Experimental study on the seismic performance of coal gangue concrete frame columns

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Abstract. The aim of this paper is to investigate the seismic performance of coal gangue concrete columns, a total of 5 specimens were subjected to low-cycled repeated loading tests. The replacement ratio of coal gangue aggregate is the main parameter. The failure mode, hysteresis curve, skeleton curve, stiffness degeneration, energy dissipation capacity and ductility of specimens are analyzed. The results show that the replacement ratio of coal gangue aggregate has a greater impact on the seismic performance. Increasing the replacement rate of coal gangue aggregate will result in an increase in energy dissipation capacity, a slower stiffness degradation, and an improvement in ductility. The practical application of the coal gangue concrete column has feasibility.

1. Introduction
Coal gangue concrete (CGC) is formed by mixing coal gangue coarse aggregate (CGA), sand, cement and water in a certain proportion. CGA comes from washed coal gangue with a certain grade after crushing and screening. At present, the research mainly focuses on the performance of CGC and the performance of parts under static load[2]-2[3]. The seismic performance of CGC columns has not been investigated yet. In order to make CGC can be applied to the structure, the failure phenomenon, carrying capacity, and deformation capacity of CGC under different parameters[4] need to be understood, and the skeleton curve, hysteresis curve, stiffness degradation and energy dissipation capacity of CGC column under the low-cycled repeated loading need to be analyzed.

2. Experimental process
2.1. Design of specimens
A total of 5 specimens of cast-in-situ concrete columns with rectangular cross-sections were designed for this experiment, referring to related papers[4], combined with the MTS test device. The specimen is composed of the upper column and the concrete base at the bottom, those two parts are poured with concrete of the same mix ratio. The reinforcement and size parameters of the specimen are shown in Figure 1 and Table 1. Material properties of steel are shown in Table 2.

| Specimens | Concrete strength fcm (MPa) | Replacement ratio(%) | Axial compression ratio | Volumetric stirrup ratio ρv(%) |
|-----------|-----------------------------|----------------------|------------------------|-----------------------------|
| KZA-1     | 38.40                       | 0                    | 0.3                    | 0.91                        |
| KZA-2     | 31.00                       | 30                   | 0.3                    | 0.91                        |
Table 2. Material properties of steel

| Bar types | Diameter (mm) | Yield strength (MPa) | Elastic modulus (MPa) |
|-----------|---------------|----------------------|-----------------------|
| HPB300    | 6             | 444.1                | 2.0×10⁵               |
| HPB300    | 8             | 366.7                | 2.0×10⁵               |
| HRB400    | 20            | 439.5                | 2.0×10⁵               |

2.2. Test setup
The test adopts the low reversed cyclic load in the key laboratory of Structure and Seismic Resistance of the Ministry of Education, Xi’an University of Architecture and Technology. The upper hydraulic jack applies the vertical load and MTS actuator applies the horizontal low reversed cyclic load. Load-stabilizing device ensure the stability of axial compression during loading. The loading device is shown in Figure 2.

![Figure 2. Test setup](image2)

2.3. Loading system
The test adopts a dual-control mixed loading system of load and displacement[6]-[7][6]. Before the specimen yields, The method of loading is to increase the force of 10KN each time; After the specimen yields( the slope of the load-displacement curve is changed )[8], The loading method is to load according to the multiple of the yield displacement, and each displacement is cycled three times. The sign of the end of loading is that the force drops to 85% of the peak load.

3. Experimental phenomena and damage form
By observing the test phenomenon, it is found that the damage Form of CGC is similar to that of reinforced concrete, which can be divided into three forms: bending failure, bending shear failure and shear failure[9]. The crack behaviour of the specimens is shown in Figure 3.

![Figure 3. Experimental phenomena and damage form](image3)
Shear-bending failure: At the initial stage of the load-control, tiny crack appeared and extended horizontally at the corner of the columns. At the later stage of load-control, at the root of the columns longitudinal reinforcement had yielded. The existing crevices extended through the surface of the columns, and a few of crevices began extending diagonally. The width of cut-through crevices reached 0.03 mm. In the stage of the displacement-control, both the root longitudinal reinforcement yielded. There were not new horizontal crevices on the surface of the columns. But more and more vertical cracks are extended and oblique cracks continue to expand. As the stirrups yield, the diagonal cracks suddenly widen and the bearing capacity decreases.

4. Experimental results and analysis

4.1. hysteretic curve

Figure 4 shows hysteretic curve of specimens. The hysteresis curve is a comprehensive index of the seismic performance of specimens, which can reflect the stiffness degradation, Strength degradation, energy dissipation capacity and deformation characteristic. (1)At the initial stage of experiment, the specimens are in elastic condition. Load and displacement are linear relationship. There is few residual deformation. (2)With the specimens yielding, the load begins using displacement-control. The stiffness and the slope of curve of bending failure's specimen(KZA-4) reduce little. But the stiffness and the slope of curve of shear-bending failure's specimens reduce gradually. Because the initial stiffness of the shear-bending failure's is larger. Stirrups yield gradually during the displacement loading stage. The hysteretic curve are spindle-shape and full, and don’t display ‘rheostriction’. It shows good plastic deformation ability and energy dissipation capacity. (3)Compared with the hysteresis curve of KZA-2 and KZA-3, the hysteretic curve of KZA-4 ( r=70% ) is fuller than KZA-2( r=30% ) and KZA-3( r=50% ), which is indicated that concrete column of higher replacement ratio of CGA has a better hysteretic behavior.
4.2. Skeleton curve

Figure 5 shows the skeleton curve of CGC column. The load carrying capacity of the specimens shows incomplete symmetry. Because the mechanical properties of concrete have a lot of dispersion and the forward damage affects reverse loading performance. The lower replacement ratio of CGA is, the larger slope of curve at the failure stage. With the replacement ratio of CGA being higher, the ultimate displacement of specimens is improved. At the same time, the descending branch is more flat, and the speed of stiffness degeneration is slower. Its later carrying capacity is rather steady. Therefore, the replacement ratio of CGA is an important index, and that has a significant impact on horizontal carrying capacity and deformation of specimens.

4.3. Stiffness degradation

This paper adopts the secant stiffness to evaluate the stiffness degeneration of specimens. The stiffness degradation curve of the specimen is shown in Figure 6, which is summarized as follows: When the displacement is 5-15mm, the stiffness degradation of the specimen is the most obvious.
initial stiffness of KZA-3 is higher than that of KZA-4. The initial stiffness of KZA-8 is higher than that of KZA-2. The specimen with high replacement ratio of CGA has stable stiffness.

4.4. Energy consumption capacity
This paper adopts the equivalent viscous damping coefficient to evaluate the energy dissipation capacity. The coefficient of specimens at failure stage is listed in Table 3, which is summarized as follows: The equivalent viscous damping coefficient of KZA-4 is higher than that of KZA-3. Replacement ratio of CGA makes energy dissipation capacity increase. But ordinary concrete has stronger energy dissipation capacity.

| specimens | Equivalent viscous damping coefficient |
|-----------|--------------------------------------|
| KZA-1     | 0.280                                 |
| KZA-2     | 0.198                                 |
| KZA-3     | 0.195                                 |
| KZA-4     | 0.238                                 |
| KZA-8     | 0.204                                 |

4.5. Displacement ductility
The displacement ductility factor is a measure of ductility. The yield displacement is calculated by the energy method. The displacement ductility factor is listed in Table 4. With the replacement ratio of CGA increasing, the displacement ductility factor increases rapidly. The coefficient of the high replacement specimen at reasonable axial compression ratio is above 3. Therefore, CGC columns’ ductility conforms to the requirements of code.

| specimens | Ductility factor |
|-----------|-----------------|
| KZA-1     | 4.27            |
| KZA-2     | 2.86            |
| KZA-3     | 2.33            |
| KZA-4     | 3.73            |
| KZA-8     | 3.57            |

5. Conclusion
(1) Compared with reinforced concrete, CGC has similar mechanical properties and failure forms. (2) The replacement ratio of CGA has a great influence on displacement ductility, energy dissipation capacity and stiffness. With the replacement ratio of CGA increasing, displacement ductility and energy dissipation capacity of specimens are improved to some extent. (3) Taking reasonable structural measures, specimens with high replacement ratio of CGA can conform the ductility requirements of seismic design. (4) The practical application of the coal gangue concrete column has feasibility.

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