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Effect of thermal cycling on bond between reinforcement and fiber reinforced concrete

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Abstract

The role of synthetic and short brass-coated steel fibers in preserving bond between reinforcing steel and concrete, subjected to cycles of heating and cooling, was investigated. The bond behavior was evaluated by means of cylindrical pullout specimens (75×150 mm) reinforced with 18 mm rebars embedded along the full length of the specimens. The specimens were prepared using fiber reinforced concrete mixes with polypropylene fibres at 0.15% and 0.30% (by vol) or with short brass-coated steel fibres at 0.5% (by vol). Standard cylinders (75×150 mm) were also cast in order to evaluate splitting tensile strength. After curing for 90 days, specimens were subjected to heating and cooling cycles of a temperature range from 35 to 150 °C during a period of 24 h; 4 h for heating and 20 h for cooling. The splitting tensile strength and bond behaviors were evaluated under cycles of heating and cooling of up to 80.

The results showed that heating and cooling cycles caused a significant loss in splitting tensile and bond strengths after 80 cycles of heating and cooling that reached as high as 44% and 28%, respectively. Fibres contributions to preserving bond strength of reinforced concrete were dependent upon both fiber type and content. Results showed that the use of fibres would allow relatively high free-end slippage between embedded steel and reinforcement prior to failure. The study showed that the percentage loss in bond strength at various heating and cooling cycles was larger than that in splitting tensile strength.

1. Introduction

Under normal conditions of environmental exposure, concrete is subjected to temperatures below 40 °C. However, many modern concrete engineering structures may be subjected to higher temperatures, after exposure to an aggressive fire or heat from various machines, pipes, or chemical process vessels. Periodic shutdown of the latter systems gives rise to thermal cycling of reinforced concrete. These will induce in concrete large volume changes that will result in large internal stresses, which ultimately lead to concrete cracking. Hence, concrete's strength, durability, and most importantly the bond with reinforcing steel would be substantially reduced. As well stipulated, anchorage is essential for tensile stress transfer from concrete to reinforcing steel and its loss results therefore in a reduced carrying capacity of the deteriorated structure. This may lead under moderate to high external loads to structural failure. Many studies had investigated the impact of thermal cycling on mechanical properties of concrete and on concrete–steel bond behavior [1–5].

Studies concerned with the effect of thermal cycling on plain concrete indicated significant reductions in compressive and tensile strengths that reached up to 45% when adopting a thermal cycling of up to 300 °C [1–3]. It showed that the amount of damage is dependent on concrete proportions and type of aggregate used, and on whether specimens were sealed during testing or not. Davis [4,5] investigated the effects of heating–cooling cycles between 40 and 200 °C, and 40–350 °C on bond strength using pullout specimens. The results indicated that high percentage of total bond loss to take place after the first cycle and that the percentage loss reached as high as 28% after 20 cycles of heating and cooling.

Research investigated the bond topic, and the major factors that contribute to it showed that bond between concrete and steel is established through three mechanisms: chemical adhesion, friction, and mechanical interlock between the steel bar ribs and the concrete [6–8].

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It revealed that the major factors that affect bond strength and mechanism of bond failure are mainly bar size and characteristics, spacing between bars, thickness of concrete cover, embeddment length, lateral confining pressure, and rebar's coating type. Bond failure occurs by one of two possible modes, pullout of reinforcing rebar from concrete or splitting of concrete along the full length of rebar. The main factors that control the failure type are the amount of confinement around the rebar, the characteristics of the rebar (rib-spacing ratio, and rib face angle), and concrete strength [9,10].

Various types of bond test specimens have been used over the past 40 years for bond tests. The popular ones are the concentric pullout test, specified in ASTM and RILEM test methods, and the modified beam test [11–13]. Others used different specimens and setup arrangements to simulate similar stress condition on concrete surrounding reinforcing as that in real beams. For example, Tepfers [14] used a simply supported beam to study the performance of lab splices under varying steel confinement. Whereas, Navaratnarajah [15] used a double tension pullout specimen in which two test bars were pulled in opposite directions at the same time so that the concrete surrounding the test bars would be in tension. The pullout test is criticized because concrete surrounding embedded steel bar is being compressed during pulling-out, contrary to its behavior in real beams. This is the way ASTM, and RILEM [11,12] specifies that the concentric pullout test can be used only for comparison purposes. On this basis, many researchers used the pullout test as described by the above standards or after modification to account for the case studied. The modification included using lateral reinforcement, applying lateral pressure during testing to simulate confinement, or using different configuration of steel reinforcement [16,17].

Recently, different types of fibres (steel, plastic, glass, etc.) have been used in reinforced concrete structures and in rigid pavements subjected to heavy or dynamic loads. This was achieved after scientific research had proven that fibres, especially those made of steel, contributed to improving concrete tensile, and flexural strengths, and most importantly ductility [18,19]. Fibres embedded in concrete improved its surface skin resistance to cycles of wetting and drying in seawater, and contributed significantly to arresting and delaying concrete cracking due to alkali-aggregate reaction [20,21]. Fibers were also used in reinforcing concrete with corroding steel in order to maintain steel bond to concrete, and at the same time, reduce resulting concrete cracking [22,23]. Use of straight steel fibers help improving the bond between concrete and reinforcement in structural joints [24].

Many researchers [25–27] had investigated the effect of H/C cycles or elevated temperature (up to 800 °C) on the mechanical properties of fiber reinforced concrete (FRC). Faiyadh and Al-Ausi [25,26] and Faiyadh [27] showed that the percentage reduction in tensile strength of glass or steel FRC after being subjected to high temperatures was lower than that for plain concrete. On the contrary, use of fibres had a limited contribution to maintaining the compressive strength of concrete exposed to high temperatures. In another investigation, polypropylene fibres played a minor role in reducing Portland cement mortar damage by H/C cycles in the temperature range from 25 to 150 °C [28].

As noteworthy, most studies have overlooked the potential of fibres in preserving bond between concrete and embedded steel after being damaged by H/C cycles. This paper aims at investigating this potential considering two types of fibres, polypropylene and brass-coated steel. Plain concrete and FRC mixtures were prepared at a w/c ratio of 0.4 using type I Portland cement and crushed fine and coarse limestone aggregates. FRC mixtures incorporated polypropylene fibres at contents of 0.15% and 0.3% (by vol) and short brass-coated steel fibres at a content of 0.5% (by vol). Pullout cylindrical specimens (75×150 mm) reinforced by 18 mm deformed steel bars were cast. The diameter of the pullout cylinders was chosen in order to achieve a practical concrete cover of about 3 cm. Standard cylinders (75×150 mm) were also cast to evaluate splitting tensile strength. Specimens were cured for 90 days before being subjected to H/C cycles in the temperature range of 35–150 °C, during which splitting tensile strength and bond behavior were evaluated during this period.

Notwithstanding the objections raised regarding the concentric pullout setup tests, they have been used by the authors, due to their simplicity to achieve two objectives. The first objective is to simulate prevalent H/C cyclic regime. The second objective is to establish the relative effect of research parameters such as number of H/C cycles, and the induction of fibers on H/C cycles–bond relationship.

2. Experimental work

2.1. Materials

Crushed coarse and fine limestone aggregates were used to prepare different FRC mixes. The crushed coarse limestone had a maximum aggregate size of 12.5 mm. The grading and the fineness moduli of fine and coarse aggregates were determined according to ASTM testing method C136. The specific gravity and the absorption for coarse and fine aggregate were determined according to ASTM testing methods C127 and C128, respectively. The unit weight for coarse aggregate was obtained according to ASTM testing method C29. The physical

Table 1
Mineral aggregate physical properties

Aggregate type	Maximum size (mm)	Specific gravity			Absorption (%)	Fineness modulus
		Dry	SSD	Apparent		
CA	12.5	2.55	2.57	2.64	2.21	NA
FA	4.75	2.57	2.61	2.66	2.66	2.8

NA: not applicable; CA: coarse aggregate; FA: fine aggregate.

Table 2
Chemical compositions of Type I Portland cement and limestone crushed aggregate

Oxide	Type I cement	Limestone aggregate
Si_2O	21.21	0.98
CaO	63.69	55.46
Fe_2O_3	3.11	0.31
Al_2O_3	5.54	0.31
MgO	1.5	0.25
SO_3	2.63	0.0
Na_2O	0.18	0.0
K_2O	0.71	0.0
$(Na_2O)_e$	0.65	0.0
IR[a]	0.12	–
LI[b]	0.96	42.5

[a] Insoluble residue.
[b] Loss on ignition.

properties and the chemical composition of the aggregate used are listed in Tables 1 and 2, respectively. Type I Portland cement was used to prepare specimens from different mixes. The chemical analysis of the basic oxides of cement is listed in Table 2. Polypropylene and brass-coated steel fibres were incorporated in concrete mixes at different volumetric fractions. Specifications are listed in Table 3. Grade 60 reinforcing deformed steel rebars of 18-mm diameter were embedded in pullout specimens along the full length of the specimen. The stress–strain diagram characteristics and surface properties of the rebars were determined. Results are summarized in Table 4.

2.2. Mix design and preparation

FRC and plain concrete mixes were designed according to ACI-211 mix design procedure at a w/c ratio of 0.4 using coarse and fine limestone aggregate and Type I Portland cement. Mix proportions for different FRC mixtures are listed in Table 5. Constant water content was used and a slump of about 100-mm was maintained for all mixes using a water-reducing agent (Cormix). Such a mix consistency allowed easy placing and compaction of plain concrete or FRC in the pullout molds. Polypropylene fibres at 0.15%, and 0.30% (by vol), and brass-coated steel fibres at 0.5% (by vol) were pre-blended with aggregate prior to mixing. Mixing was performed according to ASTM testing method C192 using a tilting drum mixer of 0.04 m^3.

2.3. Specimen preparation and curing

Special cylindrical molds, each with a circular opening of 20 mm at the bases were used to cast pullout specimens. The specimens had a diameter of 75 mm and a length of 150 mm. The reinforcing rebars were placed inside the molds and were held in a vertical position from the bottom by the mold's circular base opening, and from the top by a special circular cap with a 2-cm centered circular opening. The cap was fitted around the perimeter of the mold after concrete casting and surface finishing. Casting was done in two layers; each was consolidated by blowing 25 times using a standard rod. Specimens were stored under moist conditions for 24 h

Table 3
Properties of fibres at 20 °C, as provided by the manufacturer

Fiber	Melting point (°C)	Tensile strength (MPa)	Young modulus (GPa)	Specific gravity (g/cm^3)	Fiber length (mm)	Fiber diameter (mm)
PP	160–170	550–760	3.5	0.91	12	–
BCS	1510–1524	2950	200	7.8	6	0.15

PP: polypropylene; BCS: brass-coated steel.

Table 4
Steel rebar mechanical and geometrical properties

F_y (MPa)	F_u (MPa)	E (GPa)	Rib height (mm)	Rib spacing (mm)	Face angle
585	755	200	1.2	10.0	35

F_y: yielding stress; F_u: ultimate strength; E: modulus of elasticity.

Table 5
Mix proportions for different FRC mixtures

Ingredient (kg/m^3)	Fiber content-type			
	0	0.15%-PP	0.30%-PP	0.50%-BCS
Water	253	253	253	253
Cement	538	538	538	538
Coarse aggregate	798	798	798	798
Fine aggregate	756	756	756	756
Fibers	0	1.367	2.738	39.196
Superplasticizer	7.532	8.393	8.877	8.877

PP: polypropylene; BCS: brass-coated steel.

before being demolded and submerged in water for 90 days until the day of testing. Cylinder specimens (75 × 150 mm) were also cast for evaluating splitting tensile strength over H/C cycles.

2.4. Thermal cycling process

Pullout and standard cylinder specimens, cured under standard conditions for 90 days, were exposed to the H/C cyclic regime. This involved heating for 4 h to a temperature of 150 °C, followed by cooling for 20 h to a temperature of 35 °C (Fig. 1). During the cooling process the relative humidity ranged from 35% to 50%. The H/C cycles were performed in an electrical oven controlled by an electronic timer.

2.5. Pullout testing

The bond behavior of pullout specimens was evaluated by a specially designed concentric pullout setup, shown in Fig. 2. The setup consisted of a steel frame, designed to hold the specimens horizontally, a hydraulic driven jack to pullout the steel rebar at a constant displacement rate of 0.01 mm/s, and an LVDT to measure slippage. The pullout was carried out at a constant displacement rate to allow: (a) using the free-end slip at failure (FESF) as an evaluation parameter; and (b) collecting more data points in the pre- and the post-failure stages. The hydraulic jack has a maximum load capacity of 100 kN and a measuring precision of 0.1 kN. The pullout rate was chosen so that bond failure took place within 3–5 min. The pullout loads versus slippage readings were collected by an electronic panel and a computer setup, as shown schematically in Fig. 3. The results presented are the average of two specimens, of which performance was quite similar.

Fig. 1. Temperature–time schedule for one cycle of heating and cooling.

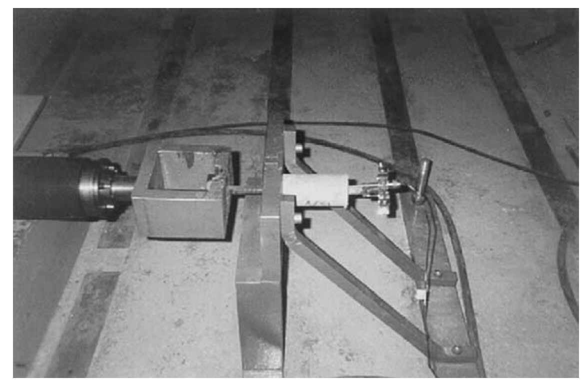

Fig. 2. Pullout setup used for experiment.

2.6. Splitting strength evaluation

Plain concrete and FRC standard cylinders subjected to different H/C cycles were tested for splitting tensile strength according to ASTM testing method C 496. The average of two specimens was taken for each test. The 90-days splitting tensile strengths data are summarized in Table 6 along with measured hardened densities.

3. Results and discussion

The following discussion covers three aspects. Firstly, assessing the amount of damage that is due to H/C cycles. Secondly, studying the bond between reinforcing steel and concrete subjected to H/C cycles by means of the bond stress (BS) versus free-end-slip (FES) curves, bond strength, and FESF. Thirdly, investigating the role of fiber type and content in preserving bond in reinforced concrete subjected to H/C cycles. The significance of the results was substantiated using analyses of variance (ANOVA), and least significant difference (LSD) tests. The statistical analysis results are presented and discussed in a separate section.

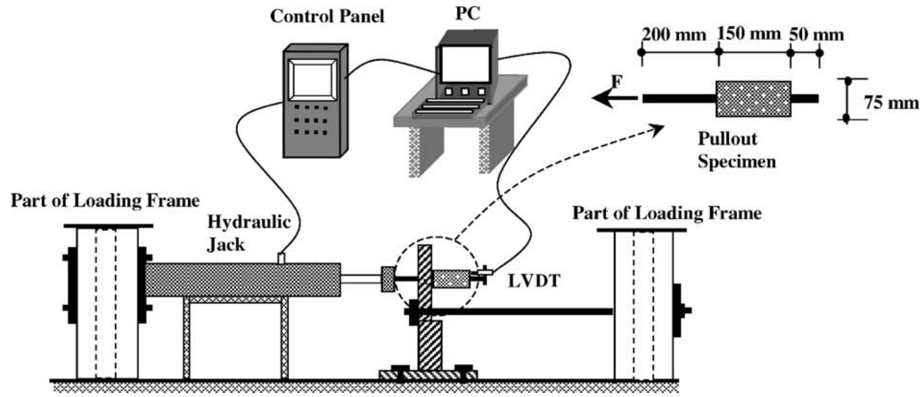

Fig. 3. Schematic view of pullout test arrangement.

Table 6
Mechanical properties of the different FRC mixes

Mix	Fiber type	Fiber content	Dry density (kg/m^3)	Splitting strength (MPa)
I	NA	0	2319	3.3 ± 0.17
II	PP	0.15%	2302	3.2 ± 0.16
III	PP	0.30%	2262	3.3 ± 0.17
IV	BCS	0.50%	2360	4.4 ± 0.22

NA: not applicable; PP: polypropylene; BCS: brass-coated steel.

3.1. Loss of tensile strength due to H/C cycles

Damage of concrete was assessed on the basis of splitting tensile strength reduction of specimens subjected to different H/C cycles. Figs. 4 and 5 show the splitting tensile strength reduction versus H/C cycles for FRC prepared with polypropylene and brass-coated steel fibres, respectively. Obviously, fiber type and content exerted their influence on strength loss. After 80 cycles, FRC mixes revealed at 0%, 0.15%, and 0.30% fibres a strength loss of 28%, 11.5%, and 13%, respectively, while about 28% and 7.5% were found for mixes with 0%, and 0.50% brass-coated steel fibres, respectively. The damage (cracking) induced by H/C cycles resulted from the difference in thermal properties between the cement paste and the embedded aggregate grains. The higher residual strength for FRC as compared to the plain concrete case is caused by the crack-arresting capacity of the fibres.

3.2. Effect of H/C on bond behavior between concrete and reinforcing steel

The effect of H/C cycles on BS versus FES relation pertaining to plain concrete, and all polypropylene and brass-coated steel FRC is depicted in Figs. 6–9, respectively. Herein, BS was calculated from external load on the bar and total surface area of the embedded portion

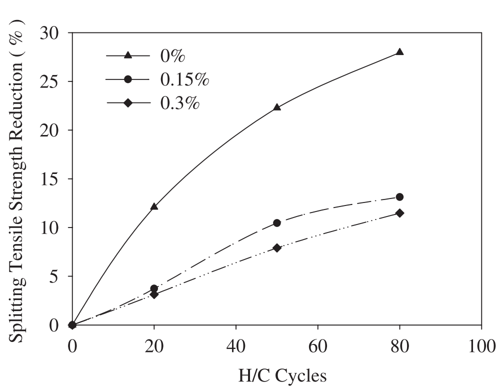

Fig. 4. Splitting tensile strength reduction versus number of heating–cooling cycles for FRC at different volumetric fractions of polypropylene fibres (strengths before thermal cycling are listed in Table 6).

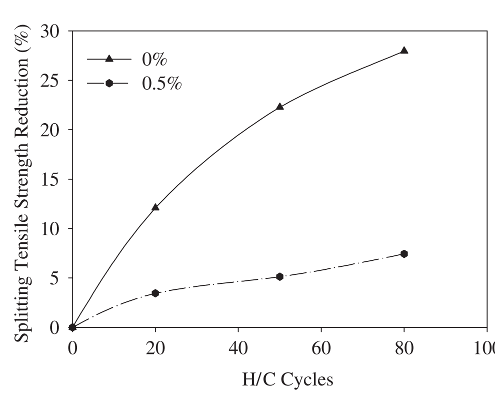

Fig. 5. Splitting tensile strength reduction versus number of heating–cooling cycles for FRC at different volumetric fractions of brass-coated steel fibres (strengths before thermal cycling are listed in Table 6).

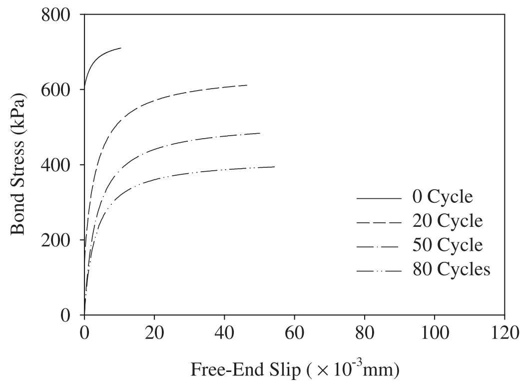

Fig. 6. BS versus FES for FRC specimens with 0% fibres (plain concrete).

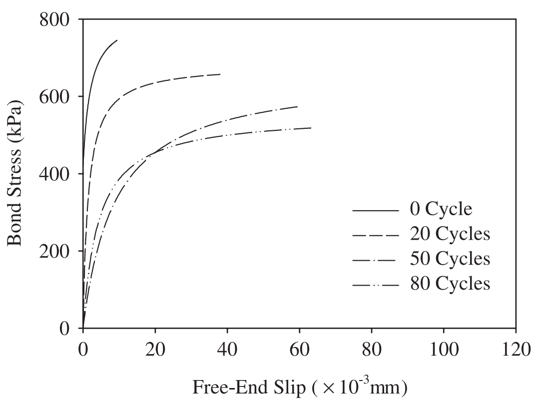

Fig. 7. BS versus FES for FRC specimens with 0.15% polypropylene fibres.

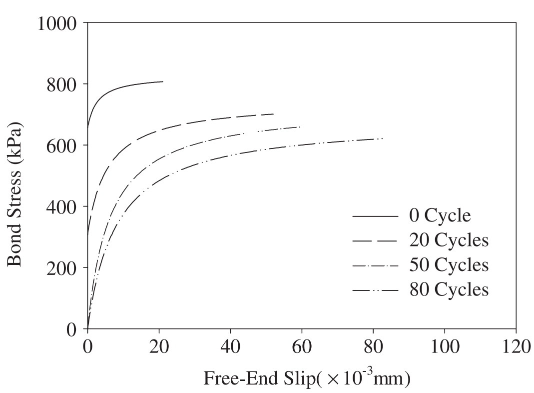

Fig. 8. BS versus FES for FRC specimens with 0.3% polypropylene fibres.

of the reinforcing bar, assuming a constant stress along the bonded length of the bar. As well stipulated, this assumption is reasonable when the embedded length of the steel rabar in concrete is fairly low, as is the case in the present work [16]. The smooth BS–FES curves resulted from non-linear regression analysis of about 400 experimental points. For each test two replicates were used.

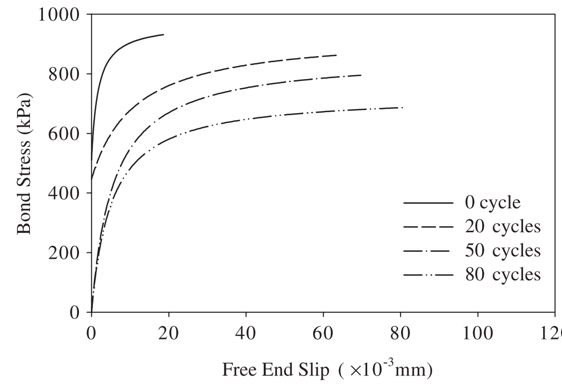

Fig. 9. BS versus FES for FRC specimens with 0.5% brass-coated steel fibres.

The curves reflect non-linear behavior in pullout up to the occurrence of a sudden splitting type of failure. The rate of change in BS decreases significantly when slip exceeds about 0.01 mm in all tests. The presented data show the ultimate slip values to increase with rising number of H/C cycles.

The observed behavior only valid for the test conditions involving in particular a relatively thin cover layer on the rebars and a displacement-controlled test setup. The failure mode observed in all specimens was typical splitting of concrete along the embedded rebar. This is referred to the relatively small concrete to rebar ratio, and to the considerably high compressive strength of different FRC. Therefore, splitting cracks, parallel to rebar axis, were developed on concrete surface, before concrete in front of the rebar ribs crushed (pullout failure). These resulted due to tensile pressure perpendicular to the bar axis and caused by the action of rebar ribs or the crushed concrete in front of the ribs. It should be indicated that while explosive splitting failure occurred for plain concrete specimens, this failure became less explosive with the inclusion of fibers. The above behaviors showed an excellent agreement with pullout test failure modes reported in literature [16,29]. As expected, when H/C cycles increased, splitting tensile strength decreased and so was the resistance to bond failure (sudden splitting) [1].

3.3. Effect of H/C cycles on bond strength, and free-end slippage at failure

Figs. 10 and 11 show that the ultimate bond strength decreased and FESF increased at rising number of H/C cycles. For example, the percentage reduction in bond strength after 80 H/C cycles was about 45 for plain concrete, and 30 and 23 for polypropylene FRC at 0.15%, and 0.30%, respectively. It mounted about 12 for FRC with brass-coated steel fibres at 0.50%. Table 7 shows that after 80 H/C cycles FESF reached almost

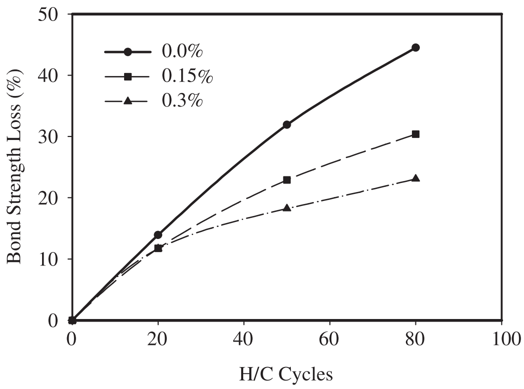

Fig. 10. Bond strength loss percentage versus number of heating–cooling cycles for plain concrete and FRC with polypropylene fibres (rebar embedded length = 150 mm).

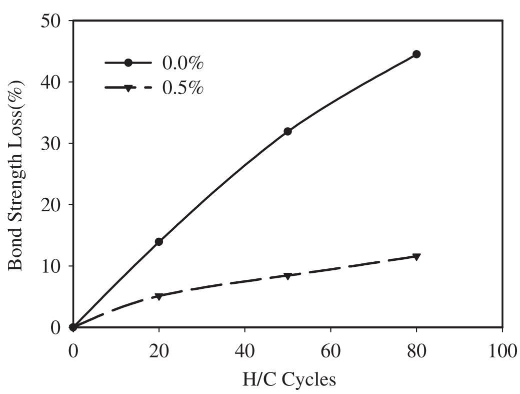

Fig. 11. Bond strength loss percentage versus number of heating–cooling cycles for plain concrete and FRC with brass coated steel fibres (rebar embedded length = 150 mm).

four to six times its initial value (before exposure to H/C cycles).

The loss in bond strength and the increase in FESF with H/C cycles can be related to a combination of three sources of internal disruption. Firstly, microcracking in concrete matrix (observed on specimens' surfaces) arises from incompatible thermal expansion between the aggregate grains and the surrounding cement paste upon exposure to H/C cycles. Secondly, the possibility of damage in the vicinity of steel fibres due to different thermal expansions of matrix and fibres. Thirdly, additional damage in the concrete surrounding the reinforcing steel due to different thermal expansions of the plain concrete (or FRC) and of the embedded steel.

Table 8 demonstrates the correlation between bond and splitting tensile strengths for different FRC mixes under H/C cycles to be poor. The H/C cyclic regime had higher impact on loss in bond strength as on splitting tensile strength, as to be expected from the aforementioned sources of disrupture. Of course, fiber type and content exerted influence on residual strength level.

3.4. Role of fibres in preserving bond between FRC and reinforcing steel

The role of the two fibre types in partly preserving bond between FRC and embedded reinforcing steel can be interpreted from the data presented in Table 7 and Figs. 10 and 11. It can be observed that the percentage loss in bond strength decreased as fibres content increased. For example, after 80 H/C cycles, the loss in bond strength for mixes with polypropylene fibres at 0%, 0.15%, and 0.3% were 44%, 30%, and 23%, respectively, whereas those for mixes with brass-coated steel fibres at 0%, and 0.5% were 44% and 11%, respectively. Furthermore, it is seen that for the same number of H/C cycles, FRC showed higher FESF values as compared to those of plain concrete. The data presented in Figs. 10 and 11 reveal the role of fibres to get more pronounced the higher the number of H/C cycles (more damage). The latter behavior can be explained by the fibres capability to arrest the splitting cracks formed along the embedded length of the steel rebar, thereby delayed splitting bond failure [18,19]. The above

Table 7
Characteristics of BS–slippage curves of FRC under H/C cycles

H/C cycles	Property	Plain concrete	PFRC		BCS-FRC
			0.15%	0.30%	0.5%
0	BS (kPa)	710	745	807	909
	FESF (mm)	0.010	0.010	0.021	0.019
20	BS (kPa)	611	658	701.1	863
	FESF (mm)	0.046	0.039	0.052	0.064
50	BS (kPa)	484	575	660	795
	FESF (mm)	0.050	0.060	0.060	0.070
80	BS (kPa)	394	519	621	687
	FESF (mm)	0.055	0.064	0.083	0.081

BS: ultimate bond strength; FESF: free-end slip at failure; PFRC: polypropylene fiber reinforced concrete; BCS-FRC: brass-coated steel fiber reinforced concrete.

Table 8
Percentage loss in splitting strength (SS) and bond strength (BS) for FRC under H/C cycles

Fiber type	Fiber content (%)	20 cycles		50 cycles		80 cycles	
		SS	BS	SS	BS	SS	BS
NA	0	12.1	13.9	22.3	31.9	28.0	44.5
PP	0.15	3.7	11.7	10.5	22.9	13.1	30.4
PP	0.30	3.1	11.7	7.9	18.2	11.5	23.1
BCS	0.50	3.5	5.1	5.1	8.5	7.4	11.6

NA: not applicable; PP: polypropylene fibres; BCS: brass-coated steel fibres.

Table 9
ANOVA test for between-subjects effects

Source	Sum of squares	df	Mean square	*F*	*P*	Criterion
Model	571903.3[a]	15	38126.9	27.99	0.0001	HS
Intercept	14415496.7	1	14415496.7	10585.16	0.0001	HS
H/C cycles (H/C)	251303.6	3	83767.9	61.51	0.0001	HS
Fiber content (FC)	303106.4	3	191035.5	74.20	0.0001	HS
H/C × FC	17493.5	9	1943.7	1.43	0.256	IS
Error	21789.7	16	1361.9	NA	NA	NA
Corrected total	593693.2	31	NA	NA	NA	NA

df: Degrees of freedom; *F*: *F* statistic = mean square/error; *P*: probability; HS: highly significant; IS: insignificant; NA: not applicable.
[a] R squared = 0.963.

discussion suggests that regardless of the relatively high temperatures of exposure, both types of fibres were able to maintain their properties in concrete.

For the limited range of fiber types and contents considered in this investigation, results indicate that brass-coated steel fibres to be more efficient than polypropylene fibres in preservation of the bond between concrete and the embedded steel rebar. This may be referred to the higher young's modulus of steel fibres and better bond between fibres and matrix.

3.5. Statistical analysis of results

To verify the significant effect of H/C cycles, fibre type and content, or their interaction on the bond strength means, ANOVA and LSD tests were performed using the statistical program SPSS. The ANOVA (carried out based on 95% confidence factor) aimed at testing the null hypothesis that the means were equal against the alternative hypothesis that at least one of the means differs from the rest. The test results indicated sufficient evidence to reject the null hypothesis of equal means, as the probability factor remained far below 0.05, and showed insufficient evidence to indicate an interaction between the experiment main experiment variables, Table 9. The latter conclusion was based on the fact that the probability factor for the interaction was considerably higher than 0.05.

Further analysis, using the LSD method, was performed to examine the significance of differences between the means, and results are listed in Table 10. As can be concluded, the differences between the bond strength means exceeded significantly the marginal error of the experiment, as the probability factors remained below 0.05. These results substantiate: (a) the detrimental effect of H/C cycling on bond strength; and (b) the significant role of fiber in preserving bond in reinforced concrete.

4. Conclusions

The following conclusions could be drawn from the experimental results.

1. Bond strength in pullout was higher for FRC than for plain concrete within the limited scope of the investigation.
2. Heating and cooling cycles had a more detrimental effect on bond strength of plain concrete than that of the FRC examined. For example, the bond strength was reduced by 44% for plain concrete, 23% for polypropylene FRC, and 12% for FRC with brass-coated steel fibres at 80 H/C cycles.
3. The reduction rate in bond strength for FRC decreased significantly, whereas for plain concrete remained unchanged when increasing number of H/C.
4. H/C cycles had a more detrimental effect on bond strength than that on splitting tensile strength.
5. The ultimate slip of the reinforcing rebars was higher in FRC than in plain concrete specimens, when subjected to the same number of H/C cycles.

Table 10
Descriptive statistical analysis using the LSD for the experiment's main parameters

Fiber content/type		Mean difference (kPa)	Std. error[a] (kPa)	P	Criterion
0%	0.15% PP	−74.5	18.5	0.005	HS
	0.30% PP	−147.5	18.5	0.001	HS
	0.50 BCS	−263.8	18.5	0.001	HS
0.15% PP	0.30% PP	−73.1	18.5	0.001	HS
	0.50% BCS	−189.3	18.5	0.001	HS
0.30% PP	0.50% BCS	−116.2	18.5	0.001	HS
Number of H/C cycles					
0	20	84.5	18.5	0.001	HS
	50	164.3	18.5	0.001	HS
	80	237.5	18.5	0.001	HS
20	50	79.7	18.5	0.001	HS
	80	153.0	18.5	0.001	HS
50	80	73.3	18.5	0.001	HS

PP: polypropylene; BCS: brass-coated steel; *P*: probability; HS: highly significant.
[a] Standard error.

6. ANOVA and LSD tests performed on bond strength results substantiated the significant role of polypropylene or brass-coated fibres in preserving bond in reinforced concrete subjected to heating and cooling cycles.

It should be indicated that all the above conclusions apply only for the specific combinations of cementitious matrix, fibers, and reinforcement size and properties used in the present work.

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