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Splitting Tensile Properties of Hybrid Fiber Reinforced Ultra High Performance Concrete After Exposure to Elevated Temperatures

Shuqi Yang, Zhongjun Hu, Zhanhang Xie, Jifeng Li, Boyang Xu, Yibo Zhang

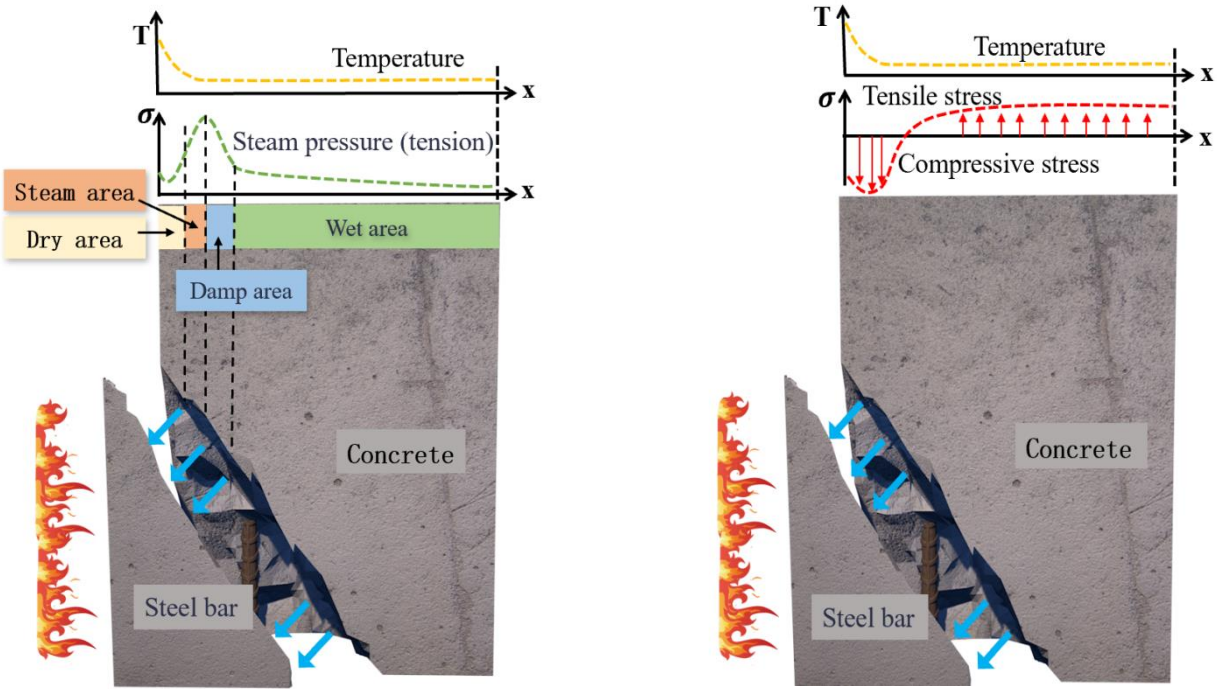
Department of Construction Engineering, Jilin University, Changchun 130026, China

Abstract: ***Ultra-high performance concrete (UHPC) is increasingly being used to reinforce and modify existing structures, but UHPC is prone to high temperature bursting under fire conditions, and how to improve the high temperature burst resistance of UHPC has become a hot topic in the current industry. In this paper, the effects of high temperature and secondary curing on the splitting tensile strength of UHPC compounded with steel and polypropylene fibers were investigated. The analyses were carried out that: 1) UHPC doped with 3% steel fiber and 0.4% PP fiber has good resistance to high temperature bursting, and even after the action of 900℃, the UHPC splitting and stretching specimen do not appear to burst and peel. 2) The tensile strength of UHPC splitting was improved by high temperature treatment at 300℃, which played a similar role to "steam curing", and the splitting tensile strength of UHPC after high temperature treatment at 600℃ and 900℃ decreased significantly, and the decline became more noticeable with higher temperatures. 3) The residual splitting tensile strength of UHPC after secondary curing is the same as that of UHPC without curing after high temperature. However, the difference is that as the temperature of the high temperature treatment increases, the effect of secondary curing on the residual strength of UHPC becomes more significant.***

Keywords: Ultra-high performance concrete (UHPC), Splitting tensile strength, Steel fiber, Polypropylene (PP) fiber, High temperature, Secondary curing.

1. Introduction

Ultra-high performance concrete (UHPC) is a cementitious composite material made of stacked and filled ultra-fine particles with dense microstructure [1,2] and excellent compressive strength (≥120 MPa). Compared with ordinary concrete, the dense microstructure of UHPC makes it worse fire resistant [3], and it is more prone to explosive spalling under fire conditions. In 1965, Harmathy first reported that ordinary concrete spalls at high temperatures [4]. Spalling is the most violent form of cracking and damaging concrete structures and buildings at high temperatures. Meanwhile, there are some less severe forms of cracking, such as surface scaling, local cracking of components, and detachment. Generally, the bursting of concrete occurs at temperatures between 300℃~600℃. Among them, the temperature stress caused by the temperature gradient (thermal stress mechanism) and the high pore vapor pressure caused by the transformation of internal water into water vapor (vapor pressure mechanism) [3,5] are the two main reasons for the explosive spalling of UHPC, as shown in Figure 1.



(a) Steam pressure mechanism (b)Thermal stress mechanism

Figure 1: Steam pressure mechanism and thermal stress mechanism

Fire is one of the most serious threats to concrete structures [6]. To alleviate the spalling phenomenon of UHPC at high temperatures, the addition of steel fiber (SF) and polypropylene (PP) fiber is a relatively effective approach [7,8].

The addition of SF can effectively increase the strength of UHPC, inhibit the generation and development of cracks [9], improve the brittleness of the matrix, and increase the matrix ductility [10], but it cannot effectively inhibit the bursting spalling of concrete. Xiong et al [11] investigated the effect of SF doping on the bursting and spalling of UHPC and pointed out that 1% SF doping alone did not effectively improve the burst resistance of UHPC. The tensile and flexural strength of UHPC was found to increase significantly with the addition of SF by Safeer et al [12]. Abdallah et al [13] showed that the bonding properties of SF reinforced concrete interface were significantly weakened at high temperatures, and SF began to melt around 800℃ or higher, leading to the degradation of UHPC performance.

Existing related studies indicate that the addition of PP fibers can enhance the permeability of cement based composites and significantly improve the ability of UHPC to resist explosive spalling [7,14]. Shen et al [15] investigated the influence of the dosage and aspect ratio of steel-PP hybrid fibers on the anti-explosive spalling performance of UHPC and pointed out that the dosage of PP fibers has a significant effect on the anti-explosive performance of steel-PP hybrid fiber reinforced UHPC, with the increase of the dosage of PP fibers, the degree of the explosion of UHPC gradually reduces. When the dosage of PP fibers reaches 0.3%, it can effectively prevent the occurrence of explosive spalling.

At the same time, secondary curing of UHPC after high temperature damage can result in low cost self-healing of UHPC without repair, and the healed strength can be restored to a high percentage of the original strength [16, 17]. Li et al [18] found that the recovered compressive strength of UHPC even exceeded the original compressive strength before heating after secondary curing with saturated lime water. Therefore, it is necessary to investigate further the impact of secondary curing on the residual strength of UHPC after high temperature damage.

Existing relevant literature contains more studies on the compressive performance of fiber mixed UHPC and relatively fewer studies on the splitting tensile strength. In summary, based on the adaptation work carried out, this paper aims to focus on subjecting the preferred UHPC with mixed SF and PP fibers to high temperature treatment (300℃, 600℃ and 900℃) and to carry out secondary curing for UHPC based on high temperature treatment. The paper aims to investigate the influence of temperature and secondary curing on the residual splitting tensile strength of UHPC.

2. Experimental Design and Raw Materials

2.1 UHPC Material and Strength Trial

The UHPC matrix used in this experimental study consisted of cement, silica fume, fly ash, quartz powder, water, and a high efficiency water reducing agent. SF used copper plated steel fiber microwires with a diameter of 200μm microns and a length of 13mm. PP fibers used low thermal conductivity monofilament polypropylene fibers with a diameter of 30μm microns and a length of 12mm were used. Fiber content was defined as the volume ratio of fibers to the UHPC mixture.

2.2 Specimen for Compressive Strength of UHPC

Six sets of 100 mm × 100 mm × 100 mm cubic specimens were produced as test fitting specimens to determine whether the UHPC specimens met the basic strength requirements and to verify whether the dosage of SF and PP fibers was reasonable.

Specimen 1 and specimen 2 were 3% SF doped UHPC and the compressive strength test was carried out using a YAW-2000 compression tester at a loading rate of 2 kN/s. The compressive strength of the Specimen 1 test block cured for 7 days was 137.7 MPa and the compressive strength of the Specimen 2 test block cured for 28 days was 150.8 MPa. Therefore, it was determined that the design of this mix meets the strength requirements of UHPC.

The specimens of specimen 3 and specimen 4 were UHPC with a 3% content of SF. Specimen 3 was exposed to a high temperature treatment at 300℃, and specimen 4 was exposed to a high temperature treatment at 600℃. It was found that specimen 3 could retain its integrity without any explosive spalling, while specimen 4 suffered from severe explosive spalling.

The specimens of specimen 5 were UHPC incorporating a blend of 3% SF and 0.2% PP fibers. After high temperature treatment at 600℃, the specimens burst and formed large cracks, suggesting that the inclusion of 0.2% PP fibers inhibited the explosive spalling of UHPC to a certain degree, but the effect was limited. The specimens of specimen 6 were UHPC incorporating a blend of 3% SF and 0.4% PP fibers. After high temperature treatment at 900℃, the specimens maintained excellent integrity, indicating that the inclusion of 0.4% PP fibers could effectively inhibit the explosive spalling of UHPC. In conclusion, the UHPC mix proportion involving a blend of 3% SF and 0.4% PP fibers was determined for the subsequent experiments.

2.3 High Temperature Resistance Test Design

Thirty circular disc-shaped specimens with a diameter of 100mm and a height of 50mm were designed and fabricated. The diagram of the specimen size and the blended fibers is presented in Figure 2.

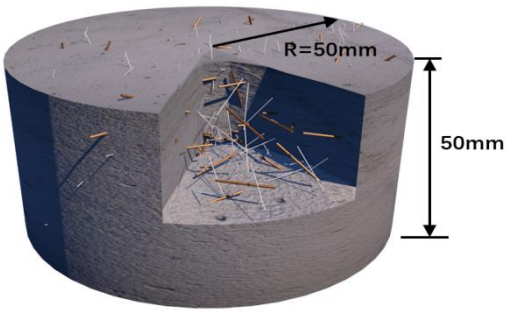


Figure 2: Diagram of the dimensions and fiber blending of the circular specimen

The design parameters of the circular disc-shaped specimens are presented in Table 2. Each specimen name is composed of four code segments. In the first segment, the letter 'U' represents UHPC, 'S' represents steel fibers, and the number after 'S' indicates the volume fraction of SF. In the second segment, the letter 'PP' represents PP fibers, and the number after 'PP' indicates the volume fraction of PP fibers. The third segment represents the heating temperatures for the high temperature resistance test. In this paper, four temperature gradients were set: normal temperature, 300℃, 600℃, and 900℃. The fourth segment is represented by the letter 'W' for spray curing and 'C' for water-CO_2 cyclic curing. For example, 'US3-PP0.4-300-W' indicates a UHPC specimen containing 3% SF and 0.4% PP fibers that have undergone a high temperature treatment at 300℃ and have been spray-cured.

Table 2: Design parameters of UHPC circular disc-shaped specimens

Name	SF (%)	PPF (%)	Curing method	Temperature (℃)	NO.
US3-PP0.4-A	3.0	0.4	—	23	3
US3-PP0.4-300	3.0	0.4	—	300	3
US3-PP0.4-600	3.0	0.4	—	600	3
US3-PP0.4-900	3.0	0.4	—	900	3
US3-PP0.4-300-W	3.0	0.4	Spray	300	3
US3-PP0.4-300-C	3.0	0.4	Water-CO_2 cycle	300	3
US3-PP0.4-600-W	3.0	0.4	Spray	600	3
US3-PP0.4-600-C	3.0	0.4	Water-CO_2 cycle	600	3
US3-PP0.4-900-W	3.0	0.4	Spray	900	3
US3-PP0.4-900-C	3.0	0.4	Water-CO_2 cycle	900	3

2.4 Fabrication and Loading of Specimens

The entire technical sequence of specimen fabrication, high temperature treatment, secondary curing, and loading is shown in Figure 3.

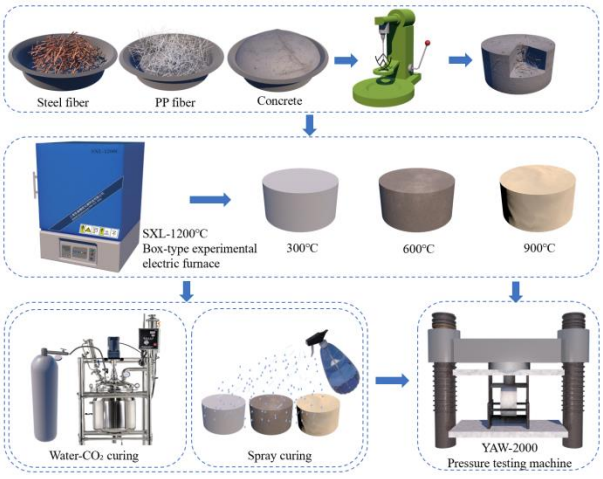


Figure 3: Technical route of the experiment

2.4.1 High temperature treatment

The specimens were subjected to high temperature treatment in the SXL-1200℃ box-type experimental electric furnace. They were uniformly heated at a rate of 3℃/min to 300℃, 600℃, and 900℃ respectively, and maintained at a constant temperature for 1 hour to ensure uniform temperature distribution within the specimens, as shown in Figure 4.

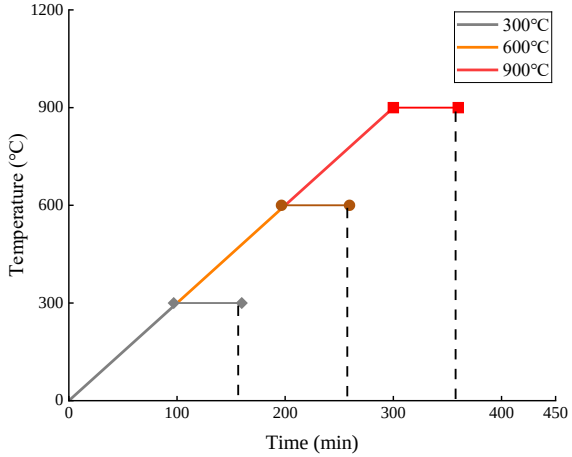


Figure 4: Temperature-Time control procedure

2.4.2 Secondary curing

This paper uses two secondary curing methods, spray curing and water-CO_2 cyclic curing.

Spray curing, the hot-damaged UHPC specimens underwent spray curing with a saturated lime water solution. The spraying was executed 8 times daily at an interval of 3 hours, and the total curing period amounted to 30 days.

Water-CO_2 cyclic curing, the hot-damaged UHPC specimens were immersed in a saturated lime water solution for 24 hours for curing. Subsequently, they were placed in a KS-20L double-layer stainless steel reactor for 4 hours of CO_2 mineralization curing (with the relative humidity maintained at 60 ± 1% and the CO_2 concentration maintained at 99 ± 0.2%). This cycle was consecutively repeated 6 times, and the total curing duration was 7 days.

2.4.3 Splitting tensile test

The test was conducted by the "Standard for test methods of concrete physical and mechanical properties" (GB/T 50081-2019), and all specimens were loaded using the YAW-2000 compression testing machine.

3. Results and Discussion

3.1 Degree of Specimen Spalling

The apparent flaking degree of the circular disc-shaped specimens after different high temperature treatments is shown in Figure 5. It was observed that the UHPC specimens at different temperatures did not show any spalling phenomenon, and the color of the UHPC specimens changed significantly with the increase of temperature: after high temperature treatment at 300℃, the UHPC specimens showed brownish yellow color, after high temperature treatment at 600℃, the UHPC specimens showed brown color with the slightly whitish surface, and after high temperature treatment at 900℃, the UHPC specimens showed brownish red color. The integrity of the specimen after high temperature treatment shows that 0.4% PP fiber doping for UHPC circular disc-shaped specimen scale resistance to high temperature cracking is very effective.

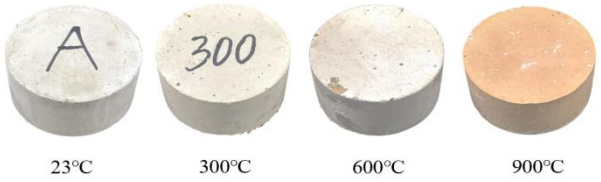


Figure 5: The apparent degree of spalling of the US3-PP0.4 Group after different high temperature treatments

3.2 The Splitting Tensile Test of UHPC

3.2.1 Failure mode

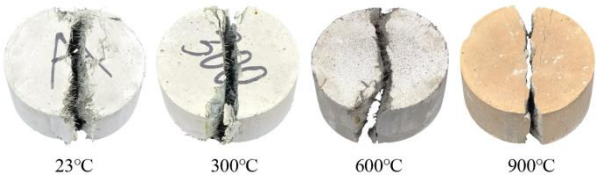


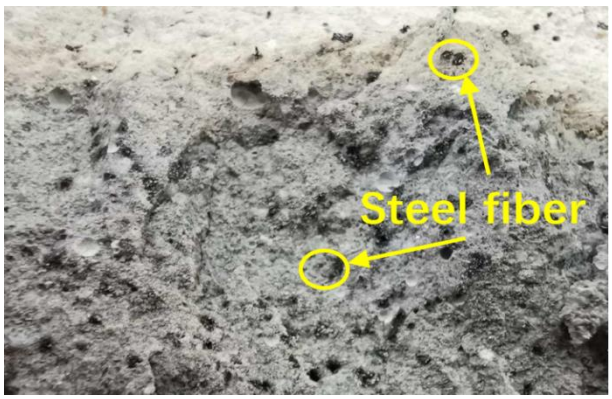
Figure 6: The failure modes of splitting tensile resistance of UHPC before and after high temperature treatment

The splitting tensile damage pattern of UHPC specimens after high temperature treatment is shown in Figure 6.

The split tensile damage patterns of the circular disc-shaped specimens after different temperatures all show typical plastic damage and the damaged specimens are still relatively intact without serious spalling, which is attributed to the restraining and bridging effects of the SF. The difference is that in specimens US3-PP0.4-A, US3-PP0.4-300, and US3-PP0.4-600 most of the SF has been pulled out. As shown in Figure 7(a) for US3-PP0.4-600, it can be clearly observed that the failure mode of SF is mainly characterized by pull-out failure.

In the US3-PP0.4-900 specimen, most of the SF was pulled off as shown in Figure 7(b), which is attributed to the fact that at temperatures of about 700°C, decarburization of steel and carbonation of iron occurs, and the SF is severely damaged, which also suggests that when the temperature reaches 900°C, the SF no longer provides a significant bridging effect.

(a) US3-PP0.4-600



(b) US3-PP0.4-900

Figure 7: The failure modes of steel fibers

3.2.2 The influence of temperature on splitting tensile strength

The changes in the splitting tensile strength of UHPC after different high temperature treatments are shown in Figure 8, in which the splitting tensile strength of UHPC after high temperature treatment shows an increasing and then decreasing trend with the temperature change.

At room temperature, the splitting tensile strength of US3-PP0.4-A is 12.8MPa, and after high temperature treatment at 300°C, the splitting tensile strength of US3-PP0.4-300 is 15.1MPa, which is 18.0% higher than that of US3-PP0.4-A. The effect of high temperature "vaporization" is similar. The mechanism of high temperature "steam curing" produces a similar enhancement effect. However, after the high temperature treatment at 600°C, the splitting tensile strength of US3-PP0.4-600 decreased to 9.8 MPa, which was 23.4% lower than that of US3-PP0.4-A. This is because, as the temperature continued to increase to 600°C, the decomposition of $Ca(OH)_2$ and the dewatering of C-S-H in the UHPC matrix led to the coarsening of the pore structure, the increase in porosity, and the decrease in the degree of densification, which in turn led to the decrease in the performance of UHPC. This in turn leads to the performance decay and damage accumulation of UHPC. Since the decomposition of C-S-H mainly occurs at about 700°C, UHPC can still maintain high compressive strength after the high temperature of 600°C. The compressive strength of UHPC can be reduced by the decomposition of C-S-H at about 700°C.

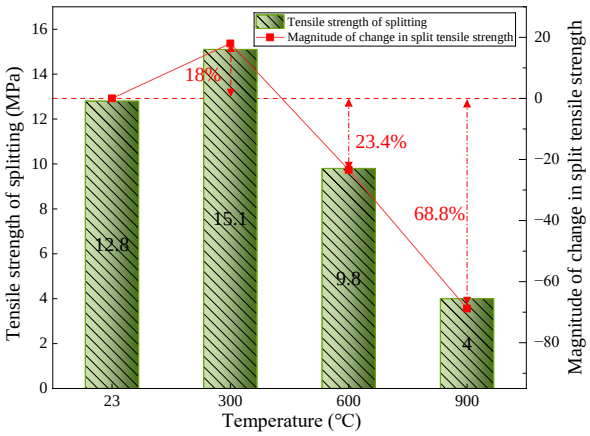


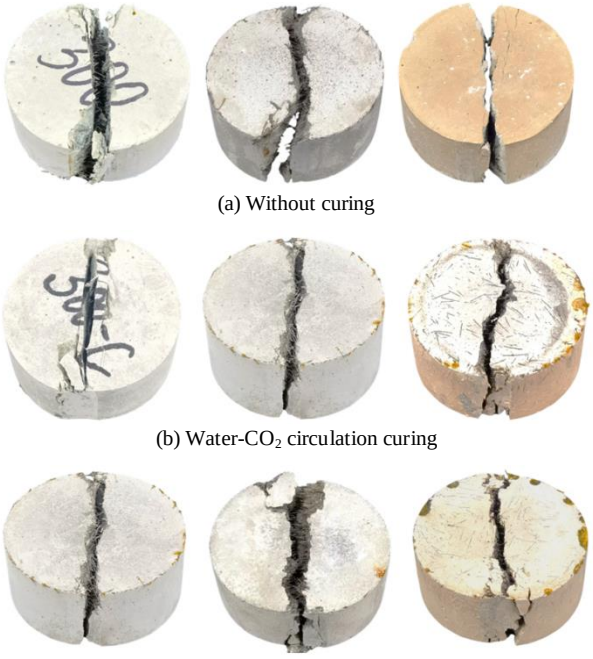
Figure 8: Splitting tensile strength of UHPC specimens after high temperature treatment.

After undergoing a high temperature treatment at 900°C, the splitting tensile strength of US3-PP0.4-900 underwent a substantial reduction, amounting to only 4.0 MPa, a decrease of 68.8% in comparison with US3-PP0.4-A. This was primarily attributed to factors such as the decomposition of

hydration products, coarsening of pores, and transformation of quartz crystal form within the UHPC.

3.2.3 The failure patterns of the specimens after the secondary curing

The splitting tensile failure modes of UHPC under diverse secondary curing conditions are presented in Figure 9.



(a) Without curing

(b) Water-CO_2 circulation curing

(c) Spray curing

Figure 9: The splitting failure mode of UHPC after secondary curing

Whether spray curing or water-CO_2 cycle curing, the splitting tensile damage mode of UHPC after secondary curing showed plastic damage, and the damaged specimens were more structurally intact without serious spalling. Among them, US3-PP0.4-300-W and US3-PP0.4-300-C, whose plastic damage characteristics were improved compared with those of US3-PP0.4-300, could further stimulate the hydration reaction and effectively improve the densification and toughness of UHPC when secondary curing was performed based on the high temperature treatment at 300℃.

3.2.4 The Impact of Secondary Curing on the Splitting Tensile Strength of Specimens after High Temperature Treatment

The change in splitting tensile strength of the high temperature damaged UHPC after secondary maintenance is shown in Figure 10. The splitting tensile strength of US3-PP0.4-A was 12.8 MPa.

Compared with the splitting tensile strength of US3-PP0.4-300 (15.1 MPa), the splitting tensile strength of US3-PP0.4-300-W after spray curing is 16.8 MPa, which is another 11.3% increase in strength, and that of US3-PP0.4-300-C after water-CO_2 cycle curing is 15.6 MPa, which is another 3.3% improvement.

Compared with the splitting tensile strength of US3-PP0.4-600 (9.8 MPa), the splitting tensile strength of US3-PP0.4-600-W after spray curing was 11.7 MPa, an increase in strength of 19.4%, and the splitting tensile strength of US3-PP0.4-600-C after water-CO_2 cyclic curing was 10.8 MPa, an increase in strength of 10.2%, recovering to about 90% of that of US3-PP0.4-A.

The splitting tensile strength of US3-PP0.4-900 is merely 4.0 MPa. In contrast, for US3-PP0.4-900-W after spray curing, the splitting tensile strength is 6.6 MPa, with an increase of 65.0%. The splitting tensile strength of US3-PP0.4-900-C after water-CO_2 circulation curing is 5.7 MPa, with an increase of 42.5%. Both types of secondary curing have significantly restored the splitting tensile strength of UHPC after high temperature treatment at 900℃. The strength has recovered from 31.25% of US3-PP0.4-A to 51.56% and 44.53% for US3-PP0.4-900-W and US3-PP0.4-900-C, respectively.

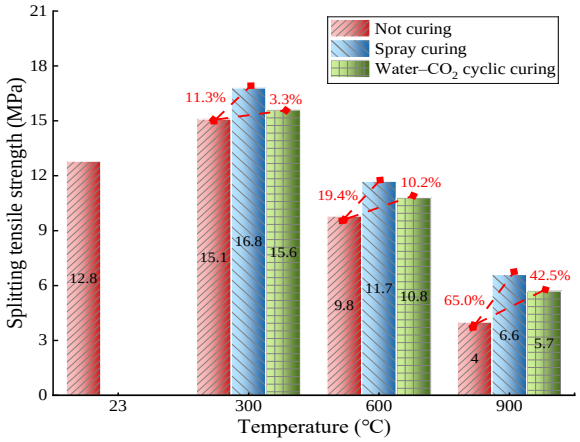


Figure 10: The influence of secondary curing on the splitting tensile strength of specimens after high temperature

In conclusion, the splitting tensile strength of heat treated UHPC after secondary curing was improved to different degrees compared with that of heat treated UHPC without secondary curing, and spray curing was more effective in improving the strength.

4. Conclusion

In this paper, taking high temperature action and secondary curing as the main test parameters, based on the results of specimens, experimental research was conducted focusing on the splitting tensile strength of UHPC and the degree of specimen spalling under the conditions of optimized fixed dosage of steel fibers and PP fibers. The main conclusions are as follows.

(1) UHPC with 3% SF and 0.4% PP fibers have a significantly improved ability to resist high temperature bursting and spalling. Even after treatment at 900°C, no bursting or spalling occurred in the circular disc-shaped specimens.

(2) UHPC splitting tensile strength with the effect of temperature shows a trend of increasing and then decreasing. 300 ℃ high temperature treatment of UHPC splitting tensile strength increased, 600℃ and 900℃ high temperature treatment, UHPC splitting tensile strength appeared to be a more pronounced reduction.

(3) The secondary curing has a significant effect on the improvement of the residual splitting tensile strength of UHPC with high temperature thermal damage, and the spray conditioning has a more obvious effect on the improvement of the residual strength of specimens compared with the

water-CO_2 cycle curing.

References

[1] AHMAD S, RASUL M, ADEKUNLE S K, et al. Mechanical properties of steel fiber-reinforced UHPC mixtures exposed to elevated temperature: Effects of exposure duration and fiber content [J]. Composites Part B: Engineering, 2019, 168: 291-301.

[2] GRAYBEAL B A, DAVIS M D J A M J. Cylinder or Cube: Strength Testing of 80 to 200 MPa (11.6 to 29 ksi) Ultra-High Performance Fiber-Reinforced Concrete [J]. ACI Materials Journal, 2008, 105: 603-609.

[3] ZHAO J, ZHENG J J, PENG G F, et al. A meso-level investigation into the explosive spalling mechanism of high performance concrete under fire exposure [J]. Cement and Concrete Research, 2014, 65: 64-75.

[4] HARMATHY T Z. Effect of Moisture on the Fire Endurance of Building Elements [R]. Philadelphia: ASTM publication STP, 1965, 74-95.

[5] [1]PIERRE K, Daniel Q, et al. Spalling and pore pressure in HPC at high temperatures [J]. Cement and Concrete Research, 2000, 30(12): 1915-1927.

[6] MINDEGUIA J C, PIMIENTA P, NOUMOWé A, et al. Temperature, pore pressure and mass variation of concrete subjected to high temperature -Experimental and numerical discussion on spalling risk [J]. Cement and Concrete Research, 2010, 40(3): 477-487.

[7] LI Y, PIMIENTA P, PINOTEAU N, et al. Effect of aggregate size and inclusion of polypropylene and steel fibers on explosive spalling and pore pressure in ultra-high performance concrete (UHPC) at elevated temperature [J]. Cement and Concrete Composites, 2019, 99: 62-71.

[8] BANGI M R, HORIGUCHI T. Effect of fibre type and geometry on maximum pore pressures in fibre-reinforced high strength concrete at elevated temperatures [J]. Cement and Concrete Research, 2012, 42(2): 459-466.

[9] WU H, LIN X, ZHOU A. A review of mechanical properties of fibre reinforced concrete at elevated temperatures [J]. Cement and Concrete Research, 2020, 135: 106-117.

[10] WANG D, SHI C, WU Z, et al. A review on ultra high performance concrete: Part II. Hydration, microstructure and properties [J]. Construction and Building Materials, 2015, 96: 368-377.

[11] XIONG M-X, RICHARD LIEW J Y. Spalling behavior and residual resistance of fibre reinforced Ultra-High performance concrete after exposure to high temperatures [J]. Materiales de Construcción, 2015, 65(320).

[12] ABBAS S, SOLIMAN A M, NEHDI M L. Exploring mechanical and durability properties of ultra-high performance concrete incorporating various steel fiber lengths and dosages [J]. Construction and Building Materials, 2015, 75: 429-441.

[13] ABDALLAH S, FAN M, CASHELL K A. Bond-slip behaviour of steel fibres in concrete after exposure to elevated temperatures [J]. Construction and Building Materials, 2017, 140: 542-551.

[14] LIANG X, WU C, SU Y, et al. Development of ultra-high performance concrete with high fire resistance [J]. Construction and Building Materials, 2018, 179: 400-412.

[15] SHEN Y, DAI M, PU W, et al. Effects of content and length/diameter ratio of PP fiber on explosive spalling resistance of hybrid fiber-reinforced ultra-high performance concrete [J]. Journal of Building Engineering, 2022, 58: 105071.

[16] QIAN Y, YANG D, XIA Y, et al. Properties and improvement of ultra-high performance concrete with coarse aggregates and polypropylene fibers after high temperature damage [J]. Construction and Building Materials, 2023, 364: 129925.

[17] QIAN Y, YANG D, LIU M, et al. Performance recovery of high temperature damaged ultra-high performance concrete under different curing environments [J]. Developments in the Built Environment, 2023, 16: 100274.

[18] LI Y, WANG H, SHI C, et al. Effect of post-fire lime-saturated water and water–CO2 cyclic curing on strength recovery of thermally damaged high performance concrete with different silica contents [J]. Cement and Concrete Research, 2023, 164: 107050.