International Journal of Architectural, Civil and Construction Sciences
ISSN: 2415-1734
Vol:9, No:5, 2015

Effect of Fiber Types and Elevated Temperatures on the Bond Characteristic of Fiber Reinforced Concretes

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Abstract**—**In this paper, the effects of fiber types and elevated temperatures on compressive strength, modulus of rapture and the bond characteristics of fiber reinforced concretes (FRC) are presented. By using the three different types of fibers (steel fiber-SF, polypropylene-PPF and polyvinyl alcohol-PVA), FRC specimens were produced and exposed to elevated temperatures up to 800 ºC for 1.5 hours. In addition, a plain concrete (without fiber) was produced and used as a control. Test results obtained showed that the steel fiber reinforced concrete (SFRC) had the highest compressive strength, modulus of rapture and bond stress values at room temperatures, the residual bond, flexural and compressive strengths of both FRC and plain concrete dropped sharply after exposure to high temperatures. The results also indicated that the reduction of bond, flexural and compressive strengths with increasing the exposed temperature was relatively less for SFRC than for plain, and FRC with PPF and PVA.

Keywords**—**Bond stress, Compressive strength, Elevated temperatures, Fiber reinforced concrete, Modulus of rapture.

I. Introduction

CONCRETE is commonly considered to have good fire resistance but chemical and physical reactions occur at elevated temperatures [1]-[4]. As a consequence, exposure to high temperatures may cause considerable variations in the physical and mechanical properties with irreversible loss of strength and stiffness [1], [5]. This behavior is influenced by microcracking and spalling, generated by thermal incompatibility of the various components, the type of aggregate, heating rate, initial moisture content and permeability. For the cement matrix, thermal treatments to high temperatures cause a reduction in the amount of chemically bonded water in the hydrate phase. In particular, with an increase in temperature, gel-like hydration products are decomposed followed by a removal of hydroxide from the calcium hydroxide [1], [6]. Moreover, the concrete has some percentage of water. When they exposed to high temperatures, the water within the internal concrete structure passes to the gaseous state resulting in an increase of pressure in the concrete voids. If concrete offers resistance to the escape of the water vapor, high pressures will be developed in the internal concrete structure, which can lead to very brittle concrete failure.

To avoid situation described above, several studies have been performed worldwide for the development of concrete compositions of enhanced fire behaviors. Concretes with steel (SF), polypropylene (PPF) and polyvinyl alcohol (PVA) fibers showed good behaviors in fire in the controlling of the spalling [7]–[9]. In case of fire the PPF and PVA fibers melts around 170 and 230^{o}C, respectively, and will create a network of micro-channels in the concrete which served as a way for the release of water vapor to the outside, and, consequently, will avoid the brittle type failure in which explosive and the concrete becomes separated from the reinforcing bars. Pullout test is frequently used to determine the bond between steel reinforcing bars and the surrounding concrete [10]–[12].

The present study investigates the contribution of three types of fibers (steel fiber (SF), polypropylene fiber (PPF) and polyvinyl alcohol (PVA) fiber)) on the compressive and flexural strengths and bond stress between concrete and steel bar at high temperatures in the range of 200–800^{o}C. The fibers were incorporated in concrete separately at a volumetric fraction of 1%. The bond and flexural strengths were evaluated using direct pullout and four point bending tests, respectively.

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II. Experimental Program

A. Materials

An ordinary Type-I Portland cement (CEM I 42.5R) and a F-type fly ash (FA) were used as binder. In all mixes, 40% of the total binder content was FA. Natural sand and 10-mm maximum size gravel stone were used as fine and coarse aggregates, respectively.

In order to improve the flowability of concrete, a polycarboxylic-ether type HRWR was used. Three types of fibers with distinct properties were selected. SF, PPF and PVA were added to the nonfibrous mixture at a concentration of 1% for the SF, PPF and PVA-reinforced concretes. The properties of the three types of fibers appear in Table I. Four concrete mixtures in total were produced and tested for compressive, flexural and bond stress properties; details of the mixtures are provided in Table II.

TABLE I
PROPERTIES OF THE FIBERS

Property	SF	PPF	PVA
Nominal strength (MPa)	1000	760	1620
Apparent strength (MPa)	690	550	1092
Diameter (µm)	20	40	39
Length (mm)	13	19	8
Young's modulus (GPa)	--	4.11	42.8
Elongation (%)	--	>30	6.0
Density (kg/m^3)	7170	910	1300

TABLE II
MIX PROPORTIONS

Mix no	w/b	W	C	FA	fa	ca	HRWR	SF	PPF	PVA
M1	0.35	175	300	200	826	895	0.6	0	0	0
M2	0.35	175	300	200	812	880	1.2	71.7	0	0
M3	0.35	175	300	200	812	880	1.4	0	9.1	0
M4	0.35	175	300	200	812	880	1.4	0	0	13

*W: Water; C: Cement; FA: Fly ash; fa: fine aggregate; ca: coarse aggregate HRWR: High-range water reducer; SF: Steel fiber; PPF: Polypropylene fiber; PVA: Polyvinyl alcohol fiber; all values are kg/m^3

B. Preparations of Mixtures

The concrete mixtures were prepared in a laboratory mixer. Fresh properties were measured just after production and detailed information about those were presented in [13]. From each concrete mixture, fifteen 100 × 200-mm cylinders and fifteen 355×50×76 mm prisms were cast for the determination of compressive and bending strength. After casting, all the molded specimens were covered with plastic sheets and water-saturated burlap, and stored in the casting room for 24 h. They were then demoulded and transferred to the moist-curing room at 23 ± 2^{o}C and 100% relative humidity until age of 28 days.

C. Pullout Test Specimen Preparation

The bond properties between 15 mm diameter reinforcing bar and fiber reinforced concretes were studied by conducting direct pullout test of reinforcing bars embedded in the 100 × 200 mm cylinder specimens. During the experimental study, 175 mm embedded lengths of rebar were used. The positions of reinforcing bars at the time of casting and the direction of concrete casting are shown in Fig. 1. The bottom side cover thicknesses for all specimens were 25 mm. Reinforcing steel bars having 15 mm nominal diameter and 400 MPa nominal yield strength were used for pullout tests.

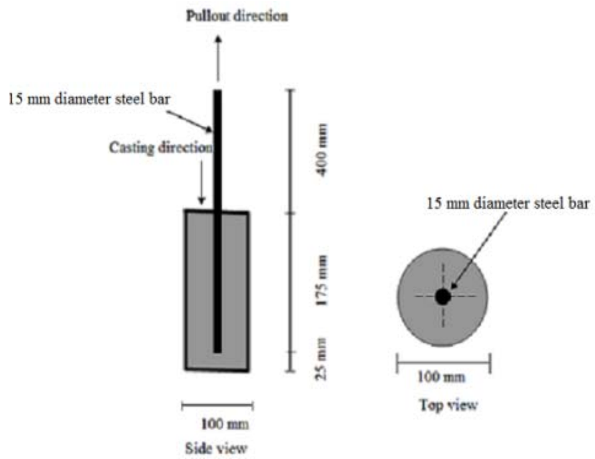

Fig. 1 Pullout test specimen

After casting, the specimens were sealed with wet burlap and stored in a temperature controlled environment. All specimens were demoulded after 24 h and transferred to a standard moist room at 23 ± 2^{o}C and 100% humidity until they were tested.

D. Heating Procedure

After 28 days standard moist room curing (at 23 ± 2^{o}C and 100% humidity), specimens for pullout, flexural and compressive strengths were subjected to temperatures of 200, 400, 600, and 800^{o}C for 1.5 hours by means of an computer controlled, electrically heated furnace In the furnace, the specimens were heated at a constant rate of approximately 15°C/min to reach the prescribed temperatures.

Three specimens from each mixture for each test were left in laboratory air as controls. When the targeted peak temperature was reached, the furnace temperature was maintained constant for 90 minutes to achieve the thermal steady state [12]. After that, the samples were allowed to cool naturally to room temperature.

III. TESTING METHODS

A. Pullout Test

The load–slip relationship for the single reinforcing bar pullout tests was established using a load cell, a hydraulic jack, a mounting system, and a linear variable differential transducer (LVDT).

The pullout loads versus slippage readings were acquired and processed to obtain the relationship between bond stress and free-end slip [12]. The pullout load is converted into average bond stress (U) based on the embedment length and reinforcing bar perimeter using (1):

$$\mathrm{U} = \frac{\mathrm{P}}{\pi.\mathrm{d_b}.\mathrm{l_e}} \tag{1}$$

where P, d_b, and l_e refer to the peak load, bar diameter (15 mm), and embedment length (175 mm), respectively.

B. Bending and Compressive Strength Tests

A four-point bending test was performed under displacement control at a loading rate of 0.005 mm/s on a closed-loop controlled servo-hydraulic material test system. During the flexural tests, the load and the mid-span deflection were recorded on a computerized data recording system. The bending load is converted into average flexural strength (σ_f) based on the maximum load, span length and specimen section dimensions by using (2).

$$\sigma_f = \frac{P.L}{bd^2} \tag{2}$$

where, σ_f , P, L, b, and d refer to flexural strength, maximum bending load, mid span length (304.6 mm), specimen width (76 mm), and specimen height (50 mm), respectively.

Compressive strength test was performed by using a Universal Testing Machine with a maximum capacity of 1200 kN. Three 100 × 200 mm cylinder specimens were tested for each temperature stage and average values were recorded.

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IV. Results and Discussions

A. Compressive Strength

Fig. 2 presents the compressive strength change and percent lose in compressive strength depend on the exposure temperatures, respectively. As shown in Fig. 2, compressive strength values of the concrete increased remarkable with inclusion of SF and PVA fiber while it decreased slightly with the PPF with respect to plain concrete. At room temperature, plain and fiber reinforced concretes produced with SF, PPF and PVA fiber had the compressive strength values of 50.4, 65.5, 45.5 and 60.9 MPa, respectively.

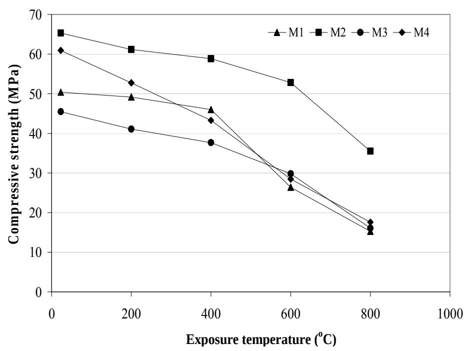


Fig. 2 Compressive strength depend on temperature level

B. Flexural Strength

Table III displays the test results of flexural strength (modulus of rupture-MOR) and ultimate mid-span deflection at the peak stress. The typical flexural stress-mid span deflection curves for plain and fiber reinforced concretes with SF, PPF, and PVA fiber are shown in Fig. 3. Each result in Table III is the average of at least three specimens.

As seen in Fig. 3, in comparison to the plain (non-fibrous) concrete, PPF and PVA fiber reinforced concretes, SF reinforced concrete specimens demonstrated more deflection at the room temperature with steel fibers that bridged the cracks and failed in bond. The fibers were rarely broken. The SFRC mixture had the greatest MOR values at all temperature levels.

TABLE III
Temperature Dependent Mid-Span Deflections and Flexural Strengths

Mix ID	23 °C		200 °C		400 °C	
	MSD mm	FS MPa	MSD mm	FS MPa	MSD mm	FS MPa
M1	0.62	6.0	0.32	5.3	0.49	4.2
M2	1.06	8.0	0.88	7.3	0.51	5.8
M3	0.49	4.5	0.49	4.3	0.30	3.7
M4	0.31	6.0	0.34	5.5	0.23	4.4

Mix ID	600 °C		800 °C	
	MSD mm	FS MPa	MS mm	FS MPa
M1	0.38	1.4	0.55	0.7
M2	0.74	4.0	0.88	1.6
M3	0.41	1.0	0.52	0.3
M4	0.35	1.2	0.39	0.4

MSD: Mid-span deflection; FS: Flexural strength

In all mixtures, flexural strength values decreased gradually up to 400°C, however, beyond that temperature, a dramatic decrease was monitored in flexural strength irrespective of fiber type. On average, at room temperature, for SFRC, the flexural strength value was approximately 12.3% of its compressive strength; however, that was 9.9% for the PPF and PVA fiber reinforced concretes. Interestingly, at 400°C, flexural to compressive strength percent rate of PPF and PVA fiber reinforced concretes was around 10%, however, as well known that both of the PPA and PVA fiber are melting around the 170 and 230°C. Melting of the PPF and PVA fiber did not alter the flexural to compressive strength percent rate. When the temperatures elevated to the 600°C, the flexural strength values of the M1 to M4 to their compressive strength values decreased to 5.4, 7.6, 3.4 and 4.3%, respectively. On the other hand, at 800°C, flexural to compressive strength percent rate of PPA and PVA fiber reinforced concretes was only 2.2 and 2.1%. These results indicated that contribution of all kinds of fibers to maintaining flexural strengths was limited in the temperature range of 400–800°C, especially at a temperature of 800°C, those fibers are not yet significant. Haddad et al. [12] mentioned that such behavior may be related to: (a) the partial loss in bond between fibers and surrounding matrix due to the difference in their expansion coefficients at high temperatures and (b) the higher sensitivity of fibrous concrete mixtures to high temperatures as compared to plain concrete, due to the greater strength of the fibrous concrete mixture at room temperature.

As seen in both Table III and Fig. 4, there was no general ascending and descending trend in the peak stress mid-span deflection values of the all mixtures, but, the mid-span deflection values of the SFRC mixture was higher than those the all other concretes at all temperature levels. The increase in temperature level from room temperature to 800°C affect the maximum flexural strength values dramatically while peak stress mid-span deflection values of the mixtures did not change remarkably. The slope of the load-deflection curve represents the stiffness of the beams. It can be easily noted from Fig. 4 that the slope decreases with increasing temperature level, thus indicating a reduction in the stiffness of the plain and fiber reinforced concretes irrespective of fiber type.

C. Bond Characteristics

As bond characteristics, ultimate pullout load, bond strength and average bar slip distance values were presented in both Table IV and Fig. 4. During the pullout tests, regardless of the fiber type and exposed temperature level, all the specimens had failure due to splitting of concrete and no pullout failure of bars was observed.

Typical splitting failure of the specimens is shown in Fig. 5. In this study, performance and bond characteristic variation of mixtures compared according to the exposed temperatures and fiber types. If the measured bond strengths are to be applied for design purposes, as mentioned by previous researchers, the characteristics of the pullout test need to be taken into consideration. As mentioned in the test method-pullout test section, in this study, bond strength was calculated taking into account the maximum pullout load sustained during the test.

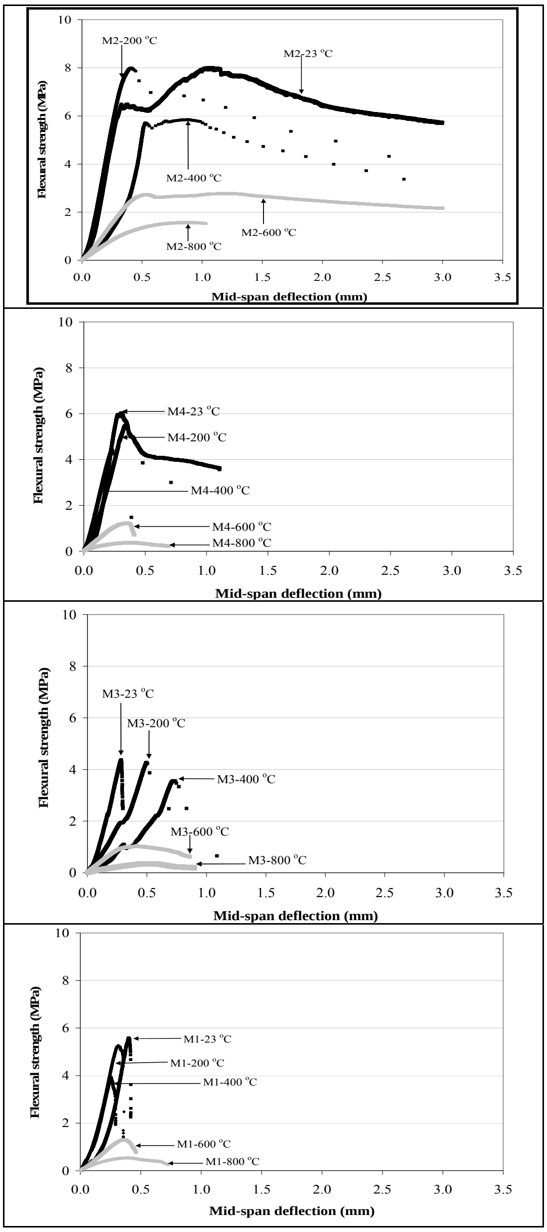


Fig. 3 Flexural strength mid-span deflection curves of mixtures

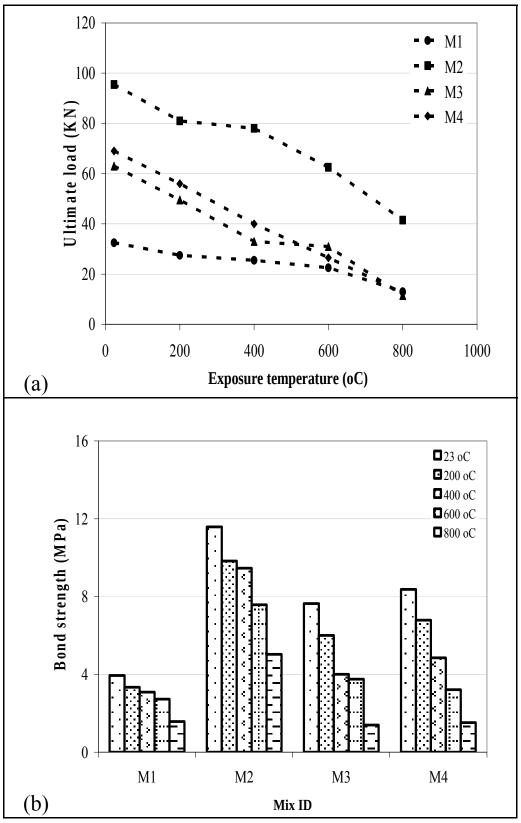
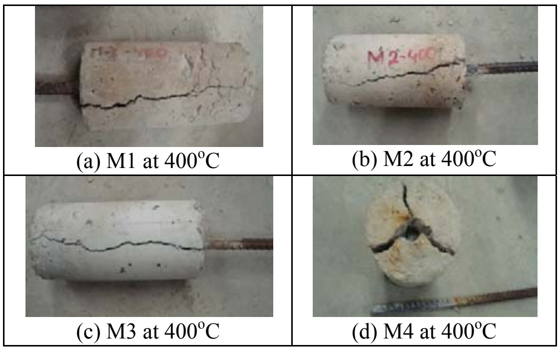


Fig. 4 Variation of (a) ultimate load (b) bond strength

TABLE IV
ULTIMATE LOADS, BOND STRENGTHS AND BAR SLIP DISTANCES OF MIXTURES

	Ultimate load (KN)				
Mix no	Temperature				
	23	200	400	600	800
M1	32.5	27.5	25.5	22.5	13.0
M2	95.5	81.0	78.0	62.5	41.5
M3	63.0	49.5	33.0	31.0	11.5
M4	69.0	56.0	40.0	26.5	12.5
	Bond strength (MPa)				
Mix no	Temperature				
	23	200	400	600	800
M1	3.9±0.6	3.3±0.1	3.1±1.1	2.7±0.9	1.6±0.0
M2	11.6±3.3	9.8±0.6	9.5±0.7	7.6±0.8	5.0±1.6
M3	7.6±0.4	6.0±0.5	4.0±0.0	3.8±1.9	1.4±0.9
M4	8.4±0.0	6.8±1.7	4.9±0.0	3.2±0.4	1.5±0.4
	Slip (mm)				
Mix no	Temperature				
	23	200	400	600	800
M1	72.5±3.5	75.5±6.4	9.0±1.4	3.5±2.1	9.5±3.5
M2	9.5±5.7	15.0±1.4	11.0±0.0	16.5±2.1	13.0±2.8
M3	1.5±0.7	4.0±5.7	6.0±8.5	37.5±41.7	56.0±39.6
M4	21.5±6.4	17.0±4.2	34.5±33.2	50.0±21.2	6.0±2.8



(a) M1 at 400°C (b) M2 at 400°C

(c) M3 at 400°C (d) M4 at 400°C

Fig. 5 Typical splitting failures of pullout specimens which were exposed to 400 °C

From Table IV and Figs. 4 (a) and (b) it can be seen that SF reinforced concrete specimens had the quite higher ultimate pullout load and bond strength values than those of the plain and PPF and PVA fiber reinforced concretes. This situation is valid for the all temperature levels. Increase in temperature level from room temperature to 800°C, decreased the both of ultimate pullout load and bond strength values significantly. This behavior is attributed to the increase in intensity, width, and extension of cracks with temperature that led to a reduction in concrete confinement of the reinforcing steel [12]. The effect of PPF and PVA fiber on the ultimate pullout load and bond strength of the concretes according to the plain concrete was more evident up to 400 °C and it was two times larger than that of the plain concrete, however, even after that temperature there were no considerable difference among them. Moreover, at 800 °C, plain concrete had slightly higher ultimate pullout and bond strength values.

Table IV also presents the bar slip distance of the plain and FRC mixtures. Bar slip distance values of mixtures showed no specific trend in its behavior depend on the exposed temperature and with/without inclusion of the fiber. The implication of the bar slip distance is that it gives an indication of the ultimate slip that can be allowed in practice prior to bond failure represented by sudden splitting of concrete along the steel bar [12].

V. CONCLUSION

Based on this study, the following conclusions are drawn:

- Explosive spalling was not observed in any plain or fiber reinforced concretes.
- At room temperature, inclusion of the steel and polyvinyl alcohol based fibers increased the compressive strength according to the plain concrete while a slight decrease was observed with the inclusion of polypropylene fiber. Exposure to the specimens up to 400°C decreased the compressive strength gradually, however, after that a dramatic decrease was observed at the plain and PPF and PVA fiber included FRC. Lose in compressive strength for those concretes increased around to 80%.
- Inclusion of PVA and especially PPF exhibit significantly less flexural strength values than that of the plain concretes. However, a remarkable increase in flexural strength and mid-span deflection values was monitored with the addition of steel fiber. As in compressive strength, flexural strength of the concretes decreased with the increase in exposed temperatures. After exposure to 600°C, the flexural strength values of the plain and FRC with PPF and PVA fiber were round 1 MPa.
- Loss of material stiffness took place with the increase in exposure temperature and it is more evident after exposure to peak temperatures of 400°C.
- Bond strength values of the concretes increased drastically with the addition of the fibers, however, after exposed to the 400°C, bond strength values of the plain and FRC with PPF and PVA fiber decreased significantly and bond values of these concretes are very close to each other.

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