Proposed Residual Punching Strength-Temperature Relationships for High Strength Concrete Panels Exposed to Elevated Temperatures

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Received: March 7, 2019 Accepted: May 18, 2019 Online Published: June 1, 2019

doi: 10.23918/eajse.v4i4p68

Abstract: This work studies the behavior of high strength concrete (HSC) slabs after exposure to high temperatures, and proposes punching strength-temperature relationship for HSC panels based on previous experimental work of the author, which tested reinforced HSC slab specimens subjected to four exposure levels. The HSC slabs have cube compressive strength of 94 MPa. The paper investigates the punching strength of HSC panels, load deflection behavior, crack patterns and failure modes and characteristics, as the temperature level of exposure is increased. The punching and compressive strengths reduced with the increase in the temperature of exposure. A parabolic equation is established that relates both strengths with the temperature of exposure. When temperature reaches 700 ºC, the residual punching strength obtained was 54% of that at room temperature, and the type of failure was a flexural failure followed by punching shear failure.

Keywords: Punching Strength, High Strength Concrete, High Temperature Exposure

1. Introduction

The exposure of structural members, including reinforced concrete slabs, to elevated temperatures causes changes in concrete and its reinforcing steel bars properties and in slabs structural response. A critical failure type of flat plate slab systems is punching shear; due to the two-way shear action around supports or due to applied concentrated forces on the slab systems.

When elevated temperatures are applied on flat plates, it is expected that the said changes in material properties and structural behavior would affect the punching strength of flat plates significantly. Thus, it is necessary to investigate and predict the reductions in punching strength in flat plates and relate reductions in punching strength to the corresponding reductions in compressive strength after exposure to elevated temperature. Lie and Leir (1979) studied the effect of the various factors affecting temperature of concrete slabs when exposed to fire. The specimens' slab thicknesses were 60, 100 and 150mm. The work followed (ASTM E119-2000a). It was found that slab thickness affects the transfer of heat from fire to slab.

Shirley, Burg and Fiorato (1988) evaluated the fire endurance of HSC slabs specimens subjected to fire following (ASTM E119-2000a). They concluded that there is no significant effect of silica fume on fire endurance of slabs. No spalling or explosive failure was observed. Fahmi and Heidyat (1996) investigated ordinary reinforced concrete slabs behavior when exposed to elevated temperatures and then cooled gradually. Eighteen reinforced concrete slab specimens were subjected to a range of temperature from 25 to 700 °C. The flexural strength was found decreased as the temperature was increased. Venkatesh et al. (2005) investigated the performance of concrete slabs reinforced with carbon fiber-reinforced polymer CFRP and with glass fiber-reinforced polymer GFRP bars when subjected to fire. Results indicated similar performance of heat transfer in concrete slabs reinforced with CFRP/GFRP bars to that of those reinforced with steel bars. The main factors affecting the fire resistance of slabs were the concrete cover thickness and reinforcement type. Al Numan and Muhammed (2012) studied experimentally punching strength of normal and high strength concrete, and lightweight concrete LWC panels exposed to high temperatures. They stated that elevated temperatures cause reduction in punching capacity for up to 46% at 700°C from the control capacity at room temperature.

From this review, it can be said that more work is needed discussing the influence of elevated temperature on both the punching strength and corresponding compressive strength of reinforced concrete HSC panels and on their failure pattern. This work addresses these issues, and establishes strength – temperature relationships.

2. Program of the Work (Al Numan and Muhammed (2012))

In the work, four reinforced concrete slab specimens were made. Their dimensions were (500 *500 *50mm) (length * width* thickness).

High strength concrete of cube compressive strength of (93.7 MPa) was obtained. The panels were reinforced with a steel ratio of 0.005. The panels were cured in a water basin for 28 days, then dried at room conditions for seven days. The panels thereafter were subjected to 3 levels of elevated temperature using electric furnace for three durations of 1 hour, 2 hours, and 4 hours. The testing performed the day after. They were loaded to failure under a concentrated load through a 30 mm square central column. The clear spans of the square simply supported panels were 0.47 m. The panels were suppressed at corners to prevent lifting up of corners. Companion 150mm cubes were used to measure compressive strength of every concrete panel at every temperature exposure.

2.1 Materials

All materials used in the work are conformed to the Iraqi specification (I.O.S) 1984. Ordinary Portland cement has been used which is complying with the Iraqi specification [(I.O.S) No.5/1984]. Normal weight fine aggregate is used and complies with Iraqi specification [(I.O.S) No.45/1984]. Coarse aggregate is used and complies with Iraqi specification [(I.O.S) No.45/1984] crushed gravel of maximum size of 10 mm is used. Six-mm plain wires were used as tensile flexural reinforcement. The wires' average yield strength was 380 MPa.

2.2 Concrete Mix

The panels were named as Group H. The mix proportioning of HSC panels of this work is detailed in Table 5.

Table 1: Panels mix proportions

Slap Group	Cement Content (kg/m^3)	Aggregate content		Water content (kg/m^3)	Superplasticizer % by weight of cement	w/c ratio	Slump (mm)	Average28-day cube compressive Strength (MPa)	Concrete density (kg/m^3)
		Sand (kg/m^3)	Gravel (kg/m^3)						
H	560	635	1085	148	1.5	0.264	56	93.7	2432

Figure 1: The furnace

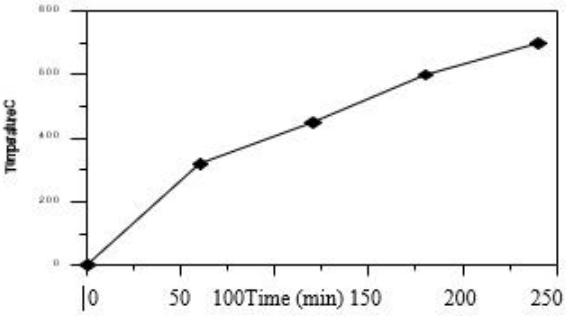

Figure 2: Furnace's temperature – time relation

2.3 Durations and Range of Temperatures

An electric furnace of capacity 1200 °C (Figure 1) was used to elevate the temperatures of the specimens (slabs and cubes). An electronic thermostat controls it. The temperatures readings were taken from two thermometers located at top and mid-height of furnace. The furnace's temperature-time relation is presented in Figure 2. It shows the time-temperature coordinate points of (0 min., room temp.), (60 min., 320 °C), (120 min., 450 °C), and (240 min., 700 °C). Two panels and three cubes were subjected to the said exposure durations. The other two panels and three cubes were tested at room temperature. Figures (3) and (4) show the testing machine and loading arrangement (Al Numan & Muhammed, 2012).

Figure 3: Testing machine

Figure 4: Loading arrangement

3. Punching Strength of Slabs Exposed to High Temperatures

The reinforced HSC panels were designed such that punching will occur before flexural failure. The strengths, deflections and failure modes of HSC slab specimens at high temperatures are shown in

Table (6). It is seen that the ultimate load capacity and compressive strengths of panels decrease as the temperature increased.

Table 2: Strengths, deflections and failure modes of HSC slab specimens at high temperatures

Specimen	Temperature Level (°C)	Compressive Strength (MPa)	Residual Compressive Strength (MPa) (%)	Residual Ultimate Load (kN)	Residual Load (%)	Deflection Failure (mm)	Mode of Failure
HC	21 (room temp)	93.7	100	26	100	7.74	punching
H1	320	91.8	98	24.5	94.2	11.72	punching
H2	450	62.6	66.8	18	69.2	4.91	punching
H4	700	36.2	38.6	14	53.8	2	Flexural

At (320˚C), the punching strength decreases by (5.8%), but for (450˚C and 700˚C), it decreases by (30.8% and 46.2%) from original strength respectively. For compressive strength, it dropped from 93.7 MPa at room temperature to 91.8 MPa (2% drop) at 320˚C, to 62.6 MPa (33.2% drop) at 450˚C, to 36.2 MPa (61.6% drop) at 700˚C, respectively. It can be said the drop in ultimate capacity of the panel follows the drop in the concrete compressive strength; see Fig. 5 which displays variation of both the percentage of residual compressive strength and the percentage of residual punching strength, with the temperature of heat exposure. The parabolic regressions of both relationships are shown so close to each other's.

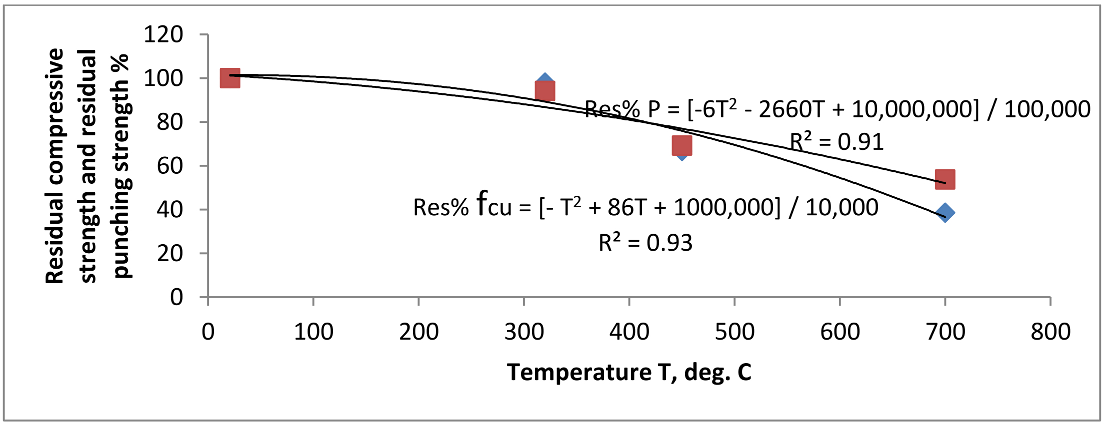

Figure 5: Variation of residual strengths for HSC panels with temperature exposures

4.1 Proposed Punching Strength - Temperature Relationship

From Figure 5, the percentages of reduction in punching strength, % Res. *P*, of HSC panel exposed to high temperatures can be related to the temperature of exposure, *T*, ºC, as expressed below, equation 1, and shown in Figure 5. The parabolic regression has excellent correlation.

$$\% \text{ Res. } P = [-6T^2 - 2660T + 10{,}000{,}000] / 100{,}000 \qquad [1]$$

The range of temperature is between 21ºC and 700ºC.

4.2 Proposed Punching-, Compressive Strength-Temperature Relationship

The similar percentages of reduction in punching strength, *P*, kN, and compressive strength, f_{cu}, MPa, of HSC panel exposed to high temperatures allow constructing a relationship between both strengths and the temperature of exposure, *T*, ºC, as expressed below, equation 2, and shown in Figure 6. The parabolic regression has excellent correlation.

$$[Res.\ P / Res.\ f_{cu}] = [2T^2 - 800T + 1{,}000{,}000] / 1000{,}000 \qquad [2]$$

The range of temperature is between 21ºC and 700ºC.

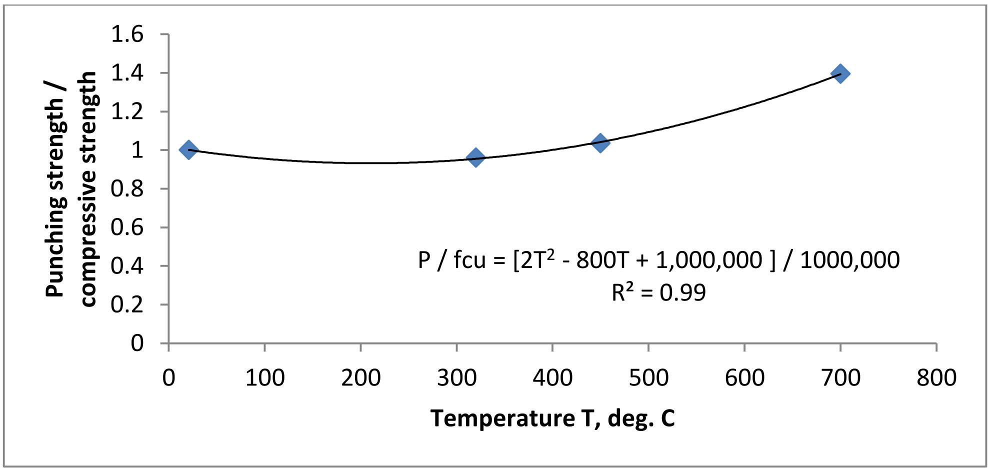

Figure 6: Relationship between both punching and compressive strengths, and the temperature of exposure

5. Load – Deflection Relationship

The load deflection relationships of all HSC slab specimens under all temperature exposures are presented in Figure 7. The load-deflection curve at room temperature exhibits initially elastic or un-cracked stage, then cracking stage; and finally plastic stage, at which reinforcements yield and cracks widen. At 320˚C, these three response stages are also obtained but with slightly less strength and deflection. At 450˚C, however, the three response stages are shown but exhibits lower stiff response and deflection indicating lower strength, stiffness and greater brittleness.

At 700˚C, the load deflection curve is shrunk, presenting the lowest stiffness and deflection, which indicates deteriorated strength, stiffness and greatest brittleness. The extreme temperature has damaged the concrete and steel bars and caused thereby reduction in modulus of elasticity of concrete, steel and increase of number and width of cracks; a significant reduction in rigidity. However, from the trends seen in Figure 7, and comparing with results of Fahmi and Heidyat (1996); Harada et al. (1972); and Umran (2002), it can be claimed that the cracks formation and intensity in HSC panels at high temperature might be less than normal strength concrete ones.

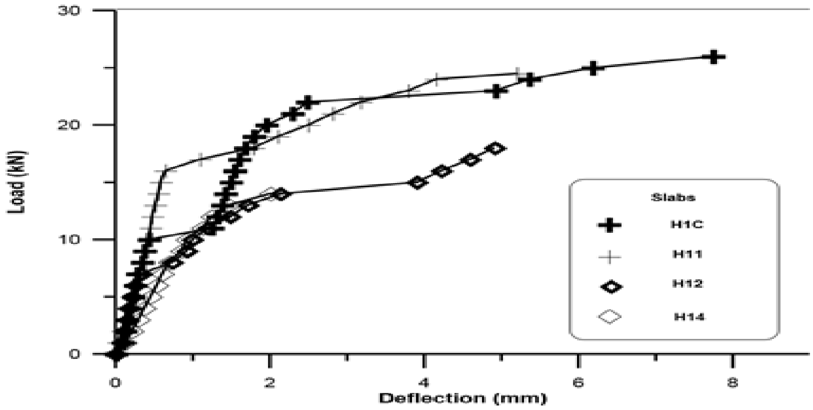

Figure 7: Load–Deflection relationship for HSC panels at various temperature exposures (Al Numan & Muhammed, 2012)

6. Crack Pattern

For all panels, radial cracks form in the tension surface below and around the loaded area and extend from a perimeter towards the specimen edges. During loading, the number of cracks increased at the center of panels, and cracking over the panels' supports occurred. As the temperature of exposure is elevated, this cracking behavior appears earlier at lower loads as temperature increases. Dominant punching failure has occurred at room temperature, 320˚C, and 450˚C exposures. Dominant flexural failure combined with minor punching is observed for HSC panels at maximum temperature (700 ˚C), in which yield lines and punching zone spalls are formed at failure. Figure (8) shows the tested panels' failure patterns.

7. Failure Zones Area, Perimeter and Angle

Figure 8 shows shapes of punching failure zones of the tested panels. It is generally as close as quadrilateral in plan, however, it may be considered circular or square. The (ACI 318-2014) code recommends reasonably shapes following support or loading configurations. The perimeters, failure angles and measured areas of failure zones were measured using AutoCAD program, and listed in Table (7). It can be concluded that heated panels have greater failure zone in general than that for panels tested at room temperature especially for the panels exposed to 320˚C. The increasing percentage in area for the panels exposed to 320°C is 115.6% more than that for panels tested at room temperature. For the panels exposed to 450 ˚C, the corresponding percentage is 30.75%.

Figure 8: Failure pattern of HSC slab specimens (Al Numan & Muhammed, 2012)

Table 7: Failure zones area, perimeter and angle

Group	Specimen Identification (exposure, $^{\circ}$C)	Measured Area (mm^2)	Measured Perimeter (mm)	Failure Angle (degree)
H (HSC)	H1C (Room temperature)	28402	825	33
	H11(320 $^{\circ}$C)	61250	1064	22
	H12(450 $^{\circ}$C)	37136	890	29

7. Conclusion

The following conclusions are drawn:

Elevated temperatures cause reduction in concrete compressive strengths for HSC. The reduction percentages after exposure to (320 ^{o}C, 450 ^{o}C and 700 ^{o}C) are about (2 %, 33.2 % and 61.6 %) from original strength respectively.

Elevated temperatures cause reduction in ultimate load capacity for HSC panels at temperatures (320 ^{0}C, 450 ^{0}C and 700 ^{0}C), recorded reductions are (5.8 %, 30.8 % and 46.2 %) from the original load respectively. Approximately similar percentages of reductions are found for both compressive strength and punching strength with increasing temperature of exposure. Proposed equations are established relating residual punching and compressive strengths to the exposure temperature for HSC panels. the load – deflection curves of HSC panels had shrunk and become less stiff as the temperature increased, which indicate deteriorated strength, stiffness and greater brittleness. At 700 ^{0}C exposure, dominant flexural failure combined with minor punching is observed for HSC panels. Heated panels have greater area of failure zone in general than corresponding area for panels tested at room temperature. the failure angle of the punching zone decreases as the temperature rises.

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