Scientific paper

Effect of Mass Loss of Organic Fiber on the Water Vapor Pressure and Moisture Migration of 150 and 200 MPa Ultra-High Strength Concrete Exposed to High Temperature

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Abstract

In this study, 150 and 200 MPa ultrahigh-strength concrete (UHSC) specimens were mixed with polypropylene and nylon fibers and heated according to the ISO 834 heating curve. The effects of mass loss of each organic fiber on moisture migration and water vapor pressure reduction in concrete were assessed. Spalling was controlled when 0.15 to 0.25 vol% fiber was added to the specimens. The mass loss of the organic fibers effect on the pore network formation in UHSC. The nylon fiber formed pores below melting temperature via drying and allowed for moisture movement, whereas the propylene fiber effectively reduced the vapor pressure because of rapid mass loss above the melting temperature.

1. Introduction

Using a very low water/binder ratio is expected to increase the strength and durability of ultrahigh-strength concrete (UHSC), because it results in dense microstructure formation and high water-tightness (Kodur and Phan 2007; Choe et al. 2015; Noumowe 2005; Lee et al. 2016). However, UHSC exposed to extremely high temperatures (e.g., during a fire) is likely to form a moisture clog, a fully saturated layer of moisture that is caused by inhibited migration of internal moisture. Moisture clog has been reported as a major factor in the spalling of UHSC exposed to high temperatures (Consolazio et al. 1998; Khoury and Majorana 2002; Ichikawa and England 2004; Dauti et al. 2019). Spalling, which means the formation of irregular and brittle fractures, occurs in high-strength concrete exposed to high temperatures. It can lead to a sudden decrease in the design cross-sectional area or to the exposure of reinforcing bars, which may lead to a sudden decrease in the structural loading bearing capacity (Choe et al. 2015; Kodur 2000; Boström and Jansson 2006). Therefore, reviewing the fire safety performance from a material standpoint, such as appropriate spalling control, is a crucial step in the application of UHSC. Previous studies (Zeiml et al. 2006; Liu et al. 2008; Bilodeau et al. 2004) have confirmed that generating a pore network and reducing the water vapor pressure by mixing organic fiber that has a high melting temperature (e.g., polypropylene fiber has a melting temperature of about 170°C) into concrete is an effective way to prevent high-strength concrete from spalling.

The spalling control performance of high-strength concrete that has been mixed with various types of fibers has recently been reviewed. Ozawa and Morimoto (2014) examined porous network formation and spalling control performance according to the geometric and chemical characteristics of each fiber. They evaluated the variations in the water vapor pressure and permeability of concrete containing jute, water-soluble polyvinyl alcohol (WSPVA), and polypropylene fibers. They found that the water vapor pressure decreased in fiber-containing concrete because of the increased permeability at high temperatures. In particular, concrete mixed with jute, which has straw structures, exhibited high permeability at room temperature. By contrast, the WSPVA fiber was flexible at 50 to 90°C, and water vapor was discharged from the interfacial transition zones (ITZs) of the fiber. Daungwilailuk et al. (2019) observed ITZ between PP fiber and cement matrix at a heating temperature of 150 to 200°C and microcracks on the cement matrix at about 200°C. And they analyzed that moisture, CO₂ gas and Cl ions can penetrate in concrete via ITZ and microcrack.

Ding et al. (2016) analyzed the spalling characteris-
tics of concrete that has been mixed with steel and two distinct types (i.e., micro size and macro size) of polypropylene fibers. They reported that the vapor pressure was discharged from steel-fiber-containing concrete through fractures created in the steel fiber ITZ. In addition, the polypropylene fiber reduced spalling better than steel fiber, and the micro polypropylene fiber performed better than the macro polypropylene fiber because the former created a larger void area within the cement matrix. Bilodeau et al. (2004) evaluated the spalling control performance of high-strength concrete that has been mixed with polypropylene fibers of two different lengths and deduced the superiority of the short fiber compared to long fiber for preventing concrete spalling. Heo et al. (2012) investigated the effects of mixing conditions and fiber shape on spalling control of high-strength concrete. The optimal fiber length depended on the gap between aggregates, size of coarse aggregate, and number of fibers. Although the long fiber was more effective at reducing the spalling as the size of the coarse aggregate increased, the short fiber exhibited a superior performance when the fiber diameter was small. The above literature review shows that various fiber types have been applied to control the spalling of high-strength concrete, and that effective spalling control strategies that consider the advantages of each type have been developed. The basic principle is based on forming a pore network and reducing the water vapor pressure between the fibers and cement matrix. The pore network is expected to form mainly by the fibers melting.

By contrast, Khoury and Willoughby (2008) analyzed the physical and chemical variations of polypropylene subjected to high temperature. They found that pressure significantly higher than the water vapor pressure was required to form a pore network capable of discharging the vapor pressure, even after the polypropylene fiber exhibited fluid-like characteristics once it was heated to the melting temperature. In other words, pore network formation has limitations even after organic fibers reach their melting temperature. Bošnjak et al. (2013) stated that polypropylene fiber, specifically extruded fibers, below the melting temperature can expand in volume in all directions. However, the volume expansion typically increases the thickness while decreasing the length, which can be detrimental to pore network formation. Thus, the effects of not only the melted state of the fiber but also its mass loss on the formation of the pore network and reduction of water vapor pressure should be reviewed. However, only a few studies have examined such effects. Besides, although 200 MPa UHSC is being considered as a cast-in-situ concrete (Kimura et al. 2007), many studies considered concrete below 100 MPa to estimate the effect of fiber to prevent concrete spalling.

Therefore, in this study, thermogravimetric analysis (TGA) and differential thermal analysis (DTA) were conducted to investigate the thermal properties of polypropylene (PP) and nylon (NY) fibers. A heating test using UHSC specimens with compressive strengths of 150 and 200 MPa and containing PP and NY fibers were carried out to evaluate the spalling properties, water vapor pressure, and moisture migration of UHSC. Finally, the effect of the mass loss of organic fibers on the water vapor pressure and moisture migration of UHSC was examined in detail.

## 2. Experimental work

### 2.1 Experimental outline

Table 1 outlines the experiment. Concrete specimens were prepared at different levels of compressive strength and mixing conditions for organic fibers. UHSC with compressive strengths of 150 and 200 MPa were mixed with 0.15 or 0.25 vol% of PP or NY fibers. In addition, concrete specimens without fibers were prepared to compare the effects of mixing organic fibers on spalling control. TGA and DTA were employed to determine the variations in the thermal properties and mass losses of the fibers as functions of the heating temperature. As the concrete specimens were heated, the vapor pressure that built up inside the concrete was measured. The specimen surfaces were visually assessed after heating, and the amount of spalled concrete was estimated from the difference in the weights before and after the heating test.

### 2.2 Specimens

In this study, two shapes of specimens were prepared. The concrete specimens for measuring the compressive

| Specimen ID | f_c (MPa) | Fiber type | Fiber dosage (% by volume) | Measured parameters |
|-------------|-----------|------------|---------------------------|---------------------|
| 150-Plain   | -         |            | 0                         | Fiber               |
| 150-P-0.15  | 150       | PP         | 0.15                      | - TGA               |
| 150-P-0.25  | 150       | NY         | 0.15                      | - DTA               |
| 150-N-0.15  | 150       | NY         | 0.25                      | - spalling shape    |
| 150-N-0.25  | 150       | NY         | 0.25                      | - weight reduction ratio |
| 200-Plain   | -         |            | 0                         | Concrete            |
| 200-P-0.15  | 200       | PP         | 0.15                      | - water vapor pressure |
| 200-P-0.25  | 200       | NY         | 0.15                      | -                    |
| 200-N-0.15  | 200       | NY         | 0.25                      | -                    |
| 200-N-0.25  | 200       | NY         | 0.25                      | -                    |
strength and moisture content were fabricated as cylinders with a diameter and height of 100 and 200 mm, respectively. Meanwhile, square-column specimens with a cross-section of 100 mm×100 mm and height of 200 mm were prepared for the heating test. After being fabricated, the concrete specimens were cured in a water bath at 20±2°C for 28 days and then cured for a maximum of 300 days at a constant temperature and relative humidity of 20±2°C and 60±5%, respectively. The moisture content in the concrete specimens was measured by applying the method of RILEM committee TC 129 (RILEM 2000). The dry mass of the concrete was defined as the invariant mass of a specimen placed in a dryer at 105°C. The moisture content was calculated using Eq. (1). The water content of concrete is an important factor regarding concrete spalling. However, the aim of this study is to find how water vapor pressure generates and how moisture migrates by mass loss of embedded organic fiber in UHSC. Therefore, the water content, although not was important for this study, is listed in Table 2 to provide information.

\[ W_{\text{moisture}} = \frac{W_{\text{initial}} - W_{\text{dry}}}{W_{\text{initial}}} \times 100 \]  

where

- \( W_{\text{moisture}} \): moisture content (%),
- \( W_{\text{initial}} \): weight of the specimen before drying (g) and
- \( W_{\text{dry}} \): dried weight of the specimen (g).

### 2.3 Materials

Table 3 presents the mix proportions and the fresh and hardened properties of UHSC. ASTM type I cement was used (density: 3150 kg/m³, fineness: 320 m²/kg). The admixtures were fly ash (density: 2210 kg/m³, fineness: 300 m²/kg), blast furnace slag (density: 2500 kg/m³, fineness: 600 m³/kg), gypsum (density: 2900 kg/m³, fineness: 355 m³/kg), and silica fume (density: 2500 kg/m³, fineness: 20 000 m³/kg). The coarse aggregate was crushed granite with a density of 2700 kg/m³, absorption rate of 0.9%, and maximum size of 13 mm. The fine aggregate was river sand with a density of 2650 kg/m³, absorption rate of 1%, and fineness modulus of 2.6.

### 2.4 Heating

Figure 1 depicts the temperature rise inside the concrete specimens according to the applied heating method. The concrete specimens were heated to a maximum temperature of 918°C for 50 min according to the ISO 834 standard heating curve. Figure 2 shows the heating device employed in this study. This device heats a con-
concrete specimen with an electric resistance heating coil and is equipped with a temperature controller to select the maximum temperature and heating rate.

### 2.5 Test setup for measuring the water vapor pressure in a concrete specimen

Figure 3 shows the schematic of the device used to measure the water vapor pressure inside the concrete specimens. It is too difficult to measure the water vapor pressure while the concrete specimens are heating. However, some researchers (Ko et al. 2011; Ozawa and Morimoto 2014) tried by embedding a steel pipe in concrete specimens. Ko et al. (2011) used an empty steel pipe and Ozawa and Morimoto (2014) used a steel pipe filled with silicon oil. A method similar to that of Ko et al. (2011) was applied in this study. The specimens were prepared by embedding stainless steel (SUS) pipes 30 and 50 mm from the test specimen surface before the concrete was deposited. The water vapor pressure released through these pipes during heating was measured with pressure sensors. The pipes were made of SUS 304 and had inner and outer diameters of 1 and 2 mm, respectively. The embedded part was bent at a 90° angle to prevent the metal pipe from being drawn out of the concrete specimen. Before concrete curing, the pipe entrance was blocked with paraffin to prevent aggregates or cement paste in the pipes from clogging the pipe inlet. The melting temperature of the paraffin was 62°C, which is below the temperature at which the water vapor pressure builds up. Hence, the pipe inlet could be opened to facilitate steam discharge. In addition, water vapor becomes the liquid state water when water vapor exposed to the temperature below the boiling point. Therefore, the pipes exposed to room temperature were wrapped with a heating coil maintained at 100°C to prevent water vapor pressure loss by condensation.

### 2.6 Weight loss ratio of the concrete specimens after the heating test

The amount of concrete that spalled from a specimen was estimated by using the specimen mass loss rate as follows:
\[ W_{\text{loss}} = \frac{W_1 - W_2}{W_1} \times 100 \]  

(2)

where

- \( W_{\text{loss}} \): the weight loss ratio (%),
- \( W_1 \): the weight of the specimen before heating test (g), and
- \( W_2 \): the weight of the specimen after heating test (g).

3. Experimental results and discussion

3.1 Thermal properties of PP and NY fibers

Figures 4 and 5 show the thermal properties of the PP and NY fibers according to DTA and TGA. In the DTA curve for PP fiber, endothermic peaks indicating the melting and burning temperatures of each PP fiber were observed at 170 and 408°C, respectively (Khoury and Willoughby 2008). According to the TGA curve, the evaporation of water vapor within the fiber below the melting temperature (170°C) reduced the total mass by 0.77%. Although the melting temperature of the PP fiber was 170°C, mass loss was observed at approximately 216°C. At the burning temperature, the mass was reduced by 96.09%, and the fiber was burned completely at 450°C. The DTA curves for the NY fiber showed endothermic peaks at 220 and 470°C, which were considered as the melting and burning temperatures, respectively. The NY fiber showed a 3.3% mass loss below the melting temperature, which is approximately five times greater than the loss of the PP fiber, because of the hydrophilic nature of the former. Above the melting temperature, the NY fiber started losing mass at about 250°C. At the burning temperature of the fiber, 88% of the initial mass was lost, and the fiber was burned completely at 550°C.

The comparison of the thermal properties of the two fibers showed that the melting point of the PP fiber was about 50°C lower than that of the NY fiber, but the NY fiber lost more mass below the melting temperature. Furthermore, the PP fiber had a higher rate of mass loss above the melting temperature, and burned off completely at a temperature 100°C lower than that for the NY fiber.

The objective of this analysis is to predict the pore formation in concrete by understanding the behavior of fiber mass loss with heating temperature. The relationship of mass loss of fiber and temperature exhibited similar to a sigmoid function, it is given by Eq. (3).

\[ R_f(T) = \left( \frac{1}{1 + \exp(-0.038(T - T_{50}))} \right) \times 100 + W_f \]  

(3)

where

- \( R_f(T) \): ratio of mass loss of fiber (%),
- \( T \): temperature (°C),
- \( T_{50} \): temperature at fiber mass loss ratio 0.5 (PP = 340,
NY = 420) and

\[ W_r : \text{water content in fiber (PP = 0.77% loss, NY = 3.3%), this value being applied only in the range of 60^\circ C \leq T < \text{vaporization temperature}.} \]

3.2 Spalling properties and weight loss ratio

Figure 7 shows the heated concrete specimen surface conditions. When the device was opened after the heating test, only piles of debris from 150-Plain and 200-Plain (i.e., specimens with no fibers) remained because of continuous spalling. Mixing PP and NY fibers into the specimens prevented spalling: the 150 MPa UHSC specimens with fiber did not experience surface concrete detachment. On the other hand, the 200-P-0.15 and 200-N-0.15 specimens spalled, which caused the surface concrete to detach, while no spalling occurred in the 200-P-0.25 and 200-N-0.25 specimens. Because the heating device used in this experiment (Fig. 2) was composed of a stainless-steel box, the concrete conditions during heating could not be observed in real time. However, Khoury (2000) reported that different types of concrete spalling yield distinct characteristic sounds. Hence, the time of spalling was estimated based on sounds from the device during the heating process. Sounds due to spalling of the 150-Plain and 200-Plain specimens were first heard approximately 8 to 9 min after the heating started. These sounds continued until the heating test was completed. In addition, several noises presumed to be generated by the 200-P-0.15 and 200-N-0.15 specimens spalling were heard 7 to 24 min and 8 to 15 min, respectively, after heating started.

Figure 8 shows the weight loss ratios of the concrete specimens obtained with Eq. (2). The 150-Plain and 200-Plain specimens, which fragmented into pieces af-
ter the heating test, were considered to have no remaining concrete mass, so their mass losses were reported as 100%. The weights of the 200-P-0.15 and 200-N-0.15 specimens, which experienced spalling, decreased by 19.8% and 10.41%, respectively. Even concrete specimens without spalling experienced mass losses of 6% to 7%. The concrete specimen mass loss without spalling was 4% to 5% higher than the moisture content (about 2%), but such a mass loss can be attributed to free water as well as evaporation and decomposition of chemically bonded water instead of spalling (Noumowe et al. 2009; Sukontasukkul et al. 2010; Hou et al. 2013).

The spalling of the 200-P-0.15 and 200-N-0.15 specimens was not fully prevented. This indicates that the fiber added ratio of 0.15% by volume would be not enough to prevent spalling for 200 MPa UHSC. But significant weight loss differences compared to those of the 150-Plain and 200-Plain specimens without organic fiber were observed. Thus, using organic fibers was verified to enhance spalling control of UHSC. Although Majorana et al. (2010) asserted that mixing organic fibers with concrete fabricated with reactive powders such as silica fume is inappropriate for reducing spalling because of the formation of closed structures, spalling was avoided in this experiment when 1.36 and 1.65 kg/m³ of PP and NY fibers were respectively mixed with concrete fabricated with reactive powders.

3.3. Water vapor pressure in the concrete specimens with the heating time

Figure 9 shows the water vapor pressures in UHSC mixed with PP and NY fibers as functions of the heating time. The water vapor pressure was measured to be stable in concrete specimens with organic fibers, but it was not measured in the 150-Plain and 200-Plain specimens without organic fibers. This was because of the difficulty of transferring moisture in UHSC without fibers and the dissipation of accumulated water vapor near the surface by repeated spalling, which impeded the vapor discharge through the pipes. The 200-P-0.15 and 200-N-0.15 specimens had the highest measured pressures of 648.9 and 695.3 kPa, respectively, at a depth of 50 mm, but the overall pressure was below 700 kPa. These pressures are remarkably lower than the reported values because the overall inner vapor pressure was reduced by the mixing of PP and NY fibers, as noted in previous studies (Bangi and Horiguchi 2011, 2012; Ozawa et al. 2013).

At 30 mm, the water vapor pressure in all specimens built up in 10 to 15 min, while the compressive strength and type of organic fiber had a negligible effect. By contrast, the time for the vapor pressure buildup at 50 mm varied according to the mixed organic fiber type. With PP fiber, the water vapor pressure at 50 mm was observed 5 to 10 min after the vapor pressure built up at 30 mm. On the other hand, with NY fiber, the difference in water vapor pressure buildup time did not significantly vary with respect to the depth.

The time at which the water vapor pressure reached its maximum at each measurement depth showed different trends according to the organic fiber type. With PP fiber, the maximum pressure at 30 mm was obtained at 15 to 20 min, while that at 50 mm was obtained as early as 11 min and as late as 26 min. For the NY specimens, the difference between the times to reach the peak water vapor pressure at the depths of 30 and 50 mm was only 5 to 10 min. The time to reach the peak vapor pressure increased while the peak pressure itself decreased as the fiber content increased, and the peak pressure decreased as the compressive strength increased. Such behavior was attributed to increased difficulty for moisture to move as the compressive strength increased and dense microstructures were formed. The vapor pressure in individual pores could then be higher, but the amount of water vapor discharged through the pressure pipe from the measurement point was smaller.

3.4. Water vapor pressure and saturated vapor pressure (SVP)

Figure 10 compares the temperature-water vapor pressure relationship against the saturated vapor pressure (SVP) curve. The SVP is a function of temperature and is the maximum pressure that water vapor can attain at a given temperature. The variation in water content and amount of water vapor can be determined by analyzing the water vapor pressure with respect to the SVP curve (Khoury and Willoughby 2008; Ozawa and Morimoto 2019).
2014; Bangi and Horiguchi 2011). Meanwhile, the water vapor pressure is affected by experimental conditions like specimen size, heating rate, and test set up. Therefore, Fig. 10 shows the data of water vapor pressure obtained under the same experimental condition in this work because it is difficult to compare the value of water vapor pressure performed in different experimental conditions. Figure 11 compares the relationship between the water vapor pressure and internal concrete temperature against the SVP curve. The water vapor pressure for all specimens was much lower than the SVP curve. Consequently, the moisture inside the concrete was unsaturated, so the moisture moved through the pore network created by the fibers and matrix cracks and discharged the increased water vapor pressure. In addition, a moisture-saturated layer did not form at depths of 30 and 50 mm in the 100 mm×100 mm fiber-containing concrete.

Fig. 9 Water vapor pressure of concrete specimens over time.
specimens that were considered in this study. The water vapor pressures at 30 and 50 mm of the PP-fiber-containing concrete specimens started to increase at about 200°C. However, the water vapor pressures at 30 and 50 mm of the NY-fiber-containing specimen rose at about 200 and 150°C, respectively. These differences can be analyzed by observing changes in the concrete state as a function of the heating temperature.

Figure 12 shows the concrete surface shape, as observed with a microscope, according to the temperature. At 100°C, no change was observed in the fibers and concrete, whereas cracks developed in the concrete around the fibers at 200°C. Cracks were observed in concrete mixed with PP and NY fibers, but the organic fiber itself did not exhibit any difference. The cracks expanded at 300°C; no changes in the PP fiber were observed, while the NY fiber became black.

Analysis of the temperature-pressure relationships of the PP and NY concrete specimens and their surfaces yielded the following results: The moisture in the con-
Concrete pores were present as superheated water and did not turn into vapor because of the rise in vapor pressure in the pores up to at least 200°C, even when the matrix temperature increased. When the pores fractured because of matrix cracking at 200°C, the atmospheric pressure and vapor pressure in the pores reached equilibrium, and the superheated water vaporized instantly. The volumetric expansion at this point was constrained and caused vapor pressure to build up.

When PP fiber was mixed in the concrete, the vapor pressure did not build up and moisture did not move at any depth until the inner concrete temperature reached 200°C. When the concrete was mixed with NY fiber, this created an environment suitable for fiber mass loss and moisture movement through concrete cracks. In other words, the vapor pressure at a 50 mm depth for the NY-fiber-containing concrete specimen increased before the previous crack temperature of 150°C was reached owing to the moisture being transported by the vapor pressure built up at 30 mm.

3.5. Buildup of the water vapor pressure and moisture migration with fiber mass loss in concrete

Figure 13 shows the relationship between the water vapor pressure and organic fiber mass loss as functions of the heating time. According to the temperature distribution inside the concrete, the fibers distributed throughout the cross-section were divided into solid and melted states and pyrolysis. In concrete specimens mixed with PP fiber, the water vapor pressure started to increase at 200°C until 220°C, at which point the PP fiber mass started to decrease. This was because of the matrix cracks fracturing the pores at about 200°C, as noted earlier. Significantly, the vapor pressure was not observed to change at the fiber melting temperature of 170°C. Fibers typically become fluidized by solid fibrous amorphization at the melting point, but there is generally insufficient pressure to move the fibers even at 4 to 8 MPa (the maximum value observed in previous studies (Kalifa et al. 2000)). As a result, fibers in the dissolved state cannot form porous networks in a concrete matrix, so water movement is not expected.

The water vapor pressure increased with the pressure at depths of 30 and 50 mm in the concrete specimens mixed with NY fiber. The NY fiber mass started to decrease at about 60°C and by 0.3% before 200°C. This caused a slightly porous network to form and created a passage for moisture movement. Because the vapor pressure built up at the same time as the matrix cracking, moisture was transferred through the previously formed porous network, so the pressures at 50 and 30 mm rose simultaneously. The small porous network allowed for moisture transfer inside the concrete but was not sufficient to discharge the internal vapor pressure. In other words, moisture transfer from the surface to inside was possible because the vapor pressure at 30 mm was higher than that at 50 mm, but the rise in vapor pressure because of the temperature increase seemed inevitable.

Moisture transfer inside the concrete could discharge vapor pressure by changing the water content at specific locations and times, but the vapor discharge was crucial for reducing the vapor pressure because the amount of water in the concrete remained the same overall. The surface vapor pressure could be reduced temporarily through moisture movement at low temperatures in the initial heating stage of the specimens with NY fiber, but this did not effectively reduce the total pressure. The fibers formed a porous network at temperatures higher than the concrete cracking point when PP fiber was mixed, but the mass loss and rapid pore formation, which occurred not too long after the rise in vapor pressure, quickly discharged the vapor and were effective at reducing the total water vapor pressure.

The results indicate that the increase in water vapor pressure inside concrete subjected to heating is remarkably influenced by the formation of a continuous porous network from matrix cracking and fiber mass...
loss. Furthermore, according to the fiber thermal properties, vapor pressure development and moisture movement are affected by the time at which fiber pores form in the concrete. Thus, mass loss trends should be considered along with basic factors such as the melting temperature of the fibers to prevent spalling of UHSC effectively under extreme heating conditions such as fires.

4. Conclusions

The vapor pressure in individual pores becomes higher than the vapor condensation layer because of the formation of a dense microstructure as the compressive strength of UHSC increases, and the lack of moisture movement impedes consistent vapor discharge. These factors can be considered as a major reason for spalling in UHSC.

In UHSC containing NY fiber, continuous pores can be expected to form because of fiber mass loss occurring below melting temperature because of moisture movement and vapor pressure distribution. Therefore, adding NY fibers can be an effective way to control the spalling of UHSC when first being heated.

Moisture movement is not expected in UHSC that has been mixed with PP fiber because pores do not form below melting temperature and water vapor pressure builds up. However, spalling can be controlled with
vapor pressure discharge catalyzed by mass loss.

In UHSC mixed with organic fibers, the formation of a porous network can be explained by fiber mass loss rather than melting, with mass loss below melting temperature being determined by the water content of the organic fiber. Thus, the selection of an appropriate fiber to control the spalling of UHSC is affected by the mass loss, which depends on not only the melting point but also the temperature distribution.

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