Experimental study on seismic behavior of gangue concrete frame middle joints with different gangue aggregate replacement rates

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Abstract: The low-cycled repeated loading experiment was carried out for gangue aggregate concrete middle joints with coal gangue aggregate replacement rates 0, 30%, 50%, 70%, 100%. The experiment was designed to investigate the joint failure modes, hysteretic characteristics, joint deformation and energy dissipation behavior of coal gangue aggregate concrete joints with different gangue aggregate replacement rates. Results show that the mechanical and failure process of coal gangue aggregate concrete frame joints, which is the same as that of normal concrete joint, may be composed of four stages: the initial cracking, the thorough cracking, the ultimate stage and the failure stage. It is found that the gangue concrete joints, with the increase of coal gangue aggregate replacement rate, are inferior to the normal concrete joint in the terms of hysteretic characteristics, joint deformation and energy dissipation behavior.

1. Introduction

Coal gangue is a kind of dark gray rock with low carbon content and harder than coal, which is associated with coal seam in the process of coal formation [1]. Random accumulation of coal gangue not only causes serious damage to the natural landscape of coal mining area, but also is likely to cause a series of major natural disasters such as landslides and debris flows. When burning, a large number of harmful gases will be generated, causing serious air pollution [2-3]. At present, many scholars have done more research on coal gangue concrete (CGC) [4-6], but less research on structural application [7][8]. In this paper, aiming at the coal gangue in Yulin mining area, Shaanxi, a low-cycle repeated loading experiment of CGC frame joints with different coal gangue aggregate (CGA) replacement rates is carried out to discuss whether the seismic performance of CGC frame joints meets the requirements of seismic fortification.

2. Experimental overview

2.1 Materials and specimens

The CGA used in this experiment is washed coal gangue, which is provided by Shenmu Ningtiaota Mining Co., Ltd. of Shaanxi Coal Group. The basic material properties of steel bars and CGC used in this experiment are shown in table 1 and table 2, and the material properties of CGA and natural aggregate (NA) are shown in table 3.
Table 1. Material properties of steel bars

| Bar types | Yield stress (MPa) | Ultimate stress (MPa) | Elastic modulus (MPa) |
|-----------|-------------------|-----------------------|----------------------|
| A6        | 444               | 523                   | $2 \times 10^5$      |
| A8        | 367               | 431                   | $2 \times 10^5$      |
| C20       | 439               | 635                   | $2 \times 10^5$      |
| C22       | 445               | 644                   | $2 \times 10^5$      |

Table 2. Mass mixture ratio of CGC and compressive strength

| Representative Specimens | Gangue replace ratio (%) | Mass mix ratio | Cube compressive strength $f_{cm}$ (MPa) | Axial tensile strength $f_t$ (MPa) |
|--------------------------|--------------------------|----------------|--------------------------------------|----------------------------------|
| ZJA-1                    | 0                        | 318: 140: 875: 1068: 0 | 38.40                     | 2.59                             |
| ZJA-2                    | 30                       | 353: 145: 855: 733: 315 | 30.97                     | 2.30                             |
| ZJA-3                    | 50                       | 395: 150: 835: 510: 510 | 27.22                     | 2.14                             |
| ZJA-4                    | 70                       | 443: 155: 810: 296: 695 | 27.30                     | 2.16                             |
| ZJA-5                    | 100                      | 500: 160: 783: 0: 958  | 23.13                     | 1.95                             |

This experiment mainly considers the influence of CGA replacement rate on the seismic performance of CGC frame middle joints. A total of 5 concrete frame middle joint specimens, whose CGA replacement rates are 0, 30%, 50%, 70%, 100% respectively, were designed. The dimensions and reinforcement information of these specimens are shown in figure 1.

Table 3. Comparison of material properties between CGA and NA

| Aggregates | Apparent density (kg·m$^{-3}$) | Bulk density (kg·m$^{-3}$) | Crushed value (%) | Water absorption (%) |
|------------|--------------------------------|----------------------------|-------------------|---------------------|
| CGA        | 2321                           | 1160                       | 21.8               | 5.38                |
| NA         | 2656                           | 1590                       | 10.7               | 0.8                 |

2.2 Loading equipment and system

In this experiment, a load-displacement mixed loading system is used to apply low-cycle repeated loads to the joints of the CGC frame. The loading method adopts the column end loading scheme to consider
the non-negligible P-Δ effect under the larger axial pressure. The experiment loading device is shown in figure 2.

Before specimen yields, it is the load control stage. The change in the slope of the hysteretic curve is used to judge whether the specimen yields. After the specimen yields, it enters the displacement control stage. In the load control stage, every 10kN is regarded as one stage, and the load cycle is once for each stage. After the specimen yields, the loading system is changed to displacement control. Each stage of displacement increases by the multiple of the displacement when the yield load is reached, and each level is cycled three times. The end of the experiment is subject to the complete failure of the specimen, that is, the horizontal load drops to 85% of the ultimate load.

3. Failure phenomena and patterns

3.1 Experimental phenomena

Analyzing the results of this experiment, it is easy to find that both CGC frame joints and NC frame joints have experienced four stages of initial cracking- thorough cracking- ultimate- failure. The failure process of each joint specimen can be summarized as follows:

(1) Initial cracking: In the initial stage of the experiment, the specimen is in the elastic working stage. As the horizontal load continues to increase, the first oblique crack appears in the joint core area, and the load at this time is the cracking load;

(2) Thorough cracking: As the horizontal load increases, the core area of the concrete joint specimen first forms two penetrating main oblique cracks, and diamond-shaped concrete blocks appear. The cracks at the end of the beam have also penetrated, and shear oblique cracks have occurred;

(3) Ultimate: As the loading continues, the phenomena that horizontal load increases slightly and the displacement increases a lot occurs, the cracks in the core area are significantly widened, and the load reaches the shear bearing capacity of the specimen;

(4) Failure: After the specimen reaches the ultimate load, as the displacement increases, the shear deformation of the core area increases, and the concrete of core area spalling on the surface, and the maximum load of each stage decreases step by step until the specimen is destructed. The failure modes of each specimen are shown in figure 3.

3.2 Eigenvalues of each stage

The load and displacement eigenvalues of each stage of each specimen are listed in table 4. Analyzing eigenvalues of these specimens, it can be obtained that the eigenvalues of specimens ZJA-2, ZJA-3, ZJA-4 are similar, indicating that these CGC frame joints with rate of 30%, 50%, 70% perform similarly in the experiment. However, the initial crack load of specimen ZJA-5 is much lower than that of the other 3 specimens. Comparing the eigenvalues of these 4 CGC frame joint specimens, it can be found that with the increase of the CGA replacement rate, the ultimate load of these specimens decreases, indicating that the CGA reduces the ultimate shear capacity of the joint specimens. The greater CGA replacement rate makes shear capacity of the CGC joint specimens lower.

Figure 3. Contrast diagram of failure mode
Table 4. Eigenvalues of four stages

| Specimen | Initial cracking | Thorough cracking | Ultimate stage | Failure stage |
|----------|------------------|------------------|----------------|--------------|
|          | Load (kN) | Displacement (mm) | Load (kN) | Displacement (mm) | Load (kN) | Displacement (mm) | Load (kN) | Displacement (mm) |
| ZJA-1    | 106.77    | 20               | 132.01    | 30               | 135.40    | 40               | 115.09    | 69.32           |
| ZJA-2    | 114.46    | 20               | 136.48    | 30               | 143.63    | 40               | 122.09    | 70.06           |
| ZJA-3    | 103.65    | 20               | 133.33    | 30               | 138.68    | 40               | 117.88    | 73.37           |
| ZJA-4    | 107.59    | 20               | 129.34    | 30               | 133.44    | 40               | 113.42    | 70.42           |
| ZJA-5    | 42.96     | 10               | 129.25    | 40               | 130.87    | 50               | 111.42    | 73.43           |

4. Analysis of experimental results

4.1 Hysteretic curves
The hysteretic curves of each specimen are shown in figure 4. Observing the hysteretic curves of these five specimens, it can be found that the hysteresis curve of NC specimen is the fullest. The specimens with lower gangue replacement rate have fuller hysteretic curve and their stiffness and bearing capacity degrade more slowly than that of specimens with higher gangue replacement rate.

![Hysteretic curves of each specimen](image)

Figure 4. Hysteretic curves of each specimen

4.2 Skeleton curves
The skeleton curves of each specimen are shown in figure 5. Observing the skeleton curves of each specimen, it is not difficult to find that the skeleton curves of the CGC joint specimens are similar to that of the NC joint specimens, indicating that the seismic performance of the CGC frame joints is similar to that of NC frame joint. It also can be seen that with the increase of CGA replacement rate, the
ultimate load of specimens shows a downward trend, indicating that the addition of CGA leads to a decrease in the shear bearing capacity of concrete joint specimens. And the value of CGA replacement rate is inversely proportional to the shear capacity of the joint specimens. The greater the CGA replacement rate, the lower the shear capacity of the specimens.

4.3 Shear deformation in core area
Affected by the horizontal load, the core area of the joint specimens cracked under the action of diagonal tension, resulting in shear deformation, and the core area of these specimens changed from the initial rectangle to the diamond shape. In this experiment, two cross-crossing displacement meters are set on the core area of the specimen to measure the length of the diagonal length of the core area of the joint specimen.

The shear deformation in core area of each specimen are shown in figure 6. Observing figure 6, it is not difficult to find that, in the first three stages, the core area shear deformations of specimens ZJA-1, ZJA-2, ZJA-3, ZJA-4 are similar. And during the load reaches the initial crack load to the ultimate stage, the core area shear deformation of specimen ZJA-5, which is much larger than that of the other specimens, increases rapidly. Compared with the NC frame joint specimens, the shear deformations of the CGC joint specimens increase faster after the horizontal load reaches the ultimate shear bearing capacity of the specimens, indicating that the CGA increases the brittleness of joint specimens.

4.4 Analysis of energy dissipation
In structural dynamic analysis, the equivalent viscous damping coefficient is often used to judge the energy dissipation capacity of the structure. The larger the equivalent viscous damping coefficient value, the stronger the energy dissipation capacity of the structure. The calculation results of equivalent viscous damping coefficients of each specimen are listed in table 5.

Observing the data listed in table 5, it is easy to find that the equivalent viscous damping coefficient of these specimens showed a downward trend with the increase of the CGA replacement rate. Compared with the NC specimen, the coefficients of the CGC specimens decrease significantly. The coefficients of the specimen ZJA-2, whose CGA replacement rate is 30%, is 21% lower than that of the NC specimen, indicating that the addition of CGA reduces the energy dissipation capacity of the joints in CGC frame.

| Specimen | ZJA-1 | ZJA-2 | ZJA-3 | ZJA-4 | ZJA-5 |
|----------|-------|-------|-------|-------|-------|
| Coefficient | 0.174 | 0.138 | 0.126 | 0.119 | 0.113 |
5. Conclusions

(1) Through the observation of this experiment, it can be found that under the action of low-cycle repeated load, the NC frame joints and the CGC frame joints with different CGA replacement rates both have gone through the elastic stage - elastoplastic stage - plastic stage - failure stage, which are represented by four characteristics: initial cracking, thorough cracking, ultimate stage and failure stage.

(2) CGC frame joints are similar to NC frame joints in terms of failure phenomena, failure form, joint core area deformation, energy dissipation performance, etc. However, it can be seen that, with the increase of CGA replacement rate, the energy dissipation performance of CGC joint specimens is inferior to that of NC joint specimens.

(3) Compared with natural aggregates, the strength of CGA is lower. It can be found that the damage of NC specimens is mainly due to the damage of the interface between mortar and NA, and the natural aggregates are kept intact. Yet the damage of the CGC specimens is more of the CGA themselves. This makes the destruction interface of the CGC specimens smoother, and the mechanical bite force decreases, resulting in the shear capacity of specimens decreases with the increase of the CGA replacement rate of the specimens.

(4) Through the analysis of the results of this experiment and the comparison of related indexes, it can be found that the CGC joints can be used in the structure of the area with seismic fortification requirements. However, a proper CGA replacement rate should be adopted when designing the CGA frame joint.

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