Effect of Temperature on the Shear Strength of Ultra-High Performance Concrete

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Abstract

Degradation of shear strength with temperature can be a significant issue for UHPC beams exposed to fire due to their slender cross sections and lower levels of steel reinforcement. This paper presents results of an experimental program conducted to investigate the loss of shear strength in UHPC when exposed to different levels of temperature. UHPC specimens with and without steel and polypropylene fibers were heated to temperatures varying from 20°C to 750°C (68 to 1382°F), and then tested under direct shear through a modification of the JSCE-SF6 (JSCE) method. Results indicate that the shear strength of UHPC can be reduced by approximately 50% when exposed to the 400-500°C (752-932°F)range and that both steel and polypropylene fibers contribute to reduce degradation of UHPC at elevated temperatures.

Keywords: UHPC; Shear strength; Shear failure, High-temperature.

1. Introduction

UHPC offers enhanced mechanical properties when compared to conventional concretes, including significantly higher compressive and tensile strengths, as well as enhanced ductility and an increased strain at ultimate strength (Graybeal). These properties allow the design of more slender structural members with reduced conventional steel reinforcement (Kodur et al.). Specifically, UHPC contributes to improve the shear strength of concrete due to the presence of steel fibers (Solhmirzaei et al.; Pansuk et al.).

The effectiveness of using fiber reinforcement to increase the shear capacity of concrete beams has been widely studied over the last decades (Imam et al.; Al-Ta'an and Al-Feel). It has been shown that the increased tensile strength inhibits the opening of the first crack and increases the ultimate tensile strength of a beam. Besides, the random distribution of steel fibers through the volume of concrete helps in better resisting shear stresses than localized rebars. In UHPC, shear strength is further improved by the high compactness of the cementitious matrix (Ngo et al.). However, when exposed to elevated temperatures, UHPC undergoes faster degradation in its mechanical properties (Banerji and Kodur). This can be an issue for I and box shaped UHPC beams and girders due to the use of slender webs and low shear reinforcement, which can lead to early shear failure and lower fire resistance (Kodur and Gil).

Determining the level of degradation of the mechanical properties of concrete with temperature is important to guide the design of concrete structures against fire. Direct shear strength tests offer a simple alternative to understand the shear behavior of concrete at the material level. This study investigates the effect of temperature on the shear strength of UHPC specimens exposed to elevated temperatures.

2. Experimental Program

An experimental program was designed to undertake direct shear strength tests on UHPC specimens exposed to elevated temperatures. Specimens with and without steel and polypropylene fibers were exposed to five levels of temperature, 20°C (68°F), 200°C (392°F), 400°C (752°F), 600°C (1112°F), and 750°C (1382°F), in the range of temperature experienced by structural members under typical fire exposure scenarios. A modification of the Japanese JSCE-SF6 (JSCE) method is utilized to undertake shear strength tests. The shear behavior of specimens is evaluated in the entire range of loading until failure.

2.1. Materials and Specimens

Table 1 presents the mixture proportions and properties of the three batches of UHPC used in this study, namely UHPC (plain, without any fibers), UHPC-ST (reinforced with steel fibers), and UHPC-ST-PP (reinforced with both steel and polypropylene fibers). Type I Portland cement, slag, silica fume, limestone powder, silica sand, and natural sand were used in all batches. Due to the high material cost of UHPC, a controlled amount of coarse aggregate (26A limestone) with maximum diameter of 12.7 mm (0.5 in) was added to all batches to reduce the content of mineral admixtures and fine aggregates, while maintaining its high packing density. To achieve adequate fiber dispersion and workability, 48.5 kg/m^3 (3 lb/ft^3) of high-range water-reducing admixture (Chryso 150 with 31% of solids content) was used together with potable water in a water-to-binder ratio of 0.14. For UHPC-ST and UHPC-ST-PP, steel fibers of straight type (without hooks) with 0.2 mm (0.008 in) diameter and 13 mm (0.51 in) length were added in 1.5% by volume fraction. In addition, for the UHPC-ST-PP batch, polypropylene fibers having a length of 13 mm (0.51 in) and a melting point of 160°C (320°F) were added to the mixture in 0.11% by volume fraction.

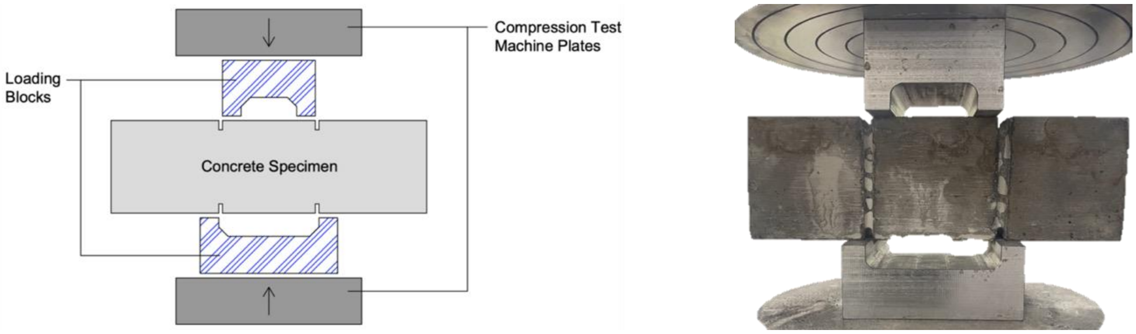
For undertaking direct shear strength tests, prismatic specimens measuring 40x50x150 mm (1.57x1.97x5.91 in) were cast. These dimensions are lower than JSCE-SF6 (JSCE) prescriptions, which consists in specimens of 150x150x500 mm (5.91x5.91x19.69 in). The decision of scaling the specimens down was made to accommodate limitations in the test equipment, such as the heating furnace and the strength testing machine. For preparation of the specimens, a 5 mm-notch (0.2 in) was made all around the specimens with the help of a power saw in order to induce shear failure through the shear plane. This procedure was proposed by Mirsayah and Banthia and has been followed by other studies as well. The notched specimens were then stored in a ventilated oven at 105°C (221°F) for seven days prior to their test date to remove excessive moisture and prevent explosive spalling during the heating procedure.

Table 1 – Batch mix proportions in kg/m^3 of different batches of UHPC

Component	**UHPC kg/m^3 (lb/ft^3)**	**UHPC-ST kg/m^3 (lb/ft^3)**	**UHPC-ST-PP kg/m^3 (lb/ft^3)**
Coarse aggregate (26A limestone)	516.7 (32.3)	516.7 (32.3)	516.7 (32.3)
Natural sand	543.9 (33.9)	543.9 (33.9)	543.9 (33.9)
Silica sand (#52)	299.2 (18.7)	299.2 (18.7)	299.2 (18.7)
Cement (Type I)	509.9 (31.8)	509.9 (31.8)	509.9 (31.8)
Silica fume	224.4 (14.0)	224.4 (14.0)	224.4 (14.0)
Slag	101.9 (6.4)	101.9 (6.4)	101.9 (6.4)
Limestone powder	183.6 (11.5)	183.6 (11.5)	183.6 (11.5)
Water	121.4 (7.6)	121.4 (7.6)	121.4 (7.6)
Superplasticizer HRWR (31%) Chryso 150	48.5 (3.0)	48.5 (3.0)	48.5 (3.0)
Steel fibers (1.5% vol.)	-	125 (7.8)	125 (7.8)
Polypropylene fibers (0.11% vol.)	-	-	1.6 (0.1)
Water-binder ratio	0.14	0.14	0.14
Binder-aggregate ratio	0.75	0.75	0.75
Compressive strength 28th day – MPa (ksi)	151 (21.9)	168 (24.4)	160 (23.2)
Compressive strength 90th day – MPa (ksi)	164 (23.8)	178 (25.8)	173 (25.1)

2.1. Test Equipment and Set-Up

The equipment for evaluating the shear strength of UHPC at elevated temperatures consisted of an electric heating furnace and a strength testing machine. A cylindrical electric furnace capable of heating at a specified heating rate (maximum to 10°C/min or 50°F/min) and maintaining a target temperature for a specified period of time was utilized to heat the specimens. For loading, a 2670 kN (600 kips) load-controlled Forney compressive testing machine was utilized. This machine has a digital interface that allows the control of different test parameters, such as loading rate and the failure point, and is capable of capturing the resulting deflection during the test. To apply shear load, a special apparatus was developed based on JSCE-SF6 (JSCE) test method. It consisted of a loading block and a support block, both made of steel with two loading knife edges each. A narrow span of 0.15 mm (0.006 in) is left between the edges of the loading and the support blocks to impose a concentrated shear stress over the specimen's notched section, where failure is expected. Figure 1 shows a schematic illustration and a photograph of the final test set-up adopted for undertaking shear strength tests.



(a) Schematic (b) Photograph

Figure 1 - Specimen and apparatus for shear strength test

2.3. Test Procedure

The UHPC specimens were tested in the unstressed testing regime. This testing regime aimed to simulate the fire behavior of concrete in a structural member with a small pre-load, such as the web of beam exposed to predominant flexural loads. Therefore, specimens were first heated to a target temperature without the application of any load. A heating rate of 2°C/min (36°F/min) was selected based on previous studies (Banerji and Kodur). After reaching the targeted temperature, specimens were kept on that temperature for 30 to 45 minutes, so the target temperature is reached throughout the core (inner parts) of the specimen. Two specimens were heated at the same time in the furnace. While the first specimen was removed from the furnace to be tested, the other one remained in the furnace at the target temperature until the first test was completed.

The heated specimens were moved into the strength test machine where the shear test apparatus was installed. The process of moving the specimen from the furnace to the strength test machine and initiating the test took approximately two minutes. The test was conducted by applying load continuously until failure. Load was applied at a rate of 2 kN/min (550 kips/min), which is within the shearing stress rate of 0.06 to 0.1 MPa/second (8.7 to 14.5 psi/second) prescribed by JSCE-SF6 (JSCE). Displacement was measured during the test by the movement of the loading plates generated by the strength test machine. Applied load and displacement data were recorded at a frequency of 0.55 Hz. Figure 3 presents the increase of loading ratio during one of trial tests.

3. Results and Discussion

Table 2 presents a summary of results from the tests conducted, including maximum temperature of exposure and the ultimate shear strength. The peak load (P_{max}) obtained in the tests was converted to ultimate shear strength (τ_{max}) through the following equation:

$$\tau_{max} = \frac{P_{max}}{2\,(b_{eff}\,.\,d_{eff})} \tag{1}$$

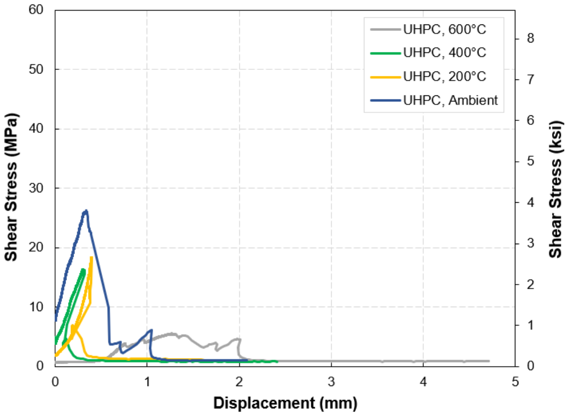
where b_{eff} and d_{eff} are the effective width and depth of the specimen, respectively. These dimensions were determined as the average of two measurements taken on each notched section of each specimen before the test. It should be noted that this equation assumes an elastic response and represents the average stress distribution between both shear sections.

Table 2 - Summary of test results

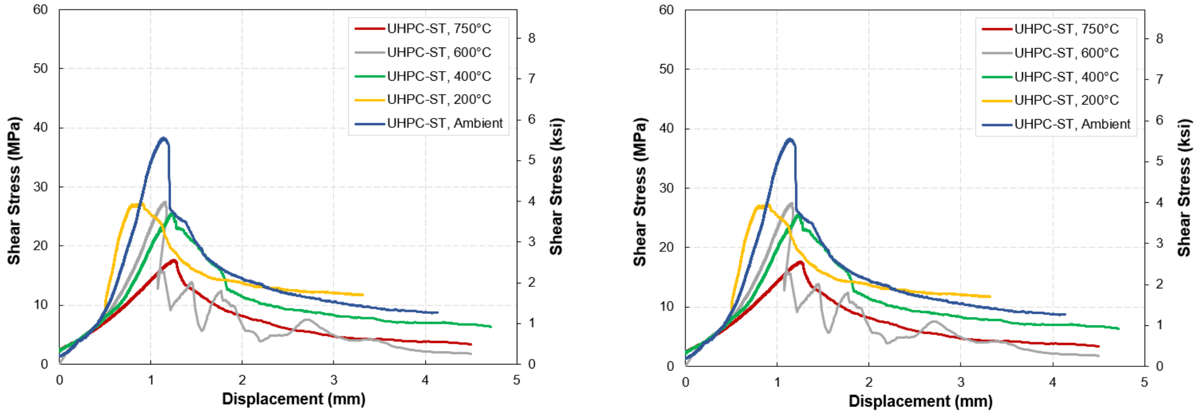
Concrete type	**Specimen name**	**Temperature °C (°F)**	**Shear strength MPa (psi)**
UHPC	U-01	20.0 (68.0)	26.3 (3814.5)
	U-02	199.8 (391.6)	18.4 (2668.7)
	U-03	414.3 (777.7)	16.4 (2378.6)
	U-04	614.9 (1138.8)	5.6 (812.2)
UHPC-ST	U-S-01	20.0 (68)	38.3 (5555.0)
	U-S-02	20.0 (68)	37.7 (5467.9)
	U-S-03	223.9 (435.0)	20.2 (2929.8)
	U-S-04	223.9 (435.0)	27.2 (3945.0)
	U-S-05	414.3 (777.7)	25.6 (3713.0)
	U-S-06	414.3 (777.7)	35.8 (5192.4)
	U-S-07	614.9 (1138.8)	27.5 (3988.5)
	U-S-08	614.9 (1138.8)	10.8 (1566.4)
	U-S-09	772.0 (1421.6)	14.2 (2059.5)
	U-S-10	772.0 (1421.6)	17.6 (2552.7)
UHPC-ST-PP	U-SP-01	20.0 (68)	49.6 (7193.9)
	U-SP-02	20.0 (68)	20.9 (3031.3)
	U-SP-03	227.9 (442.2)	19.7 (2857.2)
	U-SP-04	227.9 (442.2)	38.6 (5598.5)
	U-SP-05	423.2 (793.8)	35.7 (5177.9)
	U-SP-06	423.2 (793.8)	32.7 (4742.7)
	U-SP-07	621.8 (1151.2)	25.8 (3742.0)
	U-SP-08	621.8 (1151.2)	23.0 (3335.9)
	U-SP-09	775.6 (1428.1)	13.9 (2016.0)
	U-SP-10	775.6 (1428.1)	12.6 (1827.5)

Shear stress-displacement curves for multiple specimens tested at different levels of temperature are shown in Figure 2. It can be seen in these graphs that for some specimens there were a lot of fluctuations with abrupt increase and decrease of load. This behavior reflects crack openings and the effect of steel fibers bridging cracks in the specimen. Some variation can also be observed between specimens tested under similar conditions, as shown in Table 2. These variations can be attributed to fiber orientation due to the fact that steel fibers are randomly dispersed in the mixtures.

As expected, plain UHPC specimens presented an abrupt and sudden failure, as well as lower shear strength than the specimens reinforced with steel fibers. These specimens lost their ability to carry load instantly after cracking, without a residual load-carrying capacity beyond the peak load. There was not much difference in the behavior of specimens exposed to 200°C (392°F) and 400°C (752°F), even though there was a decrease of approximately 35% in shear strength, when compared to the specimen tested at ambient conditions. For the specimen exposed to 600°C (1112°F), there was a very significant decrease of shear strength of about 80% and a well-defined load peak cannot be observed. It should be noted, however, that the shear strength obtained for plain UHPC represents a significant portion of the shear strength of UHPC specimens reinforced with steel fibers. Besides, these strength values are much higher than obtained for plain conventional concretes in previous studies (Mirsayah and Banthi).



(a) UHPC



(b) UHPC-ST

(c) UHPC-ST-PP

Figure 2 - Shear stress-displacement curves for specimens at different levels of temperature

Fiber reinforced UHPC specimens were able to support higher shear stresses than plain UHPC. The specimens containing steel and polypropylene fibers sustained higher shear stresses than the specimens reinforced only with steel fibers. This can be attributed to the fact that polypropylene fibers melt around 160°C (320°F), creating voids inside concrete that help relieve some of the thermal stresses generated due to the development of high pore pressure during heating (Kodur; Kodur and Phan). However, a steep degradation of shear strength was still observed when specimens were exposed to higher levels of temperature. In both situations, degradation of shear strength reached 50% of its original strength at room temperature. While it is possible to see a clear degradation on the peak of stress for specimens containing polypropylene fibers, the peak of stress in specimens containing only steel fibers was very similar along the temperature range between 200°C (392°F) and 500°C (932°F).

Figure 3 presents shear strength as a function of the temperature of exposure. It can be seen that shear strength decreases with the increase of temperature and such behavior is dependent on the type of fiber reinforcement in the specimens. Such relationship can be used to model the fire behavior of UHPC beams exposed to fire and help to predict the shear capacity of the fire exposed UHPC beams.

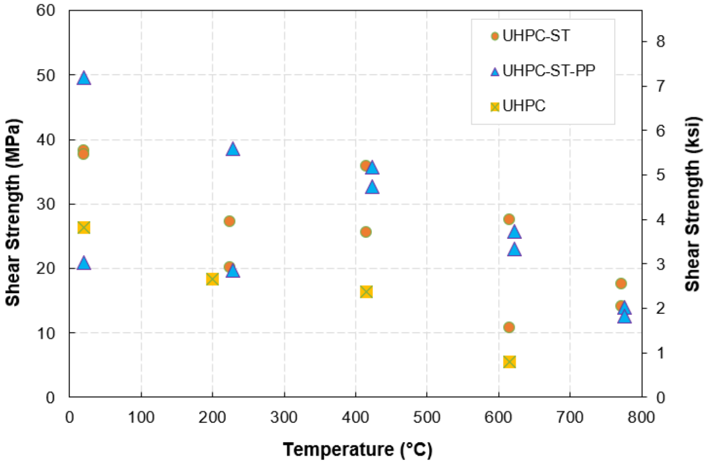


Figure 3 - Degradation of shear strength with temperature

4. Conclusions

Based on the results presented in this study, the following conclusions can be drawn:

- The JSCE-SF6 method with the modifications proposed in this study can be effectively applied to obtain shear strength of UHPC under high temperature exposure, as encountered in a fire situation.
- Both steel and polypropylene fibers provided improvements in shear strength at elevated temperatures. While steel fibers had a larger contribution due to its ability to bridge the cracks in the specimen, polypropylene fibers contributed to a higher shear strength through melting of fibers during the heating process, which lead to release of pore pressure and associated tensile stresses. This reduced the formation of microcracks during heating and increased its ability to resist higher loads.
- The three types of UHPC experienced some loss of shear strength when exposed to 200°C (392°F), but the effect of temperature became more pronounced when exposed to temperature levels higher than 400°C (752°F). Without fibers, UHPC experienced much faster degradation and the contribution of polyproline fibers became less pronounced at higher temperature levels.

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