

PAPER • OPEN ACCESS

## Preparation and mechanical properties of steel fiber reinforced high performance concrete with copper slag as fine aggregate

To cite this article: X M Li *et al* 2019 *IOP Conf. Ser.: Mater. Sci. Eng.* **531** 012037

View the [article online](#) for updates and enhancements.

### You may also like

- [Effect of fiber synergy on strength & durability of high-performance concrete](#)  
Mohit Gupta, Ritu Raj, Anil Kumar Sahu et al.
- [A mathematical model for strength prediction of HPC containing copper slag as a cementitious material](#)  
R S Edwin
- [Mechanical properties of waste copper slag filled surface activated jute fiber reinforced composite](#)  
G Kalusuraman, S Thirumalai Kumaran, M Aslan et al.



**ECS**  
The  
Electrochemical  
Society  
Advancing solid state &  
electrochemical science & technology

**DISCOVER**  
how sustainability  
intersects with  
electrochemistry & solid  
state science research

## Preparation and mechanical properties of steel fiber reinforced high performance concrete with copper slag as fine aggregate

X M Li<sup>1</sup>, S H Zou<sup>2</sup>, R G Zhao<sup>1,3</sup>, L Y Deng<sup>1</sup>, N Ji<sup>1</sup> and C L Ren<sup>1</sup>

<sup>1</sup> College of Civil Engineering and Mechanics, Xiangtan University, Xiangtan 411105, China

<sup>3</sup> School of Civil Engineering, Hunan University of Science and Technology, Xiangtan 411201, China

<sup>2</sup> Key Laboratory of Dynamics and Reliability of Engineering Structures of College of Hunan Province, Xiangtan University, Xiangtan 411105, China

Corresponding author: zhaorongguo@163.com

**Abstract.** High performance concrete is widely used in constructional engineering for its long durability, excellent volume stability, adequate compressive strength and good construction performance. In this paper, a class of high performance concretes are prepared by using copper slag instead of sand as a fine aggregate, and their mechanical properties are tested. Firstly, the high performance concrete specimens with different copper slag content and the steel fiber reinforced ones are individually prepared. Then, the compressive and flexural strength tests for cured high performance concrete specimens are operated according to the CECS13-2009 fiber reinforced concrete test method standard. The test results show that for the high performance concrete with copper slag as fine aggregate, the compressive strength reaches a peak value as the replacement ratio of copper slag to fine sand about 35%, but the flexural strength decreases with increasing copper slag replacement ratio, while for steel fiber reinforced high performance concrete, when the copper slag replacement ratio is about 40%, the concrete has a relatively high compressive strength, flexural strength and toughness. Furthermore, under an equivalent strength condition, the additional steel fiber improves the replacement rate of copper slag in the high performance concrete, so the steel fiber reinforced high performance concrete with copper slag as fine aggregate exhibits a better comprehensive mechanical property.

### 1. Introduction

The aggregate accounts for more than 70% of the concrete matrix and is considered as one of the main components of concrete [1]. Using industrial waste aggregate to replace natural aggregate or artificial one is an important issue for green development of building energy saving and emission reduction. Copper slag is the waste from copper production. For every ton of copper produced, about 2.2 tons of copper slag are produced. In 2015, the global refined copper output was 23.08 million tons, of which China's output was 7.96 million tons, accounting for about 35% of the world's refined copper output in the past two years. Copper slag produced by copper refining is piled up in waste slag yard. On the one hand, it will occupy a large amount of land resources, easily lead to heavy metal pollution, on the other hand, it will cause huge waste of resources [2]. If copper slag is utilized as a fine aggregate in concrete, it can not only eliminate dumping cost and reduce land occupied area, but also reduce the



damage caused by mining fine sand and the energy consumption needed for industrial sand production, thus realizing the rational utilization of solid waste resources [3,4].

The copper slag has been widely used in construction, and the Building Construction Management Administration in some foreign countries has stipulated that in the construction projects, the highest quality of copper slag instead of sand should not exceed 10%, and additional preventive measures have been taken. Some researches have been done for such copper slag concrete. Al-Jabri [5] pointed out that as the replacement rate of copper slag was 50%, the maximum compressive strength of copper slag concrete cured for 28 days decreased. Hwang [6] found that the addition of copper slag improved the workability and strength of concrete, and when the replacement rate of copper slag was more than 80%, it might be due to the formation of ettringite that led to the strength reduction. Li [3] and Zong [7] suggested that the mechanical properties and durability of copper slag concrete are similar to those of concrete containing conventional sand. Shi [8] studied the utilization of copper slag concrete, and found that as the replacement rate of copper slag increases, excess water emerges, which has certain effect on the strength of copper slag concrete, and some micro-defects grows in the concrete structure. Ayano [9] found that the existence of copper slag leads to the delay of solidification time. Shoya [10] discovered that the copper slag appears as a shape of irregular granular, its water absorption is low, which results in that the higher the volume fraction of copper slag fine aggregate is, the more free water content in the copper slag concrete is.

Although some researches have been worked for high strength concrete to replace traditional sand with copper slag as fine aggregate [11-15] or coarse aggregate [16], few studies have been done on adding copper slag as fine aggregate into steel fiber reinforced high strength concrete to improve its mechanic properties. In this paper, a class of steel fiber reinforced high performance concretes are prepared by using copper slag instead of sand as a fine aggregate, and their mechanical properties are tested. Furthermore, the influence of additional steel fiber on the replacement rate of copper slag in the high performance concrete is investigated.

## 2. Experimental

### 2.1. Materials

Cement is not only the main raw material for infrastructure construction, but also one of the main cementing materials for cement-based composite materials. The cement produced by Sinoma Cement Co., Ltd. is used in this test. The chemical compositions of the PO42.5 Portland cement, quartz sand and copper slag is shown in Table 1.

**Table 1.** The chemical compositions of cement, quartz sand and copper slag in weight percentage.

|                    | SiO <sub>2</sub> | Al <sub>2</sub> O <sub>3</sub> | Fe <sub>2</sub> O <sub>3</sub> | CaO   | SO <sub>3</sub> | CuO  | MgO   | K <sub>2</sub> O | Loss on ignition |
|--------------------|------------------|--------------------------------|--------------------------------|-------|-----------------|------|-------|------------------|------------------|
| PO42.5 (wt.%)      | 23.44            | 7.19                           | 2.96                           | 55.01 | 2.87            | /    | 2.24  | /                | 2.44             |
| Quartz sand (wt.%) | 99.20            | 0.20                           | 0.015                          | 0.023 | /               | /    | 0.011 | 0.056            | /                |
| Copper slag (wt.%) | 29.07            | 4.02                           | 57.80                          | 2.30  | 0.32            | 0.42 | /     | /                | 6.59             |

The water consumption for standard consistency of PO42.5 Portland cement used in this work is measured as 27.5%, the initial setting time and the final setting time are individually 115 minutes and 160 minutes. The compressive strength of PO42.5 Portland cement curing 3 days and that of cement curing 28 days are individually 26.8 MPa and 48.9 MPa, while the flexural strength of Portland cement curing 3 days and that of cement curing 28 days are 5.9 MPa and 8.3 MPa, respectively. The nominal maximum coarse aggregate size of the basalt gravel used in this test is 12 mm, and the apparent density of coarse aggregate after particle shaping is 2.77 g/cm<sup>3</sup>. The compressive strength of basalt gravel is 300 MPa, and its Young's modulus of elasticity is 98 GPa. The aggregate crushing value of basalt rock is 5.4%. Copper slag is a kind of black glassy particle with similar size range of sand. Its bulk density varies from 1.9 to 2.15 g/cm<sup>3</sup>. Compared with common sand, copper slag has relatively high density and low water absorption. The fineness modulus is about 2.8, the free water

content is less than 0.5%, and the content of silica is about 26%, which is soluble. The quartz sand used in the test is medium sand with a fineness modulus of 2.8, a density of  $2.65 \text{ g/cm}^3$ , a moisture content of 5%, a mud content of 0.7%, and the chemical composition is shown in Table 1. The steel fibers with length 13 mm and diameter 0.16 mm are adopted in this work. The water reducing agent is a high performance polycarboxylic acid one produced by Hunan Xianfeng Building Materials Co., Ltd., and the water reduction rate of mortar is 23%. The water used for mixing is directly from the tap water in the laboratory.

### 2.2. Multi-component high performance concrete mix proportion design

Two types of high performance concrete are designed in this paper. The one is a class of copper slag high performance concrete without steel fibers, numbered CS-00 to CS-100, the other is a class of copper slag high performance concrete with steel fibers, numbered FCS-00 to FCS-100, as shown in Table 2. For these two types of concrete, the water cement ratio is 0.35 and the water reducing agent content is 1%. The mixed water, silica fume, cement and coarse aggregates of basalt gravel content are  $160 \text{ kg/m}^3$ ,  $60 \text{ kg/m}^3$ ,  $475 \text{ kg/m}^3$  and  $750 \text{ kg/m}^3$ , respectively.

For the high performance concrete with copper slag and steel fiber reinforced high performance concrete with copper slag, the fine quartz sand aggregate content decreases from  $750 \text{ kg/m}^3$  to 0, while the fine copper slag aggregate content of increases from 0 to  $750 \text{ kg/m}^3$ . For the fiber reinforced high performance concrete incorporating copper slag as fine aggregates, the volume percentage of steel fiber is 2%, as shown in Table 2.

**Table 2.** The mix proportion of multi-component high performance concrete.

| No.     | Water cement ratio | concrete mix proportion ( $\text{kg/m}^3$ ) |             |        |                   |                          |                  |      |             |
|---------|--------------------|---------------------------------------------|-------------|--------|-------------------|--------------------------|------------------|------|-------------|
|         |                    | Mixing water                                | Silica fume | Cement | Steel fiber V (%) | Water reducing agent (%) | Coarse aggregate | Sand | Copper slag |
| CS-00   | 0.35               | 160                                         | 60          | 475    | 0                 | 1                        | 750              | 750  | 0           |
| CS-10   | 0.35               | 160                                         | 60          | 475    | 0                 | 1                        | 750              | 675  | 75          |
| CS-30   | 0.35               | 160                                         | 60          | 475    | 0                 | 1                        | 750              | 525  | 225         |
| CS-50   | 0.35               | 160                                         | 60          | 475    | 0                 | 1                        | 750              | 375  | 375         |
| CS-70   | 0.35               | 160                                         | 60          | 475    | 0                 | 1                        | 750              | 225  | 525         |
| CS-90   | 0.35               | 160                                         | 60          | 475    | 0                 | 1                        | 750              | 75   | 675         |
| CS-100  | 0.35               | 160                                         | 60          | 475    | 0                 | 1                        | 750              | 0    | 750         |
| FCS-00  | 0.35               | 160                                         | 60          | 475    | 2                 | 1                        | 750              | 750  | 0           |
| FCS-10  | 0.35               | 160                                         | 60          | 475    | 2                 | 1                        | 750              | 675  | 75          |
| FCS-30  | 0.35               | 160                                         | 60          | 475    | 2                 | 1                        | 750              | 525  | 225         |
| FCS-50  | 0.35               | 160                                         | 60          | 475    | 2                 | 1                        | 750              | 375  | 375         |
| FCS-70  | 0.35               | 160                                         | 60          | 475    | 2                 | 1                        | 750              | 225  | 525         |
| FCS-90  | 0.35               | 160                                         | 60          | 475    | 2                 | 1                        | 750              | 75   | 675         |
| FCS-100 | 0.35               | 160                                         | 60          | 475    | 2                 | 1                        | 750              | 0    | 750         |

### 2.3. Specimen preparation

According to CECS13:2009 Fiber Reinforced Concrete Test Method Standard [17], high performance concrete compressive specimens and bending ones were made by using  $100 \text{ mm} \times 100 \text{ mm} \times 100 \text{ mm}$  compressive specimen mould and  $100 \text{ mm} \times 100 \text{ mm} \times 400 \text{ mm}$  bending specimen mould, respectively.

In order to make the steel fibers evenly distributed, after preliminary trial mixing, the production process of high performance concrete is as follows. Firstly, the weighted sand, cement, silica fume and gravel are poured into the concrete mixer in turn, the mixer is started, and then dry mixing for 2 minutes. Secondly, as the mixer rotating at a low speed, the water and water reducing agent is added evenly, and the mixing is continued for 5 minutes until the cement mortar matrix is pasty. Thirdly, if

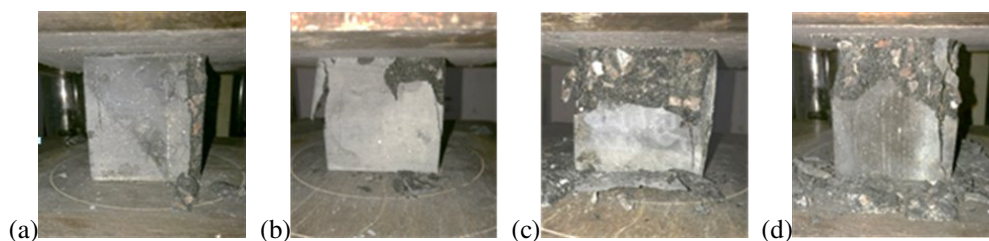
steel fibers are needed, steel fibers are uniformly added in the mixer rotating at a low speed, stirring for 5 minutes until the steel fibers are evenly dispersed in the matrix of cement mortar. Finally, the mixing concrete is discharged from the discharging tank of the concrete mixer. Through this mixing process, concrete mixing is completed, the mixture is poured into the lubricated die, and the concrete is poured using the two-layer pouring method. After pouring, the specimen is covered with impervious plastic film for 24 hours, and the surface of the specimen is smoothed after initial solidification. After demoulding by using a demoulding machine, the test specimens are marked with date and number, and cured in a standard maintenance box with relative humidity of 95% for 28 days.

### 3. Mechanical property tests and result analysis

According to the standard test methods, related technical regulations and test results processing approaches in CECS13:2009 Fiber Reinforced Concrete Test Method Standard [17] and GB-T50081-2002 Standard for Test Method of Mechanical Properties on Ordinary Concrete [18], the compressive strength and flexural strength of concrete, the conversion coefficient between standard specimens and non-standard ones, and the size effect are considered. A Hydraulic Servo Pressure Testing Machine is used to test the static mechanical properties.

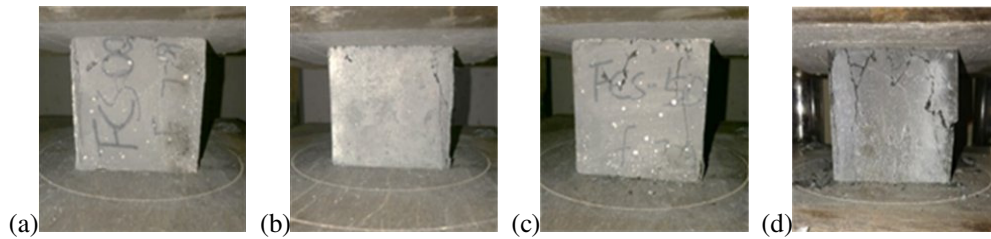
#### 3.1. Compressive strength tests

The failure modes of each group of non-fiber test concrete specimens are basically similar to those of the neat group (0% of copper slag), as shown in Figure 1. When the load is applied to a certain level, small cracks appear on the surface of concrete specimen, which are approximately perpendicular to the upper and lower stress surfaces. As the load continues to increase, the cracks further propagate, the number of cracks increases, the cracks develop to the interior, the skin of the specimen begins to swell, loading to the ultimate load, the concrete specimen is completely destroyed, accompanying with sound. When the replacement rate of copper slag is 100%, the middle part of the compression failure concrete specimen protrudes and two relatively complete pyramids remain at both ends of the specimen, as shown in Figure 4(d). This is because in the concrete compression test, although the Poisson effect causes transverse expansion, the transverse expansion at the two ends of the concrete specimen is restrained by the huge friction force between the end surfaces of the concrete specimen and the loading platform of Test Machine, its lateral expansion is inhibited. While the materials in the middle of the specimen are away from the end surface, the restraint effect is weak, which leads to concrete spalling. With the copper slag content increasing to 50%, it is observed that the shedding blocks increase significantly, and the specimen's end restraint force decreases, as shown in Figure 4(c).



**Figure 1.** Failure modes of the non-fiber high performance concrete specimens with different copper slag replacement rate in the compressive tests. (a) 0%; (b) 30%; (c) 50%; (d) 100%.

In the compressive tests of steel fiber reinforced high performance concrete specimens, the spalling amount of specimens is very small. This is because of the high bond strength between steel fibers and concrete. Due to the good bonding property, when cracks occur in the matrix, small concrete blocks are connected by steel fiber mesh to prevent its breakage, which can maintain its integrity and show good crack resistance. However, with the increase of copper slag replacement rate, more cracks can be observed on the steel fiber reinforced high performance concrete specimens, as shown in Figure 2.

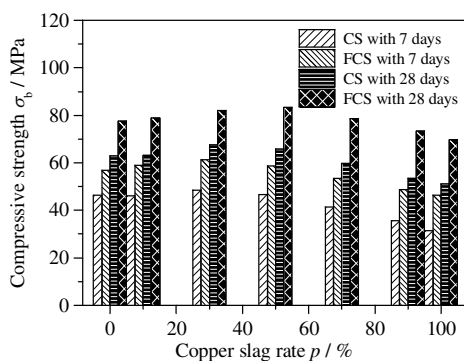


**Figure 2.** Failure modes of the steel fiber high performance concrete specimens with different copper slag replacement rate in the compressive tests. (a) 0%; (b) 30%; (c) 50%; (d) 100%.

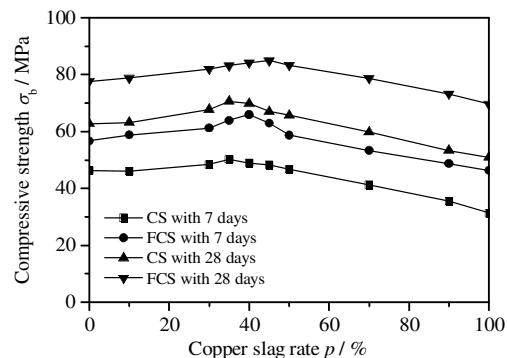
### 3.2. Compressive strength result analysis

The compressive tests of the copper slag concrete specimens are carried out in two groups. In the first group of concrete compressive tests, the compressive strength of concrete is divided into seven groups according to Table 2. The column diagrams of compressive strength of concrete specimens and fiber reinforced concrete specimens with different copper slag content are obtained as shown in Figure 3. The second group of concrete compressive test is based on the first group test. According to Figure 3, two groups of concrete specimens with a better compressive strength, namely, 30% and 50% copper slag replacement rate, are selected. The concrete specimens with the copper slag percentage ranging from 30% to 50% are designed. Then the compressive strengths for those copper slag concrete specimens are tested, and the curves of compressive strength vs. copper slag replacement rate are obtained, as shown in Figure 4. According to Figure 4, the optimum fine aggregate mix ratio of copper slag concrete and that of fiber reinforced copper slag concrete can be obtained.

It can be seen from Figure 3 that the concrete curing age has a significant effect on the compressive strength of concrete. The compressive strength of concrete cured for 28 days is significantly higher than that of concrete cured for 7 days. In addition, the compressive strength of copper slag concrete firstly increases, and then is reverse with increasing copper slag replacement rate. Comparing with the concrete with copper slag replacement rate 0%, the compressive strength of copper slag concrete has increased by 38.52%, and that of steel fiber copper slag concrete has increased by 33.46%, which is due to the presence of heavy metals in copper slag delaying the hydration of cement.



**Figure 3.** Diagram of slag rate vs. strength.



**Figure 4.** Curve of slag rate vs. strength.

Simultaneously, it can be seen from Figure 4 that for the non-steel fiber copper slag concrete, when the copper slag replacement rate is 35%, the compressive strength of copper slag concrete cured for 28 days reaches the maximum value of 70.66 MPa, and then the compressive strength of copper slag concrete decreases with increasing copper slag replacement rate. When the copper slag replacement rate is 100%, the compressive strength of copper slag concrete decreases to the minimum value of 50.94 MPa. Comparing with the concrete with copper slag replacement rate 35%, the compressive



strength of concrete with copper slag replacement rate 100% has decreased by 27.91%. For the steel fiber copper slag concrete, when the copper slag replacement rate is 45%, the compressive strength of steel fiber reinforced copper slag concrete cured for 28 days reaches the maximum value of 85.01 MPa, which has increased by 9.58% comparing with the compressive strength of steel fiber concrete without copper slag. Thereafter, the compressive strength of steel fiber copper slag concrete decreases with increasing copper slag replacement rate. When the copper slag replacement rate is 100%, the compressive strength of steel fiber copper slag concrete decreases to the minimum value of 69.62 MPa. Comparing with the steel fiber concrete with copper slag replacement rate 45%, the compressive strength of steel fiber concrete with 100% copper slag replacement rate has decreased by 18.10%. The compressive strength of copper slag concrete firstly increases and then decreases with increasing copper slag replacement rate. When the copper slag replacement rate exceeds a certain range, the compressive strength of copper slag concrete decreases whether steel fibers are contained or not. This is due to the existence of excessive water, which improves the workability of copper slag concrete. The retained excess water does not participate in the hydration process and forms internal voids, which weakens the bond between the interior of concrete and reduces its strength.

Furthermore, it can be found from Figure 4 that the compressive strength of concrete is obviously enhanced by the incorporation of steel fibers, and the optimum replacement rate of copper slag is also improved. This is because the copper slag belongs to acidic slag and has certain pozzolanic activity. The bond strength between steel fibers and acidic slag is improved under hydration. Therefore, in a certain range of replacement rate, the compressive strength of steel fiber concrete mixed copper slag as fine aggregate is higher than that of steel fiber concrete mixed quartz sand as fine aggregate.

### 3.3. Bending strength tests and result analysis

The four-point bending tests are carried out for the concrete beams. The span of the concrete beam is 300 mm. The bending failure modes of copper slag concrete beams and steel fiber reinforced copper slag concrete beams with different replacement rates are shown in Figure 5 and Figure 6, respectively.



**Figure 5.** Failure modes of the non-fiber high performance concrete specimens with different copper slag replacement rate in the bending tests. (a) 0%; (b) 40%; (c) 100%.

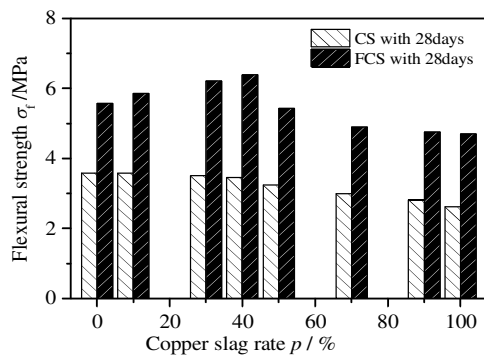


**Figure 6.** Failure modes of the steel fiber high performance concrete specimens with different copper slag replacement percentage in the bending tests. (a) 0%; (b) 40%; (c) 100%.

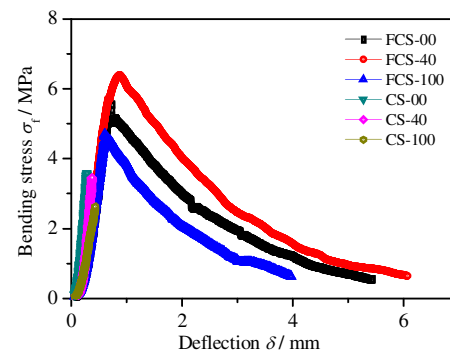
It can be found from Figure 5 and Figure 6 that the cracks firstly appear in the pure bending section of concrete beams during the loading process. With the increase of load, the crack gradually opens and propagates, forming a main crack. For the copper slag concrete beam, the ultimate bearing capacity of the beam quickly reaches and brittle failure occurs, as shown in Figure 5. For the steel fiber reinforced copper slag concrete beam, the load is transferred to the steel fibers between the broken concrete

blocks following with the concrete matrix cracking, after the peak load, more and more steel fibers failure, the crack further grows, and the compression zone height of the beam section decreases. Finally, the crack in the span of steel fiber reinforced copper slag concrete beam propagates to the whole section, and some steel fibers are pulled, even some steel fiber's tensile fractures are observed, as shown in Figure 6.

The column diagrams of flexural strength of copper slag concrete beams and steel fiber reinforced copper slag concrete beams cured for 28 days are shown in Figure 7. It can be seen from Figure 7 that the flexural strength of steel fiber reinforced copper slag concrete beam is significantly higher than that of copper slag concrete beam. The flexural strength of copper slag concrete beam decreases slowly at first and then rapidly with increasing copper slag replacement rate, while the flexural strength of steel fiber reinforced copper slag concrete beam firstly increases and then is reverse with increasing copper slag replacement rate.



**Figure 7.** Diagram of slag rate vs. strength.



**Figure 8.** Curve of stress vs. deflection.

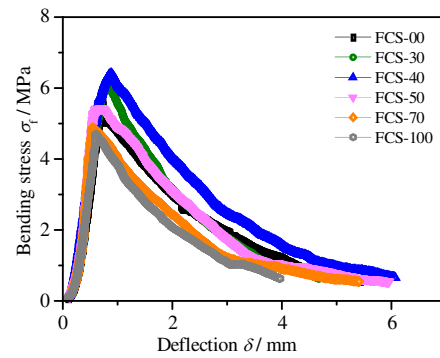
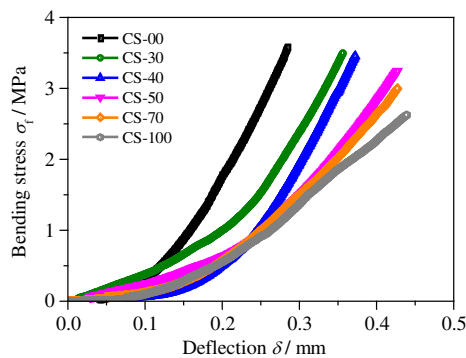
The bending stress vs. deflection curves of copper slag concrete beams and steel fiber reinforced copper slag concrete beams are shown in Figure 8. It can be seen from Figure 8 that the bending stress of copper slag concrete beam increases monotonously with increasing deflection, which indicates that the fracture mode of such beam is an instantaneous brittle fracture. The deflection of copper slag concrete beams increases with increasing copper slag replacement rate, while the flexural strength decreases with increasing copper slag replacement rate. For steel fiber reinforced copper slag concrete beams, the bending stress decreases after peak loading, showing a typical ductile failure mode. The flexural strength and deflection of steel fiber reinforced copper slag concrete beams firstly increase and then decrease with the increasing copper slag replacement rate.

Under various copper slag replacement rates, the bending stress vs. deflection curve of the copper slag concrete beams and that of the steel fiber reinforced copper slag concrete beams are individually shown in Figure 9 and Figure 10. It can be found from Figure 9 that the flexural strength of concrete beams cured for 28 days decreases gradually with increasing copper slag replacement rate. The maximum bending stress is 3.573 MPa and the minimum bending stress is 2.627 MPa, while the maximum deflection almost increases with increasing copper slag replacement rate. According to the area surrounded by the bending stress-deflection curve, the fracture toughness of a copper slag concrete beam is indirectly estimated. It is found that the toughness of copper slag concrete beams increases slightly at first and then decreases with increasing copper slag replacement rate. When the content of copper slag is 50%, the toughness is the strongest. The envelope area of stress-deflection curve is the largest, and the maximum value is 0.448 kJ/m<sup>2</sup>, as shown in Table 3.

Simultaneously, it can be seen from Figure 10 that in the case of replacement rate lower than 40%, the flexural strength of the steel fiber reinforced copper slag concrete increases with increasing of copper slag replacement rate, while in the case of replacement rate higher than 40%, the flexural strength decreases with increasing copper slag replacement rate. The maximum bending stress of steel



fiber reinforced copper slag concrete beams is 6.393 MPa, which is 1.848 times higher than that of non-fiber concrete beam with 40% copper slag fine aggregate. According to the envelope area of bending stress-deflection curve, the fracture toughness of a steel fiber reinforced copper slag concrete beam is estimated. It is found that the fracture toughness of steel fiber reinforced copper slag concrete beam firstly increases and then is reverse with increasing copper slag replacement rate. When the content of copper slag fine aggregate is 40%, the steel fiber reinforced copper slag concrete beam has the best toughness, the curve envelope area is calculated as 15.901 kJ/m<sup>2</sup>, its flexural strength, and deflection as well, reaches a maximum value, exhibiting the best flexural performance, as shown in Table 4. Overall, the fracture toughness of steel fiber reinforced concrete is greatly improved compared with that of ordinary concrete. Under a certain copper slag replacement rate, the bonding effect between copper slag and steel fiber is better than that between quartz sand and steel fiber, so steel fiber reinforced copper slag concrete beams shows an excellent toughness and flexural property.



**Figure 9.** Curve of stress vs. deflection for CS. **Figure 10.** Curve of stress vs. deflection for FCS.

**Table 3.** Flexural strength test results for the copper slag concrete beams.

| No. of CS specimen                             | CS-00 | CS-30 | CS-40 | CS-50 | CS-70 | CS-100 |
|------------------------------------------------|-------|-------|-------|-------|-------|--------|
| Area inside the curve $W$ (kJ/m <sup>2</sup> ) | 0.322 | 0.412 | 0.332 | 0.448 | 0.418 | 0.405  |
| Maximum Deflection $\delta_{\max}$ (mm)        | 0.286 | 0.359 | 0.375 | 0.430 | 0.428 | 0.441  |
| Peak stress $\sigma_p$ (MPa)                   | 3.573 | 3.499 | 3.459 | 3.246 | 3.004 | 2.627  |

**Table 4.** Flexural strength test results for the steel fiber reinforced copper slag concrete beams.

| No. of CS specimen                             | FCS-00 | FCS-30 | FCS-40 | FCS-50 | FCS-70 | FCS-100 |
|------------------------------------------------|--------|--------|--------|--------|--------|---------|
| Area inside the curve $W$ (kJ/m <sup>2</sup> ) | 11.766 | 11.730 | 15.901 | 12.318 | 9.805  | 7.902   |
| Maximum Deflection $\delta_{\max}$ (mm)        | 0.731  | 0.820  | 0.878  | 0.700  | 0.540  | 0.606   |
| Peak stress $\sigma_p$ (MPa)                   | 5.566  | 6.219  | 6.393  | 5.431  | 4.887  | 4.706   |

#### 4. Conclusions

The conclusions are given as following:

(1) The compressive tests for the copper slag concrete specimens show that the damage degree of the copper slag concrete increases with increasing copper slag replacement rate, and the restraint force at the end of specimen decreases. The crack resistance of steel fiber reinforced copper slag concrete is excellent, but the crack resistance of steel fiber reinforced copper slag concrete specimens decreases with increasing copper slag replacement rate.

(2) As the copper slag replacement rate is 35%, the copper slag concrete cured for 28 days has the best compressive strength, which is 12.53% higher than that of non-copper slag concrete. As the copper slag replacement rate is 45%, the steel fiber copper slag concrete cured for 28 days has the best

compressive strength, which is 9.58% higher than that of steel fiber concrete. The replacement rate of copper slag replacing sand as fine aggregate is improved by adding the steel fibers into concrete.

(3) For the copper slag concrete beam, the flexural strength decreases gradually with increasing copper slag replacement rate, while for the steel fiber copper slag concrete beams, as the copper slag replacement rate is 40%, it has the largest flexural strength and maximum failure deflection.

(4) As the copper slag replacement rate is lower than 45%, the steel fiber reinforced copper slag concrete beam has better flexural and toughness performance than that of the steel fiber reinforced concrete beam. It shows that when using the copper slag instead of sand as a fine aggregate to prepare concrete, the steel fiber reinforced copper slag concrete material with excellent mechanical properties can be obtained by adding appropriate amount of steel fiber into concrete.

## References

- [1] Al-Jabri K S, Hisada M, Al-Oraimi S K and Al-Saidy A H 2009 *Cem. Concr. Compos.* **31** 483
- [2] Li T and Zhang G J 2016 *Cement* **8** 22
- [3] Li F 1999 *Journal of Fuzhou University (Natural Science Edition)* **27** 58
- [4] Dash M K, Patro S K and Rath A K 2016 *Int. J. Sustain. Built Environ.* **5** 484
- [5] Al-Jabri K S, Hisada M, Al-Saidy A H and Al-Oraimi S K 2009 *Constr. Build. Mater.* **23** 2132
- [6] Hwang C L, Laiw J C 1989 *International Conference on the Use of Fly Ash, Silica Fume, Slag and Natural Pozzolans in Concrete* (Norway: SP14-82) p 1677
- [7] Zong L 2003 *Journal of Qingdao Institute of Architecture and Engineering* **24** 20
- [8] Shi C, Meyer C and Behnood A 2008 *Resour. Conserv. Recycl.* **52** 1115
- [9] Ayano T, Kuramoto O and Sakata K 2000 *J. Soc. Mater. Sci.* **49** 1097
- [10] Shoya M, Nagataki S, Tomosawa F, Sugita S and Tsukinaga Y 1997 *Proceeding of the 4th CANMET/ACI International Conference on Durability of Concrete* (ACI publication) p 879
- [11] Ambily P S, Umarani C, Ravisankar K, Prem P R, Bharatkumar B H and Iyer N R 2015 *Constr. Build. Mater.* **77** 233
- [12] Chithra S, Senthil Kumar S R R and Chinnaraju K 2016 *Constr. Build. Mater.* **113** 794
- [13] dos Anjos M A G, Sales A T C and Andrade N 2017 *J. Environ. Manage.* **196** 607
- [14] Sharma R and Khan R A 2017 *Constr. Build. Mater.* **155** 617
- [15] Rajasekar A, Arunachalam K and Kottaisamy M 2019 *J. Clean. Prod.* **208** 402
- [16] Lori A R, Hassani A and Sedghi R 2019 *Constr. Build. Mater.* **197** 130
- [17] Dalian University of Technology 2010 *Standard for Fiber Reinforced Concrete Test Method (CECS 13: 2009)* (Beijing: China Planning Press)
- [18] China Academy of Building Research 2003 *Standard for Test Method of Mechanical Properties on Ordinary Concrete (GB-T50081-2002)* (Beijing: China Architecture and Building Press)