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**Fire resistance of ultra-high performance strain hardening
cementitious composite: residual mechanical properties and spalling
resistance**

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Abstract

Ultra high performance strain hardening cementitious composites (UHP-SHCC) is a special type of cement-based composite material with outstanding mechanical and protective performance at room temperature. But its fire performance is unknown and there is a lack of research in this aspect. This study presents an experimental program to study fire resistance of UHP-SHCC under two aspects, viz. high-temperature explosive spalling resistance and residual mechanical performance after a fire. Both compressive strength and tensile strength of UHP-SHCC were found to deteriorate with increasing exposure temperature. Tensile strain-hardening feature of UHP-SHCC would be lost at 200 °C and above. It was found that PE fibers are found not effective in mitigating explosive spalling, although they start to melt at 144 °C. FE-SEM (Field Emission Scanning Electron Microscopy) and EDX (Energy Dispersive X-ray) techniques were used to study the state of fiber, fiber/matrix interaction, and

25 microcracks development. Microscopic study found that melted PE fibers were still
26 present in the cementitious matrix, and the melting did not introduce more
27 microcracks. Furthermore, it was difficult for melted PE fibers to diffuse through the
28 matrix, thus providing the reason that PE fibers did not mitigate explosive spalling in
29 UHP-SHCC.

30 **Keywords**

31 Strain hardening

32 High temperature

33 Mechanical properties

34 Explosive spalling

35 PE fibers

36 Microcracks

37

38 **1. Introduction**

39 There is a growing trend in tailoring concrete for high tensile ductility in the past few
40 decades. This type of high ductility concrete is known as strain hardening
41 cementitious composite (SHCC) [1-3], or engineered cementitious composite (ECC)
42 [4-6] if designed based on the principles of micromechanics. SHCC is distinct from

concrete and fiber reinforced concrete (FRC) in terms of deformation behavior under uniaxial tension. As illustrated in Fig. 1, in contrast to brittle behavior of concrete (Fig. 1(a)) and strain softening behavior of FRC (Fig. 1(b)), SHCC exhibits pseudo strain-hardening behavior due to development of multiple fine cracks (Fig. 1(c)). Tensile strain capacity of SHCC ranges from 1%-5%, 100-500 times that of ordinary concrete. However, compressive strength of SHCC ranges from 20-60 MPa [7].

In the past decade, researchers have developed SHCC with high mechanical strength and protective performance, termed as UHP-SHCC [8-10]. To engineer SHCC for ultra high performance, a high strength cement-based matrix should be used. However, polyvinyl alcohol (PVA) fibers commonly used in SHCC are not eligible for developing UHP-SHCC. This is because relatively low tensile strength and hydrophilic nature of PVA fibers cannot meet the requirements for steady-state and multiple cracking [11]. If PVA fibers were to be adopted in high-strength matrix, they would fracture other than pull out upon occurrence of a crack. Therefore, instead of PVA fibers, PE fibers with higher tensile strength and greater elastic modulus, are commonly used to develop UHP-SHCC [8-10]. In contrast with hydrophilic nature of PVA fiber, PE fiber is hydrophobic. These advantages make PE fibers suitable for developing UHP-SHCC.

Previous studies [12-16] contributed to understanding of fire resistance of SHCC. Compared to SHCC, fire performance of UHP-SHCC is much less understood. To

63 date, there is no published work on fire resistance of UHP-SHCC.

64 In fact, fire resistance of UHP-SHCC is questionable. Melting point of PE fibers is
65 144 °C, even lower than melting point of PVA fibers (240 °C), as shown in DSC
66 curves of the two fibers in Fig. 2. Loss of PE fibers would have two potential impacts
67 on fire resistance of UHP-SHCC. On one hand, PE fiber is an indispensable element
68 in achieving pseudo tensile ductility. Hence, the loss of PE fibers means distinct
69 feature of ductility vanishes from UHP-SHCC. On the other hand, melting of PE
70 fibers tends to influence moisture migration inside UHP-SHCC, consequently
71 reducing spalling risks. Spalling, an unfavorable phenomenon frequently occurring in
72 fire testing of concrete , may take place if pore pressure due to trapped water vapor
73 exceeds the tensile strength of concrete. It reduces concrete section and weakens
74 load-bearing capacity of concrete member at the early stage of a fire. Previously, no
75 specific test has been conducted to examine explosive spalling tendency of
76 UHP-SHCC. Whether the influence of PE fibers is positive or negative in mitigating
77 spalling and how PE fibers function to exert the influence remain unknown.

78 Previous studies [8-10] added only PE fibers in UHP-SHCC. Recent study found that
79 steel fibers improved the strength and ductility of SHCC after exposure to elevated
80 temperatures [17]. Besides, fiber cocktails are more effective to mitigate explosive
81 spalling than single type of fibers [18, 19]. Therefore, hybrid PE/steel fibers, instead
82 of PE fibers, were used in the UHP-SHCC mix studied in this paper.

The objective of this research is to study fire performance of UHP-SHCC with hybrid PE/steel fibers and the mode of action of PE fibers in mitigating explosive spalling. Fire performance of UHP-SHCC is examined in two aspects in this paper: explosive spalling resistance of UHP-SHCC at high temperature and residual mechanical properties of UHP-SHCC after exposure to elevated temperatures. To study the effect of PE fibers on explosive spalling resistance, mortar specimens (without any fiber) were used as control samples. FE-SEM and EDX techniques were used to study the states of fibers, microcracks development, and fiber/matrix interaction after moderate heat treatment to explore possible means of PE fibers to combat explosive spalling.

2. Materials and method

2.1 Materials

The mix proportions of UHP-SHCC are given in Table 1. In this mixture, CEM I 52.5N was used, and the content of silica fume was 25% of the content of cement. High strength PE fiber and steel fiber were chosen for UHP-SHCC. The properties of PE and steel fibers are listed in Table 2.

To produce UHP-SHCC, cement and silica fume were first mixed for approximately 5 min at dry state. After that, water and superplasticizer were added into the solid mixture and mixed until a good workability was achieved. Finally, PE and steel fibers were added sequentially to the fresh matrix and the mixture was stirred for 5 more

mins to ensure no clumps of fibers could be felt in the matrix. Fresh UHP-SHCC was then cast into molds and compacted using a vibration table. After casting, a plastic sheet was placed on top of the molds to prevent moisture loss. The specimens were demolded after 1 day and cured in water for 27 days. After that, the specimens were conditioned in ambient lab environment until the day of testing.

2.2 Mechanical tests

To determine residual mechanical properties of UHP-SHCC, cylindrical specimens ($\phi 100 \times 200$ mm) and dog-bone specimens (Fig. 3) were used for uniaxial compressive and tensile tests, respectively. The setups for compressive and tensile tests are shown in Fig. 4(a) and (b), respectively. A displacement-controlled loading regime was chosen for both compressive and tensile tests. The displacement loading rate was 0.2 mm/min.

To capture the full compressive stress-strain curve, compressive force was measured by a load cell and axial displacements recorded by one set of LVDTs (Fig. 4(a)). Three LVDTs were attached on the center region of the cylindrical specimen forming an angle of 120 degrees between consecutive LVDTs (Fig. 4(c) to ensure more accurate measurements of average compressive strain. The gage length of the three LVDTs was 100 mm. However, the readings of these three LVDTs were only valid up to the peak load level. After attaining the peak load, cracks in the specimen further widened rendering the three LVDT readings rather erratic. Therefore, two additional

LVDTs were used to measure deformations of the specimen between the machine platens. The deformations included the compressive strain of the specimen, the end-zone effect and the movements of the machine platens. A correction factor proposed by Mansur, et al. [20] was adopted to obtain the post-peak branch of compressive strain-strain curve of UHP-SHCC.

To develop tensile stress-strain curves of UHP-SHCC, tensile force was recorded by a load cell and displacements measured by two external LVDTs attached to the dog-bone specimen with a gage length of 100 mm as shown in Fig. 4(b). For the compressive tests, the cylindrical specimens were subjected to the following isothermal temperatures: 30 °C (ambient temperature), 200 °C, 400 °C, 600 °C, and 800 °C. For the tensile tests, the dog-bone specimens were subjected to the following temperatures: 30 °C (ambient temperature), 100 °C, 200 °C, 300 °C, 400 °C, 500 °C, and 600 °C. The temperature interval for the tensile tests is set to be smaller than that for the compressive tests, since tensile properties of UHP-SHCC are more sensitive to temperature change.

Prior to heating, the compressive and tensile specimens were dried at 105 °C to constant mass if the target exposure temperature was higher than 105 °C. This was to remove the influence of excessive water content on the mechanical properties of UHP-SHCC as well as to avoid explosive spalling. After that, the specimens were heated to target temperature at 1 °C/min. A low heating rate was adopted to prevent

explosive spalling during heating phase, since spalling risk is high when heating rate is large [21]. After reaching target temperature, the specimens were immersed in that environment for 1 hour to achieve isothermal condition before cooling down naturally in the furnace. Table 3 gives the total number of specimens for compressive and tensile tests. For each temperature exposure level, three specimens were prepared. All the specimens were tested after 28 days.

2.3 Spalling test

To evaluate spalling resistance of UHP-SHCC, cylindrical specimens ($\phi 100 \times 200$ mm) were prepared. To demonstrate the effect of PE fibers in combating explosive spalling, high strength mortar specimens were prepared with the same mix design but without any fibers as given in Table 1. To exclude the influence of steel fibers on the spalling resistance, specimens made of PE-FRCC were also prepared so that only the effect of PE fibers was studied. The mix proportions of PE-FRCC are presented in Table 1. Table 3 gives the total number of specimens for spalling tests.

The cylindrical specimens were cured in water for 28 days. They were then conditioned in ambient lab environment until the age of 90 days to achieve a balanced moisture state with ambient environment within the specimens. Then the specimens were heated to 400 °C in 7 min in the furnace, and the temperature was held constant for 2 hours. A high heating rate of 53 °C/min was adopted to study spalling sensitivity,

since it is more closer to real fire scenarios and more likely to trigger explosive spalling [22]. A perforated steel cage was used to cover the specimens to prevent spalling debris from damaging the internal heating elements while allowing heat convection to occur.

To study how PE fibers function to combat explosive spalling, FE-SEM and EDX techniques were used to study microstructural changes of UHP-SHCC and fiber status after exposed to 30 °C, 105 °C, 150 °C, and 200 °C. The UHP-SHCC sample for FE-SEM and EDX tests was a small cylinder (ϕ 12 × 12 mm) and was prepared following the same way as the UHP-SHCC specimens. The sample was heated to the target temperature at 1 °C/min and held in the isothermal condition for 15 minutes. After that, the sample was allowed to cool down at 1 °C/min to minimize micro-cracks due to thermal gradients in the sample.

3. Results and discussion

3.1 Compressive tests

Fig. 5 shows the UHP-SHCC specimens after heated to 200 °C, 400 °C, 600 °C, and 800 °C, respectively. No micro-cracks were visible after heated to 200 °C as shown in Fig. 5(a). But after being heated to 400 °C, micro-cracks were visible on the specimen surface (Fig. 5(b)), and the crack width and density of cracks increased as exposure temperature increased to 600 °C (Fig. 5(c)) and 800 °C (Fig. 5(d)). This is due to

shrinkage of UHP-SHCC at high temperature as evidenced by change in length of UHP-SHCC as shown in Fig. 6. Thermal contraction of UHP-SHCC was measured using a DIL 802 differential dilatometer. The heating rate was set to be 1 °C/min, the same as that used for residual mechanical tests. As shown in Fig. 6, UHP-SHCC started shrinking at 271 °C, and the shrinkage increased with temperature rise. The increase in shrinkage became more rapid at 700 °C and above. This explains the micro-cracks observed in UHP-SHCC specimens after exposure to 400 °C and above.

Compressive stress-strain curves of specimens at ambient temperature and post-heated specimens are presented in Fig. 7 and typical failure patterns of specimens after exposure to elevated temperatures are shown in Fig. 8. The compressive behaviors of UHP-SHCC at ambient and after heated to 200 °C are quite similar as seen in Fig. 7(a)-(b) and Fig. 8(a)-(b). Their failure patterns were characterized by a major inclined shear crack forming along the height of the specimens. For specimens subjected to 400 °C and 600 °C, the pre-peak stress-strain curves were fairly nonlinear as shown in Fig. 7(c)-(d). The initial slopes of their compressive stress-strain responses were lower than the slopes in the middle stage of tests, indicating that the initial cracks in UHP-SHCC closed up during compressive loading. At the beginning of loading the cracks were closing as the load gradually increased, resulting in a lower initial slope. After the cracks were closed, the slopes of the curves gradually increased and followed the general trend of a compression test. Multiple interacting cracks were observed on the specimens after heated to 400 °C

and 600 °C as shown in Fig. 8(c)-(d). For specimens subjected to 800 °C, the compressive behavior (Fig. 7(e)) was very different from all the others mentioned above (Fig. 7(a)-(d)). This could be caused by large thermal crack density and crack width since the specimens were unloaded. As shown in Fig. 8(e), the UHP-SHCC specimen was completely crushed at the middle part.

Fig. 9 gives compressive strength of UHP-SHCC and ordinary SHCC as a function of isothermal temperature. Each data point in Fig. 9 represents the mean value of three samples. Mix proportions of SHCC are given in Table 4. The same compressive test setup and loading scheme as used for UHP-SHCC were adopted for SHCC. Cylinder specimens of the same dimensions as those of UHP-SHCC specimens were used for residual compressive tests on SHCC. For SHCC, the heating rate was 10 °C/min and the dwelling time after reaching target temperature was 2 hour. More information about residual compressive properties of fire-damaged SHCC can be found in [23]. Compressive strength of UHP-SHCC at room temperature is 117.6 MPa as shown in Fig. 9. After exposure to 200 °C, it decreases slightly to 113.1 MPa. However, as exposure temperature increases to 400 °C and 600 °C, compressive strength of UHP-SHCC drops to 65.6 MPa and 56.9 MPa, respectively. When the exposure temperature reaches 800 °C, only 12.3% of the compressive strength of unheated specimens (14.5 MPa) remains.

Compressive strength of UHP-SHCC is much larger than that of SHCC at 30 °C and

200 °C as shown in Fig. 9. But after exposure to 400 °C and 600 °C, compressive strength values of UHP-SHCC are only slightly larger than those of SHCC. After 800 °C, compressive strength of SHCC surpasses that of UHP-SHCC.

From the perspective of strength reduction percentage, compressive strength of UHP-SHCC deteriorates much faster with elevated temperature than that of SHCC as presented in Fig. 10. Microstructure pore coarsening and decomposition of CH and CSH gel are two major factors for strength degradation of SHCC after exposure to elevated temperature [12]. For UHP-SHCC, in addition to those two factors, the shrinkage-induced cracks as shown in Fig. 5(b)-(d) contribute to strength deterioration significantly. Fig. 11 shows a SHCC specimen after exposure to 800 °C. It is quite different from the UHP-SHCC specimen after exposure to 800 °C, as no obvious cracks are visible on the surface of the SHCC specimen by naked eyes. This explains the different trends in compressive strength reduction between SHCC and UHP-SHCC after exposure to 400 °C and above. Residual compressive performance of UHP-SHCC is even poorer than those of siliceous and calcareous concrete [24] at 400 °C and 800 °C as shown in Fig. 10.

3.2 Tensile tests

Tensile stress-strain curves of UHP-SHCC at 30 °C and after heated to 100,200,300, 400, 500, and 600 °C are presented in Fig. 12(a)-(g). In general, both tensile strength

and strain capacity of UHP-SHCC decrease with an increase in exposure temperature, as shown in Fig. 12(a)-(g). UHP-SHCC has a tensile strength of 5.7 MPa and a tensile strain capacity of 2.2% at room temperature by averaging the tensile test results in Fig. 12(a). After exposure to 100 °C, tensile strength and strain capacity of UHP-SHCC decrease to 4.8 MPa and 1.8% by averaging the three tensile test results in Fig. 12(b). At 200 °C and above, tensile behaviors of UHP-SHCC (Fig. 12(c)-(g)) are quite different from those of UHP-SHCC at 30 °C and 100 °C (Fig. 12(a)-(b)). UHP-SHCC exhibits pseudo strain-hardening behavior at 30 °C and 100 °C but shows strain-softening behavior from 200 °C to 600 °C. This is because PE fibers start to melt at 144 °C as shown in Fig. 2.

The temperature-dependent tensile strength reduction factors for UHP-SHCC under various temperatures are plotted in Fig. 13. In contrast to ordinary concrete [24], tensile strength of UHP-SHCC reduces rapidly upon reaching 400 °C. Though 29.3% of tensile strength of UHP-SHCC remains after heated to 600 °C, it is a very small capacity and is negligible.

3.3 Spalling tests

Fig. 14 and Fig. 15 show the UHP-SHCC and reference mortar specimens before and after heating, respectively. The UHP-SHCC specimens remained intact (Fig. 15(a)), but there was a large circumferential crack in one UHP-SHCC specimen. If not for the

bridging action of steel fibers, the UHP-SHCC specimens would have broken into various pieces, such as the reference mortar specimens as shown in Fig. 15(b).

To confirm this finding another three specimens made of PE-FRCC were prepared for spalling tests. The mix proportions of PE-FRCC specimen are almost the same as those of UHP-SHCC, except that no steel fibers are used in PE-FRCC (Table 1). The testing method for PE-FRCC specimens followed that specified in Section 2.3. Fig. 16 shows the PE-FRCC specimens after heating. Severe spalling occurred as evidenced by many broken pieces. This proves that hybrid steel/PE fibers are more effective than mere PE fibers in mitigating explosive spalling at high temperature.

Another interesting finding was that addition of 12.5 kg/m^3 of PE fibers did not prevent explosive spalling, although they have a melting point as low as 144°C . In contrast, PP fibers which melt at about $160\text{-}170^\circ\text{C}$, can effectively prevent explosive spalling at a dosage of 2 kg/m^3 [25]. Therefore, there is a need to investigate why PE fibers are not effective in prevent spalling.

It is widely accepted that explosive spalling of concrete is mainly due to pore pressure buildup inside concrete at elevated temperature [26, 27] and PP fibers can mitigate spalling by increasing permeability of concrete [28]. But how PP fibers function to increase permeability of concrete is a controversial issue. Some researchers think melting of PP fibers generates connected empty spindly channels, thus increasing permeability of concrete [29, 30]. Others think that microcracks induced by thermal

284 expansion of PP fibers are the source of permeability increase [31, 32].

285 To check whether PE fibers create empty channels after melting, FE-SEM was used to
286 characterize status of PE fibers and fiber/matrix interaction before and after melting of
287 fibers. Fig. 17(a)-(b) show SEM images of PE fibers before and after heated to 200 °C,
288 respectively. It can be seen that the melted PE fiber was still present inside
289 UHP-SHCC at 200 °C. This finding was further confirmed by thermogravimetric (TG)
290 curve of PE fibers as presented in Fig. 18. The TG analysis was performed with a
291 heating rate of 10 °C/min and a nitrogen flow rate of 20 mL/min. As shown in the
292 figure, PE fiber does not vaporize until about 500 °C. Fig. 18 also plots the TG curve
293 of PP fiber. It is interesting to find that PP fiber has a higher melting point than PE
294 fiber but a lower vaporization point. It could be one reason that explains PE fibers are
295 less effective than PP fiber in preventing explosive spalling.

296 To find out the penetration behavior of melted PE fibers, elemental mapping was
297 conducted for the area shown in Fig. 17(b) using EDX technique. Fig. 19 shows the
298 corresponding EDX curve and element composition. It further confirms that melted
299 PE fibers are still present in the cementitious matrix. Fig. 20 shows the distribution of
300 carbon element in that area after exposure to 200 °C. A large portion of PE fiber
301 residue is still present in the fiber channel, with a small portion of PE fibers diffusing
302 into microcracks and cementitious matrix. The penetration depth of molten PE fiber
303 into the matrix is very small, approximately 20 μm, due to its high viscosity. It could

304 be another factor accounting for inability of PE fibers to suppress explosive spalling.

305 To find out whether PE fibers initiate microcracks in the matrix around them, SEM
306 images were taken at a location where no initial microcrack was present around a PE
307 fiber before and after exposed to 200 °C as shown in Fig. 21(a)-(b). No microcracks
308 were observed around the PE fiber as shown in the figure.

309 To further study the potential influence of PE fibers on microcrack development, a
310 consecutive series of SEM images (500× magnification) were taken on the same
311 location of a UHP-SHCC sample at room temperature (30 °C) and after exposure to
312 105, 150, and 200 °C. For each exposure temperature, the images were stitched
313 together and microcracks in the stitched image were identified by using adaptive
314 threshold binarization. For comparison purpose, a reference mortar sample was also
315 prepared for crack development analysis.

316 Fig. 22(a)-(d) and Fig. 23(a)-(d) show microcracks of mortar and UHP-SHCC sample
317 after exposure to 30, 105, 150, and 200 °C, respectively. Obviously, both the crack
318 lengths and widths in both the mortar and the UHP-SHCC samples increased with
319 increase in temperature. To quantify microcrack development of mortar and
320 UHP-SHCC, crack density of mortar and UHP-SHCC was calculated according to Eq.
321 (1) [33]:

$$\rho = \frac{1}{A} \sum_{i=1}^n \left(\frac{l_i}{2} \right)^2 \quad (1)$$

with A as the material surface area, n is number of cracks, and l_i is i th crack length.

Fig. 24 shows the crack density of mortar and UHP-SHCC as a function of exposure temperature. Crack density of both mortar and UHP-SHCC increased with temperature. But the increase rate in crack density of UHP-SHCC was much lower than that of mortar. It again proves that addition of PE fibers does not introduce additional microcracks.

4. Conclusion

Fire resistance of UHP-SHCC was examined from two aspects in this paper, i.e., residual mechanical properties and thermal spalling behavior. UHP-SHCC was found to perform poorly at high temperature, although it has excellent performance at ambient condition. The detailed findings are summarized as follows:

- After exposure to 400 °C and above, severe cracking was observed on the surface of UHP-SHCC specimens. The severity of cracking increased with temperature. This was because UHP-SHCC shrank as temperature increased.
- Compressive strength of UHP-SHCC decreased as temperature increased. The decreasing trend was especially obvious when UHP-SHCC specimens were exposed to 400 °C and above. After heated to 800 °C, UHP-SHCC only retained 12.3% of its ambient compressive strength. In general, deterioration in

compressive strength of UHP-SHCC was consistent with the surface crack

development of UHP-SHCC specimens after elevated temperature.

- Similar to compressive strength of UHP-SHCC, its tensile strength also decreased with temperature increase. Tensile strain capacity of UHP-SHCC decreased as temperature increased from room temperature to 100 °C. From 200 °C to 600 °C, UHP-SHCC showed tensile strain-softening behavior instead of strain-hardening behavior.

- UHP-SHCC spalled violently after exposed to 400 °C and PE fibers were found not effective in mitigating explosive spalling of UHP-SHCC although they have a melting point of 144 °C. After melting, a majority of melted PE fibers were still present inside their channels and did not penetrate deep into the matrix.

Furthermore, PE fibers did not introduce additional microcracks after melting.

These two factors explain inability of PE fibers in preventing explosive spalling.

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361

362 **Disclaimer**

363 Any opinions, findings, and conclusions or recommendations expressed in this
364 material are those of the author(s) and do not necessarily reflect the views of the L2
365 NIC.

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Tables

Table 1 Mixture proportions (kg/m³)

Name	Cement 52.5N	Silica fume	Water	PE fiber	Steel fiber	Superplasticizer
UHP-SHCC	1443	361	332	12.5	78	44
Mortar	1443	361	332	-	-	44
PE-FRCC	1443	361	332	12.5	-	44

Table 2 Properties of PE and steel fibers

Fiber	Density, kg/m ³	Length, mm	Diameter, μ m	Tensile strength, MPa	Young's modulus, GPa	Melting temperature, °C
PE	960	13	38	2204	73	144
Steel	7800	13	160	2000	200	1370

Table 3 Number of test specimens

Type of test	Compressive tests	Tensile tests	Spalling tests		
Testing mix	UHP-SHCC	UHP-SHCC	UHP-SHCC	Mortar	PE-FRCC
No. of tests	15	21	3	3	3

Table 4 Mix proportions of SHCC (kg/m³)

Cement 42.5N	Fly ash	Sand	Water	PVA fiber	Steel fiber	Superplasticizer
534.8	652.5	534.8	331.6	19.5	39	5.4

Figures

Fig. 1. Typical uniaxial tensile behaviors of plain concrete, FRC and SHCC

Fig. 2. DSC curves of PE fiber and PVA fiber

Fig. 3. Dog-bone specimen dimensions

(a) Test setup for
compressive test

(b) Test setup for
tensile test

(c) Arrangement of three
LVDTs around the
specimen

477 Fig. 4. Test setups for compressive test and tensile test

478

(a) UHP-SHCC after 200 °C

(b) UHP-SHCC after 400 °C

(c) UHP-SHCC after 600 °C

(d) UHP-SHCC after 800 °C

480 Fig. 5. UHP-SHCC specimens after exposure to (a) 200, (b) 400, (c) 600 °C and, (d)

481 800 °C

481

482

483 Fig. 6. Thermal elongation of UHP-SHCC as a function of temperature

484

(a) 30 °C

(b) 200 °C

(c) 400 °C

(d) 600 °C

(e) 800 °C

486 Fig. 7. Compressive stress-strain curves of UHP-SHCC at 30 °C and after exposure to
487 200, 400, 600, and 800 °C

(a) 30 °C (b) 200 °C (c) 400 °C (d) 600 °C (e) 800 °C

488 Fig. 8. Compressive failure patterns of UHP-SHCC specimens after exposure to

489 different temperatures

489

490

492 Fig. 9. Residual compressive strength of UHP-SHCC and SHCC as a function of

493 temperature

493

Fig. 10. Temperature-dependent compressive strength reduction factors for UHP-SHCC, SHCC, siliceous concrete, and calcareous concrete

Fig. 11. SHCC specimen after exposure to 800 °C

(a) 30 °C

(b) 100 °C

(c) 200 °C

(d) 300 °C

(e) 400 °C

(f) 500 °C

(g) 600 °C

503 Fig. 12. Tensile stress-strain curves of UHP-SHCC at 30 °C and after exposure to 100,
 504 200, 300, 400, 500, and 600 °C

504

505

507 Fig. 13. Temperature-dependent tensile strength reduction factors for UHP-SHCC and
 508 ordinary concrete

508

(a) UHP-SHCC

(b) Reference mortar

Fig. 14. UHP-SHCC and reference mortar specimens before heating

(a) UHP-SHCC

(b) Reference mortar

Fig. 15. UHP-SHCC and reference mortar specimens after 400 °C of heating

515

516

517 Fig. 16. PE-FRCC specimens after 400 °C of heating

518

(a) 30 °C

(b) 200 °C

519 Fig. 17. PE fiber before and after heated to 200 °C

520

Fig. 18. TG curves of PE and PP fibers

Fig. 19. EDX curve and elemental composition for the area shown in Fig. 17(b)

Fig. 20. Distribution of carbon element in the area shown in Fig. 17(b)

(a) 30 °C

(b) 200 °C

Fig. 21. Morphology of UHP-SHCC matrix around a PE fiber before and after heated to 200 °C

(a) 30 °C

(b) 105 °C

(c) 150 °C

(d) 200 °C

534 Fig. 22. Microcrack development of mortar with elevated exposure temperature levels

(a) 30 °C

(b) 105 °C

(c) 150 °C

(d) 200 °C

535 Fig. 23. Microcrack development of UHP-SHCC with elevated exposure temperature

537 levels

538

539

540 Fig. 24. Crack density of UHP-SHCC and mortar sample