

Research Article

Research on Basic Mechanical Properties and Fracture Damage of Coal Gangue Concrete Subjected to Freeze-Thaw Cycles

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In order to study the freeze-thaw damage law of the basic mechanical properties and fracture performance of coal gangue concrete, four kinds of coal gangue concrete specimens with different replacement rates of coal gangue coarse aggregate were designed, and then, the basic mechanical test and three-point bending loading were carried out under different times of the freeze-thaw cycle. The test results show that the compressive strength and flexural strength of concrete decrease with the increase of coal gangue aggregate content, and the higher the content of coal gangue aggregate is, the greater the freeze-thaw damage of coal gangue concrete is. The coal gangue reduces the fracture resistance of concrete, and the higher the replacement rate of coal gangue coarse aggregate is, the lower the fracture toughness and fracture energy of concrete is. The freeze-thaw cycle causes the obvious decrease of fracture toughness and fracture energy of concrete because the moisture content of coal gangue particles is higher; the freeze-thaw damage of coal gangue concrete is more serious than that of ordinary concrete, and the higher the substitution rate of replacement of coal gangue coarse aggregate is, the higher the freeze-thaw damage of fracture toughness and fracture energy is. The correlation between the freeze-thaw times and the two parameters of fracture toughness and fracture energy damage of coal gangue concrete after freeze-thaw cycles is good. The relationship between the two parameters and the freeze-thaw times can be fitted by power function $y = ax^b$, and the fitted power index value of fracture toughness is higher than that of fracture energy.

1. Introduction

Concrete is the most common building material in civil engineering, and its aggregate consumption is very huge [1, 2]. At present, the annual aggregate consumption in the world exceeds 13 billion tons [3]. Due to the lack of natural aggregate, the exploitation of natural aggregate has a great ecological impact on the global environment. So, it has become a very urgent problem in the field of concrete to solve the source of aggregate [4, 5].

Coal gangue is the solid waste produced in the process of coal mining and processing, and it is one of the largest industrial solid wastes in China [6, 7]. After crushing, cleaning, and screening, coal gangue can replace natural aggregate to produce concrete, which can not only reduce the stacking amount of solid waste but also save natural resources [8–11]. Because most of China's coal mines are located in the cold northern areas, the promotion and

application of coal gangue concrete are mainly in these areas, and its frost resistance is the main reason affecting the durability of concrete. Therefore, the research on the frost resistance of coal gangue concrete has an important practical value [12–15].

Freeze-thaw damage has become an important factor affecting the basic mechanical properties and durability of concrete. Many scholars have studied the mechanical properties of ordinary concrete after freeze-thaw cycles and achieved certain results [16–18]. After multiple freeze-thaw cycles, the compressive strength, tensile strength, and flexural strength of concrete show a significant decline, indicating that the freeze-thaw effect has produced obvious damage in the concrete, resulting in a significant reduction in the mechanical properties of concrete [19–21]. Ji et al. [22] established a frost damage failure model based on the damage mechanics and Ottosen failure model, in which elastic modulus and Poisson's ratio under damage are the

damage variables. Meanwhile, Ji established a frost damage constitutive model, and all this will be useful to the development of finite element programme. Chuanhui et al. [23] studied the freeze-thaw mechanical properties of recycled concrete, and the results show that the mechanical strength of recycled concrete decreases greatly with the increase of freeze-thaw cycles, and its frost resistance is lower than that of ordinary concrete.

Many scholars have conducted extensive research on the mechanical properties and frost resistance of coal gangue concrete [24, 25]. Li et al. [26] carried out the freeze-thaw cycle test on coal gangue concrete, which showed that the frost resistance of coal gangue concrete is lower than that of ordinary concrete. Guan et al. [27] studied the damage degree of coal gangue concrete under freeze-thaw cycle, which showed that the increase of the coal gangue content would accelerate the strength deterioration of concrete. Zhang et al. [28] studied the frost resistance of spontaneous combustion coal gangue concrete. Qiu et al. [29, 30] studied the capillary water absorption of coal gangue ceramsite concrete under freeze-thaw cycles. Wang [3] summarized the basic mechanical properties and application of coal gangue aggregate as well as some existing problems.

The above research mainly focuses on the basic mechanical properties of coal gangue concrete, but there are few research studies on the fracture properties of coal gangue concrete in the freeze-thaw environment. In this study, first, the basic mechanical properties of coal gangue concrete specimens are tested to study the changes of basic mechanical properties of coal gangue concrete under the freeze-thaw effect, and then, the coal gangue concrete specimens are loaded through the three-point bending test [31]. This study will analyze the basic mechanical properties, fracture toughness, and fracture energy of coal gangue concrete under freeze-thaw cycle and study the influence of replacement rate of coal gangue coarse aggregate and freeze-thaw cycle on the fracture performance of coal gangue concrete, so as to provide reference for the popularization and application of coal gangue concrete in cold regions.

2. Test Plan

2.1. Test Materials. The cement is P·O 42.5 Tianrui cement with the specific surface area of $380 \text{ m}^2/\text{kg}$. The main performance indexes of this kind of cement are given in Table 1.

The fine aggregate is river sand with fineness modulus of 2.68 and apparent density of 2545 kg/m^3 . The natural coarse aggregate is 5 ~ 20 mm continuous graded limestone gravel, in which the moisture content is 1.86%. The coal gangue is produced by Pingdingshan mine with a particle size of 5 ~ 20 mm, in which the moisture content is 5.50% and crushing index is 18%. The water reducing agent (SP) is polycarboxylic acid with reducing the rate of 18%.

The cubic compressive strength of design for concrete is C30. According to the replacement rate of coal gangue coarse aggregate, four groups of specimens are designed. The replacement rate of coal gangue coarse aggregate is calculated and determined according to the mass ratio of 0, 40%, 70%, and 100% of coarse aggregate. The water binder ratio is

0.4. The material ratio is given in Table 2. In the table, MG represents coal gangue concrete; 0, 40, 70, and 100 represent the percentage of replacement rate of coal gangue coarse aggregate.

2.2. Experiment Process. The compressive strength of coal gangue concrete is tested by cube specimen with the size of $150 \text{ mm} \times 150 \text{ mm} \times 150 \text{ mm}$. The concrete specimen for flexural strength and three-point bending are prism with the size of $100 \text{ mm} \times 100 \text{ mm} \times 400 \text{ mm}$. After the specimen is made into shape, it is put into the standard curing box for 24 days, and then, it is placed in full water for 4 days. According to the "Standard of test methods for long term performance and durability of ordinary concrete" (China, GB/T50082-2009) [32], the specimens were put into the TDR-16 freeze-thaw circulator (Figure 1) for rapid freeze-thaw and then were frozen and thawed to the design times (0, 25, 50, 75, 100, and 125 times), respectively.

The process of the freeze-thaw test is as follows: (i) the specimens are cured in the standard curing room for 24 days, and then, the specimens are soaked in water with a water temperature of 20°C , and the water surface should be 20 ~ 30 mm higher than the top surface of the specimens. (ii) After soaking in water for 4 days, the specimens are taken out from water and put into the freeze-thaw specimen box. The specimens should be located in the center of the specimen boxes. Then, the specimen boxes are put into the specimen rack in the freeze-thaw box, while the clean water is injected into the specimen box. During the whole test, the water level in the test box should always be at least 5 mm higher than the top surface of the specimens. (iii) The specimens of each freeze-thaw cycle are 2 ~ 4 hours, and the thawing time is not less than 1/4 of the whole freeze-thaw cycle time. (iv) The fundamental frequency of the specimens is measured every 25 freeze-thaw cycles, and the loss of dynamic elastic modulus is calculated. At the same time, three specimens of each batch are taken out for corresponding mechanical properties and fracture properties tests.

The temperature control of specimens in the freeze-thaw cycle is realized by making a temperature measuring specimen with a central embedded temperature sensor of the same shape and size as the freeze-thaw specimen. Before the freeze-thaw cycle, the temperature measuring specimen is put into the temperature measuring specimen box, and the antiicing fluid is injected into the specimen box as the freeze-thaw medium. Then, the temperature measuring specimen box is put into the center of the freeze-thaw box. The minimum temperature of the center of the specimen is set at -18°C , and the maximum temperature is set at $+5^\circ\text{C}$.

The cube compressive strength, flexural strength, and three-point bending tests of specimens are shown in Figures 2–4.

In the three-point bending test, the beam span of the specimen is 300 mm. The initial crack of the specimen is cut by the rock cutter after 28 days of curing, and the depth is 10 mm. The three-point bending loading equipment is the HUALONG600B electrohydraulic servo universal testing

TABLE 1: Properties of P.O 42.5 cement.

Test items	Soundness	Water requirement of normal consistency (%)	Setting time (min)		Compressive strength (MPa)		Flexural strength (MPa)	
			Initial setting	Final setting	3 d	28 d	3 d	28 d
Test result	Qualified	26.7	165	220	25.8	48.5	5.3	8.2

TABLE 2: Concrete mix design.

Serial	Group code number	Cement (kg)	River sand (kg)	Coal gangue (kg)	Natural crushed stone (kg)	Water (kg)	Water reducing agent (kg)
1	MG-0	355	696	0	1210	142	7
2	MG-40	355	696	484	726	142	7
3	MG-70	355	696	847	363	142	7
4	MG-100	355	696	1210	0	142	7



FIGURE 1: Concrete freeze-thaw cycle machine.



FIGURE 3: Flexural strength test.



FIGURE 2: Cube compression test.

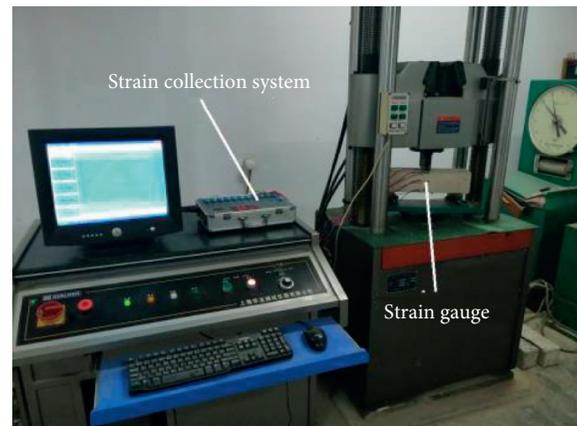


FIGURE 4: Three-point bending loading.

machine. The loading mode adopts load control, and the loading rate is controlled within 80 N/s. The crack opening displacement is measured by the clip extensometer and resistance strain gauge. The displacement and strain data can be collected and processed by the DH3818 strain acquisition instrument. The precision of the extensometer is 0.001 mm, and the measuring range is 5 mm. After the test, the V-F (displacement-load) curve can be obtained.

3. Test Results and Analysis

3.1. Basic Mechanical Properties

3.1.1. Cube Compressive Strength. Figure 5 shows the change of cube compressive strength of concrete with the increase of freeze-thaw cycles under different replacement rates of coal gangue coarse aggregate.

It can be seen from Figure 5 that before the freeze-thaw cycle, the compressive strength of concrete decreases monotonously with the increase of the

replacement rate of coal gangue coarse aggregate. The compressive strength of ordinary concrete without coal gangue is the highest, which is 41.26 MPa; when the replacement rate of coal gangue coarse aggregate is 40%, the compressive strength of concrete is 39.75 MPa, which is reduced by 3.66%; when the replacement rate of coal gangue coarse aggregate is 70%, the compressive strength of concrete is 38.27 MPa, which is reduced by 7.25%; when the replacement rate of coal gangue coarse aggregate is 100%, the compressive strength is the lowest, which is 36.89 MPa, and the decrease range is 10.59%.

It can be seen from Figure 5 that as for the compressive strength of concrete cube, after 125 freeze-thaw cycles, the compressive strength of concrete decreases significantly. The compressive strength of ordinary concrete without coal gangue decreases by 26.78%, and the corresponding

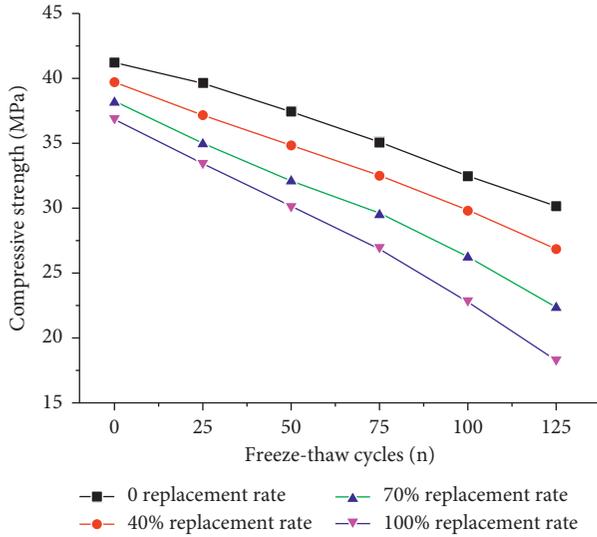


FIGURE 5: Compressive strength of coal gangue concrete under freeze-thaw cycles.

compressive strength of concrete with 40%, 70%, and 100% replacement rate of coal gangue coarse aggregate decreases by 32.45%, 41.60%, and 50.45%, respectively.

From above, we can see that the cube compressive strength of coal gangue concrete decreases obviously under the action of freeze-thaw, and the higher the content of coal gangue aggregate is, the greater the corresponding freeze-thaw loss is. It shows that the frost resistance of gangue concrete is not as good as that of ordinary concrete, which is consistent with the research in literature [26–30].

3.1.2. Flexural Strength. Figure 6 shows the change of flexural strength of concrete with the increase of freeze-thaw cycles under different replacement rates of coal gangue coarse aggregate.

It can be seen from Figure 6 that before the freeze-thaw cycle, the flexural strength of concrete decreases monotonously with the increase of the replacement rate of coal gangue coarse aggregate. The flexural strength of ordinary concrete without coal gangue is the highest, which is 5.36 MPa; when the replacement rate of coal gangue coarse aggregate is 40%, the flexural strength of concrete is 4.89 MPa, which is reduced by 8.77%; when the replacement rate of coal gangue coarse aggregate is 70%, the flexural strength of concrete is 4.47 MPa, which is reduced by 16.55%; when the replacement rate of coal gangue coarse aggregate is 100%, the flexural strength of concrete is the lowest, which is 3.92 MPa, and the decrease range is 26.87%.

It can be seen from Figure 6 that after 125 freeze-thaw cycles, the flexural strength of concrete decreases significantly, of which the flexural strength of ordinary concrete without coal gangue decreases by 32.28%, and the corresponding flexural strength of concrete with 40%, 70%, and 100% replacement rate of coal gangue coarse aggregate decreases by 36.81%, 44.84%, and 55.10%, respectively.

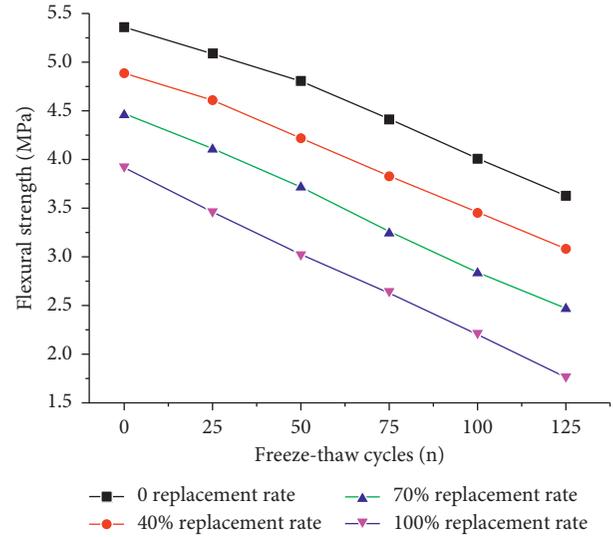


FIGURE 6: Flexural strength of coal gangue concrete under freeze-thaw cycles.

The influence of the freeze-thaw cycle on the flexural strength of coal gangue concrete is similar to that of cubic compressive strength, but the flexural strength decreases more than the compressive strength. The main reason is that the freeze-thaw cycle leads to the generation of cracks in the specimen, and the tensile stress in the specimen further intensifies the development of freeze-thaw cracks. So, the flexural strength of the specimen declines more quickly.

3.2. Fracture Performance Parameters of Concrete. Fracture toughness and fracture energy are commonly used to characterize the fracture properties of concrete.

3.2.1. Fracture Toughness. Fracture toughness is an important index used to characterize the ability of concrete to resist crack development in concrete fracture mechanics. According to the double-K fracture theory of concrete [33], the crack propagation of concrete structure can be divided into three stages: initial crack initiation, stable development, and instability. The instability toughness is an important parameter to express the critical state of fracture initiation and instability. The instability toughness is used to characterize the fracture toughness of concrete beams in this study.

The fracture toughness K [34, 35] can be calculated by substituting the measured maximum load F_{\max} and the effective crack length a_c of the test beam under three-point bending load into the following formula, respectively.

$$K = \frac{3(F_{\max} + mg/2 \times 10^{-2}) \times 10^{-3} La_c^{1/2}}{2th^2} f(\alpha), \quad (1)$$

where

$$f(\alpha) = \frac{1.99 - \alpha(1 - \alpha)(2.15 - 3.93\alpha + 2.7\alpha^2)}{(1 + 2\alpha)(1 - \alpha)^{3/2}}, \alpha = \frac{a_c}{h}. \quad (2)$$

In the formula L is the span of test piece, m ; m is the mass of test piece between supports, kg; h is the height of test

piece, m; t is the width of test piece, m; and g is the acceleration of gravity, 9.8 m/s^2 .

3.2.2. Fracture Energy. The average energy consumed by crack propagation per unit area is fracture energy, which is expressed by G_F . G_F is the ability of concrete structure to resist crack generation, development, and instability [36]. The calculation formula is as follows:

$$G_F = \frac{\int_0^{+\infty} Pd\delta}{A} = \frac{W}{t(h-a_0)}, \quad (3)$$

where P is the load, a_0 is the prefabricated crack length of the specimen, A is the cross-sectional area of the specimen, W is the work done by the external force in the fracture process of the specimen, and the external force includes load and self-weight.

W consists of four parts, in which W_1 is the envelope area of the curve $o-a-b$ and the horizontal axis of the coordinate in Figure 7, which belong to the work done by the load, and W_2 , W_3 , and W_4 are the works done by the self-weight of the beam.

3.3. Analysis for Fracture Performance. Figures 8 and 9 show the change of fracture toughness and fracture energy of concrete with the increase of freeze-thaw cycles under different replacement rates of coal gangue coarse aggregate.

3.3.1. Influence of Replacement Rate of Coal Gangue Coarse Aggregate on Fracture Performance of Concrete. It can be seen from Figure 8 that before the freeze-thaw cycle, the fracture toughness of concrete decreases monotonously with the increase of replacement rate of coal gangue coarse aggregate. Among them, the ordinary concrete without coal gangue has the highest fracture toughness, which is $0.894 \text{ MPa m}^{1/2}$; when the replacement rate of coal gangue coarse aggregate is 40%, the fracture toughness is reduced to $0.795 \text{ MPa m}^{1/2}$, which is reduced by 11.07%; when the replacement rate of coal gangue coarse aggregate is 70%, the fracture toughness is reduced to $0.716 \text{ MPa m}^{1/2}$, which is reduced by 19.91%; when the replacement rate of coal gangue coarse aggregate is 100%, the fracture toughness is the lowest, which is $0.624 \text{ MPa m}^{1/2}$, and the decrease range is 30.20%.

It can be seen from Figure 9 that before the freeze-thaw cycle, the fracture energy of concrete decreases monotonously with the increase of the replacement rate of coal gangue coarse aggregate. The fracture energy of ordinary concrete without coal gangue is the highest, which is 125.6 N/m ; when the replacement rate of coal gangue coarse aggregate is 40%, the fracture energy is 108.9 N/m , which is reduced by 13.30%; when the replacement rate of coal gangue coarse aggregate is 70%, the fracture energy is 96.8 N/m , which is reduced by 22.83%; when the replacement rate of coal gangue coarse aggregate is 100%, the fracture energy is the lowest, which is 82.3 N/m , and the decrease range is 34.47%.

The reason why the fracture toughness and fracture energy of coal gangue concrete are lower than that of ordinary concrete is that the strength and elastic modulus of coal gangue aggregate are less than that of natural crushed stone aggregate, and there are many impurities on the surface of coal gangue, which makes it easy to form a weak interface between coal gangue aggregate and cement mortar. The crack development in concrete generally follows the principle of small energy, that is, the crack front development will first develop to the material position where the strength and stiffness are relatively weak, and if the strength and stiffness are greater than the concrete matrix material, it will bypass [33]. Therefore, the initial cracks of coal gangue concrete under load tend to develop preferentially near the interface of coal gangue aggregate and even penetrate some coal gangue aggregate particles whose strength is lower than that of cement matrix, so as to shorten the actual crack propagation length in concrete, reduce the fracture resistance and energy consumption of concrete under load, and reduce the fracture toughness of concrete and fracture energy.

3.3.2. Effect of Freeze-Thaw Cycles on Fracture Performance of Concrete. It can be seen from Figures 8 and 9 that the fracture toughness and fracture energy of concrete gradually decrease with the increase of freeze-thaw cycles when the replacement rate of coal gangue coarse aggregate is constant.

It can be seen from Figure 8 that the fracture toughness of concrete decreases in varying degrees after 125 freeze-thaw cycles, especially after 50 freeze-thaw cycles. After 125 freeze-thaw cycles, the fracture toughness of ordinary concrete without coal gangue decreases by 51.45%, and the corresponding fracture toughness decreases by 55.22%, 59.36%, and 65.87% when the replacement rate of coarse coal aggregate is 40%, 70%, and 100%, respectively.

It can be seen from Figure 9 that the fracture energy of concrete also decreases in varying degrees after freeze-thaw cycles, and the overall decrease is slightly less than the fracture toughness. After 125 freeze-thaw cycles, the fracture energy of ordinary concrete without coal gangue decreases by 34.00%, and the corresponding fracture energy decreases by 41.41%, 51.65%, and 61.60% when the replacement rate of coarse aggregate is 40%, 70%, and 100%, respectively.

The results show that the fracture toughness and energy of concrete are greatly reduced after freeze-thaw cycles. This is because of the alternating circulation of expansion pressure and seepage pressure caused by ice melting and free water during the cycle of freezing and thawing of concrete, which leads to the further expansion of weak interface and crack in concrete, deterioration of the internal structure of concrete, formation of freeze-thaw damage, and ultimately the decrease of fracture toughness and fracture energy of concrete. Because the moisture content of coal gangue coarse aggregate (5.50%) is much higher than that of ordinary natural limestone aggregate (1.86%), the frost heaving stress of coal gangue aggregate in the freeze-thaw cycle is much higher than that of ordinary natural limestone aggregate. Therefore, the higher the content of coal gangue aggregate is,

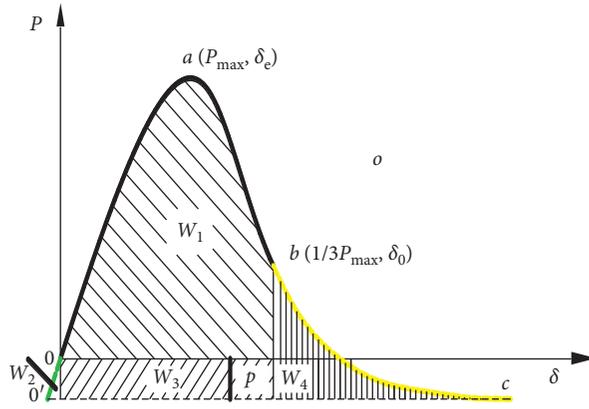


FIGURE 7: Diagram of fracture energy of concrete.

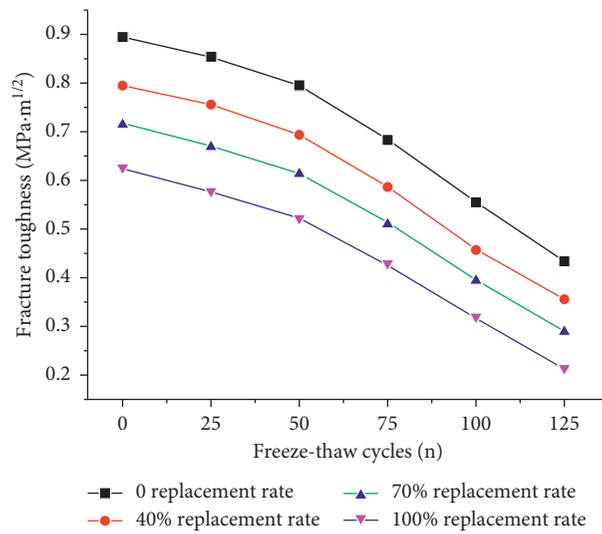


FIGURE 8: Fracture toughness of coal gangue concrete under freeze-thaw cycles.

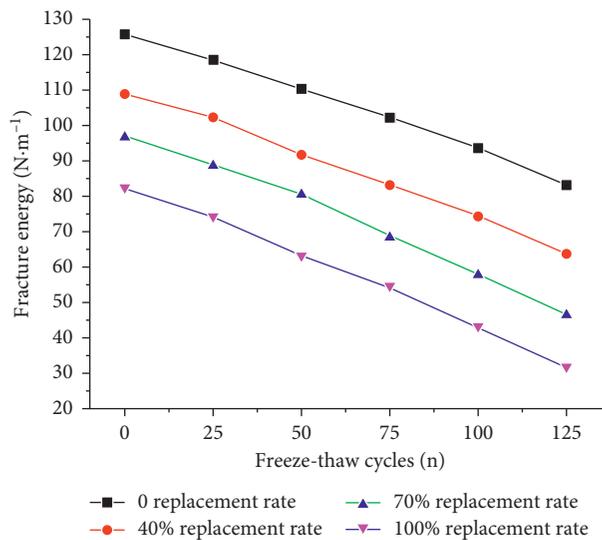


FIGURE 9: Fracture energy of coal gangue concrete under freeze-thaw cycles.

the greater the frost heaving stress of concrete in the freeze-thaw cycle is and the more serious the freeze-thaw damage is.

In addition, the strength and elastic model of coal gangue particles are lower than ordinary crushed stone. So, the freeze-thaw damage of coal gangue concrete is higher than that of ordinary concrete. The higher the replacement rate of coarse aggregate of coal gangue is, the higher the fracture toughness and fracture energy of the corresponding gangue concrete are.

3.4. Analysis of the Damage Law of Coal Gangue Concrete under Freeze-Thaw

3.4.1. Concept of Damage for Fracture Toughness and Fracture Energy under Freeze-Thaw. In this study, KD_n is set as the damage of freeze-thaw for fracture toughness of coal gangue concrete, and WD_n is set as the damage of freeze-thaw for fracture energy of coal gangue concrete. From the concrete parallel bar model [37], it can be got that

$$\begin{aligned} KD_n &= \frac{A_0 - A_n}{A_0} \\ &= \frac{E_0 - E_n}{E_0}. \end{aligned} \quad (4)$$

In the formula, A is the effective bearing area of concrete specimen, and the subscript 0 of parameter represents the initial value. The subscript n represents the value after n times of freeze-thaw cycles.

The simplified formula (4) is as follows:

$$E_n = E_0(1 - KD_n). \quad (5)$$

From formula (1), it can be seen that the fracture toughness of coal gangue concrete is positively proportional to the effective bearing area of the specimen. So we can get that

$$\frac{K_0}{A_0} = \frac{K_n}{A_n}. \quad (6)$$

From equation (4) and equation (6), it can be concluded that

$$\begin{aligned} K_n &= \frac{A_n K_0}{A_0} \\ &= K_0 \frac{A_0 - (A_0 - A_n)}{A_0} \\ &= K_0(1 - KD_n). \end{aligned} \quad (7)$$

In this formula, E is the elastic modulus of concrete, and K is the fracture toughness of concrete specimen. The subscript 0 of each parameter represents the initial value, and the subscript n represents the value after n times of freeze-thaw cycles.

From above, the following result can be obtained:

$$KD_n = 1 - \frac{K_n}{K_0}. \quad (8)$$

In the same way, it can be deduced that WD_n of coal gangue concrete is as follows:

$$WD_n = 1 - \frac{W_n}{W_0}. \quad (9)$$

In this formula, W is the fracture energy of concrete specimen. The subscript 0 of parameter represents the initial value, and the subscript n represents the value after n times of freeze-thaw cycles.

3.4.2. Damage Law for Fracture Toughness under Freeze-Thaw. According to the test data in Figure 8, the relationship between freeze-thaw cycles and damage of concrete fracture toughness under different replacement rates of coal gangue coarse aggregate can be obtained, as shown in Figure 10.

It can be seen from Figure 10 that the fracture toughness damage of coal gangue concrete caused by the freeze-thaw cycle has a good correlation with the freeze-thaw cycle, and the relationship between them can be fitted by power function $y = ax^b$. Through the analysis of the fitting parameters in the figure, it can be seen that the power exponent b of the fitting function is greater than 1, which indicates that the fracture toughness freeze-thaw damage of coal gangue concrete specimens under different substitution rates increases exponentially, and the growth curve shape is upward convex. The b value of concrete without coal gangue is the smallest, which is 1.48157, indicating that the growth rate of freeze-thaw damage is the slowest; while with the increase of replacement rate of coal gangue coarse aggregate, the b value gradually increases; when the replacement rate is 40%, the b value rises to 1.50058; when the replacement rate is 70%, the b value is 1.5124; and when the replacement rate is 100%, the b value reaches the maximum, which is 1.5203.

3.4.3. Damage Law for Fracture Energy under Freeze-Thaw. Similarly, the relationship between freeze-thaw cycles and damage of concrete fracture energy under different replacement rates of coal gangue coarse aggregate can be obtained from Figure 9, as shown in Figure 11.

According to Figure 11, the fracture energy damage of coal gangue concrete under different substitution rates has a good correlation with the freeze-thaw cycle. The change of the relationship between them can also be fitted by power function. The shape of the fitting curve is similar to fracture toughness, and the power index b value increases with the increase of replacement rate of coarse aggregate of coal gangue. The minimum b value of concrete without coal gangue is 1.07341, and when the substitution rate is 40%, the value of b increases to 1.10694; when the substitution rate is 70%, the value of b increases to 1.13443; and when the substitution rate is 100%, the value of b reaches the maximum value, which is 1.14507.

The fitting coefficient b of fracture energy is smaller than that of fracture toughness, which shows that the freeze-thaw damage of fracture toughness caused by the freeze-thaw cycle is higher than that of fracture energy.

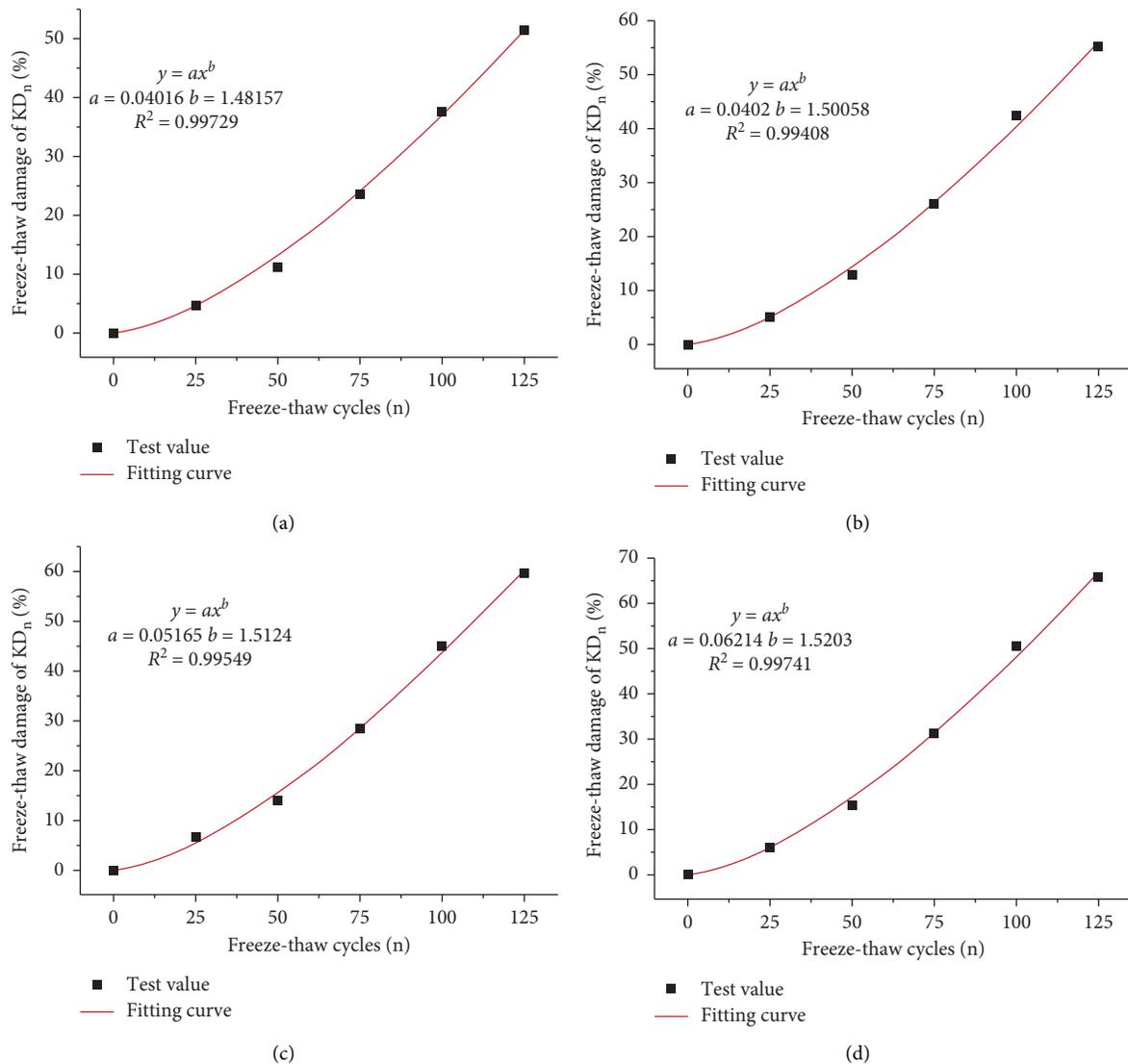


FIGURE 10: Freeze-thaw damage of fracture toughness of gangue concrete with different replacement rate. (a) Replacement rate of 0%. (b) Replacement rate of 40%. (c) Replacement rate of 70%. (d) Replacement rate of 100%.

3.5. *Reasons and Mechanisms for the Test Results.* From the test results, it can be seen that the fracture toughness and fracture energy of coal gangue aggregate concrete decrease faster than ordinary concrete under the action of freeze-thaw, which indicates that the freeze-thaw damage of coal gangue aggregate concrete is higher than ordinary concrete. There are two main reasons and mechanisms as follows.

- (1) The porosity of coal gangue aggregate is high, the water content is large, and the strength of coal gangue itself is lower than that of natural limestone aggregate. The research of literature [38] shows that the combination of limestone aggregate and mortar is "weak" (mortar) wrapping strong (aggregate), while the combination of coal gangue aggregate and mortar is "strong" (mortar) wrapping weak (aggregate). Therefore, the compressive strength and flexural strength of coal gangue aggregate concrete are low, and the strength decreases faster than

ordinary concrete under the action of freeze-thaw, and the corresponding fracture toughness and fracture energy also decrease more than ordinary concrete.

- (2) There are many interface defects between coal gangue aggregate and cement slurry. The research in literature [39] shows that the voids in the interface transition zone between limestone and cement paste are basically filled with hydration products, while there are many large capillary pores in the interface transition zone between coal gangue and cement slurry, and there are a lot of needle like crystalline ettringite and $Ca(OH)_2$ crystals in the pores. However, $Ca(OH)_2$ crystal has a small specific surface area, low surface energy, and little contribution to the strength, not conducive to the strength development of interfacial transition zone and hinders the contact between aggregate and cement paste. So the

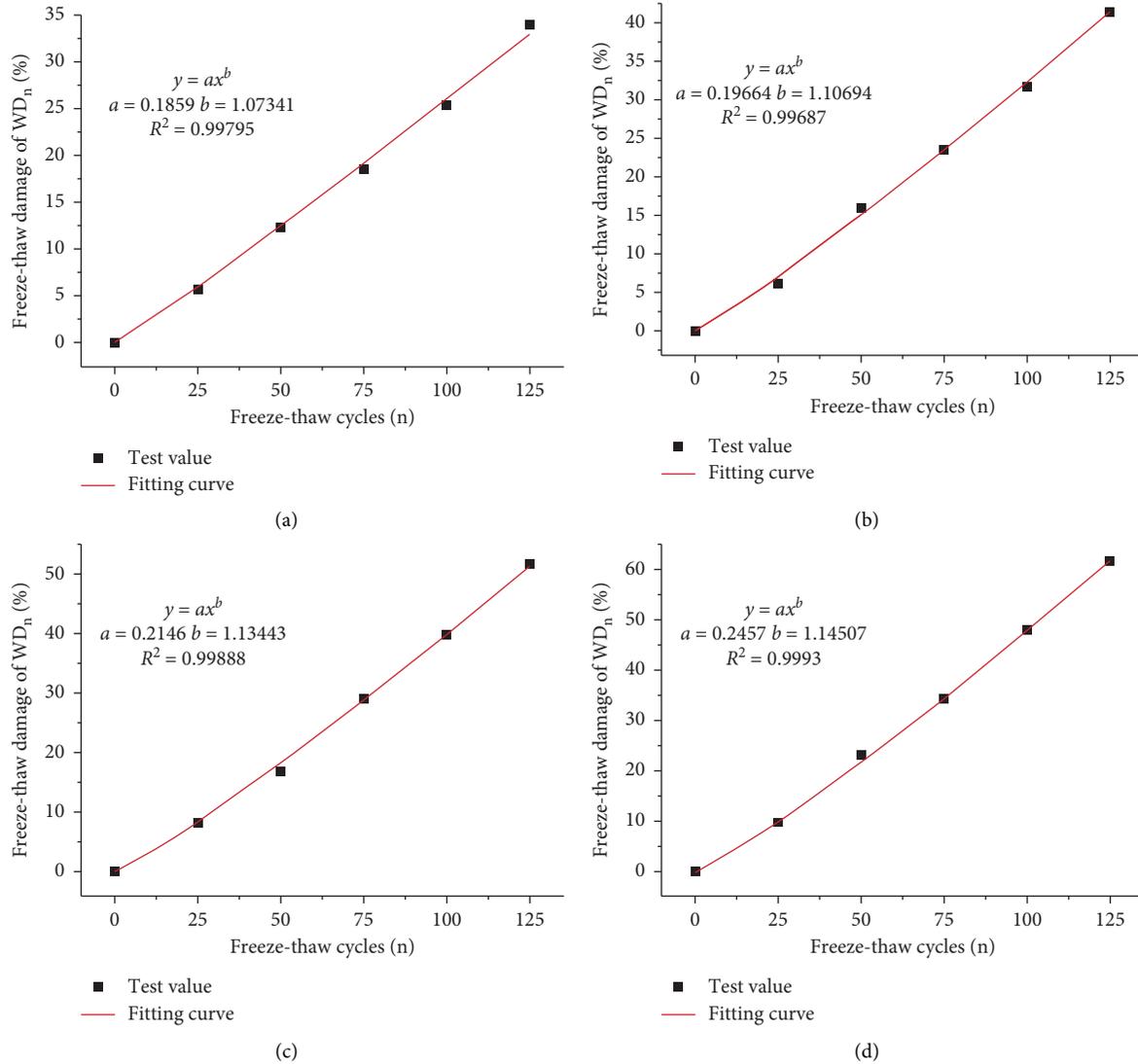


FIGURE 11: Freeze-thaw damage of fracture energy of coal gangue concrete under different replacement rates. (a) Replacement rate of 0%. (b) Replacement rate of 40%. (c) Replacement rate of 70%. (d) Replacement rate of 100%.

bonding between coal gangue and cement paste is not dense enough, which weakens the strength development of the interfacial transition zone. As a result, the overall strength of coal gangue concrete is low, and the freeze-thaw resistance is also poor.

4. Conclusion

Through the tests of cube compressive strength and flexural strength, as well as the tests of fracture toughness and fracture energy of coal gangue concrete specimens with different replacement rates under freeze-thaw cycles, the following conclusions can be drawn.

- (1) The basic mechanical properties and frost resistance of gangue concrete are not as good as ordinary concrete. The higher the content of coal gangue aggregate is, the worse its frost resistance is.

- (2) The higher the replacement rate of coal gangue coarse aggregate is, the lower the fracture toughness and fracture energy of concrete are. When the replacement rate of coal gangue coarse aggregate is 100%, the fracture toughness and fracture energy of coal gangue concrete decrease by 30.20% and 34.47%, respectively.
- (3) The freeze-thaw cycle results in the decrease of fracture toughness and fracture energy of concrete. Due to the high moisture content of coal gangue particles, the freeze-thaw damage of coal gangue concrete is more serious. The higher the replacement rate of coal gangue coarse aggregate is, the higher the freeze-thaw damage of fracture toughness and fracture energy are. After 125 freeze-thaw cycles, the freeze-thaw damage of fracture toughness and fracture energy of ordinary concrete are 51.45% and 34.00%, respectively. After 125 freeze-thaw cycles,

the freeze-thaw damage of fracture toughness and fracture energy of concrete with 100% replacement rate of coal gangue coarse aggregate are 65.87% and 61.60%, respectively.

- (4) The relationship between the two fracture parameters and freeze-thaw times can be fitted by power function, and the fitting power exponent of fracture toughness is higher than that of fracture energy.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that there are no conflicts of interest.

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