Study on the Freeze-Thaw Performance of Graphite Tailings Pavement Base Material

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Abstract. In order to address the significant weakening of mechanical properties in roadbed materials in cold regions under long-term stress-freeze-thaw coupling, this study investigates the accumulation of micro-damage and failure processes of graphite tailings roadbed materials (GSFG) during freeze-thaw cycles (F-T). By introducing box fractal dimension to quantitatively characterize the apparent cracks and internal damage severity (DS), a relationship between DS and the number of freeze-thaw cycles (N) is established. The results indicate that an appropriate amount of steel slag (SS) can significantly enhance the freeze-thaw resistance of GSFG, particularly at a mix ratio of GGBS: SS: FA = 6:1.84:2.16 and an alkali content of 8%, where the overall performance of GSFG reaches its optimal state.

Keywords: utilization of solid waste, pavement base material, graphite tailings, freeze-thaw cycles

1 Introduction

In cold regions, freeze-thaw cycles significantly affect the stability of subgrade and structures[1],leading to the formation of micro-cracks within the subgrade materials. This results in substantial changes to their microstructure and macro-mechanical properties, which not only weaken the load-bearing capacity of the materials but also trigger crack propagation and material failure. Under external forces, micro-cracks can accumulate and expand, resulting in surface cracks and damage[2]。In recent years, with the gradual promotion of solid waste resource utilization, the demand for the development of green building materials has become increasingly urgent. Moreover, a large amount of slag, steel slag, fly ash and graphite tailings are deposited, seriously affected the local ecological environment.

Therefore, the use of granulated blast-furnace slag (GGBS), steel slag (SS), and fly ash (FA) as binding materials to solidify graphite tailings (GTS) for the preparation of new environmentally friendly pavement base materials, and the investigation of their micro-damage mechanisms under freeze-thaw cycles, aligns with the national "dual carbon" strategy. Accurately describing crack evolution and quantifying freeze-thaw

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damage remains an unresolved challenge. Although existing studies primarily define freeze-thaw damage by evaluating macroscopic mechanical performance loss, the systematic and quantitative analysis of surface cracks is still insufficient. To address this, this study proposes to systematically investigate the micro-damage mechanisms of graphite tailings subgrade materials under varying numbers of freeze-thaw cycles by introducing fractal dimension methods. The study will employ box dimension to quantitatively characterize the surface cracks and internal damage degree of the materials, establishing a relationship between the damage index Dn and the number of freeze-thaw cycles N.

2 Macroscopic Mechanical Properties of GSFG F-T Cycle

The material mix proportions are as shown in Table 1.

Table 1. Mix Proportion of Graphite Tailings Subgrade Material

Amount of hardener	Number[1]	Mixture ratio(g)					28d UCS(MPa)
		GGBS	SS	FA	GTS	NaOH	
10%	SS23-10	10.8	1.70	5.50	180	1.44	1.93
	SS46-10		3.32	3.88			2.49
	SS73-10		5.24	1.96			2.22
12%	SS23-12	12.96	2.03	6.01		1.73	3.58
	SS46-12		3.99	4.65			4.26
	SS73-12		6.29	2.35			3.32
14%	SS23-14	15.12	2.37	7.71		2.02	4.94
	SS46-14		4.65	5.43			5.28
	SS73-14		7.34	2.74			4.56
16%	SS23-16	17.28	2.71	8.81		2.31	5.20
	SS46-16		5.31	6.21			5.61
	SS73-16		8.39	3.15			4.99

3 Results and Analysis

3.1 Variation Laws of Mechanical Properties

The freeze-thaw cycle test was conducted on the specified mix using specimens with dimensions of Φ50 mm × 50 mm. After curing at 20°C ± 2°C and 95% humidity for 27 days, the specimens were immersed in water for a day, then frozen at -18°C for 16 hours with 2 cm spacing between them. After freezing, they were thawed in a 20°C water bath for 8 hours, with the water level 2 cm above the specimens, completing one cycle. This process was repeated for the required number of cycles. Following the tests, the specimens were weighed, inspected, and tested for strength. [3]. The freeze-thaw cycle test results are shown in Figure 1.

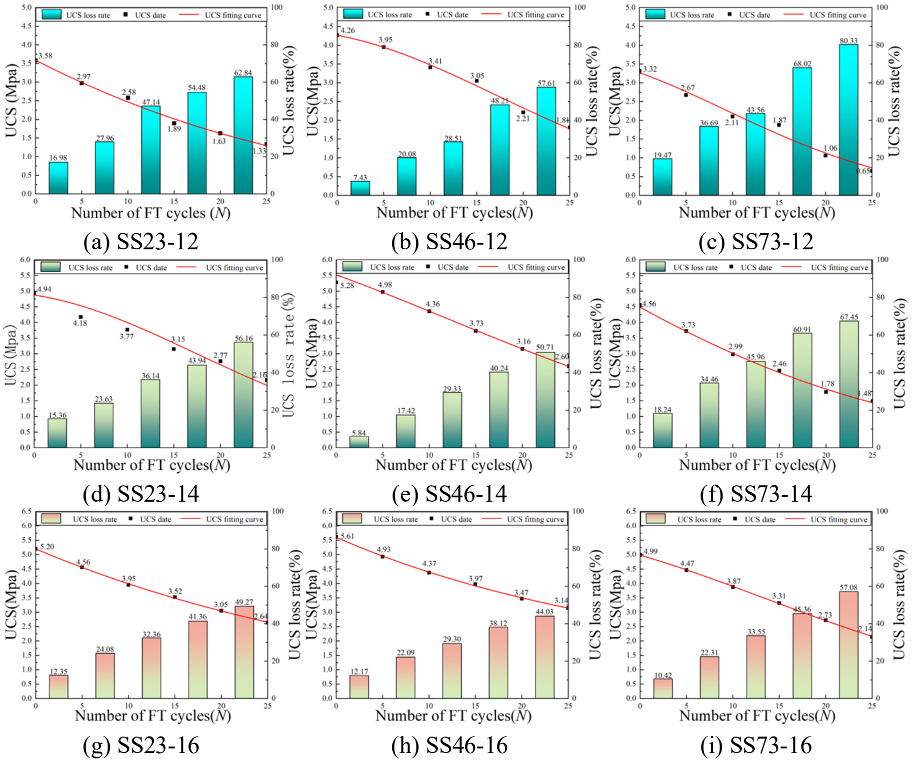

Fig. 1. UCS loss of graphite tailings subgrade material under different freeze-thaw cycles

From the figure, it can be seen that, under the same steel slag replacement rate, taking the SS46 group as an example, the initial UCS of GSFG is 4.26 MPa, 5.28 MPa, and 5.61 MPa. After 25 freeze-thaw cycles, the UCS decreases to 1.81 MPa, 2.60 MPa, and 3.14 MPa, with reduction rates of 57.61%, 50.71%, and 44.03%. Under the same stabilizer dosage, taking the SS-12 group as an example, the initial UCS of GSFG is 3.58 MPa, 4.26 MPa, and 3.32 MPa. After 25 freeze-thaw cycles, the UCS decreases to 1.33 MPa, 1.81 MPa, and 0.65 MPa, with reduction rates of 62.84%, 57.61%, and 80.33%. The results show that as the steel slag replacement rate increases, the strength of the graphite tailings subgrade material first rises and then falls. A moderate amount of steel slag improves pore structure and hydration, enhancing freeze-thaw resistance, but excessive amounts can destabilize the internal structure, reducing durability [4].

3.2 Uniaxial Compression Fracture Damage Analysis After F-T Cycle

Analysis of fracture damage after uniaxial compression for the three optimal steel slag doses (SS46-12, SS46-14, SS46-16). Figure 2 shows the surface damage patterns and binarized fracture images at maximum stress after 0, 5, 10, 15, 20, and 25 freeze-thaw cycles for different stabilizer dosages.

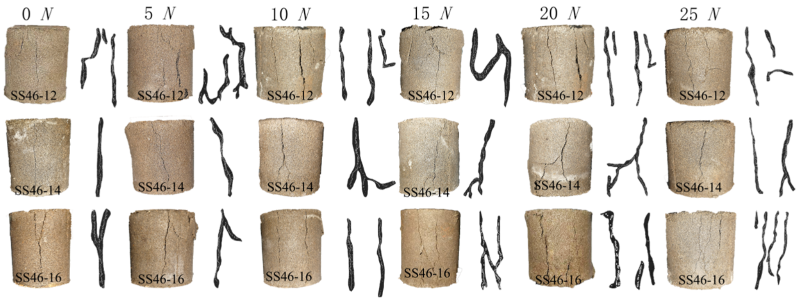

Fig. 2. Surface damage morphology of GSFG under different dosage of curing agent

As fractal geometry has advanced, various methods for calculating fractal dimensions have been developed, including Hausdorff, similarity, box, correlation, and information dimensions. The Hausdorff dimension was the first used to calculate fractal dimensions, but its application in engineering is often challenging. Consequently, the box dimension method, also called the grid covering or box-counting method, is more widely used. It involves covering a fractal object with square boxes of side length δ_k. As δ_k decreases, the number of boxes $N(\delta_k)$ increases. By applying a logarithmic transformation to the coordinates (δ_k, $N(\delta_k)$) and fitting the resulting points using least squares, the slope of the line gives the box dimension. The formula for the box dimension is expressed as[5]:

$$D = \lim_{k \to \infty} \frac{\lg N(\delta_k)}{-\lg \delta_k} \tag{1}$$

As the number of freeze-thaw cycles increases, the external morphology of GSFG changes. To quantify the degree of damage to the fracture structure, the box fractal dimension method is introduced to describe the cracks. Table 2 shows the box dimensions of the cracks at different freeze-thaw cycle counts.

Table 2. Box Dimension of Fractures under Different Freeze-Thaw Cycles

Number	0 *N*	5 *N*	10 *N*	15 *N*	20 *N*	25 *N*
SS46-12	1.82	1.93	1.91	1.95	1.96	2.01
SS46-14	1.81	1.85	1.85	1.86	1.89	2.05
SS46-16	1.85	1.87	1.88	1.89	1.9	1.92

Based on this, the evolution of GSFG freeze-thaw damage patterns was analyzed, with the fitting results shown in Figure 3.

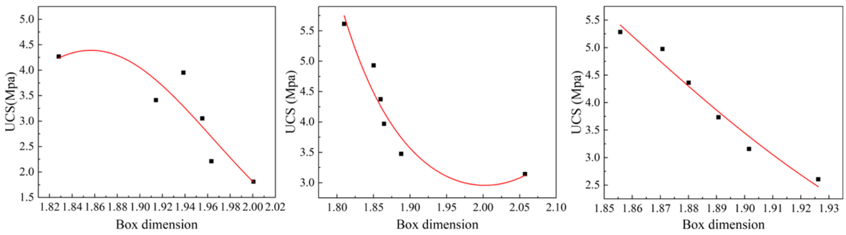

Fig. 3. Relationship between Box Dimension and UCS of Graphite Tailings Subgrade Material with Different Contents: (a) 12% Dosage, (b) 14% Dosage, (c) 16% Dosage

From the above figure, it can be seen that there is a negative correlation between the box dimension and the compressive strength of the graphite tailings roadbed materials. Therefore, the box dimension can be used as an effective indicator to characterize the degree of crack damage in the materials, allowing for the assessment of changes in durability and mechanical properties under freeze-thaw conditions. To analyze the extent of damage in the crack structure, a freeze-thaw damage variable D_n is introduced for quantitative characterization. Based on the gradual increase in box dimension after freeze-thaw cycles, a formula for calculating freeze-thaw damage using fractal dimension is proposed:

$$D_n = \left| \frac{d_n - d_0}{d_o} \right| \tag{2}$$

In the formula, d_n and d_o represent the fractal dimensions of the surface cracks in the graphite tailings roadbed materials after n freeze-thaw cycles and after 0 freeze-thaw cycles, respectively. The damage factor calculated from the box dimension according to this equation is shown in Table 3.

Table 3. Damage Factor Calculated Using Box Dimension

Number	0 *N*	5 *N*	10 *N*	15 *N*	20 *N*
SS46-12	0.0604	0.0471	0.0695	0.0740	0.0943
SS46-14	0.0222	0.0275	0.0301	0.0431	0.1367
SS46-16	0.0081	0.0131	0.0188	0.0247	0.0379

To better describe the damage extent of rocks under freeze-thaw cycles, the damage values for 0, 5, 10, 15, 20, and 25 freeze-thaw cycles were fitted. The results are shown in Figure 4.

As shown in the figure, the damage factor of the specimens decreases as the solidifying agent content increases, while it increases with the number of freeze-thaw cycles. This indicates a reasonable correlation between the freeze-thaw damage and the damage factor, which is consistent with the trends observed in the mechanical performance.

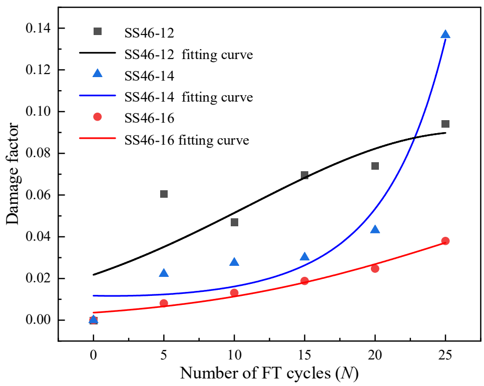

Fig. 4. Graph of the Relationship between Freeze-Thaw Damage and Cycle Number

4 Conclusion

(1) Under the same slag content and alkali dosage, the unconfined compressive strength (UCS) of GSFG exhibits a trend of initially increasing and then decreasing with the increase in steel slag substitution rate. Furthermore, UCS continues to rise with the increasing dosage of curing agents. This study indicates that an appropriate amount of steel slag can significantly enhance the freeze-thaw resistance of graphite tailings road-bed materials. Especially under the ratio of slag: steel slag: fly ash =6:1.84:2.16 and 8% alkali content, the comprehensive performance of graphite tailings roadbed material reaches the best state.

(2) The damage severity (D_S) exhibits a significant positive correlation with the number of freeze-thaw cycles (N), indicating that D_S can serve as an effective indicator for assessing the freeze-thaw damage extent of GSFG.

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