EFFECTS OF ELEVATED TEMPERATURES ON BOND STRENGTH BETWEEN EPOXY-COATED REINFORCEMENT AND FIBER-REINFORCED CONCRETE

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Abstract

The bonding strength between fiber-reinforced concrete and steel reinforcing bars subjected to elevated temperatures has been studied by several researchers. The use of epoxy-coated reinforcing bars has become commonplace in construction over the last 20 years. The use of epoxy-coated bars helps to increase the durability of reinforced concrete when the concrete structure is located in harsh environments. However, the effect of an epoxy coating on the bonding strength between the reinforcement and the concrete when the structure has been subjected to high temperatures has not been studied. In this current research study, the authors investigated the bonding strength between 20-mm-diameter, epoxy-coated steel bars and concrete subjected to temperatures in the range of 350 °C to 700 °C. Forty modified pullout specimens were prepared using high-strength concrete containing trap rock, sand aggregate, and different volumetric mixtures of two different fibers (hooked steel fibers, and high-modulus polypropylene fibers). The concrete was cured for 28 days under high-humidity conditions at room temperature. Selected specimens were subjected to the indicated range of elevated temperatures using a furnace. Specimens designated for control were kept at room temperature. All specimens were subjected to pullout testing up to failure. The conditions, cracking and strength of both the control and heat-treated specimens, were observed and recorded. The results and analyses are presented in this paper.

Introduction

Concrete is a rock-like material produced by mixing cement, aggregates, admixtures, and water [1]. The aggregates in concrete consist of a mass of particles such as crushed stone, gravel, and sand, although some other types of aggregates have been used in the manufacture of concrete. Concrete is known for its high compressive strength but it is very weak in tension; therefore, concrete is usually reinforced with steel bars (rebars) to prevent failure due to tensile stresses. In the resulting material, the rebars resist the tensile stresses, while the concrete resists the compressive stresses [2]. Rebars are produced in different diameters commonly formed from carbon steel with surface ribs to help them bond tightly to the concrete. The bond between the rebar and the concrete must be such that the transmission of stresses and the working of the two structural materials as a unit is ensured. The bond between steel and concrete depends on several factors, among them: the age of the concrete and the environment to which it is exposed.

Elements of reinforced concrete may be exposed to harsh environments that could lead to corrosion of steel and deterioration of the structure. Diffusion of deleterious substances into the concrete may produce changes in the internal concrete environment, leading to rupture of the passive layer protecting the steel [3]. If the passive layer breaks the steel will corrode. Corrosion on steel embedded in concrete will occur in the form of rust. Corrosion products are known to have a larger volume than the original steel, which introduces internal tensile stresses in the concrete, producing cracking and leading to spalling and further deterioration [3], [4]. Furthermore, the formation of rust will cause loss in bond strength between the steel and the concrete, resulting in a loss of overall strength capacity. Although concrete can achieve high compressive strength, it is a brittle material. Previous studies [5-8] have shown that the inclusion of fibers within the concrete matrix can significantly increase the capacity of the concrete to resist impact as well as increase its tensile and flexural strength. The introduction of fibers into the concrete mix helps improve other mechanical properties such as resistance to fatigue, thermal shock, and spalling [8-12]. The effect of introducing fibers into the concrete mixes has been extensively reported in the literature [5-12].

In situations where the steel reinforcement may be in danger of corrosion, epoxy-coated rebar can be used. Though the epoxy coating protects against steel corrosion, its bond strength with the concrete has been shown to be much lower than uncoated or galvanized steel rebar. As shown by test results on the bond strength of both epoxy-coated and galvanized rebars reported by the American Galvanized Association [13], the epoxy coating reduced the bond strength to about 85 percent of uncoated rebars and pullout failure occurred at only 65 percent of the bond strength when failure occurred by splitting. This fact leads to conclude that when corrosion is not an issue, uncoated rebar would provide better tensile strength.

In some structural concrete applications, it is necessary to determine the effect of fire on the mechanical properties of the reinforced concrete elements and the performance of the constituent materials; namely, concrete and steel, as well as the materials that make up the concrete itself. Knowledge on the behavior of steel subjected to high temperatures is quite broad. There is also extensive information on research performed on the effects of temperature on concrete [14-18]. Elevated temperatures affect both the aggregates and the cement paste with physical and chemical changes in the material as temperature increases [14]. When concrete is subjected to elevated temperatures, evaporation of free water first, and bound water later, produces shrinkage of the cement paste, while expansion of aggregate size takes place producing differential strain within the concrete structure. The magnitude of aggregate expansion depends on the type and amount of aggregate used in the mix. The strain will eventually produce cracking after transient creep has occurred [17].

Structural concrete elements built for steel manufacturing plants may be subjected to both harsh environments, where epoxy-coated bars would be recommended, and to elevated temperatures—not necessarily produced by unintentional fire—which will affect the stress-carrying capacity of the structural element. The effect of elevated temperature on the bond between the steel reinforcement and concrete at regular and high temperatures has been addressed by other researchers [18-20]. This current investigation addressed the effects of high temperatures on the bond between epoxy-coated steel reinforcement and fiber reinforced concrete.

The mechanical properties of concrete and rebars were affected by elevated temperatures producing a decrease in the stress-carrying capacity of both and of the reinforced concrete as a whole [20]. The results of these tests will help to predict the residual strength of concrete with epoxy-coated rebars and fibers that have been exposed to high temperatures. Having this information available will aid in the design of reinforced concrete that may be subjected to fire or some other source of extreme heat. The better reinforced concrete is designed, the higher residual strength it will have, which also results in improved durability.

Materials and Experimental Procedure

Four different concrete mixtures were prepared. Specimens were built to test the bond strength of fiber-reinforced concrete and epoxy-coated steel reinforcement after being subjected to extreme temperatures. Reinforcing fibers were used since they have shown to improved tensile strength and thermal shock resistance of concrete. Specimens to test the compressive strength as quality control of the concrete mixes were also prepared. Ten concrete cylinders, four inches in diameter and eight inches in height, were prepared for compression testing and ten concrete pullout specimens were prepared for pullout testing for each mix. Compressive strength testing was performed following ASTM C39/C39M Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens [21].

Aggregates

The coarse aggregate used in this study was crushed trap rock with a maximum size of 0.75 inches (19 mm). The fine aggregate used was standard sand having a maximum size of 0.187 inches (4.75mm). All aggregates were used under saturated surface-dry (SSD) conditions. Characterization of all aggregates was performed following ASTM C29 [22], ASTM C127 [23], ASTM C128 [24], and ASTM C136 [25] standards. Results from tests performed according to these standards are shown in Table 1. The particle size distribution for both aggregates is shown in Figure 1.

Table 1. Aggregate Characterization

	Coarse Aggregate	Fine Aggregate
Bulk Specific Gravity	2.59	2.61
Apparent Specific Gravity	2.61	2.67
Absorption (%)	0.37	2.42
Bulk Unit Weight (lb/ft^3)	105.7	64.2
Fineness Modulus	3.1	2.58

Concrete Mixes

The concrete mixes consisted of: a control mix with no fiber reinforcement, a mix with homopolymer propylene fibers, a mix with steel fibers and a mix using half homopolymer propylene fibers and half steel fibers. The specific quantities of ingredients in each concrete mixture are shown on Table 2. Portland cement type I was used for all concrete mixtures. A water reducer (glenium®) was used in all mixes. The propylene fibers used were Propex® Concrete Systems' *Fibermesh 150*. The steel fibers used were Propex Concrete Systems *Novocon XR*. The amount of *Novocon XR* and *Fibermesh 150* fibers were determined according to application rates recommended by Propex Concrete Systems.

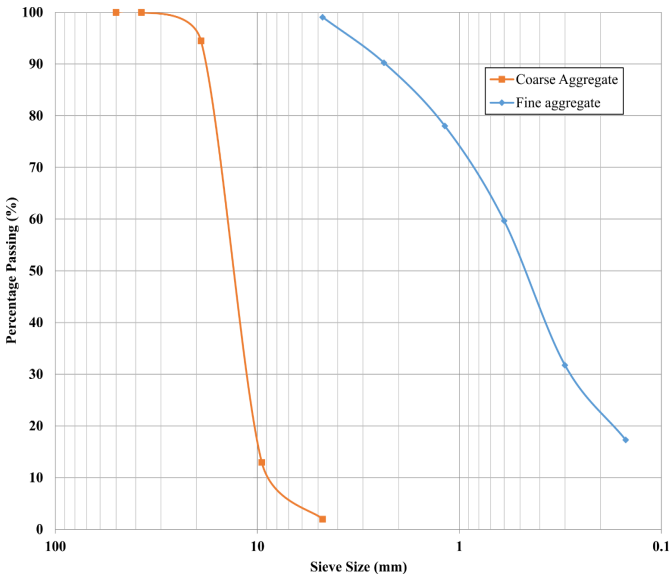

Figure 1. Particle Size Distribution for Coarse and Fine Aggregates

Table 2. Proportions of Concrete Mix Ingredients

Ingredients	Mix 1	Mix 2	Mix 3	Mix 4
Cement (lb)	28.34	28.34	28.34	28.34
Water (lb)	74.92	74.92	74.92	74.92
Coarse Aggr. (lb)	95.26	95.26	95.26	95.26
Fine Aggr. (lb)	101.7	101.7	101.7	101.7
Fibermesh 150	0	0.67	0	0.33
Novocon XR	0	0	16.67	8.33
Glenium (fl oz)	5.75	5.75	5.75	5.75

Pullout Specimens

Pullout specimens were built to those proposed by Chapman and Shah [26] and used by Haddad and Shannis [18]. Custom wooden forms with a cross-section of four inches by four inches were built using ¾-inch-thick smooth sanded plywood. The reinforcing steel consisted of No. 3 and No. 4 hot-rolled Grade 60 deformed steel bars (3/8-inch and ½-inch diameters). The 3/8-inch-diameter rebars were uncoated since their function was to be fixed in the corners of the specimens to prevent tensile failure of the concrete prior to bond failure between the concrete and the epoxy coated bar. A 4-inch by 4-inch square, ½-inch-thick steel spacer was used to hold the reinforcing bars in place during pouring (see Figures 2 and 3). A ½-inch-diameter epoxy-coated bar was placed in the center of the specimen. Two ½-inch plastic spacers were used to delimit the embedment length of the epoxy-coated rebar to six inches. On the opposite side of the spacer, a 5/8-inch-diameter hexagonal bolt fixed in the center of the cross-section of the mold was used to allow holding of the specimen by the testing machine. A Tinius-Olsen machine was used for tensile testing. This specimen design ensured a uniform distribution of shearing stress along the interface between the epoxy-coated rebar to be pulled out and the concrete.

Figure 2. Steel Spacer and Rebar Cage Reinforcement for Pullout Specimen

Mixing

The mixing procedure followed the ASTM C192 standard Practice for making and Curing Concrete Test Specimens in the Laboratory [27]. The wooden forms were coated with oil before the steel reinforcement was placed and the concrete was poured. The same amount of plasticizer (glenium®) was used in all mixes to increase workability and avoid segregation and bleeding. Slump tests were performed following the ASTM C143 Standard Test Method for Slump of Hydraulic Cement Concrete [28]. The concrete specimens (see Figure 4) were taken out of the molds 24 hours after casting and placed in a 100% humidity curing chamber.

Heat Treatment

The pullout specimens designated for heat treatment were subjected to temperatures of 350, 500, 600, and 700 °C for two hours using an electrical furnace after 28 days of cur-

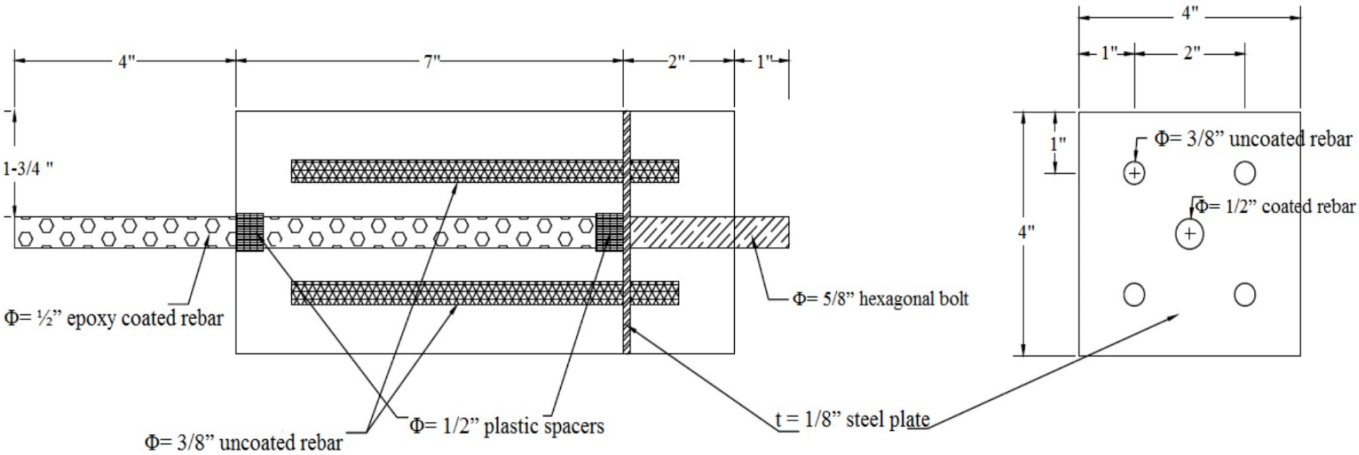

Figure 3. Pullout Specimen and Steel Spacer Diagram

ing. Duplicated specimens were subjected to the designated temperature for each mix. Also, duplicated specimens for the laboratory air for seven days before being subjected to pullout testing. The cracking and spalling of specimens exposed to heat were evaluated by visual inspection and documented before pullout testing took place.

Figure 4. Typical Concrete Pullout Specimen

Pullout Testing

The load-slip relationship for the pullout specimens was obtained by using a Tinius-Olsen testing machine. Pullout testing was performed at a loading rate of 45 lb/s [25]. The pullout loads versus slippage measurements were recorded and processed in order to obtain the bond stress and strain. The ultimate bond strength of each specimen was also recorded.

Results

Following are the results of the tests performed on the fresh concrete and hardened concrete. Results for testing of fresh concrete mixes consisted of the slump tests, as an indication of workability of the mixes being similar. Results of testing in the hardened concrete cylinders consisted of compressive strength and the pullout testing strength. Table 3 and Figure 5 show the results of the slump tests performed on the fresh concrete as an indication of workability. Results for compressive strength at 14 days and 28 days are shown in Table 4 and Figure 6. Results of the bond strength for the four mixes after being subjected to heat treatment as well as the untreated mixes (at 25 °C) are shown in Table 5 and in Figures 7 and 8.

Table 3. Concrete Slump Test Results

Mix	Mix 1	Mix 2	Mix 3	Mix 4
Slump (in.)	9.5	9	9.25	9.25

Discussion

Compressive Strength

The compression strength test results are shown in Table 4 and Figure 6. Mix 3, containing Novocon XR steel fibers,

showed the highest compression strength at both ages, while Mix 2 containing propylene fibers (Fibermesh 150) showed the lowest compressive strength. However, Mix 2 still showed compressive strength greater than 5000 psi in 90% of the specimens tested and an average compressive strength of only 18.6% below the highest average compressive strength of the whole testing program. For Mixes 3 and 4, the presence of fibers indicated a slight improvement of the compressive strength of the mixes, while for Mix 2, a decrease of 17.6% with respect to the average compressive strength of the control, Mix 1, was noted.

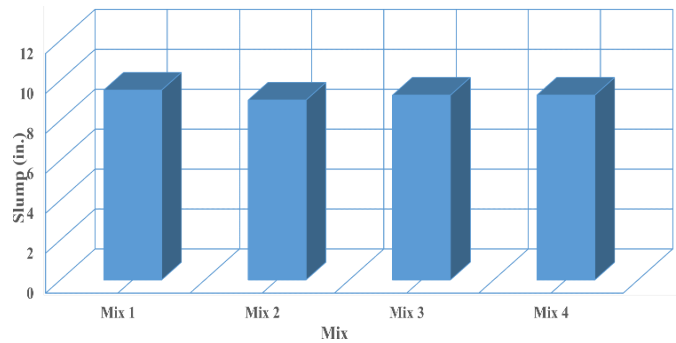

Figure 5. Concrete Slump Test Results

Table 4. Compression Strength of Concrete Mixes

Curing Age		14 Days					28 Days				
Specimen No.		1	2	3	4	5	1	2	3	4	5
Mix 1 Control	Ultimate Load (lb)	78900	67800	90600	86400	75100	89100	102300	98700	100800	76100
	Compression Strength (psi)	78900	67800	90600	86400	75100	7088.3	8138.4	7852.0	8019.1	6054.1
Mix 2	Ultimate Load (lb)	78900	67800	90600	86400	75100	74900	75000	76100	79000	79900
	Compression Strength (psi)	78900	67800	90600	86400	75100	5958.6	5966.6	6054.1	6284.8	6356.4
Mix 3	Ultimate Load (lb)	78900	67800	90600	86400	75100	94100	99400	79400	104400	95400
	Compression Strength (psi)	78900	67800	90600	86400	75100	7486.1	7907.7	6316.6	8305.5	7589.5
Mix 4	Ultimate Load (lb)	78900	67800	90600	86400	75100	83000	78600	72900	83800	76400
	Compression Strength (psi)	78900	67800	90600	86400	75100	6603.0	6253.0	5799.5	6666.7	6078.0

Table 5. Ultimate Load and Bond Strength of Concrete Pullout Specimens

		Mix 1 Control		Mix 2		Mix 3		Mix 4	
Designated Temperature	Specimen No.	Ultimate Load (lbf)	Bond Strength (psi)	Ultimate Load (lbf)	Bond Strength (psi)	Ultimate Load (lbf)	Bond Strength (psi)	Ultimate Load (lbf)	Bond Strength (psi)
Room Temperature	1	5230	555.2	9400	997.9	9530	1011.7	7180	762.2
	2	5570	591.3	8230	873.7	6880	730.4	4860	515.9
350 °C	3	3410	362.0	2800	297.2	5470	580.7	3580	380.0
	4	2830	300.4	2040	216.6	4720	501.1	4290	455.4
500 °C	5	1815	192.7	1716	182.2	3280	348.2	2260	239.9
	6	2230	236.7	1633	173.4	3150	334.4	3130	332.3
600 °C	7	1457	154.7	1453	154.2	2650	281.3	2070	219.7
	8	1638	173.9	1277	135.6	2410	255.8	1900	201.7
700 °C	9	1233	130.9	652	69.2	2230	236.7	728	77.3
	10	925	98.2	132	14.0	2150	228.2	956	101.5

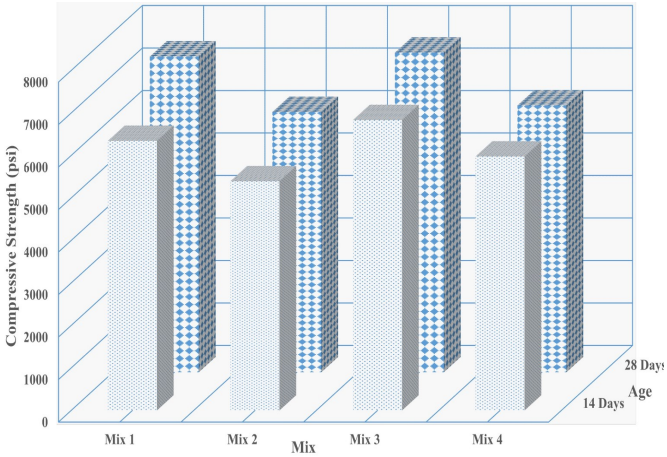

Figure 6. Compressive Strength of Concrete Mixes

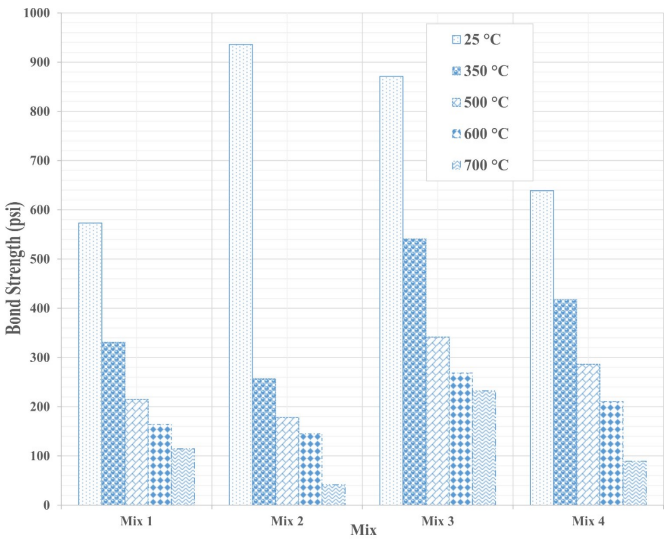

Figure 7. Bond Strength versus Mix Design

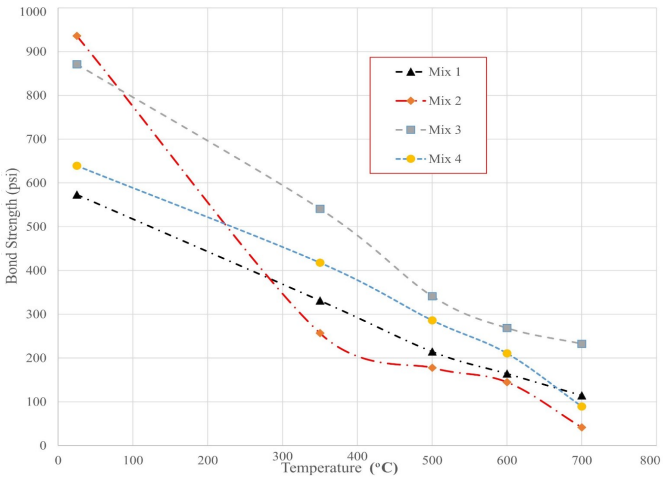

Figure 8. Bond Strength versus Temperature

Damage of Concrete Due to Heat

The damage of the concrete specimens due to heat exposure was documented and visually evaluated. The difference in the amount and size of cracks on specimens from different mixes was slight. For the control mix, it was observed that at 350 °C the concrete specimens color turned darker and formed a few small cracks on the surface. As the heat treatment temperature increased, the amount and size of the cracks increased, with spalling being noticeable at the two highest levels of heat treatment (see Figure 9). Previous studies have indicated the detrimental effects of increased temperature on concrete. Elevated temperatures cause physicochemical changes in the cement paste and the aggregates and thermal incompatibility between aggregate and cement paste leading to a decrease in strength and explosive spalling [14], [17-20]. It has been reported that up to about 100 °C a series of hydrothermal reactions occur within the concrete matrix, resulting in a loss of free, adsorbed, and chemically bonded water and an increase in permeability. The severity of spalling after being subjected to high temperatures depends on the type of aggregate, quality of concrete, moisture content, and permeability of the concrete. Around 300 °C, permanent strength loss begins and dehydration of fine aggregate may take place.

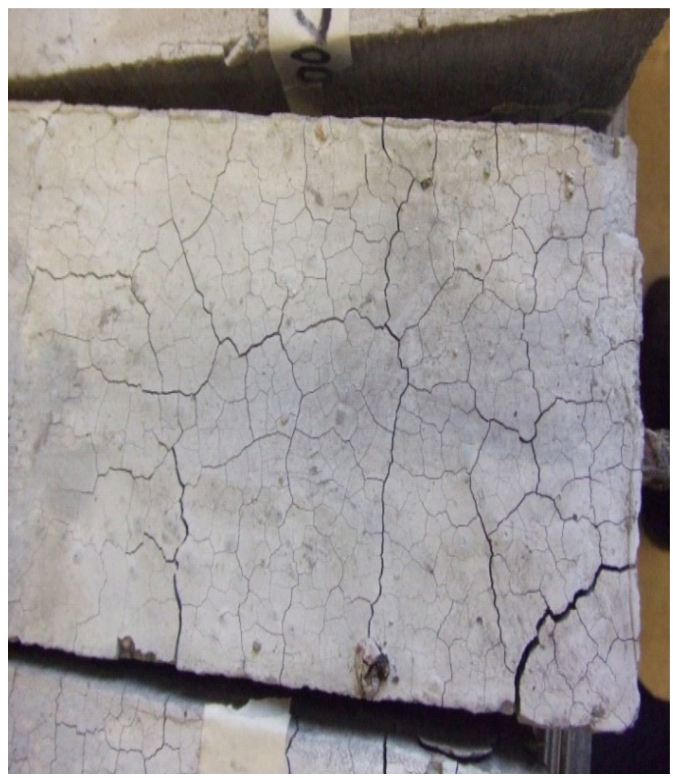

Figure 9. Control Mix Pullout Specimen after Being Subjected to 700 °C

Expansion of aggregate and, at the same time, shrinkage of the cement paste would introduce internal stresses and subsequent cracking with calcium hydroxide dissociation and calcium carbonate dissociating at around 700 ^{o}C [14]. Khoury [14] and Khoury et al. [17] reported an increase in creep in both cement pastes and concrete around 500 ^{o}C, with spalling showing at a higher degree as the temperature increases. The control mix with no fiber reinforcement showed the most dramatic behavior, in terms of widespread cracking and their size, consequence of the expansion of concrete beyond the elastic limit, increase in the water vapor in the pore structure, and decomposition of the cement hydration product. In general, all mixes containing fiber reinforcement developed smaller-size cracking. Mix 3 showed slightly less concentration and smaller-size cracking than Mix 2; however, Mix 3 showed more spalling than Mix 2. This behavior is attributed to the presence of the steel fibers in Mix 3, which increased the rate of absorbing heat and producing an expansion of the steel, thereby introducing tensile stresses in the concrete and, as a consequence, the spalling; similar results were reported by Haddad and Shannis [18].

Inspection of the specimens performed after the pullout tests revealed loss of bond between the fibers and concrete, which explains why fibers had only a small effect in reducing cracking caused by heat treatment. The propylene fibers tended to melt and be absorbed into the cement paste, explaining why Mix 2 showed small amounts of spalling, since the melting of the fibers leaves behind voids, which act as expansion chambers, where steam can be stored, decreasing the water vapor pressure and, as a result, decreasing the amount of internal stresses introduced into the pore structure [29].

Rebar Evaluation

Regarding the observation on the bars, as expected, at 350 ^{o}C, the epoxy coating on the exposed section of the rebar started to acquire a darker color with the surface getting rougher and the coating getting thinner, as the heat treatment temperature increased (see Figure 10). After the pullout testing, the section of the rebar covered by concrete was also visually inspected and on which deterioration of the epoxy coating was noticed. Figure 10 shows a comparison of bar specimen starting on the left with the control specimen kept at room temperature, and farther to the right showing the rebar of specimen subjected to 700 ^{o}C. Jau and Huang [29] reported that the temperature at the center of the concrete specimen subjected to heat continued to increase two to three hours after the fire was stopped, helping to explain the damage occurring on the coating of the covered section of the steel rebars.

Figure 10. Epoxy-Coated Rebars after Heat Treatment and Pullout Tests

Bond Strength

For all mixes, the bond strength between epoxy-coated rebars and concrete decreased as the heat treatment temperature increased (see Table 5 and Figures 7 and 8). As mentioned earlier, the concrete showed losses in strength when subjected to heat. Therefore, the bond strength decreases when the reduction in the compressive strength of the concrete was added to the possible plastic deformation of the steel within the concrete. These effects may be considered individually or together as responsible for the loss of bond strength observed after heat treatment. Similar results were obtained by Haddad and Shannis [18]. Cracking of the heat-treated specimens was inspected before and after pullout testing. During pullout testing, as an increasing load was applied, the cracks that were already formed during the heat-treatment process increased in size, thereby reducing the concrete confinement around the rebar and showing a decrease in the bond strength.

Failure appeared to have occurred first because of the local crushing of concrete at the tips of the bar ribs, followed by the concrete splitting along the steel rebar. All specimens showed splitting failure along the steel rebar and radial cracking on their cross-section. The deterioration of the epoxy coating also appeared to weaken the bond with the surrounding concrete. The deterioration of the epoxy coating most likely created gaps between the steel rebar and the surrounding concrete.

Effect of Fibers on Bond Strength

The addition of fibers to the concrete matrix also had an effect on the residual bond strength of the specimens. Figures 11 and 12 show the results of pullout testing for the four mixes at room temperature. For this case, the bond strength for both the steel fibers and propylene fibers appeared to increase with the epoxy-coated rebar. This is most likely the result of the added tensile strength that the presence of fibers provides to the concrete mix. Similar results were reported by Haddad and Shannis [18].

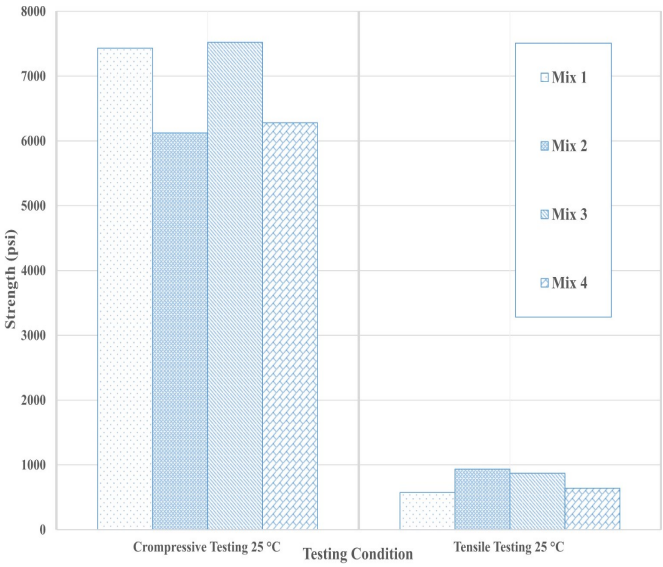

Figure 11. Comparison of Strength (compressive versus tensile) at 25 °C

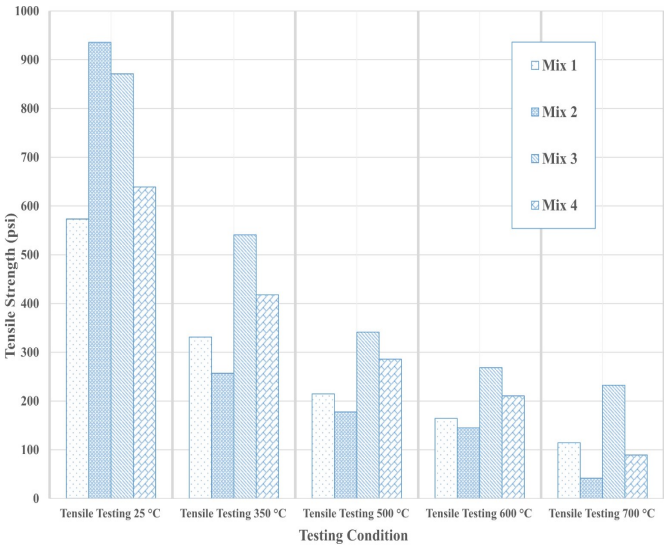

Figure 12. Comparison of Tensile (pullout) Strength for All Mixes

The mixes that included the *Novocon XR* steel fibers had much higher residual strengths during the pullout tests (Figure 12). This behavior is likely the result of the steel fibers limiting the cracking in the concrete caused by heat. Meanwhile, Mix 2, containing *Fibermesh 150* propylene fibers, showed consistently lower residual bond strengths than that of the control mix. These were surprising results because the propylene fibers were shown to limit the amount of damage caused by heat. This loss in bond strength may have been a result of the propylene fibers reacting at high temperatures and weakening the bond between the epoxy-coated rebar and the surrounding concrete. Mix 4, having both steel and propylene fibers, still had consistently higher bond strengths than the control mix at all temperatures.

This was most likely the result of the steel fibers limiting concrete damage caused by heat. This mix was consistently lower at all temperatures than Mix 3 containing steel fibers only. This appears to have been a result of the negative effects the propylene fibers had on the residual bond between epoxy-coated rebar and concrete. In all mixes, as the temperature increased, the residual bond strength decreased. This was most likely a result of the damage caused by heat to the concrete cover. It also may have been caused by the deterioration of the epoxy coating on the steel rebar.

Conclusions

Based on the results of the test program, it can be concluded that:

1. In general, an epoxy coating on the steel reinforcement embedded in concrete will start to show signs of deterioration around 350 °C.
2. The addition of propylene and/or steel fibers to the concrete mix will tend to decrease the cracking and spalling in concrete subjected to high temperatures.
3. The presence of steel fibers in the concrete mix appears to increase the bond strength between epoxy-coated rebars and concrete at all temperatures.
4. The addition of propylene fibers in concrete appears to decrease the bond between epoxy-coated rebars and concrete, when subjected to heat treatment.
5. The higher the temperature, the lower the bond strength between epoxy-coated rebars and concrete. This decrease in strength must be considered when designing slabs in the steel manufacturing industry that may be subjected to both harsh corrosive environments and elevated temperatures.

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