Study on Mechanical Properties of Recycled Concrete Block Mixed with Coal Gangue and Plant Fiber

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Abstract: In this paper, the recycled aggregates of waste coal gangue and waste concrete crushed by a crusher are used as coarse aggregates, mixed with plant fibers. By changing the mixing rate of plant fibers and coal gangue, the mix design of plant fiber recycled concrete and experiment. According to the compressive strength values of 7d, 14d and 28d concrete, the optimal mix ratio is selected. Correct the calculated value of the compressive strength bearing capacity according to the specific strength value of the plant fiber concrete and ordinary concrete obtained by the test, and obtain the correction coefficient k. According to the best mix ratio, the plant fiber recycled concrete hollow block was designed, and its compressive strength was analyzed by ANSYS finite element. In this paper, the recycled aggregates of waste coal gangue and waste concrete crushed by a crusher are used as coarse aggregates, mixed with plant fibers.

1. Introduction

Coal gangue is the waste produced by coal mines, and the general coal gangue emissions account for 15% -20% of coal production. The annual emissions of coal gangue in China amount to 380 million tons, and more than 7 billion tons have been accumulated[1-2]. The generation of coal gangue will not only occupy a lot of land, but also cause pollution to the environment, so the research on the rational use of coal gangue is urgent.

China’s straw resources have the largest number in the world, with an annual output of about 650 million t. Straw is not only an important biological resource, but also an ecological and environmentally friendly building material. Western countries such as Europe and the United States have used straw for building materials for a long time[3].

In this paper, according to the literature, by adding coal gangue and plant fiber as materials, we developed a double-gangue gangue and plant fiber recycled concrete block in line with the national sustainable development strategy.

2. Test overview

2.1. Experimental design

In this test, double-doped coal gangue and plant fibers were selected, and flocculent straw with a particle size of about 0.5 mm was selected, and the mechanical properties of the concrete were tested using 150 * 150 * 150 mm test blocks. The mix design of the concrete mixed with coal gangue and plant fiber is shown in Table 1.
Table 1. Test mix ratio of plant fiber concrete (kg / m³)

| Number | cement  | Fly ash | Coal gangue | Natural gravel | Recycled coarse aggregate | Straw | Water |
|--------|---------|---------|-------------|----------------|--------------------------|-------|-------|
| MS-0  | 0       | 0       | 0           | 0              | 0                        | 0     | 0     |
| MS-1  | 11.98   | 456.984 | 342.738     | 342.738        | 180                      | 23.96 | 0     |
| MS-2  | 299.47  | 74.87   | 571.23      | 228.492        | 180                      | 17.97 | 0     |
| MS-3  | 23.96   | 0       | 0           | 0              | 0                        | 11.98 | 0     |
| MZ-0  | 0       | 0       | 0           | 0              | 0                        | 0     | 0     |
| MZ-1  | 11.98   | 456.984 | 342.738     | 342.738        | 180                      | 23.96 | 0     |
| MZ-2  | 299.47  | 74.87   | 571.23      | 228.492        | 180                      | 17.97 | 0     |
| MZ-3  | 23.96   | 0       | 0           | 0              | 0                        | 11.98 | 0     |
| MD-0  | 0       | 0       | 0           | 0              | 0                        | 0     | 0     |
| MD-1  | 11.98   | 456.984 | 342.738     | 342.738        | 180                      | 23.96 | 0     |
| MD-2  | 299.47  | 74.87   | 571.23      | 228.492        | 180                      | 17.97 | 0     |
| MD-3  | 23.96   | 0       | 0           | 0              | 0                        | 11.98 | 0     |

Note: MS means 20% coal gangue, MZ means 30% coal gangue and MZ 40% coal gangue. 0, 1, 2, and 3 indicate that the straw dosage is 0, 4%, 6%, and 8%, respectively.

3. Test results and analysis

3.1. Destructive form
The destruction pattern after the completion of the test loading is shown in Figure 1. a) and b) in the figure are the compressive strength test of the concrete cube. It can be seen from the figure that the concrete block with plant fiber is damaged and the appearance is more complete; after the concrete block without fiber is damaged, the surface peeling is serious. c) and d) are the tests of the concrete cube splitting tensile strength. From the failure mode, it can be seen that the crack width of the concrete test block added with plant fibers is small after the failure, and it is not completely broken. After the failure of the concrete block without fiber, the crack was wide and the test block was completely broken.

![Image](a) add plant fiber cube compression b) no plant fiber cube compression c) add plant fiber cube split d) no plant fiber cube split)

Figure 1. The failure form of a concrete test block mixed with coal gangue and plant fibers

3.2. Analysis of test results
The test data on the mechanical properties of the concrete mixed with coal gangue and plant fibers are shown in Table 2.
### Table 2. Experimental data of concrete mixed with coal gangue and plant fibers

| Number | Compressive strength | Splitting strength | Tension-compression ratio |
|--------|----------------------|--------------------|--------------------------|
|        | (MPa) |                      | (MPa) |                  |                        |
|        | 7d    | 14d | 28d | 28d | 28d |
| 0      | MH-0  | 29.87 | 34.36 | 37.51 | 2.78 | 0.074 |
| 1      | MS-1  | 28.74 | 33.93 | 36.14 | 2.81 | 0.078 |
|        | MS-2  | 23.17 | 28.59 | 31.62 | 2.47 | 0.078 |
|        | MS-3  | 19.36 | 21.67 | 26.84 | 2.26 | 0.084 |
| 2      | MZ-1  | 22.43 | 27.85 | 31.66 | 2.69 | 0.084 |
|        | MZ-2  | 20.98 | 25.77 | 29.32 | 2.45 | 0.085 |
|        | MZ-3  | 16.69 | 19.34 | 23.25 | 2.38 | 0.102 |
| 3      | MD-1  | 23.16 | 25.74 | 28.33 | 2.54 | 0.090 |
|        | MD-2  | 16.93 | 22.37 | 25.65 | 2.35 | 0.092 |
|        | MD-3  | 14.82 | 17.98 | 21.89 | 2.08 | 0.095 |

It can be seen from the table that the compressive strength of concrete gradually decreases with the increase of the amount of coal gangue under the condition of unchanged plant fibers. When the plant fiber is blended in more than 6%, the compressive strength of concrete grows slowly in the early stage, and the strength growth is relatively gentle by 28d. Although the addition of plant fibers did not improve the tensile and compressive strength of concrete, it increased the tensile-compression ratio to a certain extent. It can be calculated from the calculation that with the increase of the plant fiber blending, the tension-compression ratio of the concrete mixed with coal gangue and plant fiber is increased by 2.6% -7.8%. Generally speaking, the addition of plant fibers can improve the toughness of concrete to a certain extent.

### 4. Calculation of ultimate bearing capacity

With reference to "Code for Design of Concrete Structures" (GB50010-2010) [4], the compressive ultimate bearing capacity of concrete is calculated. Equation (1) is the calculation formula of concrete compressive strength:

\[
f_{cu,o} = f_{cu,k} + 1.645 \sigma
\]  

In the formula: \( f_{cu,o} \) is the concrete test strength (MPa), and \( f_{cu,k} \) is the standard value of the compressive strength of the concrete cube (ie strength level) (MPa), and \( \sigma \) is the standard deviation of the concrete strength (MPa).

The calculation results from equation (1) are shown in Table 3.

| Fiber content (%) | \( f_{cu}(\text{MPa}) \) | \( f_{tcu}(\text{MPa}) \) | \( f_{cu}/f_{tcu} \) | \( f_{cu}^{1}(\text{MPa}) \) | \( f_{cu}/f_{tcu}^{1} \) |
|-------------------|--------------------------|--------------------------|----------------------|--------------------------|----------------------|
| 0                 | 37.51                    | 27.99                    | 1.34                 | 27.71                    | 1.35                 |
| 4                 | 31.66                    | 27.99                    | 1.13                 | 27.71                    | 1.14                 |
| 6                 | 29.32                    | 27.99                    | 1.05                 | 27.71                    | 1.06                 |
| 8                 | 23.25                    | 27.99                    | 0.83                 | 27.71                    | 0.84                 |

The compressive strength ratio strength value of concrete mixed with coal gangue and plant fiber and ordinary concrete is used to modify the calculated value of compressive strength bearing capacity. The change curve of plant fiber blending amount and specific intensity value is shown in Figure 2. It can be seen from the figure that as the plant fiber content increases, the specific strength value decreases and decreases in a parabolic manner.

The Origin software is used to perform regression analysis on the specific strength value, and the regression equation for calculating the correction coefficient of the compressive strength of concrete mixed with coal gangue and plant fiber is \( k = 0.997 - 0.021n - 0.003n^2 \), and \( f_{cu,o} = f_{cu,k} + 1.645 \sigma \) is multiplied by the correction coefficient \( k \) to obtain the correction formula for calculating the compressive strength of concrete mixed with coal gangue and plant fibers:

\[
f_{cu,o} = k(f_{cu,k} + 1.645 \sigma)
\]  

(2)
Figure 2. Relationship curve between specific strength value and plant fiber incorporation

It can be seen from the table that the maximum value of \( \frac{f'_{cu}}{f_{cu}} \) of the modified concrete mixed with coal gangue and plant fiber is 1.35, and the minimum is 0.84, and the average value is 1.10, and the standard deviation is 0.094, and the coefficient of variation is 0.16. It shows that the revised calculation formula has high accuracy, and also provides a reasonable safety reserve for the compressive strength of plant fiber concrete.

5. Block design and finite element analysis

5.1. Block structure design
The structure design and finite element modeling of recycled concrete block type mixed with coal gangue and plant fiber are shown in Figure 3.

5.2. ANSYS finite element analysis
The size of the block is 390 * 190 * 190mm. According to the heat transfer characteristics of the block, making the hollow part into a rectangle can improve the thermal performance of the block. According to the literature, it can be seen that compared with the solid block, a row of holes can be added. Increasing the thermal resistance by about 20% \(^5\), and when the thickness of the rib wall meets the conditions, the reasonable location of the partial holes and the number of rows can improve the compressive strength of the concrete block \(^6\). Therefore, on the premise of ensuring sufficient hollowness, a block with double rows of holes and staggered holes is designed, and a plant fiber concrete block with an outer rib wall thickness of 30 mm.
The solid65 unit is created in ANSYS software. The unit size is input according to the block size, the elastic modulus is 220 * 102MPa, the Poisson's ratio is 0.2, the concrete tensile strength is set to 7.2, and the compressive strength is 0.90. This test is mainly to simulate the loading process of the block, so when the constraint is applied, the constraint is applied on the entire surface of the bottom.

According to the experimental simulation analysis, it can be seen that during the loading process, as the load increases, the stress value distribution area also gradually increases. When the load is 10MPa, the stress distribution area has developed to most of the area, the maximum stress is 12.892 MPa, to meet the compressive strength requirements of MU10.0 blocks. It can be seen from the figure that the block has stress concentration on both sides of the bottom, and the cracks gradually extend from both sides.

6. Conclusion
(1) By carrying out 7d, 14d and 28d compressive strength tests on concrete test blocks with double coal gangue and plant fibers, the fitting equation of plant fiber concrete is obtained. When plant fibers are mixed in less than 4%, the concrete 7- The increase in compressive strength at 14d has little effect; when the plant fiber content exceeds 6%, the growth rate of concrete in the early stage will decrease by 40%-55% compared with 4%.

(2) With the addition of plant fibers, the tensile-compression ratio of concrete is increased by 2.6%-7.8%, which improves the toughness of concrete. This shows that coal gangue aggregates and plant fibers are feasible as concrete materials and are in line with the green and low-carbon sustainable development strategy.

(3) Combining the compressive strength and tensile-compression ratio of concrete, the best mix ratio of concrete is proposed. That is, the amount of coal gangue incorporated is 30% and the plant fiber is 6%.

(4) Through regression analysis, the correction coefficient k of compressive strength of plant fiber concrete is obtained, and the corrected calculation formula has higher precision, which also provides a reasonable safety reserve for the compressive strength of plant fiber concrete.

(5) The ANSYS finite element analysis of the compressive strength of the block meets the design strength of 10.0.

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References
[1] Chen Weilin.(2010) Basic research on the feasibility of coal gangue as cement concrete aggregate . Beijing University of Technology.
[2] Zhang Yunfei.(2019) Effect of coal gangue replacing part of coarse aggregate on mechanical properties of thermal insulation concrete. Building Technology and Application. 15-17.
[3] Fan Jun, Liu Fusheng, Liu Yong, Hu Yuqiu.(2010) Experimental Research on the Strength and Thermal Insulation Performance of Straw Fiber Concrete Blocks. Building Science. 45-47.
[4] Specification for design of concrete structures. (2010) GB50010-2010. Beijing: China Building Industry Press.
[5] Lightweight aggregate concrete small hollow block. (2011) GB/T15229-2011. Beijing: China Construction Industry Press.
[6] Yong Yuli, Jiang Xiping. (2012) Research on a new type of composite self-insulating block. Concrete.1: 109-112.
[7] Zhou Jinghai, Li Tingting, Yang Guozhi. (2013) Experimental research on the strength of waste fiber recycled concrete. Concrete. 1-4.