Effect of Polyvinyl Fiber-Steel Slag Powder on Mechanical Properties of High Toughness Cement-Based Composites

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Abstract. Steel slag micro powder is steel slag after special process grinding, is a by-product in the process of steel production. This paper studied the basic mechanical properties and crack control ability through the compression strength test (0.8%, 14%, 20%) by compressive strength test and four-point bending test of thin plate. The results show that the inclusion of steel slag has a negative effect on the compressive strength of high toughness cement base composite and not against folding strength. When the steel slag powder reaches 20%, the test matrix can still show large toughness characteristics and crack control capacity.

1. Introduction
Slag is a solid waste discharged in the process of steel production, its main components include CaO, Fe\textsubscript{2}O\textsubscript{3}, SiO\textsubscript{2}, MgO, etc., similar to cement clinker in composition, is a by-product of the production of steel process. For each 1 ton of steel production, about 15% of the steel slag is produced\cite{1}. In 2018, the crude steel output was 929 million tons and 995 million tons in 2019\cite{2}. According to the output of steel slag, the crude steel slag output was about 139 million tons in 2018 and 149 million tons in 2019.

In recent years, steel slag has been comprehensively used in construction, medicine, environmental protection, metal smelting and agricultural production. According to statistics, as of 2020, the accumulated steel slag stock of steel slag reached more than 1 billion tons, and the comprehensive utilization rate of steel slag increased to 60%, and the utilization rate of some developed countries in Europe and Japan has reached more than 90%, basically realized the balance between the emission and utilization of steel slag is still far lower than the level of developed countries. The mountain of steel slag not only occupies a lot of land, but also seriously pollutes the air, water quality, etc., bringing a lot of pressure to the environment. Therefore, to solve the problem of steel slag waste accumulation pollution, it is necessary to vigorously improve the comprehensive utilization rate of steel slag, to use the steel slag resources to make its waste into treasure. The chemical composition of steel slag is similar to cement clinker, which is rich in three calcium silicate and two calcium silicate\cite{3}. The potential activity of grinding steel slag micro powder can be improved, so it can be used as an admixture in the production of cement-based composite materials. Compared with special cement prepared for mixture, steel slag powder is cement-based admixture. Many test results in recent years show that too high steel slag powder mixing volume can have a negative effect on the formation and strength development of the cement slurry\cite{4}.

High toughness cement-based composite is a new cement-based material with various different functional characteristics, its main characteristics have high ductility, good deformation and crack control ability under the hardening state, the limit tensile strain value can reach more than 3%, which is
easier to meet the needs of different projects, so that it has a wide application prospect[5]. At present, for high toughness cement-based composite materials, cement, fly cement, slag are mainly used as cementing materials, and suitable water reducing agent is selected for material design, and then mixed with fiber to achieve its functional goal. Some researchers have also used silica ash, cement powder, calcium carbonate whiskers and other auxiliary gel materials to prepare high-toughness cement-based composites[6-7]. This paper mainly from the perspective of resource saving and environmental protection, using the preparation of industrial waste steel slag and polyvinyl alcohol fiber, to achieve high performance and greening, and to achieve the purpose of energy saving and emission reduction.

2. Test raw materials and methods

2.1. raw material
Cement: P • O 42.5 General Portland cement, the chemical composition is as shown in Table 1, and the performance meets the requirements of GB175-2007-General Portland Cement. Steel slag micropowder: selected by Maanshan steel converter steel slag powder, the main chemical composition of 25~38 μm, is as shown in Table 2. Fly ash: select grade fly ash, black powder, whose chemical composition and main physical properties are shown in Table 3. Fine aggregate: choose 1.5-2.5mm grain size range and well graded fine sand. Polyvinyl alcohol (PVA) fiber: The high strength and high mode polyethylene alcohol fiber produced by Shanghai Kai Yuan Chemical Technology Co., Ltd. The main physical parameters are shown in Table 4. Water reducer: polycarboxylic acid high-performance water reducer, white powder, water reduction rate reached about 30%.

| CaO   | Al₂O₃ | SiO₂ | Fe₂O₃ | SO₃ | K₂O | Na₂O | MgO | P₂O₅ | TiO₂ |
|-------|-------|------|-------|-----|-----|------|-----|------|------|
| 61.43 | 5.358 | 21.35| 3.802 | 3.54| 0.926| 0.146| 1.68| 0.124| 0.312|

2.2. experimental method
The test methods used in this test include cube compressive strength test, folding strength test and sheet four-point bending test. Cube compressive strength test block size is 70.7mm*70.7mm*70.7mm, test load rate of 0.4MPa/s; folding strength test adopts GB/T17671-1999 cement cement strength test method, test piece size of 40mm*40mm*160mm standard prisms, test loading rate of 50N/S; four point bending...
test piece size of thin plate is 30mm*100mm*450mm, displacement loading, control loading rate is 0.5 mm/min. All test parts adopt standard maintenance method: maintain in the maintenance box with temperature kept at (20 ± 1) °C and relative humidity not less than 90% to 28d.

2.3. Test mix ratio
Replacing the cement in the cement-based composite materials, the substitution rate is 8%, 14% and 20%, respectively, with the matching materials of each component as shown in Table 5.

| number | Cement Kg/m³ | Steel slag for replacement of cement Kg/m³ | Flyash Kg/m³ | Fine sand Kg/m³ | Water Kg/m³ | water reducer Kg/m³ | Fiber volume rate% | Water-glue ratio |
|--------|---------------|--------------------------------------------|--------------|-----------------|------------|---------------------|-------------------|------------------|
| HS0    | 550           | 0                                          | 0            | 650             | 550        | 3                   | 2                 | 0.32             |
| HS8    | 506           | 44                                         | 8            | 650             | 550        | 3                   | 2                 | 0.32             |
| HS14   | 473           | 77                                         | 14           | 650             | 550        | 3                   | 2                 | 0.32             |
| HS20   | 440           | 110                                        | 20           | 650             | 550        | 3                   | 2                 | 0.32             |

3. Test results and the analysis

3.1. Cube compression test
The compressive strength test results of steel slag powder-PVA fiber high toughness cement composite are shown in Figure 1. From the figure, when the steel slag powder is not more than 8%, the compressive strength of fiber cube block is significantly higher than that of fiber mixed cube reaches 14%, the compressive strength of fiber is higher than that of fiber composite, indicating that the compression strength of the steel slag is not more than 8%.

At the same time, it can be seen that the compressive strength of the cube test generally decreases with the increase of steel slag powder. For the fiber group, when the compressive strength of the slag reaches 14% from 34.2MPa to 22.8MPa, close to 34%, indicating that the strength development of the steel powder within 28d age, which is related to the activity of the powder reaches 20%, the compressive strength is close to 40%, but can still meet the compressive strength requirements of the general project. For the test block of 2% volume rate fiber group, when the powder mixing of steel slag is 8%, the compressive strength is the highest, the compressive strength rises first and then decreases, and the reduction is small. When the mixing of steel slag micro powder reaches 20%, it can basically meet the compressive strength requirements required by the general project. Therefore, the slag powder strength is recommended not more than 20%.
3.2. Defold-bending strength test

The tensile strength test results of PVA fiber high toughness cement based composite are shown in Figure 2. As is seen from the figure, The tensile strength of the fiber group decreases with the increase of steel slag. When the amount of steel slag powder reaches 20%, Reduction reduction over 41%, This is basically consistent with the change law of the compressive strength, All are related to the activity of steel slag micropowder; For the fiber-mixed group test blocks, Lower folding strength under 20% steel slag powder, The bending strength of the test block is basically the same, And its folding strength is generally higher than the unadulterated fiber group test block, Explain that the fiber addition can greatly improve the bending strength of the test block, Reducing the activity of steel slag.

3.3. Four-point bending test of thin plate

According to the load and displacement data collected in the four-point bending test, the load-cross-medium displacement curve of the thin plate specimen is shown in Fig. 3; the specimen bending strength is calculated by formula (1), and the calculation results are shown in Table 6.

\[ M_f = \frac{NL}{bh^2} \]  

Type: \( M_f \) —Plate bending strength; \( N \)— failure load; \( L \) — span between supports; \( b \) — Width of thin sheet specimens; \( h \) — sheet test piece thickness.

![Figure 1 Change curve of relationship between compressive strength and steel slag](image)

![Figure 2 Relationship between specimen bending strength and micropowder mixing volume of steel slag](image)
In the four-point bending test, the initial load grows linearly with the deflection, with no cracks in the base, the test base bears most of the bending load, and the first crack reaches the initial crack strength of the base (as shown in Figure 4). Then a sudden drop or turning point occurs on the load-displacement curve. Generally, the initial crack often occurs in the weak section of the test section. After the initial crack of the specimen, the load grew fluctuating. When the PVA fiber at the crack opening began to bridge, the new cracks occur when the stress transmitted by the fiber reaches the cracking strength of the specimen matrix. As the intermediate deflection of the specimen increased and the crack width gradually widened, the new cracks in the middle of the two bearings. When the fiber bears the maximum load and reaches the fracture stress, the fiber of the base with small fiber density is pulled off or pulled out. Then the crack develops into the main crack, and the remaining crack width decreases, until the main crack is through, and the fiber bears the matrix until the fiber is pulled off or pulled out from the matrix, when the test piece is damaged.
As can be seen from Fig 3, the bending bearing capacity of the test piece matrix is significantly improved. In the initial stage of the test piece cracking, with the continuous increase of the span deflection of the specimen, the bending strength of the test piece is also growing slowly. Before reaching the maximum bending bearing capacity, the test piece curve development tends to be consistent, reflecting the unique strain hardening characteristics of the cement-based material. It can also be seen from the figure that the load-cross-middle displacement curve of the test sample mixed with 20% steel slag is relatively moderate, and the load fluctuation is within a certain range, and there is no obvious violent fluctuation in the curve. It is shown that the inclusion of steel slag powder makes the thin plate substrate more uniform, and the small cracks are more and evenly distributed. Therefore, it can avoid the stress concentration of local defects, expand the crack, and then ensure the good high toughness and crack control ability of the cement substrate.

The bending strength test results of steel slag micro powder-PVA fiber high toughness cement based composite material are shown in Table 5. It can be seen from the results that the bending strength of the steel slag at 28d age. The bending strength decreased from 6.7 MPa in the base group (HS0) to 4.8 MPa, by 48.4% in 20% and the initial crack load to 52.7%, which is basically the same with the compressive strength of the insufficient activity of steel slag, the early strength and the slow growth of the existing research results. Therefore, the long-term mechanical properties of steel slag micro-powder-PVA fiber will be studied in the later test.

4. Conclusion
This test has studied the basic mechanical properties of steel slag powder-PVA fiber high-toughness cement-based composite materials, and the following conclusions are mainly obtained from the research results: (1) Steel slag micro powder has a negative impact on the compressive strength of high toughness cement-based composite, and the greater the influence, the more obvious. Recommended in the engineering application according to the test results. (2) From the folding strength of the test results, we can show that the fiber mixing significantly improves the folding strength of the base group, weakens the adverse impact of the lack of activity of steel slag micropowder, indicating that the fiber addition can greatly improve the toughness and ductility of the test piece. (3) The inclusion of steel slag micro-powder can significantly improve the bending performance of high-toughness cement-based composite materials. Under the maximum mixing amount of 20%, it can also basically meet the bending strength requirements required by the project. (4) Steel slag micropowder-PVA fiber cement-based composite material provides a feasible road to solve the problem of a large number of steel slag stacking, replace cement with steel slag micro powder, greatly reduce cement consumption, save resources, reduce carbon emissions, and provides an effective method for the comprehensive application of steel slag and the preparation of green and environmentally friendly building materials.

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