Experimental study on mechanical properties of fly ash-silica fume-polypropylene fiber concrete

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Polypropylene fiber concrete is one of the high performance concrete materials with high utilization rate in the world. In this experiment, the basic mechanical properties of polypropylene fiber concrete are studied to provide reference for its application in engineering practice. Nine groups of specimens with different proportions of fly ash, silica fume and polypropylene fibers were subjected to compressive, splitting tensile and flexural tests by using the three-factor and three-level orthogonal test method. The optimal mix proportion of three dosages in different mechanical environments was obtained through range analysis. The results show that the optimum mix proportion of compressive strength is 30% fly ash, 10% silica fume and 1.5% polypropylene fiber. The optimum mix proportion of splitting tensile strength is 40% fly ash, 8% silica fume and 2% polypropylene fiber. The optimum mix proportion of flexural strength is 40% fly ash, 10% silica fume and 2% polypropylene fiber.

Key Words: *polypropylene fiber concrete, mechanical properties, orthogonal experiment, fly ash, silica fume*

1. Introduction

With the rapid development of social economy, people's requirements for the quality of construction projects are increasing. Traditional concrete has been unable to meet the requirements of engineering construction on concrete performance due to its low tensile strength, high brittleness, easy cracking, poor toughness and self-weight, and its development and application are greatly limited[1]. At present, a large number of studies have shown that the incorporation of fibers can improve the original defects and working performance of concrete. Polypropylene fiber is a new type of concrete reinforcement fiber. It is easy to disperse in concrete materials, so it can better play a reinforcing role. Compared with other synthetic fibers, polypropylene fibers have better chemical resistance, better processability, wider sources and better economy[2]. Studies[3-7] have shown that the addition of polypropylene fiber can significantly improve the compressive strength, tensile strength, flexural strength, impact and fracture toughness and durability of concrete. Polypropylene fiber can reduce or prevent plastic shrinkage cracks in concrete, and can bear external force with cement base material, thus inhibiting the expansion of cracks in concrete under external force. When the polypropylene fiber content exceeds the appropriate range, the strength of concrete will not increase but decrease[8-10]. Therefore, it is very important to study the influence of fiber content on the practical application of polypropylene fiber concrete.

Due to the filling effect and pozzolanic effect of mineral admixtures such as silica fume and fly ash, they can improve the microstructure of cement-based materials, adjust and improve their various properties. So they are increasingly becoming an important component of modern concrete[11]. At present, many scholars use fly ash and silica fume to make concrete by single or double mixing[12], but the experimental study on mixing fly ash, silica fume and polypropylene fiber into concrete is relatively few.

A large number of engineering practice has proved that polypropylene fiber concrete mixed with fly ash and silica fume has been widely used in the basement of high-rise buildings, sewage tank of sewage treatment plants, port pavement, highway pavement, wharf cargo yard, underground caverns and slope protection projects, and the effect is good.

The main purpose of this experiment is to study the influence of different dosages of polypropylene fiber, fly ash and silica fume on the mechanical properties of polypropylene fiber concrete. The com-pressive strength, splitting tensile strength and flexural strength are analyzed. The test data are compared by experiments, so as to obtain the mechanical properties of polypropylene fiber concrete, and provide reference for the application of polypropylene fiber concrete in practical engineering.

2. Test

The test was carried out in the road and bridge laboratory of Wuhan University of Science and Technology. The mixing and maintenance of concrete were strictly in accordance with the relevant provisions of the specification 《Standard Test Method for Mechanical Properties of Ordinary Concrete》 (GB/T 50081-2002) and 《Reactive Powder Concrete》 (GB/T 31387-2015).

(1) Materials

Cement: ordinary Portland cement with Huaxin brand number 42.5. Its 28d compressive strength is 48.5 MPa. Fly ash: Hou-gang grade I fly ash, 45μm sieve residue is 11.5%, burning loss is 3.89%. Silica fume: silica fume is between light gray and dark gray, density is 2.2g/cm^3, specific surface area is 20-28 m^2/g. Polypropylene fiber: it is a kind of high strength bundled monofilament fiber, which is made of polypropylene by special production process. Its physical properties are shown in Table 1. Fully disperse the fiber before the test. Sprinkle fibers evenly during stirring. Fine aggregate: ordinary river sand with fineness modulus of 2.58, apparent density of 2600kg/m^3 and bulk density of 1650kg/m^3. Water reducing agent: polycarboxylate high-performance water reducing agent, with water reducing rate of 25%-35% and pH value of 6-8. Water: urban tap water in Wuhan, Hubei.

Table 1 Physical properties of polypropylene fiber

Fiber type	Density	Fiber length	Fiber diameter	Elastic modulus	Tensile strength	Stretch limit	Thermal conducti-vity	Acid and alkaline resistance	Hydro-philia
Bundle filaments	0.91 g/cm³	12 mm	18-48 μm	>3.5Gpa	>358Mpa	>15%	low	high	no

Table 2 Test mix ratio

Group number	Cement	Fly ash	Silica fume	Sand	Water	Water reducing admixture	Polypropylene fiber
C1	792	220	88	550	275	11	9.1
C2	770	220	110	550	275	11	13.65
C3	748	220	132	550	275	11	18.2
C4	682	330	88	550	275	11	13.65
C5	660	330	110	550	275	11	18.2
C6	638	330	132	550	275	11	9.1
C7	572	440	88	550	275	11	18.2
C8	550	440	110	550	275	11	9.1
C9	528	440	132	550	275	11	13.65

(2) Pilot scheme

a) Concrete fit ratio design

The experiment adopts 0.25 water-binder ratio and 0.5 sand-binder ratio. According to three factors and three levels orthogonal design: The mass fraction of fly ash(A) instead of cement is 20%, 30% and 40%. The mass fraction of silica fume(B) instead of cement is 8%, 10% and 12%. The volume fraction of polypropylene fiber(C) is 1.0%, 1.5% and 2.0%. A total of nine groups of experiments were designed, and the proportion of experimental groups is shown in table 2.

b) Compression test

The compression test of polypropylene fiber reinforced concrete is carried out with a cube specimen of 100 mm × 100 mm × 100 mm. The loading instrument is a universal testing machine. Before the test, appearance of the testing machine is checked to ensure that the universal testing machine can be used normally. The upper and lower pressure plates are wiped clean, and then the test block without obvious defects is placed on lower pressure plate of the testing machine. Position of the center of the specimen and lower pressure plate of the testing machine is aligned. Testing machine is started to raise the lower pressure plate. When the upper pressure plate is close to the specimen, it stops and begins to load. The instrument is kept continuously and evenly loaded at the speed of 0.5 MPa/s, and the corresponding data in test process are recorded. Compressive strength of the test is calculated according to the formula (1).

$$f_{cc} = 0.95\frac{F}{A} \quad (1)$$

In the formula, f_{cc} is the cube compressive strength of polypropylene fiber reinforced concrete (MPa), F is the load (N) when the specimen is damaged, and A is the bearing area of the cube specimen (mm^2)

c) Splitting tensile strength test

Test specimens are non-standard cube specimens of 100 mm × 100 mm × 100 mm, and the loading instrument is a digital display press. Firstly, the test block is placed in the fixture, and the wooden pad is put on it. Then, the fixture equipped with the test block is placed on the press and is aligned with the axis position of the test machine. The loading speed of the press is adjusted to 0.08 MPa / s and is loaded at a constant speed. The appearance change of the test block is observed. The hearing of the crack of the test block is to achieve the ultimate load of the test block. At this time, the adjustment of the oil valve is stopped until the test block is completely broken. The relevant data are recorded, and the oil supply valve is closed. The oil return valve is opened and the test block is taken out.

The splitting tensile strength of test specimens is calculated according to the formula (2).

$$f_{ts} = 0.85\frac{2F}{\pi A} \quad (2)$$

In the formula, f_{ts} is the splitting tensile strength of polypropylene fiber concrete (MPa), F is the load when the specimen is destroyed (N), A is the splitting surface area of the specimen (mm^2).

d) Flexural strength test

The specimen size is 100 mm × 100 mm × 400 mm. Test device is installed and adjusted according to the test device shown in Figure 1, and then the base height is increased until the distance between the cushion block on the test block and the upper plate is about 2 mm. The adjustment is stopped, and the computer is used to set the speed of 0.08 MPa/s uniform loading. Then the corresponding test phenomena and data are recorded.

The flexural strength of the test is calculated according to the formula (3).

$$f_f = 0.85\frac{Fl}{bh^2} \quad (3)$$

In the formula, f_f is the flexural strength of polypropylene fiber concrete (MPa), F is the load when the specimen is destroyed (N), l is the span between the two seats (mm), h is the height of the specimen (mm), b is the width of the specimen (mm).

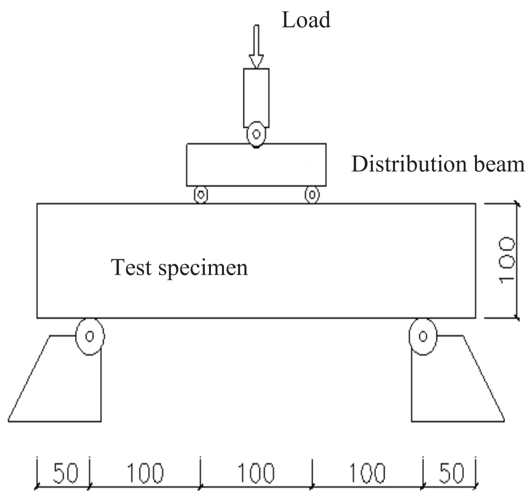

Fig.1 Test loading device (size unit: mm)

3. Test results and analysis

(1) Test results

The results of three basic mechanical properties tests are shown as follows :

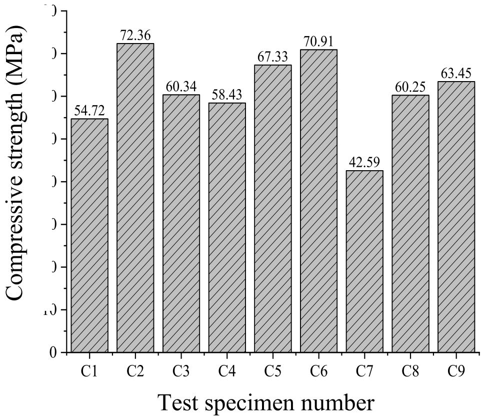

Fig.2 Compressive strength test results

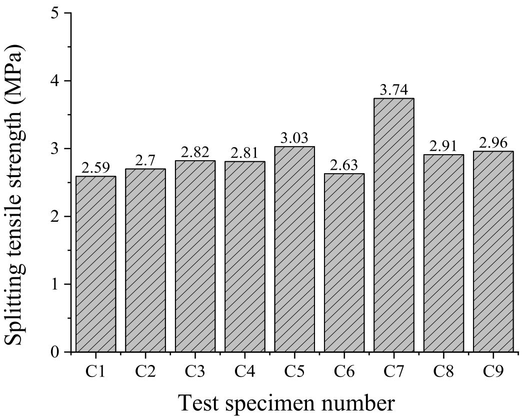

Fig 3 Splitting tensile strength test results

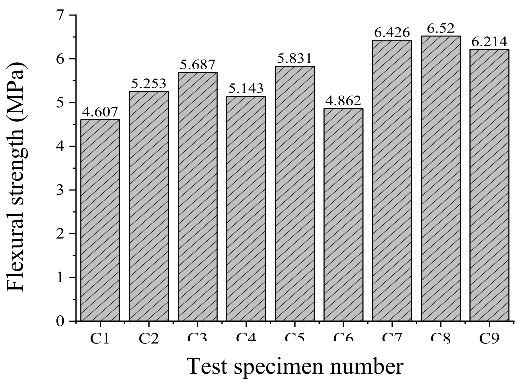

Fig 4 Flexural strength test results

(2) Analysis of the results of the compression test

The range analysis of compressive strength test results is presented in table. A, B and C represent fly ash, silica fume and polypropylene fiber respectively. K1, K2, K3 is the sum of compressive strength corresponding to each factor content and each level, k1, k2, k3 is the average compressive strength. The magnitude of R is calculated in the last column of the table, that is, the difference between the maximum and minimum values of the average compressive strength k1, k2, k3 obtained above. The range R of each factor can evaluate the influence of each factor on the test results. The larger the R value is, the greater the influence of the factor is. On the contrary, the smaller the R is, the smaller the influence of the factor is. It can be concluded from Table 3 that R(B) is greater than R(A), and R(A) is greater than R(C). The test results show that silica fume has the greatest impact on the compressive performance of polypropylene fiber reinforced concrete, followed by fly ash, and polypropylene fiber has the smallest impact, namely, silica fume is greater than fly ash, and fly ash is greater than polypropylene fiber.

Table 3 Range analysis table of orthogonal test results of compressive strength (unit: MPa)

Factors / Average variance	A	B	C	Empty column
K_1	187.42	155.74	185.88	185.5
K_2	196.67	199.94	194.24	185.86
K_3	166.29	194.7	170.26	179.02
k_1	62.47	51.91	61.96	61.83
k_2	65.56	66.65	64.75	61.95
k_3	55.43	64.9	56.75	59.67
R	10.13	14.74	8.0	2.28

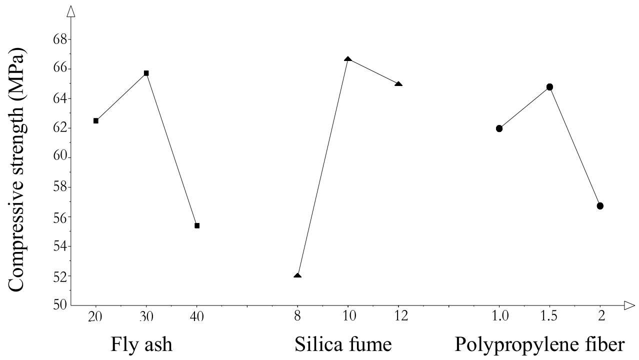

Fig.5 Influence of horizontal change of three factors on compressive strength

The following results can be obtained from the analysis in Table 3 and figure 5:

(a) Compressive strength increases first and then decreases with the increase of fly ash content. When the fly ash content increases from 20% to 40%, the compressive strength increases by 4.9%, and then decreases by 15.5%. It indicates that the less the fly ash content is, the greater the compressive strength is. When the mass fraction of fly ash is 30%, it has the greatest impact on the compressive strength of polypropylene fiber concrete.

(b) When the silica fume content increases from 8% to 10%, compressive strength increases by 28.4%. When the content increases from 10% to 12%, compressive strength decreased by 2.6%. It shows that the greater the content of silica fume is, the greater the compressive strength of polypropylene fiber concrete is. When the content is 10%, it has the greatest impact on the compressive strength of polypropylene fiber concrete.

(c) When the content of polypropylene fiber is 1.5%, it has the greatest influence, and the compressive strength of 1.5% is 4.5% higher than that of 1.0%, and the compressive strength of 2% is 12.3% lower than that of 1.5%. It indicates that the compressive strength value corresponding to the volume fraction content of polypropylene fiber at the level of 1.5% is the largest.

(d) The range R of empty train is 2.28, which indicates that the test accuracy is acceptable. At the same time, according to the range analysis of flexural strength as the evaluation index, the optimal mix ratio is A2/B2/C2, that is, the content of fly ash is 30%, the content of silica fume is 10%, and the content of polypropylene fiber is 1.5%.

(3) Analysis of splitting tensile strength test results

It can be seen from Table 4 that R(A) is greater than R(C), and R(C) is greater than R(B). The influence of the horizontal changes of the three factors on the splitting tensile strength of polypropylene fiber concrete is in the order of fly ash, polypropylene fiber, silica fume.

Table 4 Range analysis table of splitting tensile strength orthogonal test results (unit: MPa)

Factors / Average variance	A	B	C	Empty column
K_1	8.11	9.14	8.13	8.58
K_2	8.47	8.64	8.47	9.07
K_3	9.61	8.41	9.59	8.54
k_1	2.703	3.047	2.710	2.860
k_2	2.823	2.880	2.823	3.023
k_3	3.203	2.803	3.197	2.847
R	0.5	0.244	0.487	0.176

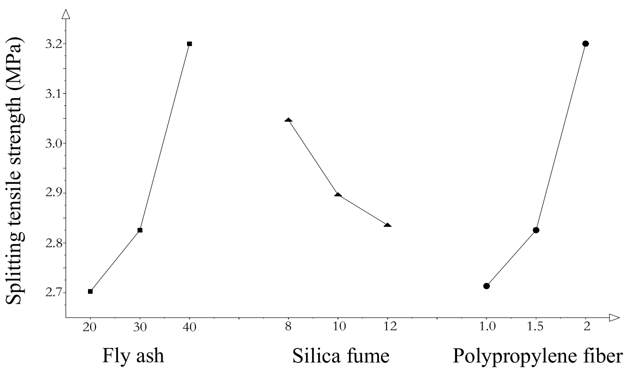

Fig.6 Effect of horizontal variation of three factors on splitting tensile strength

According to the analysis of table 4 and figure 6:

(a) When the fly ash content increases from 20% to 40%, the splitting tensile strength increases gradually, and the horizontal increase increases from 4.4% to 13.5%. Similarly, when the polypropylene fiber content increases from 1.0% to 2.0%, the splitting tensile strength of concrete increases gradually, from 4.2% to 13.2%. The test results show that the incorporation of fly ash and polypropylene fiber will improve the splitting tensile strength of polypropylene fiber concrete, and it will increase with the increase of dosage.

(b) With the increase of silica fume content, the splitting tensile strength decreases gradually. When the content increases from 8% to 12%, the splitting tensile strength decreases by 13.2%. The test results show that when the silica fume content is between 8% and 12%, the splitting tensile strength cannot be improved.

(c) The empty column range R is 0.176, which is acceptable as an estimate of the error. At the same time, the range analysis of splitting tensile strength as the evaluation index shows that the optimal mix ratio is A3/B1/C3, that is, the content of fly ash is 40%, the content of silica fume is 8%, and the content of polypropylene fiber is 2%.

(4) Analysis of experimental results of flexural strength

By analyzing the R values of various factors in Table 5, it can be seen that R(A) is greater than R(C) , and R(C) is greater than R(B), that is, fly ash has the greatest impact on the flexural strength of polypropylene fiber reinforced concrete, followed by polypropylene fiber, and silica fume has the smallest impact.

Table 5 Range analysis table of flexural strength orthogonal test results (unit: MPa)

Factors / Average variance	A	B	C	Empty column
K_1	15.547	16.176	15.989	16.652
K_2	15.836	17.604	16.610	16.541
K_3	19.16	16.763	17.944	17.350
k_1	5.182	5.392	5.330	5.551
k_2	5.279	5.868	5.537	5.514
k_3	6.387	5.588	5.981	5.783
R	1.205	0.476	0.651	0.269

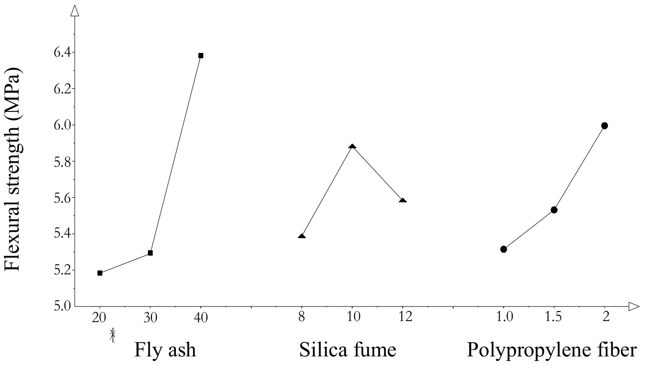

Fig.7 Influence of horizontal variation of three factors on flexural strength

According to Table 5 and Figure 7:

(1) When the fly ash content increases from 20% to 40%, the flexural strength increases, and when the fly ash content increases from 20% to 30%, the flexural strength increases by 1.87%. When the fly ash content increased from 30% to 40%, the flexural strength increased by 21%.

(2) When the silica fume content increases from 8 % to 12%, the flexural strength increases first and then decreases. There is an optimal dosage of silica fume, and the rate of its increase and decrease is similar. When it increases from 8% to 12%, the flexural strength increases by 8.8%, and then decreases by 4.6%. It shows that when the silica fume content is 10%, the flexural strength of polypropylene fiber concrete is the largest. When the silica fume content is more than 10%, the flexural strength decreases gradually.

(3) The flexural strength increases with the increase of polypropylene fiber volume fraction. When the fiber volume fraction increases from 1.0% to 2.0%, the flexural strength increases by 8.02%. It shows that the greater the fiber content in the concrete foundation, the greater the tensile stress it can bear, and the stronger the flexural performance of concrete.

(4) The empty column range R is 0.269, which indicates that the test accuracy conforms to the test results as the estimated value of the error. At the same time, the range analysis of flexural strength as the evaluation index shows that the optimal mix ratio is A3/B2/C3, that is, the dosage of fly ash is 40%, the dosage of silica fume is 10%, and the parameter of polypropylene fiber is 2%.

4. Conclusion

In this paper, the basic mechanical tests of polypropylene fiber reinforced concrete are carried out, and the range analysis method is used to explore the effects of fly ash, silica fume and polypropylene fiber on the mechanical properties of polypropylene fiber reinforced concrete. Finally, the following points are summarized :

(a) The influence of the three factors on the compressive strength of polypropylene fiber concrete is arranged from small to large as silica fume, fly ash, polypropylene fiber. The more the silica fume content is, the higher the compressive strength is. The compressive strength of polypropylene fiber concrete is the largest when the content of fly ash and polypropylene fiber is 30% and 1.5%, respectively. The failure mode of polypropylene fiber concrete is very different from ordinary concrete, but the final integrity is good. The optimum mix proportion of compressive strength is 30% fly ash, 10% silica fume and 1.5% polypropylene fiber.

(b) The influence of three factors on splitting tensile strength of polypropylene fiber concrete is arranged from small to large as fly ash， polypropylene fiber，silica fume. The effect of silica fume on splitting tensile strength of polypropylene fiber concrete is not significant, and decreases with the increase of silica fume content. The failure mode is multi-crack failure，accompanied by fiber pull-out phenomenon. The optimal mix proportion of splitting tensile strength is 40% fly ash, 8% silica fume and 2% polypropylene fiber.

(c) The flexural strength of polypropylene fiber concrete increases with the increase of fly ash and polypropylene fiber content, and increases first and then decreases with the increase of silica fume content. When the silica fume content is 10%, the flexural strength of polypropylene fiber concrete is the largest. The optimum mix proportion of flexural strength is 40% fly ash, 10% silica fume and 2% polypropylene fiber.

Acknowledgments

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