STRENGTH AND BOND CHARACTERISTICS OF HYBRID FIBRE REINFORCED CONCRETE SUBJECTED TO ELEVATED TEMPERATURE

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Reinforced concrete structures exposed to high temperatures may significantly reduce the characteristics of concrete in terms of strength, plastic deformation of reinforced steel bar and most precisely, the bond between the concrete and the reinforcing steel. Since there are only limited literature available in the field of concrete reinforced with hybrid fibres, which contain natural fibres subjected to elevated temperature, a thorough investigation needs to be done in this area. Hence, this investigation was carried out to evaluate the strength properties of concrete after adding different types of fibres under normal and elevated temperature conditions (27°C, 200°C, 400°C and 800°C). Micro steel, polypropylene and sisal fibres were used monolithically and in hybrid form with a volume fraction of 1%. The fresh property of the mixes was evaluated by conducting slump cone test, and the hardened properties were evaluated by density, compressive strength and split tensile strength tests. In addition, the bond between the concrete and the reinforcing bar was evaluated, and the residual properties were compared with the control mix. The results reveal that in elevated temperature conditions, the inclusion of micro steel fibres has a significant role in enhancing concrete strength and bond characteristics. The addition of polypropylene and sisal fibres mainly helps prevent spalling and has a slight effect on the bond characteristics of concrete compared to that of the control specimen subjected to elevated temperature.

Keywords: *fibres; hybrid fibres; microsteel; polypropylene; sisal; strength properties; bond; pullout; elevated temperature.*

1. Introduction

Plain cement concrete (PCC) is termed to be a brittle material with a low tensile strength that makes it vulnerable to cracking under tensile loading. To increase the tensile strength of the concrete, fibres were employed, which are indiscriminately spread; thereby, the cracks that develop under tensile stress can significantly be bridged, and further development can be arrested. The reduction in the crack and its development with the addition of fibres leads to the improved mechanical properties of PCC [1] in terms of compressive and splitting tensile strength [2] with improved ductility, toughness characteristics, energy absorption characteristics [3,4] and impact resistance[5,6].

In natural calamities and accidents, concrete in their service period may be subjected to fire attack and elevated temperature conditions, which may cause relentless damage to the structures, resulting in a remarkable loss in property and life [7]. This may be due to the descent in the mechanical properties of the concrete under high temperatures as a result of transforming physicochemical characteristics during the process of heating [8-10]. As concrete is widely applied in the construction sector, research on concrete resistance against high temperature is becoming significant in the case of nuclear and thermal power plants where the temperature of exposure may go up to 2000°C [11], which has led to the shift in the research on concrete on their mechanical and physicochemical characteristics during as well as post-fire exposure [12]. To overcome the negative effect of spalling in concrete with a low water-cement ratio, fibres were introduced to reduce cracks' development and propagation. Fibre-reinforced concrete (FRC) exposed to elevated temperature may result in loss of structural integrity due to deteriorating mechanical properties [13,14]. Hence, a complete investigation on the characteristics of FRC subjected to elevated temperature exposure is of significant need.

The addition of steel fibres in concrete increases the mechanical properties, whereas the release of water vapour pressure could not escape from the concrete matrix since steel has a very high melting point. This has led to the development of hybridization in FRC in the recent past [15,16], where the steel fibres will be accompanied by synthetic or organic fibres, which result in improved mechanical properties of concrete since one type of fibre facilitates the efficient use of impending characteristics of the other type. With various combinations of hybrid fibres in concrete, a blend of steel and polypropylene fibres has earned greater attention. Similar to steel fibre, polypropylene fibres also tends to enhance the impact resistance [17,18] with the properties of non-corrosive and lightweight compared to steel fibre.

The inclusion of short natural fibres tends to condense the stress at peak load, failure strain,

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and elastic modulus of the matrix resulting in improved toughness and tensile strength properties and low cost [19,21]. The presence of cellulose and absorption characteristics of sisal fibres tends to absorb water available in the matrix at the initial stage, and release at later ages will offset the necessity of water for hydration. Under elevated temperature exposure, a variety of fibres reinforced in concrete may play a variety of roles in augmenting the performance of concrete. For instance, the inclusion of steel fibres tends to improvise the tensile strength, toughness, strain capacity and energy absorption characteristics of the concrete [18]. The addition of polypropylene fibres is valuable in improving the performance of concrete subjected to fire by reducing the pore water pressure and vulnerability towards spalling. Most of the past works of literature have investigated the performance of adding high volume content (> 1% by volume of concrete) of polypropylene fibre in concrete and hence, concrete with less volume content (< 1% by volume of concrete) under fire exposure [22-24] is the need for the hour.

Due to the limited availability of literature in the field of concrete reinforced with hybrid fibres with the inclusion of natural fibres subjected to elevated temperature, it is necessary to have a thorough investigation on the performance of concrete reinforced with hybrid fibres subjected to elevated temperature. This will enable us to evaluate the deterioration rate of mechanical properties of hybrid fibre reinforced concrete and to suggest the utility of sisal fibres in the production of fibre reinforced concrete. Therefore, this investigation was carried out to evaluate the residual mechanical properties of concrete reinforced with three types of fibres, namely microsteel, polypropylene, and sisal, and their hybrid mixes in terms of density, compressive strength, and split tensile strength after exposing them to different (27°C, 200°C, 400°C, and 800°C) elevated temperatures. In addition to the mechanical properties, the investigation was further extended to evaluate the bond characteristics of concrete with reinforcing steel at the above-mentioned temperature conditions.

2. Materials and Methods

2.1 Materials

Ordinary Portland Cement (OPC) of grade 53 conforming to IS 12269 [25] with specific gravity of 3.13, fineness 340 m^2/kg, initial setting time 38 minutes, 3 mm soundness and standard consistency 28% was utilized in this investigation. Class F type fly ash conforming to IS 3812 [26] with fineness 535 m^2/kg, specific gravity 2.10 and bulk density 1197 kg/m^3 was obtained from nearby thermal power station was used as a partial replacement for OPC in this investigation. For theentire set of investigations, OPC was partially replaced with 20 % fly ash. The chemical composition of OPC and fly ash are detailed in Table 1.

Due to the non-availability and focus on sustainable construction techniques, natural sand has been replaced with Manufactured-sand (M-sand) in the entire investigation. M-sand characterized with a nominal diameter of less than 4.75 mm was used as fine aggregate with a specific gravity of 2.62. Natural granite type stones with a nominal size ranging between 4.75 mm and 16 mm with a specific gravity of 2.73 were employed as coarse aggregate fractions. The particle size distribution curves for the fine and coarse aggregate samples are shown in Figure 1a. To assess the thermal stability of the coarse aggregate employed in this investigation, a thermal treatment technique was adopted for the aggregates up to 800°C, and their results are projected in Figure 1b. Three types of fibres (micro steel, polypropylene and sisal) were employed in this investigation, and their properties and appearance supplied by the manufacturer are detailed in Table 2. Chemical admixture used was named Tec mix-640 and it is a Polycarboxylic ether (PCE) based superplasticizer .16 mm diameter TMT bar of 500 grade was used as reinforcing steel in the determination of bond properties and the properties of the bar before and after exposing to different elevated temperature and subsequent cooling to room temperature are detailed in Table 3.

2.2. Experimental investigation

The proportioning of the concrete mixes was done according to IS10262 [27], in which cement was partially replaced with fly ash by 20% constant in all the mixes. The mixes were prepared considering the workability. The fibres were added in mono and hybrid forms to maintain a constant 1% volume of fibres. The detailed concrete mixes proportioned for varying fibre volumes are detailed in Table 4.

Compressive strength test (IS 516) [29], and split tensile strength test (IS 5816) [30] were conducted to evaluate the hardened properties using cube specimens of size 150 mm and 150 mm diameter and 300 mm height cylindical specimens, respectively, after providing moisture curing for 28 days and exposure to different

Table 1.
Chemical composition of OPC and Fly ash

Concentration (%)	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	Na_2O	K_2O	SO_3
OPC	21.80	6.60	4.10	60.10	2.10	0.40	0.45	2.20
Fly ash	54.07	26.84	7.38	3.23	1.73	0.42	0.74	0.23

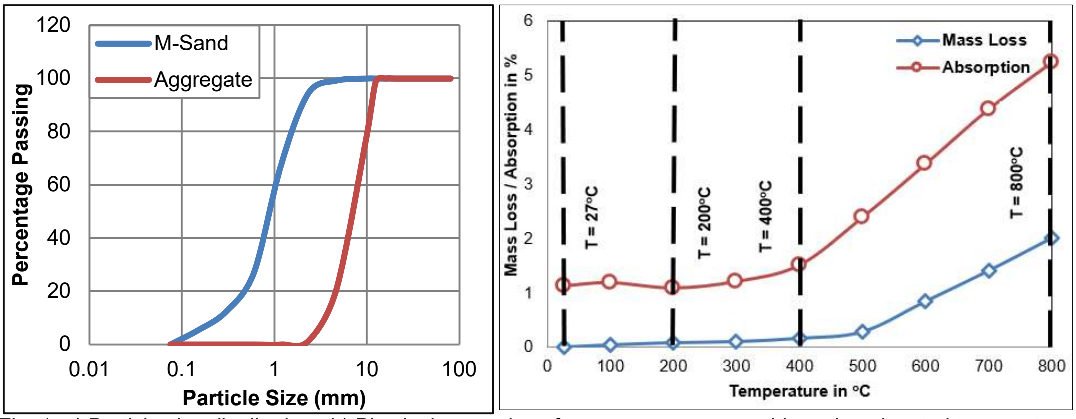

Fig. 1. a) Particle size distribution b) Physical properties of coarse aggregates subjected to elevated temperatures

Table 2

Fibre properties

Properties	**Micro steel (MSF)**	**Polypropylene (PPF)**	**Sisal (SiF)**
Appearance			
Geometry	Distinct Filament	Monofilament	Fibre bundles
Length	13 mm	12 mm	20 mm
Diameter	0.25 mm	13 µm	0.8 mm
Aspect ratio	65	920	25
Specific Gravity	7.8	0.91	1.33
Tensile strength	2200	360	385
Young's Modulus (GPa)	210	5.50 – 7.00	7.47

Table 3

Reinforcing steel properties

Exposing Temperature (°C)	Yield strength (MPa)	Ultimate strength (MPa)	Elongation (%)	Rib spacing (mm)
27	557	673	16.5	5.8
200	542	655	16.7	5.8
400	499	587	17.5	5.9
800	212	247	18.9	6.1

Table 4

Material Composition

Mix Designation	Quantity in kg/m^3						Volume Fraction(%)		
	Cement	Fly ash	Sand	Aggregate	Water	SP	MSF	PPF	SiF
C1	404	101	687	1106	149	5.05	0	0	0
C2	404	101	687	1106	149	5.05	1	0	0
C3	404	101	687	1106	149	5.05	0	1	0
C4	404	101	687	1106	149	5.05	0	0	1
C5	404	101	687	1106	149	5.05	0.5	0.5	0
C6	404	101	687	1106	149	5.05	0.5	0	0.5
C7	404	101	687	1106	149	5.05	0.5	0.2	0.3
C8	404	101	687	1106	149	5.05	0.5	0.3	0.2

temperature conditions. The primary goal of the proposed experiment was to study the bond characteristics of concrete at elevated temperatures using cylindrical specimens of 150 mm diameter and 300 mm height reinforced with 16 mm diameter TMT bar placed along a length after exposing to different temperature (27, 200, 400 and 800°C) condition for 1 hour.

According to IS 456 (2000), the development length of the bar can be calculated by the formula given in Eq. (1),

$$L_d = \frac{\emptyset \sigma_s}{4\tau_{bd}} \qquad (1)$$

where, $\emptyset$ = Bar diameter, σ_s = stress in the bar at the section considered, τ_{bd} = Design bond stress (3.04 for deformed bars)

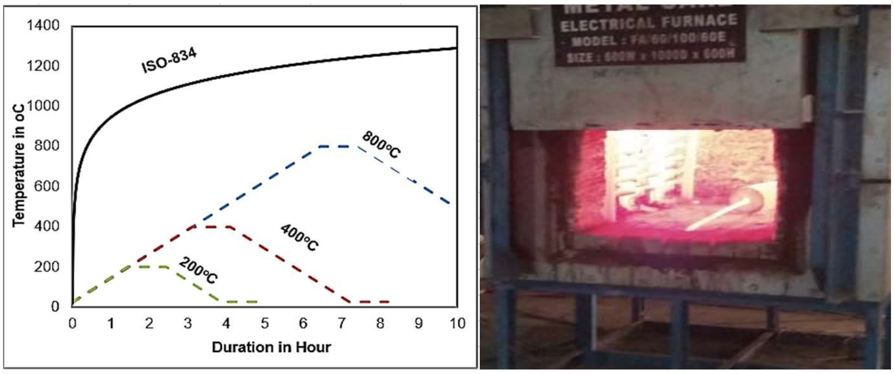

Fig. 2 - (a) Heat curve and ISO 834 curve (b) Specimen kept in Furnace

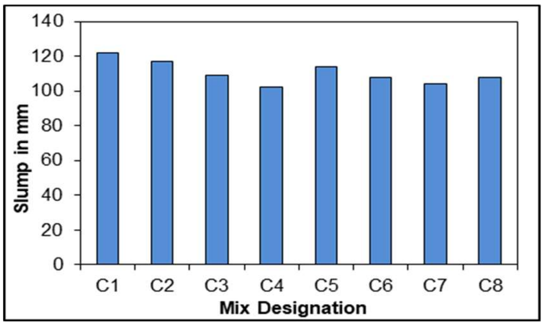

Fig. 3 - Slump cone results of the tested mixes

The extreme temperatures (200, 400, and 800 ° C) were selected in such a way that the free water from the cement will be lost after attaining 150 ℃, in addition to ettringite dehydration and the initiation of chemically bonded water loss. The concrete elements were heated in an electric furnace at a constant rate of 2°C/min until the desired temperature was reached, as recommended by RILEM, to ensure uniform heating and no spalling at the higher temperature. The specimens were subjected to the appropriate high temperature for 1 hour before being allowed to reach room temperature. Figure 2a depicts the development of heat and cooling rate over the time applied to the concrete samples, as well as that of the ISO-834 specification [33], and Figure 2b displays the sample placed in the furnace at high temperatures.

3. Results and Discussion

3.1 Fresh Property

The workability of the fresh concrete mixes was assessed with the aid of slump cone test and the variation in the test results are projected in Figure 3. In general, adding steel fibres in concrete tends to reduce the slump value slightly. The reduction might be due to the presence of fibres that resist the cement paste to flow [31]. However, the partial replacement of steel fibre with polypropylene and sisal fibres tends to reduce workability significantly. In addition, the insignificant reduction in the workability properties of the mixes with the introduction of fibres were greatly influenced by the addition of chemical admixtures, which has a significant role in improving the slump properties of concrete as well as the fly ash with low calcium has the tendency to reduce the demand of water and improved workability [36].

3.2 Compressive strength

The variation in the compressive strength results at the age of 28 days moisture curing condition after being exposed to various elevated temperatures are shown in Figure 4. The results projected are the average of three specimens and their standard deviation ranges between 1.05 MPa and 1.28 MPa. It can be seen from the figure, the compressive strength of the mixes increase with the addition of micro steel fibre at the rate of 12%, whereas a reduction in the compressive strength was observed with the case of polypropylene and sisal fibres at the rate of 11% and 2% respectively for the specimens without exposed to elevated temperature. In the case of specimens exposed to 200°C, the compressive strength was found to increase for the FRC specimen compared to the control specimen. Under 400°C and 800°C exposure, the compressive strength increased for MSF and reduced with PPF and SiF, respectively. Slight reduction was observed in the rate of compressive strength results for the mixes with hybrid fibres. For instance, the mixes with 0.5% MSF and 0.5% PPF reduce compressive strength than the mixes with 1% MSF. Similarly, the mixes with 0.5% MSF and 0.5% SiF reduce compressive

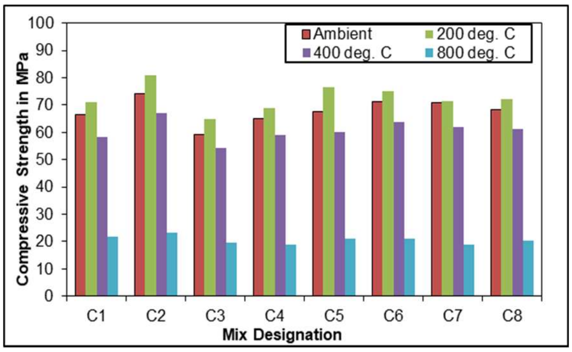

Fig. 4 - Compressive strength results

Fig. 5 - Failure pattern of 800°C exposed specimen

strength than the mixes with 1% MSF. In the case of mixes with hybrid fibres, the compressive strength was found to increase for hybrid mix up to 400°C than the control mixes and reduction was observed at exposure temperature of 800°C.

Non-fibrous concrete deems to be dense with compact microstructure, which, when heated, delay the vapour pressure escape from the specimen leads to increased development of internal pressure which may result in spalling, which can be visualized from Figure 5, which shows the failure pattern of the control specimen and fibre-reinforced specimen after exposure to 800°C. In case the concrete mixes with fibres, the vapour pressure gets depleted due to the bridging mechanism, and connectivity takes place due to melting, evaporation and formation of channels [38], and this results in improvement of spalling resistance property of concrete surface even after exposure to 800°C. The improved performance of PPF and SiF could be attributed to the low melting point of PPF and SiF than MSF, which may tend to volumetric expansion when it gets melted, leading to the development of the microcracks resulting in improvised release in water vapour pressure inside the concrete.

3.3 Split tensile strength

The variation in the split tensile strength results at the age of 28 days moisture curing condition after being exposed to various elevated temperatures are shown in Figure 6. The results projected are the average of three specimens, and their standard deviation ranges between 0.15 MPa and 0.35 MPa. It can be seen from the figure, the split tensile strength of the mixes increased up to 32% with the addition of 1% micro steel fibres 32% than the mixes without fibre. In the case of mixes with 1% PPF, the split tensile strength was found to reduce up to 400°C temperature and a slight increase of 1% at 800°C than the corresponding control mix. Similarly, the mixes with 1% sisal fibre reduce the split tensile strength of 3% at 27°C compared to the control mix; whereas, a slight increase in the split tensile strength up to 800°C than the mixes without fibre. In the case of mixes with hybrid organic fibre combination, there is a slight increase in the split tensile strength of the mixes up to 400°C and reduction in strength at 800°C for the combination of 0.5% MSF, 0.2% PPF and 0.3% and mix with 0.5% MSF, 0.3% PPF and 0.2% SiF.

The availability of micro steel fibres, which tends to bridge the cracks developed due to the stresses developed in the concrete, resulting in a reduction in the propagation of cracks developed by providing a higher surface area with the dense matrix, is primarily responsible for the significant improvement in the split tensile strength results of the tested mixes with fibres. Conversely, PPF and SiF tend to absorb water present in the matrix, thereby increasing the porosity and reducing strength. Similar to the compressive strength results, the improvement in the split tensile strength results might be due to the depletion of water vapour pressure on the addition of fibres; thereby, spalling of concrete gets reduced as a result of melting and evaporation of PPF and SiF even at 800°C.

3.4 Bond strength

3.4.1 Visual observation

After exposure to elevated temperatures, the specimens show a different crack pattern, as evident from the photographic assessment of the tested specimens, as shown in Figure 7. As anticipated, the number and intensity of the cracks were governed by the type of fibres used, and the temperature level at which the specimen was exposed and observed to be more significant at 400°C and not much variety was observed at 800°C. It has been observed that the specimens exposed to 200°C experience microscopic hairline cracks even with and without fibres. Whereas, when exposed to 400°C, the specimens without fibres experienced map-type cracks developed as well and extensive as the specimens with fibres where short arbitrary cracks were observed, which is similar to the observation made by Haddad et al. [38].When subjected to 800°C, the specimen without fibre resulted in the creation of wider cracks with an increase in number and a maximum width of 1.2 mm, whereas specimens with hybrid fibres resulted in a minor reduction in the number of cracks .

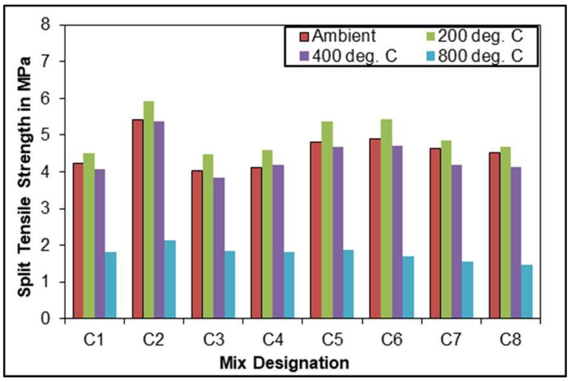

Fig. 6 - Split tensile strength results of the tested mixes at different temperature exposure

3.4.2 Failure Mechanism

It was observed that the controlled specimens without fibres experienced a brittle failure with the increase in the exposing temperature, which might be attributed to the formation of plastic shrinkage cracks, which tends to develop with the increase in the exposing temperature. The failure of specimens may result from the local crushing of concrete at the tip of the reinforcing bar, which was then followed by the splitting of the specimens. In the case of FRC specimens, the failure was ductile with the development of microcracks on the surface at room temperature. Mainly, all the tested specimens resulted in splitting failure along the axis of the reinforcing bar with a subsequent formation of radial cracks on the cross-section of the specimens. The specimens reinforced with PPF and SiF resulting in slightly improved performance than the control mixes without fibres may be attributed to the formation of escape channels resulting from melting of PPF and SiF, which were also evident from the compressive and split tensile strength results. The development of the cracks may be associated with the vapour pressure developed due to the pore and gel water; concrete gets expanded outside its limit of elasticity, and hydration products of cement get decomposed [35].

3.4.3 Residual bond strength

The reduction in the bond strength characteristics of the tested specimens at different temperature exposure is detailed in Table 5. It has been observed that the residual bond strength of the specimens decreases with the increase in the exposing temperature. The addition of SiF has the tendency to emit absorbed water at a later stage due to the availability of the cellulose content may result in improved performance at higher temperature exposure conditions. The reduction in the bond strength at 400°C is mainly attributed to the intensity and width of the cracks developed with the increasing temperature, resulting in a reduction in the confinement of the reinforcing bar with surrounding concrete [35].

3.4.4 Bond strength vs Free end slip

It is evident from the bond-slip characteristics of the tested specimens, as shown in Figure 8, the addition of PPF and SiF doesn't have a significant effect on the bond-slip characteristics between the concrete and the reinforcing bars. The slip corresponding to the maximum bond strength was found to increase in the addition of steel fibres irrespective of the exposing temperature. In the case of mixes with PPF and SiF, the maximum slip was found to be less than the control specimens. In all the cases, the bond-slip curve attains a linear curve until it reaches the peak value and a subsequent decline in the curve were observed when the specimens are not exposed to elevated temperature. Whereas in the case of specimens exposed to elevated temperature, the linearity of the curve was not attained; instead, a non-linear curve was obtained. This might be due to the insignificant effect of fibres at elevated temperatures. The improved performance of the specimens reinforced with MSF may be attributed to the higher anchorage of steel fibres than other fibres in the matrix, which may arrest the development of heat-generated cracks effectively during pulling out [38].

3.4.5 Compressive strength and bond strength relationship

An attempt has been made to propose linear regression functions based on the acquired experimental data, and the corresponding R^2 coefficients have been determined. A correlation between bond strength and compressive strength is determined using linear regression equations.The results were achieved with b_s (bond

Table 5

Residual bond strength of the specimens after exposed to thermal load

Mix Designation	Residual bond strength at different temperature of exposure (%)			
	27°C	200°C	400°C	800°C
C1	100	91	74	28
C2	100	95	89	37
C3	100	90	84	32
C4	100	92	84	34
C5	100	92	79	35
C6	100	89	82	37
C7	100	88	77	34
C8	100	88	80	30

Fig. 7 - Visual observation of the exposed specimens (a) Development of cracks under testing, (b) spalling of concrete at corners, (c) crack width variation with and without fibres, (d) split specimens after testing.

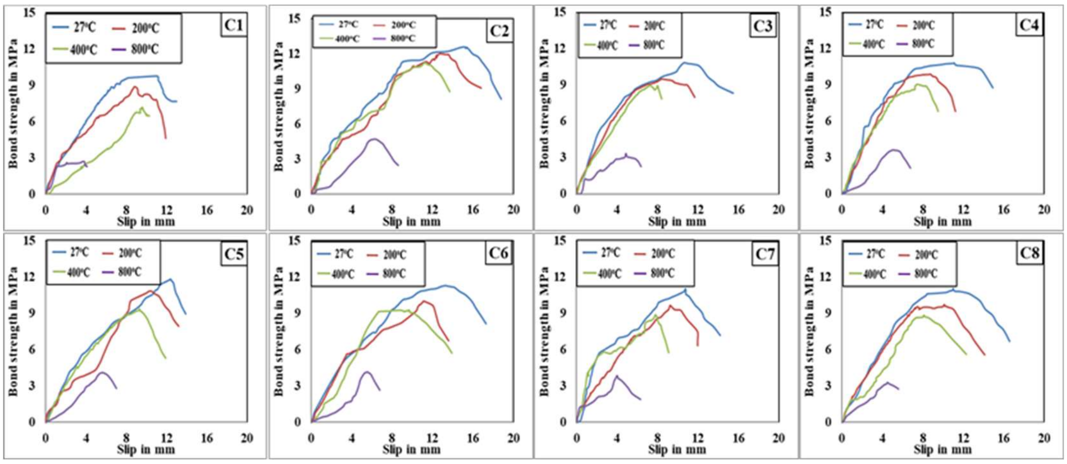

Fig. 8 - Bond-slip characteristics of the tested specimens

Table 6

R^2 coefficients for the linear regression of peak b_s as a function of F_{ct}

	C1	C2	C3	C4	C5	C6	C7	C8
R^2	0.9507	0.968	0.9388	0.9691	0.9282	0.9485	0.9539	0.9485

stress) as a function of F_{ct}(compressive strength): in this case, the linear regressions for each of the batches are represented in Figure 9, and the R^2 coefficients are shown in Table 6. The following equations obtained are:

Equations

$b_s = 0.1368\ F_{ct} - 0.3111$….(2)

Equation 2 corresponds to the relationship with peak bond strength and compressive strength of concrete without fibre at different exposure temperatures, and the obtained R^2 value of 0.9507 gives a good correlation between both the parameters.

$b_s = 0.139\ F_{ct} + 1.6099$…. (3)

$b_s = 0.167\ F_{ct} + 0.5741$ ….(4)

$b_s = 0.1417\ F_{ct} + 1.1854$…(5)

Eq. (3,4 and 5) corresponds to concrete with micro steel, polypropylene and sisal respectively in mono form with a constant (V_f = 1%) and the linear regression equations and the R^2 values range from 0.92 to 0.96 and from these R^2 values, and good correlation has been obtained between bond strength and compressive strength. These equations can predict the bond strength of mono fibre reinforced concrete with steel, polypropylene and sisal fibres.

$b_s = 0.1364\ F_{ct} + 1.3703$…. (6)

$b_s = 0.1219\ F_{ct} + 1.6527$….(7)

Eq. (6) and Eq. (7) correspond to the relationship between bond strength and compressive strength of concrete samples with hybrid fibres (0.5% of microsteel fibres and 0.5 % of polypropylene fibres)

$b_s = 0.1198\ F_{ct} + 1.2865$….(8)

$b_s = 0.1374\ F_{ct} + 0.4947$…..(9)

Eq. (8) and Eq. (9) corresponds to the relationship between bond strength and compressive strength of concrete samples with hybrid fibres (0.5 % microsteel + 0.2 % polypropylene + 0.3% sisal) and (0.5 % microsteel

+ 0.3 % polypropylene + 0.2 % sisal) respectively. From the obtained R^2 values in the case of hybrid fibres greater than 0.90, which is a good correlation, the compressive strength can also be used to predict the bond performance of concrete at all the temperature conditions. This equation is entirely based on the information provided in this paper. At high temperatures, there is a disparity, which could be attributable to the existence of aggregates and their siliceous nature. From the obtained results, it can be concluded that the variation of compressive strength and bond strength of concrete samples and also the strength degradation after being exposed to different elevated temperature conditions are similar.

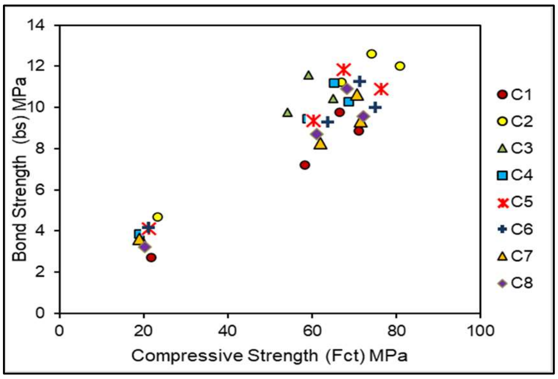

Fig.9 - Peak bond strength and compressive strength correlation graph

4. Conclusions

An experimental investigation was carried out to evaluate the strength and bond characteristics of concrete specimens without and with fibres (microsteel, polypropylene and sisal), both monolithic as well as hybrid under different (27°C, 200°C, 400°C and 800°C) exposing temperatures after 28 days of conventional moisture curing technique. From the results obtained from the experimental investigation, the following conclusions can be made:

- Fibres slightly influenced the fresh property of concrete; the addition of fibres resulted in reduced slump properties of concrete.
- Compressive and split tensile strength properties of the fibre reinforced specimens were superior to the control mixes, which might be due to the improved bridging mechanism of the matrix at elevated temperature with no spalling of concrete.
- Incorporating steel fibres in concrete reduces the cracking rate, and the addition of hybrid fibres in concrete spalling tendency can be remarkably arrested.
- Concrete with micro steel fibres resulted in superior bond strength compared to the mixes of other types of fibres and hybrid fibres.
- The addition of sisal fibres also improved the concrete performance at elevated temperatures compared to the control specimen.
- The incorporation of fibres improves the ductility nature of the concrete irrespective of the exposed temperature.

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