These findings demonstrate the feasibility of using industrial solid wastes as stabilizing materials, and the parameters obtained from compaction tests can provide reference for subsequent mechanical tests and engineering applications.

(2) The unconfined compressive strength (UCS) test results indicated that the incorporation of carbide slag and fly ash had significant effects on the mechanical properties of the modified loess. Increasing the carbide slag content continuously improved the bearing capacity of the stabilized soil, while the fly ash content exhibited a trend of first increasing and then decreasing, suggesting the existence of an appropriate dosage range. The composite stabilization system could achieve higher strength levels than single incorporation under suitable mix proportions, indicating a synergistic enhancement between carbide slag and fly ash. In summary, the composite modification of loess using carbide slag and fly ash can effectively improve its compressive strength and exhibits practical engineering feasibility.

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