Experimental study on the complete stress-strain curve of gangue aggregate concrete

Guoliang BAI1, Yuxiang SU1, Hanqing LIU1

1 Key Lab of Structural Engineering and Earthquake Resistance, Ministry of Education (XAUAT), Xi’an 710055, China
hqliu@xauat.edu.cn

Abstract: In order to study the complete stress-strain curve of Chinese YuShenFu district’s gangue concrete. This experiment contains seven groups of gangue concrete which are all made by different water cement ratio and different gangue replacement rate, altogether 15 standard prismatic specimens. After the axial compression of concrete’s specimens, stress-strain curves of gangue concrete were obtained. In order to study the complete stress-strain curve of gangue concrete. In this paper, 15 coal gangue prism samples (150mm×150mm×300mm) were prepared for axial compression test. The main parameters are water-cement ratio and replacement rate of gangue aggregate. The result shows that there are four stages including the whole process of gangue concrete under uniaxial compression, but the descent stage exists the phenomenon of sudden break-down. Based on the data, the gangue concrete complete stress-strain curves’ constitutive equation is fitted. The parameter of ascending section fits favorably and the parameter of descending section is dispersed.

1. Introduction
At present, the quantity of coal gangue in China has reached about 7 billion tons, and the annual growth rate is 300 million tons. The accumulation of coal gangue and spontaneous combustion are harmful to the ecological environment. At the same time, the treatment of coal gangue also caused some economic pressure on local coal enterprises. Therefore, the comprehensive utilization of coal gangue is urgent. Using coal gangue as concrete aggregate not only alleviates the economic pressure of enterprises, but also protects the local ecological environment [1-3]. In this paper, the Yushenfu district’s coal gangue of Ningtiaota mine area is mixed into concrete as coarse aggregate. At present, some scholars have already studied using coal gangue as coarse aggregate to mix into the concrete [4-9]. In this experimental study, we hope to obtain the complete stress-strain curve and constitutive equation of the gangue concrete.

The axial compression performance is the concrete’s basic mechanical properties, and it’s also one of the main basis for studying the deformation and bearing capacity of gangue concrete. The complete stress-strain curve of concrete is a necessary condition to study the whole process of concrete under compression [10-11]. The constitutive relation of concrete is indispensable in the study of the section’s stress distribution and the anti-seismic ductility and restoring force characteristics when the concrete member reaches the limit condition.
2. Experiment overview

2.1 experiment materials
The strength grade of cement is P.O42.5 Yaobai ordinary portland cement, the sand is natural river sand, the mixing water is urban tap water, the natural coarse aggregate is continuous graded ordinary crushed stone, the gangue used as coarse aggregate is the gangue from Ningtiaota mining area of Yushenfu, which is crushed and screened, and the maximum particle size of coal gangue is 30mm.

The physical properties of gangue are shown in Table 1.

| physical property       | Particle size distribution | Bulk density | Apparent density | Crushing index | Water absorption |
|-------------------------|---------------------------|--------------|-----------------|----------------|-----------------|
| gangue                  | 5~31.5mm                  | 1160g/m³     | 2321g/m³        | 21.8%          | 5.38%           |
| Natural crushed stone   | 5~31.5mm                  | 1590g/m³     | 2656g/m³        | 10.7%          | 0.8%            |

2.2 Specimen design and production
In this experiment, 15 specimens with the size of 150 mm×150 mm×300 mm prism were designed. There are five kinds of water cement ratio (0.44, 0.41, 0.38, 0.35, 0.32)The five kinds of water cement ratio (0.44 ~ 0.32) include five kinds of gangue replacement rate (0%, 30%, 50%, 70% and 100%).

2.3 Mix proportion design
Due to the difference between the performance of gangue and ordinary crushed stone, according to JGJ 55-2011 Specification for mix proportion design of ordinary concrete [12] and GB 50119-2003 Technical specification for application of concrete admixture [13], appropriate water reducing agent is added for corresponding adjustment, and the gangue concrete is expected to reach the target strength. After calculating, the specific mix proportion is shown in Table 2.

| Water cement ratio | Gangue replacement rate/% | Material consumption/(kg•m⁻³) |
|-------------------|--------------------------|-------------------------------|
|                   |                          | Water | Cement Sand ratio | Sand | Natural crushed stone | Gangue | Water reducer |
| 0.44              | 0%                       | 140   | 317.5 0.45       | 875  | 1067.45               | 0.0    | 1.59          |
| 0.41              | 30%                      | 145   | 352.5 0.45       | 855  | 732.50                | 315.0  | 1.76          |
| 0.38              | 50%                      | 150   | 395.0 0.45       | 835  | 510.00                | 510.0  | 2.37          |
| 0.35              | 70%                      | 155   | 442.5 0.45       | 810  | 297.50                | 695.0  | 4.43          |
| 0.32              | 100%                     | 160   | 500.0 0.45       | 782  | 0.00                  | 957.5  | 6.00          |

2.4 Experimental process and loading method
The loading equipment is WAW-1000 microcomputer controlled electro-hydraulic servo universal testing machine, and the data is collected by TDS-530 data acquisition instrument. During the loading process, the loading surface of the equipment should be cleaned. Ensuring that the loading surface is in full contact with the specimen, so the stress concentration will not appear. In order to collect the specimens’ strain data, to measure the axial compression of the specimen, displacement meters are installed on the front and the rear sides of the specimen. And strain gauges are pasted on the left and the right sides of the specimen to measure the axial compression of the specimen. When the specimen is put into the testing machine, it’s necessary to center the test piece and the instrument. In order to get the descending section of the complete gangue concrete stress-strain curve, on the premise of meeting the standard for test methods of mechanical properties on ordinary concrete (GB/T 50081-2002). After the load reaches 60% of the peak load, the loading rate is adjusted to the control displacement, and the experiment is carried out at the speed of 0.05mm/s to get the descending section. The data acquisition of stress and strain is completed manually and stored in the computer.
3. Analysis of the gangue concrete’s stress-strain curve

3.1 Experimental results of gangue concrete under uniaxial compression

According to GB/T50081-2002 the standard for test methods of mechanical properties on ordinary concrete [14], the characteristic values of the stress-strain curve are shown in Table 3.

The axial compressive strength $f_{cp}$ is the mean value of the peak stress of different specimens under the same target strength and the same gangue replacement rate;

The peak strain is the strain of the specimen under the load corresponding to the peak stress;

The limit strain is the strain corresponding to the stress value of $0.85\sigma_p$ in the descending section of the curve during the uniaxial compression test;

| Specimen number | Uniaxial compressive strength $f_{cp}$/MPa | Peak strain $\varepsilon_p$/10^{-3} | Ultimate strain $\varepsilon_{0.85}$/10^{-3} |
|-----------------|------------------------------------------|-----------------------------------|------------------------------------------|
| S-0.44-0        | 32.4                                     | 1.63                              | 3.29                                     |
| S-0.41-30       | 31.1                                     | 2.48                              | 3.01                                     |
| S-0.38-50       | 27.9                                     | 2.39                              | 2.69                                     |
| S-0.35-70       | 28.1                                     | 3.25                              | 3.48                                     |
| S-0.32-100      | 27.0                                     | 2.70                              | 3.17                                     |

3.2 Complete stress-strain curve of gangue concrete

3.2.1 Analysis of the process of stress-strain curve

Figure 1 is the complete stress-strain curve of gangue concrete

Figure 1 The complete stress-strain curve of gangue concrete

The complete stress-strain curve of gangue concrete is an important part to study the gangue used as coarse aggregate. It can be seen from the figure that the whole stress-strain curve includes four stages. The first stage is the elastic stage, the specimen at the beginning of compression, the stress and strain increase linearly, and the slope is the elastic modulus of gangue concrete. The second stage is the internal cracking stage of concrete. At this stage, there is no obvious crack on the specimens’ surface, but the relationship between stress and strain is no longer linear, and their slope is decreasing. The concrete specimens’ stiffness is decreasing, and the specimens’ stress is close to the peak stress. It can be seen from Figure 1 that the gangue concrete’s peak stress is decreasing with the increase of the replacement rate. In the third stage, the cracks inside the concrete develop outward. At this stage, the specimens’ stress state has reached the peak stress, and the curve presents a downward trend. It can be seen from Figure 1, when the specimen reaches the peak stress, the decline rate of the curve is larger than the ordinary concrete, and the stress-strain curve’s response is the curve’s sudden decline, The falling section of some specimens is accompanied by obvious sound. It can be seen that the gangue
concrete is very brittle. The fourth stage is the residual stress stage, in which the superficial cracks grow more and the stress grows slowly with the increase of strain. Moreover, in this stage with the gangue replacement rate increasing, most of the specimens have the phenomenon of sudden failure.

4. Regression analysis of complete stress-strain curve

4.1 Constitutive equation

According to the stress-strain curve and the characteristic value of the corresponding process, for further research the complete process of gangue concrete prism in uniaxial compression test. Taking $y=\sigma/f_{cp}$ as the ordinate and $x=\varepsilon/\varepsilon_p$ as the abscissa, the complete dimensionless stress-strain curve is established to study the relationship between stress and strain of gangue concrete. The piecewise function proposed by Guo Zhenhai [15] describes the ascending and descending sections of the stress-strain curve. The formula is as follows:

$$
y = \alpha x - (3 - 2\alpha)x^2 + (\alpha - 2)x^3, (0 \leq x < 1)
$$

$$
y = \frac{x}{\beta(x-1)^2 + x}, (x \geq 1)
$$

In the formula, $\alpha$, $\beta$ are parameters. Table 8 is obtained after fitting and calculating the test data of each group.

According to the data in Table 8, the $\alpha$’s value is stable, and the correlation coefficient shows that the fitting result is very good. When the gangue concrete target strength is determined, $\alpha$ decreases with the the gangue replacement rate is increasing. When the gangue replacement rate increases from 0% to 30%, the value of $\beta$ increases by 9.2 times. It is proved that the complete stress-strain curve suddenly becomes steep, and the brittleness of the material is enhanced. When the gangue replacement rate reaches 70%, the value of $\beta$ is 18.5466 which is highest in the group. The main reason is that quantity of gangue and the pressure is increasing, the specimen has the possibility of sudden failure and the failure process is faster than the ordinary group. When the gangue replacement rate is 70%, the correlation coefficient of $\beta$ is 0.5387, so this group’s fitting results are not very ideal. We need to do follow-up research to demonstrate the formula.

Table 4 parameter values and correlation coefficients of stress-strain curve of gangue concrete

| Specimen number | Value of $\alpha$ | correlation coefficient($R^2$) | Value of $\beta$ | correlation coefficient($R^2$) |
|-----------------|------------------|-------------------------------|----------------|-------------------------------|
| S-0.44-0        | 2.0826           | 0.9962                        | 0.8158         | 0.8421                        |
| S-0.41-30       | 1.9924           | 0.9994                        | 7.5057         | 0.9274                        |
| S-0.38-50       | 1.4152           | 0.9979                        | 17.2758        | 0.9321                        |
| S-0.35-70       | 1.1932           | 0.9930                        | 18.5466        | 0.5387                        |
| S-0.32-100      | 1.437            | 0.9843                        | 6.6463         | 0.8696                        |

Figure 2 shows the comparison of test curve and fitting curve. It can be seen from the figure that the ascending part of the image fits well, and the fitting results almost coincide with the experimental results. In the descending section, the properties of gangue concrete are greatly affected by the physical properties of gangue itself, so the image of descending section has a certain discrete type.
5. Conclusion
(1) There are four stages including the whole process of gangue concrete under uniaxial compression. The deformation characteristics of the earlier three stages are similar to the ordinary concrete, but in the fourth stage, there is the sudden-failure’s possibility of gangue concrete.
(2) The complete stress-strain curve of gangue concrete is similar to the ordinary concrete. After regression analysis of 15 specimens, the correlation coefficients $\alpha$ and $\beta$ of the rising and falling sections are obtained. $\alpha$ decreases first and then increases with the increase of replacement rate. When the replacement rate is 70%, $\alpha$ falls to the minimum value which is 1.1932, while the value of $\beta$ is low and discrete due to partial fitting correlation coefficient. Therefore, further experiments are needed to fit the parameter $\beta$ in the descending section.

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