

Research Article

Crack Propagation Phenomenon in Gangue Concrete Using the Digital Image Correlation (DIC) Method

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Received 2 November 2022; Revised 26 February 2023; Accepted 1 March 2023; Published 30 January 2024

Academic Editor: Shengwen Tang

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In order to study the mode I crack propagation mechanism of coal gangue concrete with different contents, the digital image correlation (DIC) method was used to carry out the three-point bending fracture tests on coal gangue concrete with different contents. The results show that the process of the mode I crack propagation of coal gangue concrete with different contents can be divided into three stages as follows: the elastic stage before crack initiation, extended viscoelastic stage, and extended fracture stage. The amount of coal gangue has a significant impact on the crack propagation path. The more the amount of coal gangue, the more the crack penetrates through the coal gangue coarse aggregate, the smaller the bending degree of the failure path, and the faster the crack propagation to the penetration speed. The crack initiation load, ultimate load, external force work, gravity work, and fracture energy all decrease with the increase of the coal gangue content. The data obtained by the DIC method and displacement extensioneter are in good agreement, which proves that the DIC method is feasible. Based on the DIC method, before reaching the horizontal displacement on both sides of the crack tip, the horizontal displacement of the horizontal pixel is very small and there is a jump increase after the ultimate load. There are obvious inflection points on the left and right, and the horizontal displacement remains unchanged after the inflection point. After the horizontal displacement field of crack propagation reaches the limit load, there is an obvious limit; the limit gradually extends upward, and the corresponding crack tip strain field is also gradually enhanced. The more the coal gangue is added, the smaller the corresponding horizontal displacement and strain field is at the same limit load moment. The shape of the crack generation area of coal gangue concrete takes the crack tip as the axis of symmetry and is "gourd shaped." The more the content of the crack, the larger the crack generation area.

1. Introduction

China is a dominant producer and consumer of coal, and coal energy plays a leading role in the energy structure of China. According to the National Bureau of Statistics, although the coal energy proportion has shown a downward trend in recent ten years, the proportion of coal energy structure is still more than 55%. Gangue is the largest solid waste associated with coal mining, with a discharge of about 10%–15% of the coal yield [1–4]. There is clearly too much gangue in the stack, and the overabundance of gangue will adversely harm the natural environment and endanger human safety. The Chinese "Fourteenth Five-Year Plan" proposed that by 2025, the utilization rate of gangue, fly ash, and other bulk solid wastes should be enhanced significantly and the stockpiling of solid wastes should be reduced. Due to increased environmental protection measures, natural aggregate extraction is limited, raw material prices have risen drastically, and demand for concrete materials is rising. Therefore, using coal gangue as coarse aggregate to make concrete can not only reduce gangue pollution and occupation of air and land but also effectively alleviate the shortage of natural energy, responding to the national appeal of "strengthening disposal of solid waste and garbage" and "promoting comprehensive resource conservation and recycling."

Gangue needs to be crushed, cleaned, screened, and reprocessed before utilization, resulting in the microcrack,

loose structure, and performance reduction of gangue. When gangue is used as coal aggregate to produce gangue concrete, the performance of the resultant gangue concrete is far lower than that of natural gravel concrete, so the additive ratio of gangue should be controlled to achieve the strength requirement. The slump, mechanical performance, and high-temperature compressive strength of gangue concrete with different replacement rates and water-cement ratios were studied by Zhao et al. [5]. It was found that the watercement ratio had a significant impact on the gangue concrete slump. Furthermore, the larger the replacement rate of the coal gangue, the smaller the slump and the lower the basic mechanical properties. The higher the replacement rate of gangue concrete after high temperature, the lower the overall strength, but the decrease rate of the residual strength is slower than the conventional concrete. The performance study of gangue concrete with different replacement rates and particle sizes by Hao et al. [6] revealed that as the replacement rate of gravels with gangue increases, the influence on the properties of concrete becomes more significant. When the gravel was completely replaced, the compressive strength, tensile strength, and elastic modulus were 19.4%, 36.1%, and 32.2% lower than those of conventional concrete, respectively. Guan et al. [7] carried out an experimental study on the influence of the gangue replacement rate, age, and water-cement ratio on the shrinkage and compressive strength. The results revealed that with the increase of age, the gangue concrete compressive strength gradually increased, the influence of the water-cement ratio on the gangue concrete compressive strength decreased in a reverse nonlinear manner, and the optimal adjustment range for the performance of the gangue concrete was found to be in the range of 0.46-0.60. Furthermore, when the gangue replacement rate was within a certain range, it improved the postpeak-bearing capacity and prevented impact damage to the sample. Zhu et al. [8] investigated the mechanical performance and microstructure of gangue concrete with two different replacement rates and found that raw gangue concrete showed a consistent shear failure with conventional concrete. The higher the spontaneous combustion gangue concrete replacement rate was, the failure mode would gradually transformed to splitting failure, but the density of the transition zone at the interface of the spontaneous combustion gangue concrete was larger than that of the raw gangue concrete. The slopes of the stress-strain curve and ultimate strengths of the two gangue concretes decreased with the increase of the replacement rate, while the peak strain increased, and a compressive strength prediction model was established based on the curve.

Zhang et al. [9] proposed a prediction model for the elastic modulus of gangue concrete with different replacement rates based on 150 tests and found that gangue replacement rates had a great impact on the elastic modulus, which was reduced by half if the gravels were completely replaced. The proposed elastic modulus prediction model considered parameters such as the replacement rate, compressive strength, and density.

The mechanical properties of concrete produced by coal gangue instead of coarse aggregate are lower than that of

ordinary crushed stone concrete. However, when making the ratio of coal gangue coarse aggregate concrete, the microcrack of coal gangue itself has a certain water absorption effect; the water-cement ratio of the surface area of gangue decreases and the contact compactness between the coal gangue coarse aggregate surface and cement is enhanced. Moreover, the mineral surface of coal gangue has the activity of volcanic ash, which enhances the hydration reaction between cements and enhances the bonding force and makes the mechanical properties of coal gangue concrete with a certain ratio close to that of ordinary concrete. On the basis of the basic mechanical properties of gangue concrete, many scholars have also studied the microscopic characteristics and durability of gangue concrete. He et al. [10] conducted freeze-thaw cycle tests on gangue concrete with different replacement rates. The curve characteristic parameters were measured by acoustic emission technology. It was found that with an increased number of freeze-thaw cycles, the water absorption initially increased rapidly and then became steady with a gradual rate of increment and finally became saturated. The higher gangue content in concrete led to a rapid change in the water absorption rate, quick decreases in the mechanical properties of concrete, a high level of damage degree, and an increase in the peak strain. However, the initial elastic modulus, ultimate stress, and toughness gradually decreased. Gao et al. [11] conducted salt freezing tests on gangue concrete with varying replacement rates and found that the cycles of salt freezing affected the surface structures of gangue concrete significantly. The severity of the erosion was found to increase with the gangue content in concrete. However, within a certain amount of coal gangue, the salt freezing durability can meet the requirements. Taking the salt freezing compressive strength as a variable, the evolution equation of salt freezing and denudation of coal gangue concrete is established. Li et al. [12] carried out microhardness tests to locate the interface transition zone during spontaneous combustion of gangue concrete. It was found that the microhardness of coal gangue concrete gradually increases with the decrease of the water-cement ratio and the increase of prewetting time. From the perspective of hydration reaction, the water-cement ratio is too low and the microhardness gradually decreases. The water-cement ratio was so low from the standpoint of the hydration process that it caused the microhardness of the concrete to steadily decline or even vanish. The transition zone of the gangue concrete interface was the weakest link of the concrete microstructure, and the microhardness was lower than that of the conventional concrete. Qiu et al. [13] carried out macro- and microtests on gangue concrete under freezethaw cycles, sulfate erosion in single external conditions and coupling external conditions, and found that the greater the water-cement ratio, the worse the frost resistance. The damage degree of concrete under single freeze-thaw conditions was significantly higher than that under sulfate erosion conditions. Overall, the damage degree was the most severe during coupling circumstances, with 50-70 times the single freeze-thaw damage and 25-50 times the coupling damage. The microscopic test

results showed that freeze-thaw cycles caused microcracks in the gangue concrete, and the crystals and ettringite crystals were produced in the internal structure under the sulfate attack, which can damage the internal structure of gangue concrete. The energy spectrum showed that the sulfate attack was serious.

Sutton et al. [14–16] have continuously improved the digital image correlation method since 1983 and continuously optimized the measurement accuracy of the digital image correlation method. In 1988, they first applied the digital image correlation method to the strain tests on composite materials and obtained the two-dimensional strain field of cracks. In 1993, they applied the method to elastoplastic fracture mechanics and obtained the deformation field at the crack tip with satisfactory results. Later, many scholars have studied the fracture performances of ordinary retarding soil based on the DIC method. Golewski [17] used DIC technology to conduct extensive research on concrete fracture parameters based on seasonal adhesives. Zhu et al. [18] evaluated the fracture behavior of high-strength hydraulic concrete damaged by freeze-thaw cycle tests. Golewski [19], based on the highly diversified cement matrix, contrastively measured the fracture toughness of concrete using the DIC technology and visually analyzed the crack propagation. Lian et al. [20] explored the fracture properties of basalt fiber nano-CaCO3 concrete based on the DIC technology and observed the feasibility of the DIC technology in analyzing the fracture properties of concrete, revealing the fracture mechanism of ordinary concrete. Zhang et al. [21] carried out numerical analysis on the propagation characteristics and influencing factors of plane microcracks in zigzag structure. Yang et al. [22, 23] studied the influence of wing crack propagation on the failure process and strength of the specimen, studied the correlation between the crack propagation process and the peak strength of the rock-like material specimens with a single preinduced defect, and the influence of different crack types on the fracture properties of the specimens was analyzed.

To date, previous studies on gangue concrete focused on the mechanical properties and durability, while numerous scholars have begun to study the microscopic mechanism. However, there are limited studies on the crack damage propagation mechanism of gangue concrete. The present study is based on the study of the mechanism of type I crack propagation in gangue concrete with precracks. This study was carried out by using the digital image correlation (DIC) method. This research could provide a basis for the structural safety and engineering applications of gangue concrete, as well as a reference for improving the global ecological environment and promoting the green transformation of the economy and society.

2. Experimental Details

2.1. Materials Used. Cementing materials: Portland cement (P·O 42.5, China) with the 28d compressive strength of 45.8 MPa, specific surface area of $345 \text{ m}^2/\text{kg}$, and chemical composition, as shown in Table 1.

Coarse aggregate (M): the natural gravel of Linghe in Jinzhou and the crushed-sieved-cleaned gangue gravel of Qinghemen Mine in Fuxin, and particle sizes are continuously graded at 5~20 mm, satisfying the requirements of GB/T 14685-2011. The replacement rates of gangue quality are r = 0, 30%, 50%, 70%, and 100%. Figure 1 shows the characteristics of coarse aggregate micromorphology.

Fine aggregate: river sand of Linghe in Jinzhou, the apparent density is 2.7 g/cm^3 , the particle size is under 5 mm, the apparent density is 2760 kg/m^3 , the bulk density is 1650 kg/m^3 , the silt content is 0.9%, and the fineness index is 2.7. Figure 2 shows the grading curves of the coarse aggregates, and Table 2 shows specific mix proportion.

Water reducer: powder polycarboxylic acid with model CQJ-JSS.

Fiber: black regenerated polypropylene particle fibers with a rough surface, particle size is 2-3 mm, height is 2-4 mm, and density is 0.9 g/cm^3 . Replacing coarse aggregate with an equal volume of fiber improves the ductility of concrete.

Water: tap water.

2.2. Specimen Preparation. The concrete specimen of 515 mm deep \times 100 mm wide \times 100 mm high were considered for the study. Three specimens were prepared for each group test. We used the T-shaped steel plate with a height of 30 mm, a thickness of 3.5 mm, and a knife edge thickness of 1.3 mm to prefabricate the crack with a joint height ratio of 0.3. The plate was taken out after the initial setting of the gangue concrete and before it reached the final setting.

We selected the 30 mm area on the left and right sides of the prefabricated crack of the specimen as the image acquisition area and evenly spray the level 7 light automatic paint, as shown in Figure 3.

2.3. Experimental Apparatus. The type I crack fracture test of concrete with different gangue contents was carried out using the WAW-300 series microcomputer-controlled electrohydraulic servo universal testing machine and was in accordance with the hydraulic concrete fracture test specification DL/T 5332-2018 [24]. On the back of the test piece, taking the prefabricated crack tip of the test piece as the center position, the strain gauges were pasted on the left and right sides with a 5 mm distance from the central line, respectively, and a displacement extensometer was installed in the ligament direction, as shown in Figure 4. In the specific test process, the continuous displacementcontrolled loading mode was adopted and the loading rate was set at 0.05 mm/min until the complete fracture of the specimen occurred. A high-configuration acquisition camera was placed in front of the UTM such that the central axis of the camera lens was in line with the horizontal center line of the specimen. The camera angle and the left and right lighting sources were adjusted properly to obtain the optimal definition of images, and the acquisition rate of the camera was set at 15 frames per second. The acquisition system included the DH-SV1410 GM/C-TCR0071001005V10 industrial camera and an acquisition system with the

TABLE 1: Chemical composition of cementing materials (%).

Materials	SiO ₂	Al_2O_3	Fe ₂ O ₃	CaO	MgO	SO ₃	Na ₂ O ₃	K ₂ O	TiO ₂	Else
Cement	21.23	6.32	4.98	59.04	1.81	2.60	1.31	0.75	0.69	1.27



FIGURE 1: Micromorphology of coarse aggregate. (a) Macadam. (b) Gangue.



FIGURE 2: Grading curves of the coarse aggregates.

resolution of 1392×1040 pixel, the pixel sizes of $5.2 \,\mu\text{m} \times 5.2 \,\mu\text{m}$, focal length of lenses: 50 mm, and the CMOS digital image sensor.

3. Results and Discussion

3.1. Failure Analysis. The crack propagation process of concrete with different gangue contents occurred along the precrack tip, which was consistent with the conventional concrete. However, the higher gangue content in concrete

led to early crack initiation time with a quicker rate of crack propagation. The path of fracture damage gradually became straight with the increase in the gangue content. When the gangue content was 30%, the crack propagation path was very similar to the conventional concrete, which bypassed the coarse aggregate to cause bending failure. With the increase of the coal gangue content, due to the microcrack induced by the self-defect of gangue coarse aggregate and secondary crushing, screening and reprocessing before the gangue were reused. During the expansion of precrack, the probability of encountering gangue coarse aggregates containing microcracks increased. Therefore, under the effect of the load, the crack propagation passed through the coarse aggregate, resulting in the path of precrack propagation gradually becoming straight and short, which accelerated the crack propagation rate, as shown in Figure 5.

3.2. Fracture Behavior. Figure 6 shows the load-crack mouth opening displacement curves (P-CMOD curves) obtained from the test. From the figure, the crack propagation process of coal gangue concrete with different admixtures can be divided into three stages as follows: the elastic section before crack initiation, extended viscoelastic section, and extended fracture section. Under the load, the more the amount of coal gangue, the greater the slope of the curve rising section and the faster the crack opening. This is due to the cohesive nature and lower tensile stress of gangue concrete as compared to that of conventional concrete. In the process of increasing the load, the tensile stress at the crack tip becomes larger. The microcrack of the internal structure expanded before reaching the crack initiation load, which was in the

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Design strength	Water-cement ratio	Water (kg/m ³)	Cement (kg/m ³)	Coarse aggregate (natural crushed stone + coal gangue) (kg/m ³)	Fine aggregate (kg/m ³)	Sand/coarse aggregate ratio (kg/ m ³)	Additive (kg/m ³)	Polypropylene fiber (kg/m ³)
C30	0.53	180	337	1041 + 0	852	0.45	1.36	21
M30C30	0.53	180	337	711.9 + 305.1	831	0.45	1.36	21
M50C30	0.53	180	337	497.5 + 497.5	814	0.45	1.36	21
M70C30	0.53	180	337	291.8 + 681.1	796	0.45	1.36	21
M100C30	0.53	180	337	0 + 941	770	0.45	1.36	21

TABLE 2: Mix proportioning.



FIGURE 3: A view of the measuring area of a single specimen with black speckles prepared for the testing of fracture toughness using the DIC technique: (a) specimen with random black speckles and (b) image acquisition field.



FIGURE 4: Three-point bending test apparatus.

elastic stage. The specimen entered the viscoelastic stage, where the crack initiation load was achieved and the crack propagation was inhibited by the cohesion of the crack tip. Unrecoverable plastic damage and failure occurred in the viscoelastic stage which was during the process of continuous increase of load, and the macrocrack resulted in the failure. From the fullness of the curve descending section, coal gangue concrete is similar to ordinary concrete. After reaching the ultimate load, the crack resistance was lost immediately and energy was consumed continuously. The



FIGURE 5: Fracture failures of the gangue concrete specimens.

abovementioned phenomenon was due to the defect of gangue coarse aggregates, which caused microcracks to be present throughout the whole concrete specimen. After the load was applied, the stress concentration phenomenon occurred due to the initial defect. The stress field is distributed in the direction of prefabricated crack propagation, and the gradually enhanced stress field eventually leads to the fracture failure of the specimen. The higher gangue content led to a higher number of microcracks in the



FIGURE 6: P-CMOD curves of gangue concrete.

specimen. Thus, the initial microfissure is the reason for the acceleration in the rate of internal cracking to macrocrack propagation.

3.3. Crack Initiation Load and the Ultimate Load. Figure 7 shows the strain-load relationship of the prefabricated crack tip of concrete. The cracking load and the ultimate load of concrete specimens can be obtained from Figure 7. Figure 8 shows the crack initiation and ultimate loads of gangue concrete with different contents. As observed, crack initiation and ultimate loads of gangue concrete were generally less than those of conventional concrete. Both the loading parameters were observed to be decreasing with the increase of the gangue content in concrete. It shows that the increase of coal gangue content reduces the cracking resistance and fracture resistance of concrete. The reason is that there are many cracks in coal gangue itself, and the more coal gangue is added, the lower the stress required for the initiation and penetration of cracks. Compared with conventional concrete, the concrete crack initiation loads of gangue concrete with the gangue content of 30%, 50%, 70%, and 100% decreased by 7.28%, 14.25%, 20.76%, and 30.04%, respectively, and the ultimate loads decreased by 5.07%, 10.28%, 15.16%, and 22.37%, respectively. The decreasing range of the ultimate load index was less than that of the crack initiation load, indicating that the addition of gangue in the hardening stage had a fracture-delaying effect. According to the ratio of the two indices, the addition of gangue made the ratio of the two indices gradually decrease. The smaller the index ratio, the weaker the brittleness since the chosen spontaneous combustion gangue coarse aggregate had a stronger surface pozzolanic activity. Moreover, the hydrogenation reaction was found to be sufficient in the hardening stage and the weak area interface was compacted.

3.4. Analysis of the Damage and Fracture Evolution Process. In the image area of the specimen's DIC method, the crack tip is the origin (O point), and the coordinate system was created as shown. A pixel point is arranged every 6 mm on the horizontal axis and 4 pixels on each side. Due to the crack initiation and propagation to fracture under the load, the



FIGURE 7: Strain-load relationship of a prefabricated crack tip of concrete.



FIGURE 8: Coal gangue concrete crack load and the ultimate load ratio.

relative displacement of the pixels on the horizontal axis changes significantly and the vertical displacement is almost unchanged. Thus, the horizontal displacements of the crack tip of concrete with different gangue contents were monitored.

The DIC method's images of the ascending (+) and descending (-) 10%, 50%, 90%, and +100% ultimate load moments were processed and analyzed before the test. The horizontal displacement variation of each pixel is shown in Figure 9. For the concrete specimens with different gangue contents, the horizontal displacement at each monitoring point on the horizontal axis had the same variation trend. With the gradual increase of the load, the horizontal displacement at each monitoring point changed from being stable to slight increase and finally increased significantly. Furthermore, there were leaping turning points at both ends of the crack once the displacement changed. The horizontal displacements of the monitoring points after the turning point were almost the same for each gangue content percentage. There were no obvious horizontal displacements at the monitoring points on both sides of the crack





FIGURE 9: Continued.



FIGURE 9: Horizontal displacements of individual monitoring points on the horizontal axis at different times. (a) C30. (b) M30C30. (c) M50C30. (d) M70C30. (e) M100C30.

within 90% of the ultimate load on the ascending branch. When the rising section is 90%–100%, the monitoring point has a weak displacement and moves to both sides of the origin, respectively. At this time, the specimen is tensilely damaged and cracked. After the descending section is 100%, the horizontal displacement of the monitoring points on both sides increases significantly, there is a significant turning point at the left and right 6 mm monitoring points, and the horizontal displacement of the monitoring points greater than 6 mm remains unchanged. In the process of 90%–50% of the falling section, the crack propagation speed is the largest, and after 50%, it is obviously slowed down.

At 90% and 100% of the rising section and 90%, 50%, and 10% of the falling section, the horizontal displacement cloud diagram of the crack tip of different coal gangue concrete specimens is shown in Figures 10-14. The horizontal displacement contours revealed that the regions on both sides of the fracture tip shifted somewhat to the left and right sides, or to the same side, before the ultimate load. After reaching the ultimate load, the displacements on both sides of the precrack tip of the specimen gradually increased in the opposite directions with clear boundaries. Significant higher tensile stress appeared at the crack tip, and the type I crack feature appeared. The difference between the two sides of the crack tip increased significantly, which represents the crack tip opening displacement (CTOD). The larger the gangue concentration, the clearer the border, indicating greater crack displacement. With the continuous loading, the left and right boundaries gradually extended upward, indicating that the crack propagation direction changed and the displacement difference between the two sides of the crack propagation gradually increased. During the whole process, the crack tip crack width remains the largest. When the boundary area is penetrating to the top, it indicates that the

crack penetrates completely and the fracture damage occurs. When the crack was finally destroyed, the crack propagation width reached the maximum value of the whole process. The content from small to large is 0.46; 0.43 mm, 0.39 mm, 0.37 mm, and 0.35 mm, which is 6.52%, 17.95%, 24.32%, and 23.91% lower than that of ordinary concrete.

The horizontal strain cloud diagram of the crack tip of coal gangue concrete specimens with different dosage is shown in Figures 15–19. From the horizontal strain evolution cloud map, it can be seen that during the three-point bending test of concrete specimens, when the load is small, the stress concentration phenomenon first occurs at the tip of the prefabricated crack. When the load in the ascending section is small, the strain field is weak and the energy change at the crack tip is weak. For further positions away from the crack, the strain field almost had any change and the internal energy distribution was more uniform. As the load continues to increase, the stress concentration effect at the crack tip gradually strengthens after the specimen reaches the crack initiation load. The strand field region of the crack tip steadily expanded upward, indicating that the fracture tip absorbed more energy under the load, but the change in the strain field was still minimal at a distance from the tip. After reaching the ultimate load, the strain field extended to a larger area, the absorbed energy gradually increased, and the crack propagation rate accelerated. In the descending section, the strain field area steadily increased and lost stability. At this time, the absorbed energy is the largest, and the specimen was fully destroyed. In the whole process, the strain field changed like a "flame," from the crack tip to the top of the specimen. Under the load, the flame gradually burns upward from the weak flame. At the same relative ultimate load, the more the coal gangue content, the weaker the fire. It shows that the more the coal gangue content, the smaller the energy required for crack damage propagation.



FIGURE 10: Horizontal displacement evolution process of the C30 crack tip.



FIGURE 11: Horizontal displacement evolution process of the M30C30 crack tip.



FIGURE 12: Horizontal displacement evolution process of the M50C30 crack tip.



FIGURE 13: Horizontal displacement evolution process of the M70C30 crack tip.



FIGURE 14: Horizontal displacement evolution process of the M100C30 crack tip.



FIGURE 15: Horizontal strain evolution process of the M100C30 crack tip.



FIGURE 16: Horizontal strain evolution process of the M30C30 crack tip.



FIGURE 17: Horizontal strain evolution process of the M50C30 crack tip.



FIGURE 18: Horizontal strain evolution process of the M70C30 crack tip.



FIGURE 19: Horizontal strain evolution process of the M100C30 crack tip.

3.5. Fracture Parameters

3.5.1. Fracture Toughness. Based on the stress intensity factor, the initial fracture toughness and unstable fracture toughness in the fracture parameters are calculated [25], as shown in Figure 20. As observed, both parameters decreased with the increase in the gangue content in concrete specimens. The content of coal gangue has a little effect on the initial fracture toughness but has a significant effect on the unstable fracture toughness. The more the coal gangue content, the faster the unstable fracture toughness decreases. Compared with conventional concrete, the initiation fracture toughness decreased by 3.99%, 9.29%, 11.97%, and 14.61%, respectively, while the instability fracture toughness decreased by 6.18%, 17.29%, 27.67%, and 39.47%, respectively. The results demonstrated that at the time of crack initiation, hardened cement mortar and coarse aggregate could collectively provide the crack resistance. At the later stage of unstable fracture, the gangue content had a significant impact on the crack resistance.

3.5.2. Fracture Energy. The external force work and gravity work are solved by the origin to integrate the area of the load-deflection curve. The fracture energy is calculated based on the method recommended by RILEM in the three-point bending beam test [26]. The calculated results of external work, gravity work, and fracture energy are shown in Figure 21. As can be seen, the higher the gangue content, the lower the three performance indices. When compared with conventional concrete, the external force work decreased by

3.98%, 16.97%, 31.87%, and 46.94%, respectively, the gravity work decreased by 5.01%, 14.06%, 27.04%, and 45.07%, and the fracture energy decreased by 4.06%, 17.03%, 31.07%, and 46.97%, respectively. The reason is that coal gangue is spontaneous combustion coal gangue; the spontaneous combustion process leads to loose surface and internal structure, and as a coarse aggregate to produce concrete, it has undergone secondary crushing and reprocessing before use. More microcracks were generated inside, which caused the gangues to have a lower material strength and elastic modulus than natural gravel. Therefore, the more the content, the more the number of initial microcracks for the entire concrete specimen, so the performance indicators such as fracture energy are lower than ordinary concrete.

3.6. Microcrack Initiation Area. Through the strain equivalence of linear elastic fracture mechanics and damage mechanics, the main stress field at the crack tip of coal gangue concrete expressed by Cauchy stress is obtained as follows [27, 28]:

$$\begin{cases} \sigma_1 = (1-D)\sigma \sqrt{\frac{a}{2r}} \cos \frac{\theta}{2} \left(1 + \sin \frac{\theta}{2}\right), \\ \sigma_2 = (1-D)\sigma \sqrt{\frac{a}{2r}} \cos \frac{\theta}{2} \left(1 - \sin \frac{\theta}{2}\right). \end{cases}$$
(1)

Combining (1) with Hooke's law [29], the main strain field at the crack tip of coal gangue concrete is obtained as follows:



FIGURE 20: Fracture toughnesses of concrete with different coal gangue contents.



FIGURE 21: External force work, gravity work, and fracture energy of coal gangue concrete.

$$\begin{cases} \varepsilon_1 = \frac{\sigma}{E} \sqrt{\frac{a}{2r}} \cos \frac{\theta}{2} \left[(1 - \nu) + (1 + \nu) \sin \frac{\theta}{2} \right], \\ \varepsilon_2 = \frac{\sigma}{E} \sqrt{\frac{a}{2r}} \cos \frac{\theta}{2} \left[(1 - \nu) - (1 + \nu) \sin \frac{\theta}{2} \right]. \end{cases}$$
(2)

The principal stress field around the crack tip was substituted into the Willam–Warnke's five-parameter plastic yield function [30] to obtain the microcrack initiation area boundary interface equation for $r_{\rm W}$ of the stress space as follows:

$$r_{\rm W} = \frac{a + (0.66 + 0.63r)R_{\rm Ic,0}}{2} \cos^2 \frac{\theta}{2} \left[\frac{1 - 0.058r}{1 - 0.032r} + \left(2 - 0.18r + 3.71 \times 10^{-3}r^2\right) \sin^2 \frac{\theta}{2} \right]^2.$$
(3)

When $\theta = 0$, the critical length of the microcrack formation zone of coal gangue concrete on the x axis is obtained as follows:



FIGURE 22: The form of the microcrack formation zone of concrete with different coal gangue contents.

$$r_{\rm W0} = \frac{a + (0.66 + 0.63r)R_{\rm Ic}}{2} \cdot \left[\frac{1 - 0.058r}{1 - 0.032r}\right]^2.$$
 (4)

Figure 22 shows the microcrack initiation areas of concrete specimens in the plane space obtained by using equations (4) and 7. As observed, in the plane space, the boundary of the entire microcrack generation zone extends outward at the crack tip and the top of the fracture. The leftright symmetrical "gourd" shapes were formed by the shapes of microcrack initiation areas of gangue concrete specimens with different gangue contents, considering the crack tip extension line as the axis of symmetry. The boundary surface of the microcrack initiation area extended with the increase in the gangue content under the action of the continuous displacement load. This phenomenon was because of the existence of microcracks in gangue coarse aggregate. In addition, under the action of the external load, the mechanical properties of coal gangue concrete are lower than those of conventional concrete and the stress concentration around the crack tip and extension line is the most obvious. For the same external load, the impact was larger for the specimen with weaker internal strength.

4. Conclusions

The more the coal gangue is added, the smaller the bending degree of the failure path and the faster the crack failure speed. The opening crack will bypass the natural gravel coarse aggregate but will penetrate the coal gangue coarse aggregate. The crack propagation process of the coal gangue concrete specimen is divided into three stages as follows: the elastic section before crack initiation, extended viscoelastic section, and extended fracture section. The ultimate load and crack opening displacement of coal gangue concrete decrease with the increase of the coal gangue content. The cracking load and the ultimate load are both lower than those of ordinary concrete. With the same amount of coal gangue, the reduction of the limit load is less than the cracking load and the ratio of the two indicators is gradually smaller, indicating that the cohesion of coal gangue coarse aggregate and hardened cement mortar is better than that of natural gravel.

The data obtained by the DIC method and displacement extensometer are in good agreement, indicating that the DIC method is feasible. Based on the DIC method, the horizontal displacement at both sides of the crack tip changes slightly before reaching 90% of the limit load and increases significantly after reaching the crack initiation load. The horizontal displacement remains unchanged after the inflection point occurs. It can be seen that the influence range of the stress field at the crack tip is local. The horizontal displacement field of the crack tip changes little before the ultimate load. After the ultimate load, there is a significant reverse displacement on both sides of the crack tip and the strain field at the crack tip is gradually strengthened. The more the amount of coal gangue, the smaller the horizontal displacement and strain field at the same ultimate load moment.

The more the content of coal gangue, the smaller the fracture toughness and fracture energy. The content of coal gangue has a significant impact on the fracture parameters. The more the content is, the smaller the fracture parameters are. Based on the damage mechanics, fracture mechanics, Hooke's law, and five-parameter plastic yield model, the principal stress field and principal strain field at the crack tip, as well as the boundary equation of the microcrack formation zone of coal gangue concrete with different contents, are obtained, and the change mechanism of the microcrack formation zone of coal gangue concrete is revealed.

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 they have no conflicts of interest.

Acknowledgments

This work was supported by the National Natural Science Foundation of China (grant no. 51774167), the Key Laboratory Project of Liaoning Province (LJZS002), the Liaoning Province "Xing Liao Talents Program" Technology Innovation Leading Talent Project (XLYC1802063), and the Liaoning University of Technology Ph.D. Start-up Fund (XB2021012).

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