



Spalling behavior and residual resistance of fibre reinforced Ultra-High performance concrete after exposure to high temperatures

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ABSTRACT: Experimental results of spalling and residual mechanical properties of ultra-high performance concrete after exposure to high temperatures are presented in this paper. The compressive strength of the ultra-high performance concrete ranged from 160 MPa~185 MPa. This study aimed to discover the effective way to prevent spalling for the ultra-high performance concrete and gauge its mechanical properties after it was subjected to fire. The effects of fiber type, fiber dosage, heating rate and curing condition were investigated. Test results showed that the compressive strength and elastic modulus of the ultra-high performance concrete declined slower than those of normal strength concrete after elevated temperatures. Polypropylene fiber rather than steel fiber was found effective to prevent spalling but affected workability. The effective fiber type and dosage were recommended to prevent spalling and ensure sufficient workability for casting and pumping of the ultra-high performance concrete.

KEYWORDS: High Performance Concrete; Temperature; Fiber Reinforcement; Polymer; Mechanical Properties

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RESUMEN: *Comportamiento y resistencias mecánicas residuales de hormigones de ultra altas prestaciones reforzados con fibras tras su exposición a altas temperaturas.* En este trabajo se presentan los resultados más relevantes del trabajo experimental realizado para valorar la laminación y las propiedades mecánicas residuales de hormigón de ultra-altas prestaciones tras su exposición a altas temperaturas. La resistencia a la compresión del hormigón de ultra-altas prestaciones osciló entre 160 MPa~185 MPa. El objetivo de este estudio fue descubrir una manera eficaz de prevenir desprendimientos y/o laminaciones en este hormigón y medir sus propiedades mecánicas después de ser sometido al fuego. Las variables estudiadas fueron la presencia y dosificación de fibras, velocidad de calentamiento y condiciones de curado. Los resultados mostraron, tras la exposición a altas temperaturas, que la resistencia a compresión y el módulo de elasticidad del hormigón de ultra-altas prestaciones disminuían más lento que las de un hormigón con resistencia normal. La fibra de polipropileno resultó más eficaz para prevenir desprendimientos que la fibra de acero pero la trabajabilidad se vio afectada. Tras el estudio realizado se recomienda el tipo de fibra más efectiva y la dosis para evitar desprendimientos y garantizar la suficiente capacidad de trabajo para la puesta en obra y bombeo del hormigón de ultra-altas prestaciones.

PALABRAS CLAVE: Hormigón de altas prestaciones; Temperatura; Refuerzo de fibra; Polímeros; Resistencias mecánicas

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1. INTRODUCTION

With the development of concrete technology and the availability of variety of materials such as silica fume and high-range water-reducing admixtures, the production of ultra-high performance concrete (UHPC) with compressive strength higher than 160 MPa is possible nowadays. However, the UHPC has been limited to special applications such as offshore and marine structures, industrial floors, pavements, and security barriers, etc. It has not been used in building structures due to concerns on the brittleness and the spalling behavior under fire. These concerns lead to the situations that the current state-of-the art design codes allow the use of concrete only up to C90/105 for concrete structures and C50/C60 for composite structures (1–4).

It is well known that high strength concrete (HSC) is prone to spall under high temperatures. The spalling is caused by the thermal stress due to the temperature gradient during heating, and by the splitting force owing to the release of vapor around 100 °C (5, 6). It is reported that steel fiber or polymer fiber is effective to prevent spalling of the HSC under high temperatures (7–10). The steel fibers increase the tensile strength and thus resist the thermal stress. The polymer fibers melt after the temperature inside concrete reaches approximately 170 °C. Therefore the built-up vapor pressure is released through the channels left by the melted polymer fibers. The effect of fibers on spalling has not been reported for the UHPC. Since the UHPC is more likely to spall than the HSC, it is necessary to investigate the spalling behavior and provide recommendations for preventing such spalling.

Residual mechanical properties (compressive strength and elastic modulus) are generally measured after the concrete specimen cools down to room temperature. There are three types of residual properties: unstressed without pre-load, heated-stressed, stressed-heated (11). The unstressed residual properties are mostly investigated in literature, which are affected by strength, aggregate type, heating rate, cooling rate, cylinder size, etc. Generally, the compressive strength and elastic modulus of HSC are reduced faster than those of normal strength concrete (NSC) after exposed to high temperatures (12, 13). However, there is little information on the residual resistance of UHPC in literature; the test results presented in this paper are expected to fill the research gap.

The present study targets to study the spalling behavior of the UHPC when it is exposed to high temperatures up to 800 °C. An effective way for preventing such spalling, meanwhile maintaining the workability, is to be discovered. In pursuit of better assessment on the residual resistance of structural members made from the fiber reinforced UHPC impaired by fire, the mechanical properties such as

compressive strength and elastic modulus are to be provided after it is subjected to temperatures of up to 800 °C using various heating rates, fiber dosages, and curing conditions.

2. BASIC MATERIALS

The basic materials used in this study to produce UHPC were water and Ducorit[®] D4. Ducorit[®] D4 is one of the commercial Ducorit[®] products (see <http://www.densit.com/>). It is made from cementitious mineral powder, superplasticizer and fine bauxite aggregates with maximum sizes less than 4.75 mm and 49% less than 0.6 mm. The mixing proportions for the UHPC are shown in Table 1 (14). Workability of the fresh UHPC was tested using the slump flow test in accordance with ASTM C1611/C1611 M-09b. The slump flow spread was 735 mm (15).

3. EFFECTS OF FIBER TYPES ON PREVENTION OF SPALLING

3.1. Experimental program

Steel and polypropylene (PP) fibers were used in present study. The properties of steel and polypropylene fibers are given in Table 2. Four batches of UHPC mixtures were prepared as follows:

- UHPC:** Plain concrete without fibers, the room temperature compressive strength was 166.6 MPa; and
- UHPC-S:** Plain concrete with 1.0% steel fibers in terms of volume, the room temperature compressive strength was 170.1 MPa; and
- UHPC-P:** Plain concrete with 1.0% PP fibers in terms of volume, the room temperature compressive strength was 144.1 MPa; and
- UHPC-SP:** Plain concrete with 0.5% steel fibers and 0.5% PP fibers in terms of volume, the room temperature compressive strength was 155.8 MPa.

Three cylindrical specimens with a diameter of 100 mm and height of 200 mm were cast for each batch. The specimens were cured in lab air for 28 days with plastic sheet covered. The relative humidity of lab air was approximately 85% and the room temperature was around 30 °C at daytime and 25 °C at night. After curing, the specimens were firstly heated up in an electrical oven to a target temperature of

TABLE 1. Mixing proportions of plain UHPC

Water/D4	Water (kg)	D4 (kg)	UHPC Volume (liters)
0.076	1.9	25	9.4

TABLE 2. Properties of steel fiber and polypropylene fiber

Fiber	Code/Type	Diameter (mm)	Length (mm)	Density (kg/m ³)	Tensile Strength (MPa)
Steel	SF13/80	0.16	13	7850	2300
Polypropylene	Monofilament	0.03±0.005	13	910±0.01%	≥450

800 °C with a heating rate of 5 °C/min. Then, the target temperature was maintained for 4 hours to reach a uniform temperature distribution inside the specimen. After that, the specimen was kept in oven and cooled down naturally to room temperature. During the process of heating and cooling, the specimen was laterally covered by a steel casing with drilled holes for heat flow.

3.2. Discussions on test results

There was no spalling observed for specimens of UHPC with PP fibers (UHPC-P, UHPC-SP). However, the specimens of UHPC with steel fibers (UHPC-S) spalled when the temperature inside oven was approximately 490 °C. The spalled specimens are shown in Figure 1. Although the UHPC specimens with steel fibers spalled, there was little debris blown away laterally. The peripheral concrete was peeled off, but still attached to the core concrete by the steel fibers. The electrical oven was damaged by debris from the top of specimen as shown in Figure 1. Following the UHPC-S specimen, the UHPC specimen without fibers was heated where the top of steel casing was welded with additional steel plate. The thickness of the steel plate was 1.5 mm. The plain UHPC specimen also spalled and the spalling debris bent the top cover plate and pushed the steel casing to further damage the oven, as shown in Figure 2. It can be seen

that the peripheral concrete was peeled off and broken into pieces, this was different with the steel fiber reinforced specimen. Due to the spalling hazard, the other UHPC-S and the plain UHPC specimens were not heated in case the spalling would further damage the oven. Thus their residual compressive strengths after heating to 800 °C were not measured.

The residual compressive strengths were tested for all the unspalled specimens after cooling down. The residual compressive strengths and their reduction factors which are the ratios between the residual compressive strengths and their counterparts at room temperature are shown in Table 3. As mentioned above, the steel fiber slightly increased the room temperature strength, owing to the confinement effect of the steel fibers which increased the radial and circumferential strengths of the cylindrical specimen. The UHPC with 1.0% of PP fibers or a combination of 0.5% steel fibers and 0.5% PP fibers exhibited lower strengths than that of UHPC without fibers. This was attributed to the effect of PP fibers on workability, resulting in poorer consolidation of the concrete. The difference in residual compressive strengths of UHPC-P and UHPC-SP was approximately 7.5%. Their reduction factors showed the same difference.

The test results indicated that the incorporation of steel fibers was not effective to prevent spalling for the UHPC even with dosage of 1.0% by volume.



FIGURE 1. Spalled UHPC specimens with steel fibers.



FIGURE 2. Spalled UHPC specimens without fibers.

TABLE 3. The residual compressive strength of UHPC mixtures after 800 °C

Specimen	Strengths (MPa)		Reduction factor
	Room temperature	After 800 °C	
UHPC	166.6	Spalling (not heated to 800 °C)	–
UHPC-S	170.1	Spalling (no strength was tested)	–
UHPC-P	144.1	33.8	0.235
UHPC-SP	155.8	39.8	0.255

The addition of 1.0% PP fibers was effective. However, the PP fibers affected the strength of the UHPC specimens due to poor workability caused. As recommended in EN 1992-1-2, more than 2 kg/m³ (0.25% by volume) of monofilament propylene fiber should be included in high strength concrete mixtures to prevent spalling. Hence, 1.0% PP fibers could be too high to achieve good workability. It is necessary to further reduce the PP fiber dosage.

4. EFFECT OF POLYPROPYLENE FIBERS ON PREVENTION OF SPALLING

4.1. Experimental program

UHPC mixtures with PP fibers and NSC C50 were investigated. The PP fiber dosages were 0, 0.1%, 0.25% and 0.5% in terms of volume. Two heating rates were considered: 5 °C/min and 30 °C/min. NSC C50 was prepared from ordinary Portland cement, sand, coarse aggregates with maximum size 10 mm, and water. The mixing proportions of C50 are shown in Table 4. There was no PP fibers added

TABLE 4. The mixing proportions of NSC C50

Water/Cement	Water (kg/m ³)	Cement (kg/m ³)	Sand (kg/m ³)	Coarse Aggregate (kg/m ³)
0.5	225	450	625	1005

into the C50. The specimens were also 100×200 mm cylinders. They were covered by plastic sheet and cured in lab air for 28 days. The target temperatures included room temperature (30 °C), 200 °C, 400 °C, 600 °C and 800 °C. The heating and cooling processes were the same as mentioned in Section 3.1.

4.2. Test observations

No spalling was observed for any specimens with the PP fibers. This indicates that 0.1% PP fibers is effective to prevent spalling of the UHPC specimens under high temperature up to 800 °C. The UHPC specimens without PP fibers were not heated after 400 °C in case the spalled debris would damage the electrical oven. After heating, standard compression tests were carried out to evaluate the residual compressive strength and residual elastic modulus after the UHPC specimens were naturally cooled down to room temperature. The failure modes of the UHPC specimens subjected to various temperatures and compression are shown in Figure 3.

It was observed that the unheated UHPC specimen was crushed into pieces very noisily. However, it exhibited better ductility and lower noise after exposure to the high temperatures. The appearances of the UHPC specimens were different after heated to different target temperatures due to the changes of microstructures.

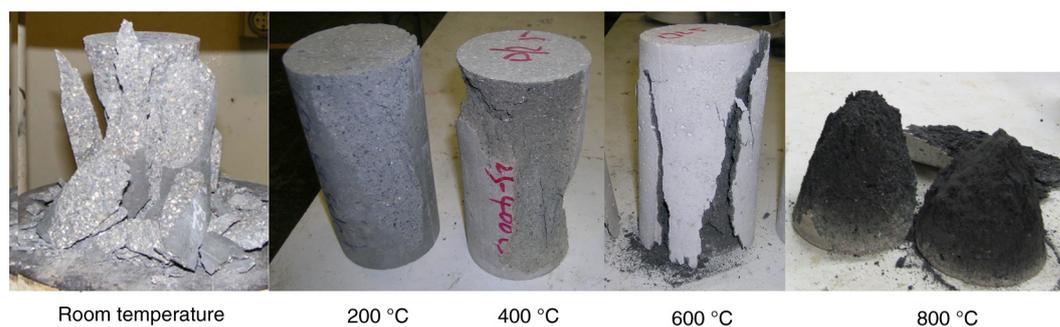


FIGURE 3. Failure modes after subjected to target temperatures and compression.

4.3. Residual compressive strength

The residual compressive strengths of the UHPC mixtures and NSC C50 are shown in Table 5. Due to running out of the pre-blended mixture, the batch of UHPC with 0.1% PP fibers under heating rate of 30 °C/min was cast using the pre-blended mixture from second shipment. Table 5 shows that the room temperature strength from the second shipment was higher than those from the first shipment. In general, the residual compressive strength decreased as the dosage of PP fibers increased for the same testing temperature and heating rate, due to the reduced workability.

Compared with the room temperature strength, the residual compressive strength of UHPC slightly increased for temperature at 200 °C, but decreased beyond 200 °C. The reason for the increase of strength at 200 °C is unclear. There are some hypotheses in the literature (16–18). The prevailing hypothesis is that the increase of strength is attributed to the increase in the forces between the gel particles (Van der Waals forces) due to the water removal and the consequent shrinkage (19, 20). The decrease of strength at 400 °C, 600 °C, and 800 °C were related with the decomposition of hydration products such as calcium silicate hydrate (C-S-H) and calcium hydroxide $\text{Ca}(\text{OH})_2$, deterioration of aggregates, and cracking due to thermal incompatibility between the aggregate and cement paste which led to stress concentration.

The residual factor in this paper is defined as the ratio of the compressive strength or elastic modulus after heating divided by its counterpart at room temperature. The residual compressive strength factors of UHPC were larger than those of C50 as shown in Figure 4. This is due to the fact that the bauxite aggregate in UHPC exhibited better fire resistance than the conventional siliceous aggregate used for C50. There was no increase of strength at 200 °C for C50. This could be related with the water removal which induces shrinkage of concrete while making the microstructure of concrete more porous. Thus, there is a trade-off between the shrinkage and the porosity. The shrinkage increases the Van der Waals forces between gel particles and thus the compressive strength of concrete. However the increase of porosity reduces the strength of concrete. NSC C50 has higher water content than the UHPC. Hence the loss of strength by the increase of porosity overwhelms the increase of strength by shrinkage. As a result, the compressive strength of NSC C50 did not increase at 200 °C.

The effects of PP fiber dosage on the residual compressive strengths of UHPC mixtures are shown in Figure 5 and Figure 6. At the heating rate of 5 °C/min, the residual compressive strength factors of UHPC with 0.25% and 0.5% PP fiber at 400 °C and 600 °C were lower than those of UHPC with 0.1% PP fiber with a difference of approximately 18%. For the other temperatures, they were very similar.

TABLE 5. Residual compressive strengths based on fiber dosage and heating rate (MPa)

Temp. (°C)	UHPC without fiber	C50 without fiber	UHPC with 0.1% fiber		UHPC with 0.25% fiber		UHPC with 0.5% fiber	
	5 °C/min	5 °C/min	5 °C/min	30 °C/min	5 °C/min	30 °C/min	5 °C/min	30 °C/min
30	163	46	161	183	151	151	147	147
200	171	44	171	184	164	159	153	149
400	128	35	126	128	101	105	97	95
600	–	19	74	80	59	60	52	55
800	–	9	41	28	36	31	34	31

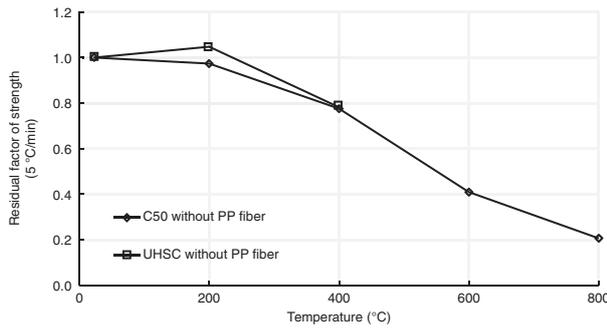


FIGURE 4. Residual compressive strength of UHPC and C50 without PP fiber.

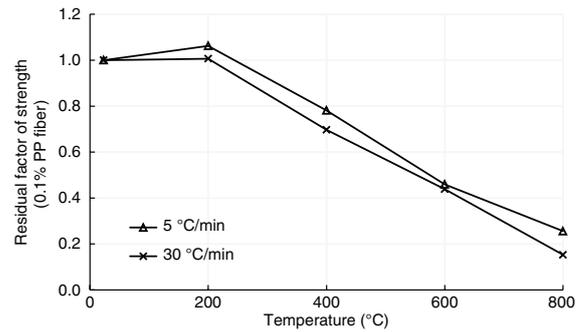


FIGURE 7. Residual compressive strength of UHPC with 0.1% PP fibers.

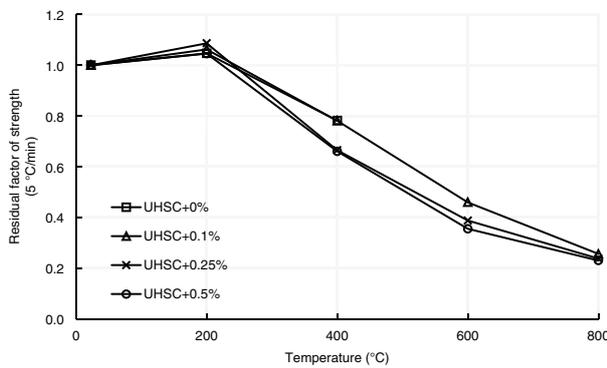


FIGURE 5. Residual compressive strength of UHPC at heating rate of 5 °C/min.

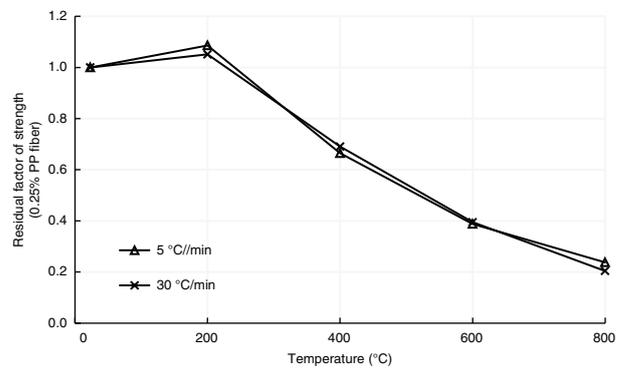


FIGURE 8. Residual compressive strength of UHPC 0.25% PP fibers.

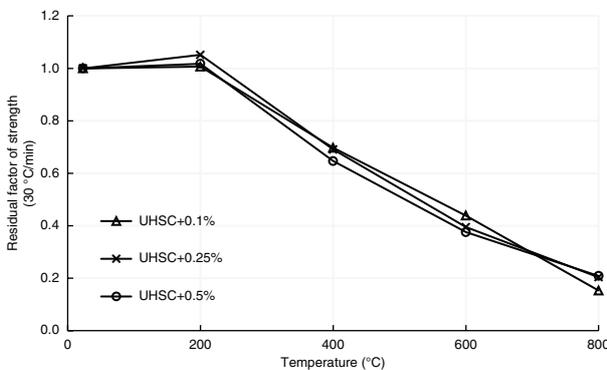


FIGURE 6. Residual compressive strength of UHPC at heating rate of 30 °C/min.

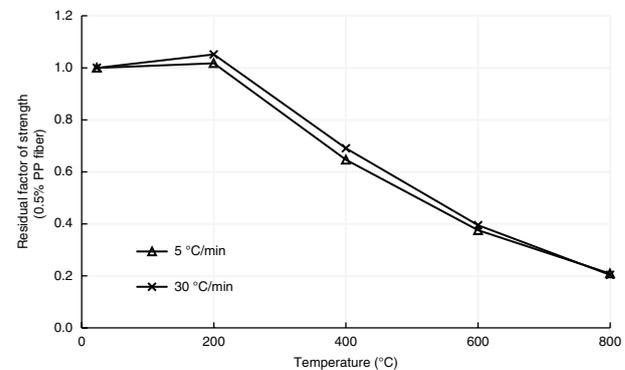


FIGURE 9. Residual compressive strength of UHPC 0.5% PP fibers.

At the heating rate of 30 °C/min, the differences were not significant and the compressive strengths were similar. It could be concluded that the compressive strength was reduced slightly faster as PP fiber dosage increased at heating rate of 5 °C/min, but similar at 30 °C/min.

The effects of heating rate on the residual compressive strength are shown in Figure 7, Figure 8 and Figure 9. The maximum difference between the

residual factors at 5 °C/min and 30 °C/min were 40.3%, 14.3% and 9.2% as the PP fiber dosage increased from 0.1% to 0.5%. The trend showed that the compressive strength of UHPC with 0.1% PP fibers at 30 °C/min was reduced faster than that at 5 °C/min. However as the PP fiber dosage increased, the difference at different heating rates regarding the deterioration of strength was not significant.

TABLE 6. Residual elastic modulus (GPa) based on fiber dosage and heating rate

Temp. (°C)	UHPC without fiber	C50 without fiber	UHPC with 0.1% fiber		UHPC with 0.25% fiber		UHPC with 0.5% fiber	
	5 °C/min	5 °C/min	5 °C/min	30 °C/min	5 °C/min	30 °C/min	5 °C/min	30 °C/min
30	60	27	61	65	54	54	53	53
200	58	22	56	61	51	47	52	43
400	32	10	28	30	24	22	24	20
600	–	3	22	17	18	15	18	12
800	–	1	21	9	20	12	19	10

4.4. Residual elastic modulus

According to ASTM C469-02 (21), the elastic modulus is the secant modulus between the stress equal to 40% of peak stress and the stress corresponding to strain of 5×10^{-5} . Generally, the residual elastic modulus decreased with increasing temperature as given in Table 6, there was no increase at 200 °C. This indicates that the shrinkage of UHPC after water removal has minor effect on the elastic modulus since the primary factors affecting the elastic modulus are the type of aggregate and the presence of sustained stress during heating (22). Comparing the UHPC with the NSC C50 both without addition of PP fibers as shown in Figure 10, the residual modulus factors of C50 were smaller than those of UHPC at 200 °C and 400 °C. The difference was approximately 13% and 35%, respectively. Similarly, this was attributed to the type of aggregate.

The effects of PP fiber dosage on the residual modulus factors of UHPC mixtures are shown in Figure 11 and Figure 12. At heat rate of 5 °C/min, no clear difference was observed with regard to the effect of PP fiber dosage. However at heating rate of 30 °C/min, the elastic modulus was reduced faster with the increase of the dosage of PP fiber.

The effects of heating rate on the residual modulus factors are shown in Figures 13–15. For PP fiber dosage of 0.1%, the difference between the residual factors at 5 °C/min and 30 °C/min was minimal up to 400 °C. As the PP fiber dosage increased, the said difference became significant. The difference at 600 °C and 800 °C was significant, irrespective of fiber dosage. It could be concluded that the elastic modulus was reduced faster at higher heating rate. The difference between the residual factors of 5 °C/min and 30 °C/min increased as the PP fiber dosage increased.

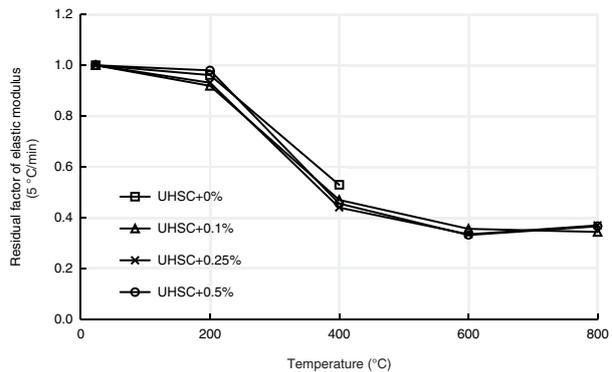


FIGURE 11. Residual elastic modulus for UHPC at heating rate of 5 °C/min.

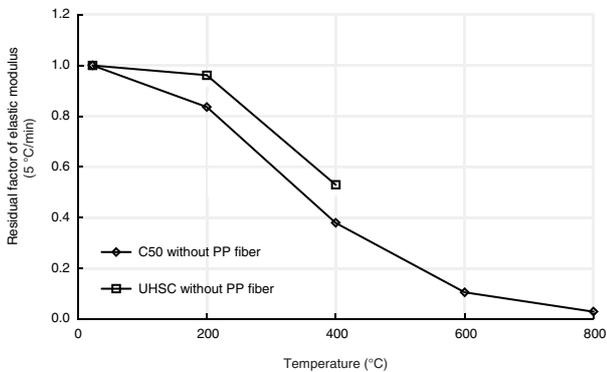


FIGURE 10. Residual elastic modulus for UHPC and C50 without PP fiber.

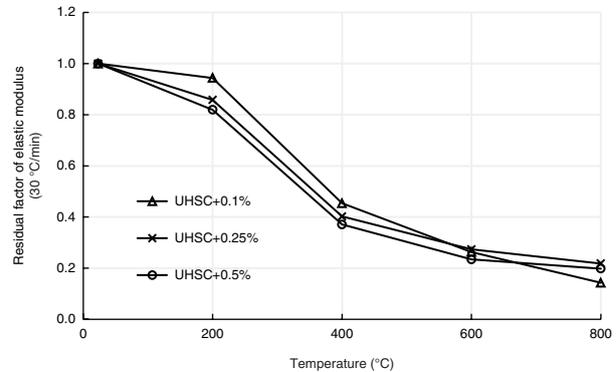


FIGURE 12. Residual elastic modulus for UHPC at heating rate of 30 °C/min.

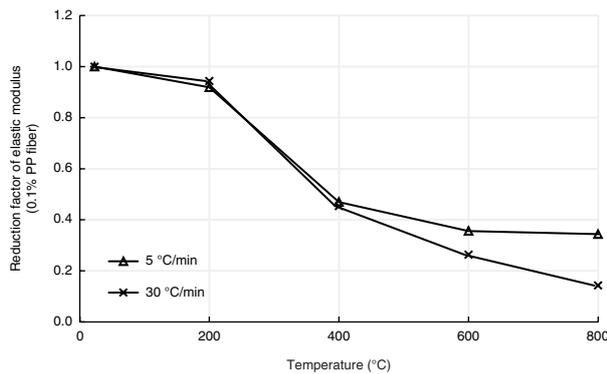


FIGURE 13. Residual elastic modulus for UHPC with 0.1% PP fibers.

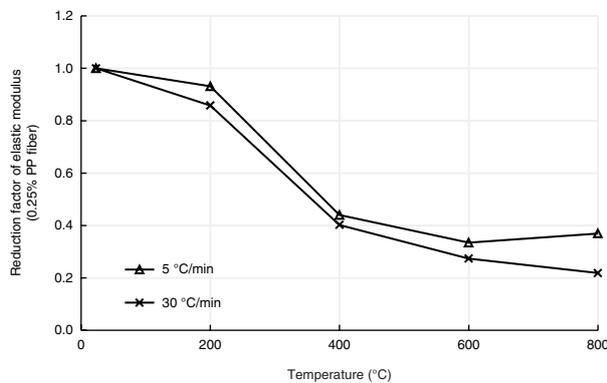


FIGURE 14. Residual elastic modulus for UHPC with 0.25% PP fibers.

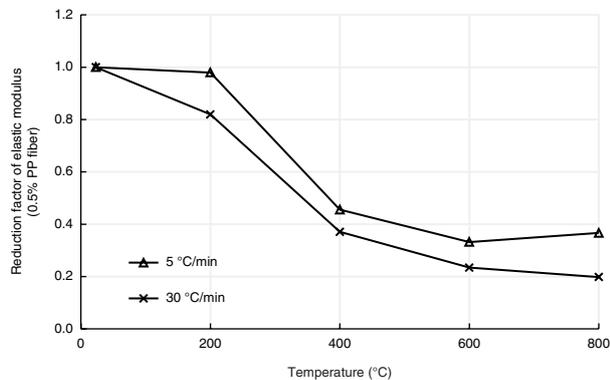


FIGURE 15. Residual elastic modulus for UHPC with 0.5% PP fibers.

5. EFFECT OF CURING CONDITION

5.1. Experimental program

UHPC with 0.1% PP fibers by volume was investigated. The UHPC was made by using the pre-blended mixture from the second shipment as mentioned above. The cylindrical specimens (100×200 mm) were cured in three conditions as follows:

- UHPC-D:** Bare specimens were cured in open lab air with a relative humidity (RH) of 85% and temperature of 30 °C for day-time and 25 °C for night; and
- UHPC-H:** Bare specimens were cured in fog room with a constant RH of 100% and temperature of 28 °C; and
- UHPC-S:** Specimens were sealed with aluminum foil and cured in lab air. The specimens were prepared to reflect the curing condition where UHPC is encased in hollow steel tubes.

Three cylinders were prepared for each batch. After 28 days curing, the specimens were heated. The heating rate was 30 °C/min. The heating, cooling, and testing procedures were the same with those aforementioned.

5.2. Discussions on test results

There was no spalling observed during heating for all specimens due to the addition of 0.1% PP fibers. The residual compressive strength and modulus are shown in Table 7. At room temperature, the strength and modulus of UHPC mixtures were not significantly affected by the curing conditions. This might be due to the fact that UHPC is very dense and the permeability is low. Thus, little water was absorbed even cured in fog room for 28 days. Regarding the site inspection during building construction, the test results implicitly indicated that the mechanical properties of UHPC cured in the open environment can be used for the one encased in hollow steel tubular columns. This facilitates site inspection since it is difficult to take out UHPC specimens from the composite columns for static tests.

The residual factors of compressive strength and elastic modulus with various curing conditions are plotted in Figure 16 and Figure 17. No clear difference was observed with regard to the effects of curing conditions. This is because the residual compressive strength and elastic modulus were measured after the water was removed by heating. Thus the residual properties would be similar regardless of how much water have been absorbed before heating. Comparing the residual compressive strength and the residual elastic modulus as shown in Figure 16 and Figure 17, the residual modulus was reduced faster under all curing conditions. Especially at 400 °C, the residual elastic modulus was reduced by 55% but 30% for the residual compressive strength. It indicated that the elastic modulus was more sensitive to fire compared with the compressive strength. Thus, the composite columns filled with the UHPC may be more likely governed by buckling failure rather than cross-sectional failure under fire.

TABLE 7. Residual compressive strength and residual elastic modulus based on curing conditions

Temp. (°C)	UHPC-D		UHPC-H		UHPC-S	
	f_{ck} (MPa)	E_c (GPa)	f_{ck} (MPa)	E_c (GPa)	f_{ck} (MPa)	E_c (GPa)
30	183	65	181	67	186	66
200	184	61	186	60	189	60
400	128	30	137	29	129	30
600	80	17	74	18	77	18
800	28	9	31	10	30	9

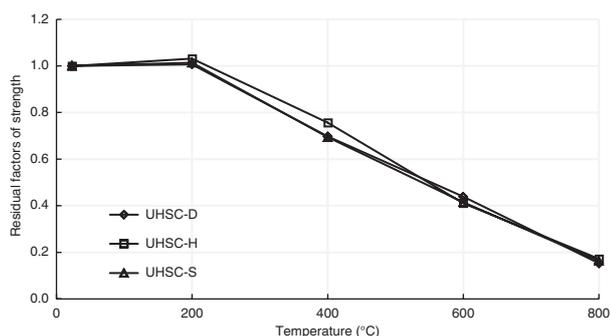


FIGURE 16. Residual factors of strength under all curing conditions.

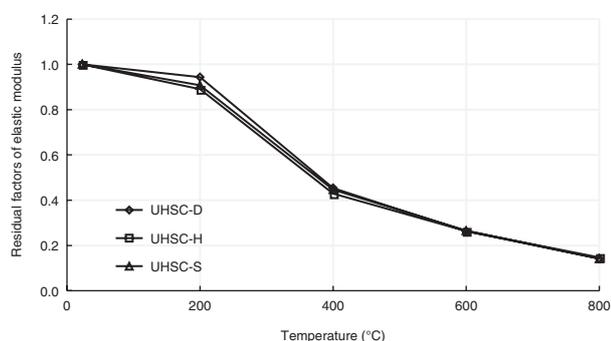


FIGURE 17. Residual factors of elastic modulus under all curing conditions.

6. CONCLUSIONS

The spalling behavior and residual resistance of ultra-high performance concrete were introduced in this paper. The effective way has been found to prevent spalling of the ultra-high performance concrete through this research. Fiber dosage, heating rate and curing conditions were investigated for the residual resistance of the ultra-high performance concrete specimens. Some main findings can be obtained as follows.

(1) Steel fiber is not effective to prevent spalling of the ultra-high performance concrete even its

dosage is 1.0% by volume. Polypropylene fiber with dosage of 0.1% is found to be effective for temperature up to 800 °C since the polypropylene fibers melt and then leave voids for release of vapor.

- (2) Strength of the ultra-high performance concrete at heating rate of 30 °C/min is reduced faster than that at 5 °C/min when the polypropylene fiber dosage is 0.1%. As the polypropylene fiber dosage increases, the reduction is similar at different heating rates. At 5 °C/min, strength is reduced faster as the polypropylene fiber dosage increases. At 30 °C/min, the reduction of strength is similar for various polypropylene fiber dosages.
- (3) Elastic modulus of the ultra-high performance concrete is reduced faster at higher heating rate. The difference between residual factors at 5 °C/min and 30 °C/min increases as the polypropylene fiber dosage increases. The polypropylene fiber dosage does not significantly affect the residual modulus factor at 5 °C/min, however at heating rate of 30 °C/min, the elastic modulus is reduced faster with the increase of PP fiber dosage.
- (4) There is an increase of strength after exposure to 200 °C, due to the shrinkage by water removal. The increase is not found for elastic modulus.
- (5) Strength and elastic modulus of the ultra-high performance concrete are reduced slower after heating than those of C50, due to the fire resistant bauxite aggregate in the ultra-high strength concrete.
- (6) Curing condition exhibits insignificant effects on the residual compressive strength and residual elastic modulus of the ultra-high strength concrete. For all curing conditions, the elastic modulus is generally reduced faster than the strength after heating.

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