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STUDY ON THE INFLUENCE OF DIFFERENT TYPES OF POLYPROPYLENE FIBER CONCRETE ON FIRE RESISTANCE

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ABSTRACT

The open flame calcination test method was employed to assess the residual stress of fiber concrete in a study aimed at understanding the fire resistance of fiber concrete mixed with different types of polypropylene fibers, both alone and in combination with steel fibers. The results indicated a significant improvement in the fire resistance of concrete with the incorporation of fibers. Notably, concrete mixed with polypropylene monofilament fiber and steel fiber (PSCF1) exhibited minimal compressive strength loss, highlighting its superior performance under fire exposure. Among the various types of polypropylene fibers tested, polypropylene monofilament fiber (a) demonstrated better fire resistance compared to the other two types of polypropylene fibers. This suggests that the specific type of fiber used in the mix plays a crucial role in enhancing the fire resistance properties of concrete. The study underscores the importance of fiber selection in optimizing the fire-resistant capabilities of concrete structures. By incorporating appropriate fibers, the resilience of concrete in high-temperature conditions can be significantly enhanced, which is crucial for the safety and longevity of structures exposed to fire hazards. The findings of this research provide valuable insights for the construction industry, offering guidance on the use of fiber-reinforced concrete in applications where fire resistance is a critical requirement. Overall, the study contributes to the development of more robust and fire-resistant building materials, potentially leading to safer architectural designs.

Keywords:
Polypropylene fiber; steel fiber; fiber concrete; fire resistance

INTRODUCTION

Under the action of high temperature, the compressive strength of ordinary concrete decreases as the temperature rises. According to recent research, at 600°C, the compressive strength of concrete is reduced to approximately 45%, and at 1000°C, it completely loses its pressure-bearing capacity (Chen et. al., 2023). When the temperature exceeds 500°C, its compressive strength cannot recover, and steel-concrete materials lose their tensile capacity at around 600°C. In actual building fires, concrete completely loses its elastic modulus within 0.5-1 hour. The impact of high temperature on concrete materials is significant and cannot be ignored. Compared with ordinary concrete, high-strength concrete is more prone to explosive damage when exposed to high temperatures or open flame conditions (Nguyen et. al., 2023). This explosive damage endangers the integrity of the component, and the loss of bearing capacity of high-strength concrete at and after high temperatures is significantly greater than that of ordinary concrete (Althoey, 2023). Research shows that there are two main reasons for the explosion of high-strength concrete. One is the principle of vapor pressure. Due to the high density and low permeability of high-strength concrete, the water vapor inside the concrete cannot be discharged normally at high temperatures, causing a large accumulation of water vapor inside the concrete (Hager, I., and Mróz, G. ,2019). Vapor pressure generates expansion pressure. As the temperature increases, the expansion pressure inside the concrete gradually increases, causing bursting. The second is the principle of thermal stress, that is, when a fire occurs, a temperature gradient is generated inside the concrete, and the thermal stress caused by the thermal gradient is eventually causing the concrete to burst

The measures proposed to solve the high-temperature explosion protection of high-strength concrete due to these two reasons mainly include two aspects; increasing the pores of concrete to reduce vapor pressure and reducing the temperature difference between concrete substrates to reduce thermal stress (Khoury, 2023). Studies have shown that adding polypropylene fibers to concrete can achieve the purpose of reducing vapor pressure. The principle of action is: the melting point of polypropylene fibers is about 200°C. Therefore, the polypropylene fibers scattered inside the concrete structure will be in the concrete during a fire. Since the melting point has been reached during the self-evaporation stage, it melts to form numerous small pores. These pores leave space for water vapor inside the concrete, effectively relieving the vapor pressure of the concrete, thereby reducing concrete bursting; another measure is to mix steel into the concrete. Fiber, because steel fiber is a material with high thermal conductivity, it is helpful to improve the temperature difference between the matrix, thereby reducing the thermal stress of concrete (Zhan Sun et. al., 2024). At present, there is no unified and authoritative standard for the high temperature performance and fire resistance of concrete in China. In general laboratory research, concrete is heated in a high-temperature furnace to conduct research on the high-temperature properties of concrete. However, the temperature field generated by heating in the high-temperature furnace is very different from the actual fire situation. In order to simulate the fire situation of concrete components more closely, this article uses an open flame heating experiment. This article mainly studies the effects of three different types of polypropylene fibers mixed alone or mixed with steel fibers on the fire resistance of high-strength concrete.

TEST RAW MATERIALS

The Ordinary Portland cement produced by Guangzhou Zhujiang Cement Factory whereas the fly ash used is from Dongguan Humen Shajiao Power Plant standard Grade II ash, which complies with the provisions of GB 1596-2005 "Fly Ash Used in Cement and Concrete". The sand used is having fineness modulus of 2.5 and a bulk density of 1500 kg/m^3 whereas the coarse aggregate is within the range of 5-20mm. Coarse aggregate used is granite gravel with a bulk density of 1630kg/m^3. The water reducing agent used is polycarboxylic acid high performance water reducing agent HPC-R The polypropylene fiber is produced by Changzhou Zhuwei Building Materials Co., Ltd. and steel fiber produced by Chongqing Yizhu Trading Co., Ltd. The physical properties of the fibers are shown in Table 1 and Figure 1.

Table 1: Physical properties of fibers

Fiber type	Length/mm	Tensile strength/MPa	Elastic modulus/GPa
Polypropylene monofilament fiber (a)	25	≥500	≥3.5
Polypropylene mesh fiber(b)	25	≥560	≥3.5
Polypropylene crude fiber(c)	25	≥530	≥7.0
steel fiber	25	≥1200	≥200

Polypropylene monofilament fiber (a)

Polypropylene mesh fiber (b)

Polypropylene crude fiber (c)

steel fiber

Figure 1: Polypropylene fiber and steel fiber

MIX RATIO DESIGN

The water-cement ratio of the matrix concrete used in the test is 0.29. Water: cement: fly ash: sand: stone = 160: 440: 110: 703: 1054 per cubic meter of concrete. According to the experimental results of previous studies on the effect of fiber content on the mechanical properties of concrete, the volume ratio of the steel fiber content in this article is 0.9%, that is, the steel fiber content per cubic meter of concrete is 70.2kg, and the polypropylene fiber content is 0.05%. , that is, the polypropylene fiber content per cubic meter of concrete is 0.45kg. The specific mix ratio is shown in Table 2. The test uniformly uses CF to represent benchmark concrete, SCF to represent steel fiber concrete alone, PCF to represent polypropylene fiber concrete alone, and PSFC to represent steel fiber and polypropylene fiber hybrid fiber concrete.

Table 2: Concrete mix ratio /(kg/m3)

Mix	Cement	Fly ash	Sand	Gravel	Steel fiber	Polypropylene fibers	Water	Water reducing agent HPC-R
CF	440	110	703	1054	—	—	160	6.6
PCF1	440	110	703	1054	—	0.45(a)	160	6.6
PCF2	440	110	703	1054	—	0.45(b)	160	6.6
PCF3	440	110	703	1054	—	0.45(c)	160	6.6
PSFC1	440	110	703	1054	70.2	0.45(a)	160	6.6
PSFC2	440	110	703	1054	70.2	0.45(b)	160	6.6
PSFC3	440	110	703	1054	70.2	0.45(c)	160	6.6

TEST METHODS

The test uses the water mixing method as the mixing process, that is, first put the gravel, sand, cement, and fly ash into the mixer and stir, and at the same time, sprinkles the steel fibers evenly into the mixing mixture to ensure that the process is completed within 1 minute. Stir for another 1 minute, add the polypropylene fiber to the water, and stir gently with a glass rod until completely dispersed. Finally, pour the water, polypropylene fiber, and water-reducing agent into the mixer and stir for 3 minutes before ending. The test was carried out in strict accordance with the national standards "Standard for Test Methods of Mechanical Properties of Ordinary Concrete" (GB/T 50081-2019) and "Standard for Test Methods of Fiber Concrete CECS 13: 2009" for specimen preparation and strength experiments. The test used 100 mm × 1 Compressive strength and splitting tensile strength tests were carried out before conducted an open flame test after curing for 28 days using SBI single combustion test equipment provided by Guangdong Jianke Construction Engineering Quality Inspection Center (Figure 2). The medium-scale combustion test was developed based on GB/T 20284-2006 "Single Combustion Test of Building Materials or Products" Test device. It is mainly composed of combustion chamber system, burner, propane mass flow controller, propane and standard gas supply system, smoke exhaust system, comprehensive measurement system, flue gas measurement system, and data acquisition and processing system.

Figure 2: SBI monomer combustion experimental equipment

Taking into account the melting point of polypropylene fiber and the temperature changes during actual fires, the test uses a fire temperature of 800°C, a heating rate of 50°C/min, and the maximum fire temperature is reached within 20 minutes. The specimen continues to be exposed to fire for 60 minutes and is closed after 60 minutes. The air supply valve allows the specimen to cool naturally (Figure 3). Take out the concrete cube test block from the single combustion experimental equipment, and after leaving it at room temperature for 24 hours, strictly follow the national standards "Standard for Test Methods of Mechanical Properties of Ordinary Concrete" (GB/T 50081-2019) and "Standard for Test Methods of Fiber Concrete" CECS 13 : 2009 to carry out the residual strength test of the test block.

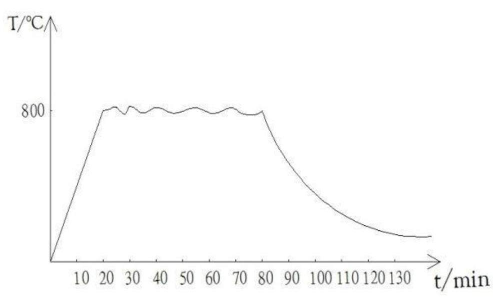

Figure 3: Temperature-time curve of fire resistance test

TEST RESULTS AND ANALYSIS

Appearance changes of concrete specimens after fire

After the fire resistance test, the fire surface of the specimen was basically milky yellow, and there was no obvious difference between the unfired surface and the unfired surface before calcination. The transition surface between them gradually changed from milky yellow to off-white to dark red and then to natural color; the fire surface of the specimen. There are obvious cracks on the surface, and some specimens even have peeling, missing corners, looseness, etc. However, the unfired surface shows good integrity and even no cracks. Since the flame temperature is around 800 °C, there is no strong explosion phenomenon in the specimen.

Table 3: Appearance of concrete with different proportions after fire

Serial Number	Color	Crack	Peeling Off Skin	Missing Corner	Loose	Burst
CF	Creamy yellow, light gray	interpenetrating, dense, wider	serious	have	Seriously, it will fall off if you hit it	none
PCF1	Same as above	Interpenetrating and dense	Slightly less	none	more serious	none
PCF2	Same as above	Interpenetrating and dense	Slightly less	none	more serious	none
PCF3	Same as above	interpenetrating, dense, wider	Slightly less	have	more serious	none
PSFC1	Same as above	Dense	less	none	none	none
PSFC2	Same as above	Dense	less	none	none	none
PSFC3	Same as above	Dense	less	none	none	none

Figure 4: Appearance of the concrete test block after being exposed to fire

RESIDUAL STRENGTH AND ANALYSIS OF CONCRETE AFTER HIGH TEMPERATURE

Residual compressive strength of concrete

The compressive strength of concrete after a fire determines the integrity, stability and post-disaster load-bearing capacity of the entire concrete component. It is an important evaluation basis for structural damage and an important guarantee for casualties and property losses in fires (Sifat *et. al*., 2024).

(1) Comparison of concrete residual compression test results

Since the experiment uses open flame heating, the specimen is subjected to non-uniform high temperatures, which makes the residual compressive capacity of each part of the specimen inconsistent. The fire-receiving surface and the unfired surface are not used as stress-bearing surfaces during loading. Therefore, the damage pattern of the specimen after fire is quite different from that of standard cured concrete. After the specimen was compressed, the corners of the fire surface were seriously damaged, and the damage pattern was different from that of the standard cured specimen. The damage pattern of the middle part was similar to that of the two ends. The damage basically occurs at the aggregate-slurry interface and inside the cement paste, and some aggregates also suffer comminuted damage. The fire surface of the test block was severely damaged, mainly in the form of powder, while the unfired surface had better integrity than the fire surface. The edges and corners did not fall off seriously, but there were obvious cracks. It is difficult to distinguish the difference in residual compressive strength between baseline concrete and fiber concrete simply based on the damage pattern. However, in the hybrid fiber concrete mixed with steel fibers, the sound of steel fibers being compressed was clearly heard in the test. And by observing the damaged test block, it can be seen that after open flame calcination, the bonding degree between the steel fiber and the concrete on the fire surface of the test block decreased significantly, while the polypropylene fiber has disappeared.

Figure 5 Destruction patterns of benchmark concrete, single-polypropylene fiber concrete and hybrid fiber concrete after compression

(2) Test data and analysis

From the analysis of Table 4 and Figure 6, it can be seen that the 28-day compressive strength of concrete mixed with polypropylene fiber alone is slightly smaller than that of the benchmark concrete. However, their residual compressive strength is slightly higher than that of the benchmark concrete. It can be seen that the incorporation of polypropylene fiber has an impact on concrete. The compressive bearing capacity after fire has a positive impact; from the perspective of reinforcement ratio, regardless of the mixing method, the residual compressive strength of fiber concrete is higher than the benchmark concrete; and the reinforcement effect of polypropylene-steel fiber concrete is very obvious; From the perspective of reinforcement ratio, the residual compressive strength of concrete mixed with polypropylene crude fiber (c) is better than that of the other two types of polypropylene fiber alone, while the residual compressive strength of concrete mixed with polypropylene monofilament fiber (a)-steel fiber Better than any other fiber-incorporated concrete. Combining Table 4 and Figure 7, the compressive strength loss of fiber concrete is significantly less than that of concrete mixed with polypropylene fiber alone; among the three types of concrete mixed with polypropylene fiber alone, the compressive strength loss ratio of polypropylene monofilament fiber concrete is smaller than the other two; Among the three types of mixed polypropylene-steel fiber concrete, the compressive strength loss ratio of the concrete mixed with polypropylene monofilament fiber-steel fiber is significantly better than that of the other two ratios of concrete, and even better than any of the ones studied in this article. It can be seen that whether it is single-mixed or mixed-mixed concrete, the proportion of compressive strength loss is: polypropylene monofilament fiber (a) > polypropylene mesh fiber (b) > polypropylene crude fiber (c).

Table 4: Residual compressive strength and strength loss ratio of concrete after fire

Mix	28d Compressive strength	Enhancement ratio (%)	Residual compressive strength	Enhancement ratio (%)	Strength loss ratio
CF	73.96	-	43.64	-	0.41
PCF1	68.39	-7.54	45.82	5.00	0.33
PCF2	69.79	-5.63	45.37	3.96	0.35
PCF3	74.39	0.58	46.12	5.69	0.38
PSCF1	76.96	4.06	63.88	46.38	0.17
PSCF2	80.32	8.60	60.24	38.06	0.25
PSCF3	82.55	11.62	59.44	36.21	0.28

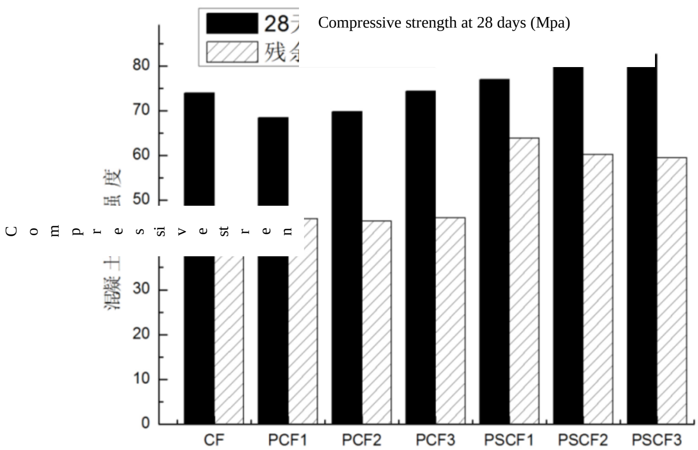

Figure 6: Compressive strength of concrete with different proportions before and after the open fire test

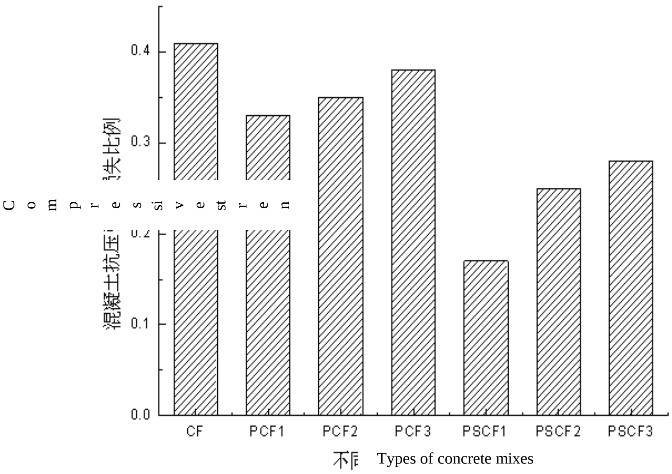

Figure 7: Compressive strength loss ratio of concrete with different proportions after the open fire test

CONCLUSION

After the concrete specimen is calcined by an open fire, the fire surface appears milky yellow and off-white, and the color of the unfired surface has not changed; the cracks in the benchmark concrete are dense and penetrate the specimen, and the skin is loose and loose, and even the corners are peeled off; single The concrete mixed with polypropylene fiber has fewer cracks and the peeling and loosening phenomenon is not obvious; although the concrete mixed with polypropylene-steel fiber has more cracks when exposed to fire, other phenomena are not obvious. It can be seen that from a macro perspective, hybrid fiber concrete is better than single-mixed polypropylene fiber concrete and better than benchmark concrete.

After the open fire test, the compression strength enhancement ratio of the concrete relative to the benchmark concrete is significantly better than that of the concrete aged 28 days. The incorporation of fibers significantly improves the pressure-bearing capacity of concrete after high temperature. In particular, the reinforcement ratio of hybrid fiber concrete after high temperature is about 10 times that of 28 days. Judging from the strength loss of concrete, the loss ratio of fiber concrete is smaller than that of the benchmark concrete. Polypropylene monofilament fiber (a) whether mixed alone or mixed with steel fiber, its compressive strength loss ratio is smaller than that of the other two polypropylene fibers, and the mixture Concrete mixed with polypropylene monofilament fiber and steel fiber (PSCF1) has the smallest compressive strength loss ratio (0.17).

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