Orthogonal test on mechanical properties of hybrid fiber reinforced slag concrete

Jiahao Liu, Jingshan Jiang*, Chao Zhang, Zhuchun Bao, Chenwei Hu

School of Civil Engineering and Architecture, Nanjing Institute of Technology, Nanjing, 211167, China

*Corresponding author's e-mail: jingshanjiang@njit.edu.cn

Abstract. The cube compressive strength and splitting tensile strength of16groups of hybrid fiber Reinforced and Slag replacing concrete (HFRSSC) were tested by orthogonal test method. The effects of basalt fiber, carbon fiber and slag on the mechanical properties of HFRSSC were studied. The test results show that the mass fraction of slag replacing for sand is a significant factor affecting the cube compressive strength of HFRSSC. With the increase of mass fraction of slag replacing for sand, the cube compressive strength increases at first and then decreases, and the maximum increase of slag to the cube compressive strength is 7.6%. Basalt fiber is a significant factor affecting the tensile strength of HFRSSC. The tensile strength increases with the increase of volume fraction of basalt fiber, and the maximum increase of basalt fiber to the tensile strength is 11.6%, but the increase of carbon fiber to the tensile strength is not obvious. The optimum volume rate of basalt fiber, carbon fiber and mass fraction of slag replacing for sand were given, which can provide the basis for the engineering application of HFRSSC.

Keywords: Hybrid Fiber Reinforced Concrete; slag replacing for sand; mechanical properties; orthogonal experiment

1 Introduction

Adding one kind of fiber into concrete to prepare fiber reinforced concrete can effectively improve its brittle failure characteristics [1-2]. The steel fiber mixes into the concrete can remarkably improve the fracture resistance of concrete, and enhance its toughness and crack resistance. Adding carbon fiber to concrete can enhance its compressive strength and improve its the brittle failure under compression [3-5]. The studies show that [6]: single fiber has great limitations in improving the performance of concrete, and two kinds of fiber hybrid can complement each other's advantages to better exert the "positive hybrid effect".

Slag, as a by-product of smelting process, has the ability of secondary hydration. At present, domestic and foreign scholars use it to replace natural sand as fine aggregate to prepare concrete. The studies show that slag promotes the later strength of concrete[7,

H. Bilgin et al. (eds.), *Proceedings of the 2023 5th International Conference on Civil Engineering, Environment Resources and Energy Materials (CCESEM 2023)*, Advances in Engineering Research 227,
https://doi.org/10.2991/978-94-6463-316-0_39

8], and the compressive strength and splitting tensile strength of slag sand replacement concrete are improved to varying degrees within a reasonable sand replacement rate[8].

Carbon fiber has high elastic modulus and strength, but poor fracture toughness. Although the elastic modulus and ultimate strain of basalt fibers are lower than those of carbon fibers, their fracture elongation is greater than that of carbon fibers. At present, there is little research on basalt fiber and carbon fiber mixed into concrete. Therefore, hybrid fiber reinforced slag concrete (HFRSSC) was prepared by adding basalt fiber and carbon fiber into concrete in small proportion and using slag instead of ultra-fine sand, in order to exert 'positive hybrid effect'.

The HFRSSC prepared in this paperhas low cost and accords with the concept of green building. The HFRSSC prepared in this article has a low cost and accords with the concept of green building. In order to further study the effects of basalt fiber, carbon fiber and slag on the mechanical properties of HFRSSC, a three-factor and four-level L16 (45) orthogonal test was designed for carbon fiber volume ratio, basalt volume ratio and slag replacement ratio. The cube compressive strength and splitting tensile strength of HFRSSC were conducted.

2 Test Overview

2.1 Test materials

The main performance parameters of basalt fiber and carbon fiber used in the experiment are shown in Table1. The sand used in the test is natural superfine quartz sand with silica content of 97.89% and fineness modulus of 1.40. The fineness modulus of slag is 3.31, and the main components are shown in Table 2.

Table 1. Main performance parameters of basalt fiber and carbon fiber.

Fiber	Density/ (g/cm^3)	Tensile strength/MPa	Modulus of elasticity/GPa	Monofilament diameter/μm	Length /mm	Elongation at break/%
Basalt fiber	2.8	4000	100	12	12	3.1
Carbon fiber	1.76	3800	230	8	6	1.5

Table 2. Chemical composition of copper slag.

Fe_2O_3	SiO_2	Al_2O_3	CaO	Cu_2O	P_2O_5	Burning loss
41.5	29	4.2	7	0.5	—	3

2.2 Test design

In order to study the influence of fiber and slag on the mechanical properties of HFRSSC, the factorsconsidered are the volume ratio of basalt fiber in concrete V_b, the volume ratio of carbon fiber in concrete V_c and the slag replacement ratio R_s, and each factor is set at four levels, which are listed in Table 3.

Table 3. Factors and levels of tests.

Level	Factor				
	V_b(A)/%	V_c(B)/%	R_s(C)/%	Blank column (D)	Blank column (E)
1	0.1	0.1	20	1	1
2	0.2	0.2	40	2	2
3	0.3	0.3	60	3	3
4	0.4	0.4	80	4	4

Notes: V_b stands for volume ratio of basalt fibers in concrete, V_c stands for volume ratio of carbon fibers in concrete, and R_s stands for the ratio of slag replacing for sand.

2.3 Specimens preparation and test methods

For each set of mix proportion, three 100mm×100mm × 100mm cube specimens were prepared for cube compressive strength test and splitting tensile strength test. Both concrete cube compressive strength and splitting tensile strength shall be tested by Y AW -4206 pressure testing machine of Meters Industrial Systems (China) Co., Ltd..

3 Results

The cube compressive strength, cube splitting tensile strength and tension-compression ratio of 16 sets of HFRSSC obtained from the test are shown in Table 4. It can be seen from the table that the maximum cube compressive strength appears in ZJ-3, the maximum splitting tensile strength appears in ZJ-15. In order to investigate the influence of fiber and slag on the cubic compressive strength, splitting tensile strength and tension-compression ratio of HFRSSC, the data in Table 4 are analyzed by using the data processing and analysis software SPSS, and the range and variance analysis results of the three factors on the cubic compressive strength, splitting tensile strength and tension-compression ratio are obtained, which are listed in Table 5 and Table 6 respectively.

It can be seen from Table 5 that the range of three factors for cube compressive strength, splitting tensile strength and tension-compression ratio is greater than the range of empty columns, indicating that the orthogonal test results are credible, and the test results can accurately reflect the deformation mechanism of mechanical properties of HFRSSC. According to Table 6, the trend of each factor for different levels of cube compressive strength f_{cu}, splitting tensile strength f_{ts}, and tension-compression ratio(f_{ts}/f_{cu}) is plotted in Figure 1.

Table 4. Results of tests.

Material types	Factor			Cube compressive strength f_{cu} /MPa	Splitting tensile strength f_{ts}/MPa	Tension-compression ratio(f_{ts}/f_{cu})
	A/%	B/%	C/%			
S-1	0	0	0	44.3	3.31	0.074718
ZJ-1	0.1	0.1	20	47.2	3.70	0.078390

ZJ-2	0.1	0.2	40	48.7	3.79	0.077823
ZJ-3	0.1	0.3	60	53.6	4.18	0.077985
ZJ-4	0.1	0.4	80	47.8	4.17	0.087238
ZJ-5	0.2	0.1	40	48.1	4.11	0.085447
ZJ-6	0.2	0.2	20	47.9	3.99	0.083299
ZJ-7	0.2	0.3	80	48.0	4.24	0.088333
ZJ-8	0.2	0.4	60	50.4	4.30	0.085317
ZJ-9	0.3	0.1	60	51.8	4.40	0.084942
ZJ-10	0.3	0.2	20	47.3	4.26	0.090063
ZJ-11	0.3	0.3	80	50.1	4.24	0.084631
ZJ-12	0.3	0.4	40	52.2	4.38	0.083908
ZJ-13	0.4	0.1	80	45.5	4.41	0.096923
ZJ-14	0.4	0.2	60	50.4	4.45	0.088294
ZJ-15	0.4	0.3	40	51.0	4.48	0.087843
ZJ-16	0.4	0.4	20	49.8	4.33	0.086948

Notes: S stands for reference concrete, ZJ stands for hybrid fiber reinforced and slag replacing for sand concrete.

Table 5. Range analysis of slump and strength of hybrid fiber reinforced and slag replacing for sand concrete.

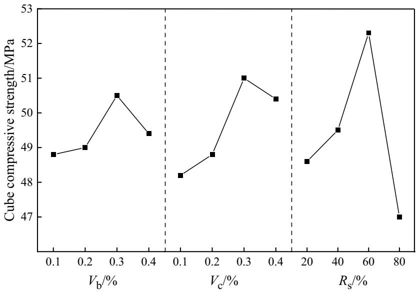
Examination index	Range calculation	Basalt fiber	Carbon fiber	Slag	Blank column(D)	Blank column (E)
Cube compressive strength/f_{cu} (MPa)	B_{i1}	48.8	48.2	48.6	49.6	49.0
	B_{i2}	49.0	48.8	49.5	49.6	49.8
	B_{i3}	50.5	51.0	52.3	48.7	49.1
	B_{i4}	49.4	50.4	47.0	49.7	49.6
	R_i	1.7	2.8	5.3	1.0	0.8
Splitting tensile strength/f_{ts} (MPa)	B_{i1}	3.96	4.16	4.07	4.19	4.19
	B_{i2}	4.16	4.12	4.19	4.26	4.24
	B_{i3}	4.32	4.29	4.33	4.19	4.24
	B_{i4}	4.42	4.30	4.27	4.22	4.19
	R_i	0.46	0.18	0.27	0.07	0.05
Tension-compression ratio(f_{ts}/f_{cu})	B_{i1}	0.080359	0.086425	0.088317	0.084731	0.085403
	B_{i2}	0.085990	0.084870	0.083755	0.085831	0.085529
	B_{i3}	0.085886	0.084698	0.084135	0.086174	0.086402
	B_{i4}	0.090002	0.085853	0.090640	0.085111	0.084512
	R_i	0.009643	0.001727	0.006885	0.001442	0.001891

Notes: B_{ij} is the average of the test results of factor i at level j. R_i stands for range value of factor i.

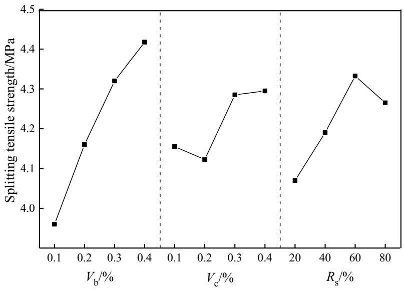
Table 6. Variance analysis of slump and strength of hybrid fiber reinforced and slag replacing for sand concrete.

Examination index	Sources of variation	SS	DOF	MS	F	Significance
Cube compressive strength/f_{cu} (MPa)	Basalt fiber	6.372	3	2.124	2.848	−
	Carbon fiber	17.142	3	5.714	7.661	*
	Slag	41.848	3	13.949	18.703	**
	Error	4.475	6	0.746		
Splitting tensile strength/f_{ts} (MPa)	Basalt fiber	0.480	3	0.160	37.765	**
	Carbon fiber	0.094	3	0.031	7.376	*
	Slag	0.160	3	0.053	12.566	*
	Error	0.025	6	0.004		
Tension-compression ratio(f_{ts}/f_{cu})	Basalt fiber	0.000	3	6.247E-5	30.272	**
	Carbon fiber	8.062E-6	3	2.687E-6	1.302	−
	Slag	0.000	3	4.811E-5	23.313	*
	Error	1.238E-5	6	2.064E-6		

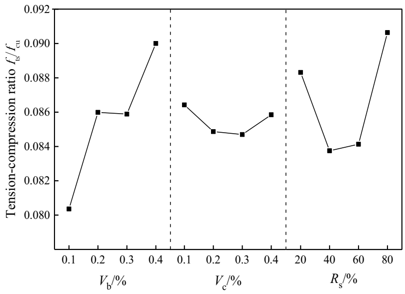
Notes: SS stands for sum of squares, DOF stands for degree of freedom, MS stands for mean square, and F represents F-value. **represents highly marked, * represents marked, and − represents no marked. $F_{0.05}(3,6)$ =4.76.



(a) Cube compressive strength



(b) Splitting tensile strength



(c) Cube compressive strength

Fig. 1. Effect of three factors on strength of hybrid fiber reinforced and slag replacing for sand concrete

4 Discussion

4.1 Failure Mode of HFRSSC

The final failure morphology of the HFRSSC cube compression test is shown in Figure 2. At the initial stage of loading, the phenomena of whitening and initial cracking appeared in the middle and lower parts of the specimen. In the middle stage of loading, the bottom corner of the specimen cracked and peeled off, and the adjacent short cracks on the side connected to form longer cracks. At the later stage of loading, the specimen enters the unstable stage, and several long cracks are formed inside the specimen. The fiber plays the role of bridging and stress transfer, and effectively improves the stress distribution in the concrete. When the total volume fraction of basalt fiber and carbon fiber in concrete is greater than 0.3%, it can be considered as high fiber volume ratio concrete. From the figure, it can be seen that the specimen is subjected to compression failure, but there is still pyramid remaining under the hoop effect at the loaded end. The integrity of HFRSSC specimen is relatively high, and the higher the fiber volume ratio, the less the surface peeling of the specimen.

The failure mode of HFRSSC splitting tensile test is shown in Figure 3. In the actual test, the internal material distribution of concrete is uneven, the splitting tensile failure part of specimen mainly occurs in the transition zone between aggregate and mortar, and the failure mode is relatively discrete. It can be seen from the figure that the fracture surface of HFRSSC specimen with low fiber volume fraction has two cracks, one is main crack and the other is branch crack. The fracture surface of HFRSSC specimen with high fiber volume fraction is mainly "H" type, and the integrity of fracture surface is poor. The cement mortar around the fiber is damaged during the fiber pull-out, so the higher the fiber content, the better the stress transfer effect.

(a)Low fiber volume ratio (Vb+Vc≤0.3%) (b)High fiber volume ratio (Vb+Vc>0.3%)

Fig. 2. Failure form of cube compressive test for hybrid fiber reinforced and slag replacing for sand concrete

(a)Low fiber volume ratio (Vb+Vc≤0.3%)

(b)High fiber volume ratio (Vb+Vc>0.3%)

Fig. 3. Failure form of splitting tensile test for hybrid fiber reinforced and slag replacing for sand concrete

4.2 Cube compressive strength

It can be seen from Table 5 that slag has the greatest influence on the cube compressive strength of HFRSSC, with the range of 5.3MPa, followed by carbon fiber, with the range of 2.8MPa, and basalt fiber has the smallest influence on the cube compressive strength of, with the range of only 1.7MPa.

According to Figure 1 (a), the influence of basalt fiber on the cube compressive strength is not obvious, and the overall variation range is within 3%. When V_c increases from 0.1% to 0.3%, the cube compressive strength increases by 5.8%, but when V_c increases from 0.3% to 0.4%, the cube compressive strength decreases. The cube compressive strength of HFRSSC shows a trend of first increasing and then decreasing with the addition of fiber, indicating that a reasonable fiber volume fraction is beneficial for improving compressive strength and excessive fiber volume fraction can lead to negative hybrid effects. The reason is that when a proper amount of fiber is added, the fiber can be uniformly dispersed in the concrete and form a certain bonding force with the mortar to produce a certain crack resistance effect, and the non-directional support system formed by the fiber can also bear the load together with the concrete to improve the compressive strength. However excessive fiber will make it gather in concrete, form stress concentration point, reduce the effective utilization of fiber, and lead to the reduction of cube compressive strength of HFRSSC.

The cube compressive strength increases by 7.6% with the increase of R_s from 20% to 60%. But as R_s continue to increase, the cube compressive strength decreases. This indicates that the compressive strength of concrete can be improved by using slag instead of natural fine sand, but the high ratio of slag instead of sand is actually not conducive to improving the compressive strength of concrete. The reason for this is that a certain amount of slag mixed with the extra-fine sand makes the grading of fine aggregate better, reduces the pores inside the concrete, and improves the compressive strength. However, the porosity of slag itself is large, and excessive mixing will lead to excessive cement slurry used to fill the pores rather than wrapping the aggregate, which will lead to the reduction of compressive strength. If only considering improving the cube compressive strength of the concrete, the optimal combination is $A_3B_3C_3$.

According to the analysis of variance of the cube compressive strength of HFRSSC in Table 6, slag is a highly significant factor for the HFRSSC cube compressive strength, carbon fiber is a significant factor, and basalt fiber is a non-significant factor.

4.3 Splitting tensile strength

Analysis of the range value of splitting tensile strength of HFRSSC in Table 5 shows that the order of influence of the three factors on splitting tensile strength is basalt fiber (0.46MPa)> slag (0.28MPa)> carbon fiber (0.18MPa).

Figure 1 (b) shows that both basalt fiber and carbon fiber show an increasing trend in improving the splitting tensile strength. V_b increased from 0.1% to 0.4%, and the splitting tensile strength increased by 11.6%. Carbon fiber also improved the splitting tensile strength, but the degree of improvement was not as obvious as basalt fiber. This indicates that fiber mixing can exhibit good synergistic effects, improving the splitting tensile strength. If only the splitting tensile strength is considered, the optimum volume ratios of basalt fiber and carbon fiber are A_4(0.4%) and B_4(0.4%), respectively.

The effect of R_s on splitting tensile strength is similar to its effect on compressive strength, both of which increase first and then decrease. The splitting tensile strength increases by 6.4% when R_s increases from 20% to 60%, and decreases slightly when R_s increases from 60% to 80%.

The reason may be that the addition of slag improves the gradation of fine aggregate, enhances the bonding effect between fine aggregate and cement slurry, and can be re-hydrated, which improves the splitting tensile strength to some extent. However, the particle strength of slag is inferior to that of sand, and excessive mixing leads to the advantage of its chemical activity can not make up for its physical performance disadvantage, resulting in the reduction of splitting tensile strength. For splitting tensile strength, the optimum slag replacement ratio is C_3 (60%).

According to the results of variance analysis of splitting tensile strength of HFRSSC in Table 6, basalt fiber and slag are highly significant factors of splitting tensile strength; carbon fiber and slag are significant factors, and slag is more significant than carbon fiber.

4.4 Tension and compression ratio

According to the range analysis of HFRSSC tension-compression ratio in Table 5, the order of influence of three factors on tension-compression ratio is basalt fiber (0.009643)> slag (0.006885)> carbon fiber (0.001727).

It can be seen from Figure 1 (c) that V_b shows an overall increasing trend for the tension-compression ratio of concrete, with V_b increasing from 0.1% to 0.4%, and the tension-compression ratio increasing by 12.0%. As Vc increases, the tension-compression ratio first decreases and then increases, but the overall change range is within 2%, with little impact. The tension-compression ratio decreases first and then increases with the increase of R_s, and reaches the maximum value of 0.090640 at 80%. If only the tension-compression ratio of concrete is considered, the optimal combination is $A_4B_1C_4$.

According to the results of variance analysis of HFRSSC tension-compression ratio in Table 6, basalt fiber and slag are significant factors of HFRSSC tension-compression ratio; Carbon fiber is a non-significant factor.

5 Conclusion

1. The significant factors affecting the cube compressive strength of HFRSSC are slag and carbon fiber, and the significance of slag is greater than that of carbon fiber. Basalt fiber is a non-significant factor. For cube compressive strength, the optimal volume ratio of basalt fiber is 0.3%, the optimal volume ratio of carbon fiber is 0.3%, and the optimal replacement ratio of slag for sand is 60%.
2. The tensile strength of HFRSSC reinforced by basalt fiber and carbon fiber is larger than that of HFRSSC. The significant factors of splitting tensile strength of HFRSSC are basalt fiber and slag. High volume fraction of basalt fiber and carbon fiber will reduce the tensile strength of concrete.
3. Basalt fiber and slag are the significant factors for the tension-compression ratio of HFRSSC, while carbon fiber has little effect on the tension-compression ratio. If only considering the ratio of tension and compression, the best combination is $A_4B_1C_4$, that is, basalt fiber volume rate 0.4%, carbon fiber volume rate 0.1%, slag replacement sand rate 80%.

Acknowledgments

This work was supported by Jiangsu Industry-University-Research Cooperation Project (BY2021044), Innovation and Entrepreneurship Training Program for College Students in Jiangsu Province (202311276107Y, 202311276200H, 202311276196H), and Science & Technology Innovation Fund Project for College Students of Nanjing Institute of Technology (TB202309007, TB202309012, TB202309003).

References

1. Li Y, Zhang J, He Y, et al. (2022) A review on durability of basalt fiber reinforced concrete. Compos Sci Technol, 225: 109519.
2. Ahmad I, Qing L, Khan S, et al. (2021) Experimental investigations on fracture parameters of random and aligned steel fiber reinforced cementitious composites. Constr Build Mater, 284: 122680.

3. PAPACHRISTOFOROU M, PAPAYIANNI I. (2018) Radiation shielding and mechanical properties of steel fiber reinforced concrete (SFRC) produced with EAF slag aggregates, Dvlpmt GR DI, 20(4): 317-327.
4. WANG D, JU Y Z, SHEN H, et al. (2019) Mechanical properties of high performance concrete reinforced with basalt fiber and polypropylene fiber. Constr Build Mater, 197: 464-473.
5. Alwesabi E A H, Bakar B H A, Alshaikh I M H, et al. (2020) Experimental investigation on mechanical properties of plain and rubberised concretes with steel–polypropylene hybrid fibre. Constr Build Mater, 233: 117194, 44: 565-574.
6. Rai B, Singh N K. (2021) Statistical and experimental study to evaluate the variability and reliability of impact strength of steel-polypropylene hybrid fiber reinforced concrete. journ. BLDG Engg, 44: 102937.
7. Amran M, Murali G, Khalid N H A, et al. (2021) Slag uses in making an ecofriendly and sustainable concrete: A review. Constr Build Mater, 272: 121942.
8. VIJAYARAGHAVANA J, JUDE A B, THIVYA J. (2017) Effect of copper slag, iron slag and recycled concrete aggregate on the mechanical properties of concrete. Resour Policy,53: 219-225.