JOURNAL OF BASIC SCIENCE AND ENGINEERING

Study on Compressive and Tensile Strength of Metakaoline Based Hybrid Fiber Reinforced Concrete when Subjected at Higher temperature

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Received: 22-03-2024**, Revised:** 30-03-2024, **Accepted:** 10-04-2024

Abstract:

The addition of small closely spaced and uniformly dispersed fibers to concrete would act as crack resistor and would substantially improve its properties. This type of concrete is known as Fiber Reinforced Concrete. The addition more than one type of fiber in concrete is known as Hybrid Fibre Reinforced Concrete. Combining fibres with different geometry and mechanical properties can improve the mechanical properties of fibre reinforced concrete. These composites take advantage of different and synergistic effects on mechanical properties of each fibre type. Macrofibers of steel, due to their high modulus and improved bonding characteristics are known to improve toughness of concrete at relatively small crack openings; on the other hand, micro-fibres of polypropylene are expected to mitigate shrinkage cracking, improve the tensile strength of the matrix, improve the crack growth resistance and enhance strain capability.

In this experimental work an attempt is made to study the strength characteristics of metakaoline based hybrid fiber reinforced concrete when subjected to elevated temperature at 200°C. Different fibers used in the work are steel fibers (SF), galvanized iron fibers (GIF), waste coiled steel fibers (WCSF), high density polyethylene fibers (HDPEF), waste plastic fibers (WPF) and polypropylene fibers (PPF). Different combinations of hybrid fibers used for the study are (SF+GIF), (SF+WCSF), (SF+HDPEF), (SF+WPF) and (SF+PPF).

Key words: *Hybrid fibres, mono fibres, steel fibers (SF), galvanized iron fibers (GIF), waste coiled steel fibers (WCSF), high density polyethylene fibers (HDPEF), waste plastic fibers (WPF), polypropylene fibers (PPF)*

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1. Introduction

Cement concrete is a versatile multi-phased material, used as a construction material in various innovative design elements. This is because; it can be cast into any required shapes according to the design. Apart from this cement concrete has high compressive strength, stiffness, low thermal and electrical conductivity. Meanwhile the low tensile strength and brittleness makes restrictions for the use in various applications. To overcome low tensile strength, an additional material which is having higher tensile strength like steel is introduced into the regions, where concrete is subjected to tension. This is usually called as Reinforced Cement Concrete (RCC). Even though, RCC is capable to resist tensile forces but it lacks in some other mechanical property like toughness, ductility, crack resistance etc. To overcome these properties, it is essential to distribute the reinforcement uniformly. This can be achieved by using smaller diameter fibers made up of metallic or non-metallic material. This leads to the new dimension of concrete with improved mechanical properties as a “Fibre Reinforced Cement Composite (FRC). As metakaolin exhibits impermeable nature, its use is highly desirable where the strength and water tightness is essential. Hence, it can be used in the hydraulic structures like dams, canal lining aqueducts.

Due to early attainment of the strength the metakaolin can also be used in the structures like bridges, roads, industrial flooring, ware houses, high rise structures etc., Metakaolin possess good resisting properties in the extreme environmental conditions hence, it can be used in the off shore structures. The chemical inertness and the dense mix properties makes it suitable in the construction of nuclear power plants [1].

Metakaolin reacts rapidly with cement and increases compressive strength at early age. Addition of 8% of metakaolin in total cementitious material produces 20% more in 1 day and 40% more in 28 days compressive strength approximately. Use of metakaolin helps in dense packing and reduces permeability which increases the tensile strength. Flexural strength increases but not as significant as compressive and tensile strength.

The pore structure of metakaolin concrete has less permeability. This is due to refined pore structure with the help of secondary CSH gel formation. The low permeability structure reduces chloride ion concentration and diffusion. The products formed due to metakaolin pozzolonic reaction are able to bind free chloride ions introduced in mix water and from environment. Metakaolin of 10 to 15% in concrete reduces calcium hydroxide ions in solution. Due to reduced alkaline and lower pH in pore solution, the alkali silica reaction expansion will be reduced. Metakaolin concrete increases resistance to sulphate attack, due to less formation of gypsum and ettringite which have a high volume from the primary hydration products. Due to less calcium hydrate the sulphate ion has less reaction, efflorescence reduces, as metakaolin consumes $Ca(OH)_2$ [1]. Aiswarya et al.[2] have concluded that cement can be replaced effectively with supplementary cementitious materials(SCM) like metakaolin. In the case of strength and durability, the SCM shows better results than normal mixes. With regard to workability and setting time, metakaolin generally required more superplasticizer and it reduces the setting time of pastes as compared to control mixtures. When compared with cement, the use of metakaolin may be uneconomical due to its high cost whereas it is economical in the aspects of durability and strength. **Sanjay et al.[3]** have concluded that compressive strength of concrete with metakaolin after 28 days can be higher by 20%. Dosage of 15% of metakaolin causes decrease of workability. Increasing amount of metakaolin in concrete mix seems to require higher dosage of superplasticizer to ensure longer period of workability. Poon et al.[4] have studied the performance of metakaolin concrete at elevated temperatures up to 800°C. They prepared eight normal and high strength concrete (HSC) mixes incorporating 0, 5, 10 and 20% metakaolin. They found that after an increase in compressive strength at 200°C, the metakaolin concrete suffered a more severe loss of compressive strength. Metakaolin concrete showed a distinct pattern of strength gain and loss at elevated temperatures. After gaining an increase in compressive strength at 200°C, it maintained higher strengths as compared to the corresponding SF, FA and pure OPC concretes up to 400°C. Gruber et al. [5] have noticed that, the use of 8% and 12% HRM significantly lowered the chloride ion diffusion coefficient of concrete. The level of reduction compared to control specimens was on an average 50% and 60% for mixes with 8% and 12% HRM, respectively. Such reductions may be expected to have a significant effect on the service life of concrete in a chloride environment. Bulk diffusion values continue to reduce (improve) with increased periods of chloride exposure and support the beneficial effects of HRM. The time – dependent reduction in apparent diffusion coefficients appears to be more pronounced with increased levels of HRM. The use of 10% HRM was sufficient to prevent deleterious expansion in concrete prisms containing highly reactive aggregate after 1 year of storage at 38˚C. Srinivasa Rao et al. [6] have concluded that, the percentage loss of compressive strength and weight in 5% H_2SO_4 solution is higher than 5% HCL solution. The percentage loss of compressive strength and weight are increasing with the time of exposure to acid attack. The metakaolin concrete showed more resistance to acid attack when compared to OPCC mix. The percentage loss of compressive strength and weight are decreasing with 10% replacement of cement by metakaolin and incorporation of crimped steel fibers with higher content. Durability studies revealed that 10% replacement of cement with metakaolin along with crimped steel fibers with higher content is more durable when compared to normal concrete after exposure to the HCL and H_2SO_4 solution. Peng et al. [7] have observed that, Fiber concrete had much higher fracture energy, especially those incorporating steel fiber, than plain concrete, confirming the toughening effect of fiber on concrete. Furthermore, for fiber concrete, although residual strength was decreased by exposure to high temperatures above 400 °C, residual fracture energy was significantly higher than that before heating. Poon et al. [4] have studied the performance of metakaolin concrete at elevated temperatures up to 800°C. They prepared eight normal and high strength concrete (HSC) mixes incorporating 0, 5, 10 and 20% metakaolin. They found that after an increase in compressive strength at 200°C, the metakaolin concrete suffered a more severe loss of compressive strength. Metakaolin concrete showed a distinct pattern of strength gain and loss at elevated temperatures. After gaining an increase in compressive strength at 200°C, it maintained higher strengths as compared to the corresponding SF, FA and pure OPC concretes up to 400°C.

In this research work an attempt is made to study the behaviour of metakaoline based hybrid fiber reinforced concrete and to develop it as a special construction material at 200°C. The different fibers used in the research are steel fibers (SF), galvanized iron fibers (GIF), waste coiled steel fibers (WCSF), high density polyethylene fibers (HDPEF), waste plastic fibers (WPF) and polypropylene fibers (PPF). The different combinations of hybrid fibers used for the study are (SF+GIF), (SF+WCSF), (SF+HDPEF), (SF+WPF) and (SF+PPF). The mono-fibres are added at 1% by volume fraction and hybrid fibres are added (0.5% + 0.5%) by volume fraction.

2. Methods and Materials

2.1 Cement

In this experimental work,43 grade ordinary Portland cement (OPC) conforming to IS: 8112 – 1989 was used. The cement used was Rajashre cement from the local distributors. The properties of cement are as shown in Table 1 [8] and Fig. 1.

Table 1: Properties of cement

Properties	Results obtained
Specific gravity	3.15
Blaine's Fineness	225 mm^2/g
Normal consistency	34%
Initial setting time	30 minutes
Final setting time	5 hrs 45 minutes
Compressive strength	43 MPa

Fig. 1 OPC 43 grade cement

2.2 Metakaolin

Metakaolin supplied by 20 Microns Company Vadodhara, was used in the present experimental investigation. Metakaolin is obtained from the calcination of kaolinitic clays at temperatures in the range of 700 to 800ºC. Chemical composition of metakaoline sieve analysis data and its physical properties are presented in Table 2 and 3 and Fig. 2.

Table 2: Chemical composition of metakaolin

Description	Chemical composition, %
Silicon dioxide, SiO_2	51.34
Aluminum oxide, Al_2O_3	41.95
Ferric oxide, Fe_2O_3	0.52
Calcium oxide, CaO	0.34
Loss on ignition	0.72

Table 3 Physical properties of metakaolin

Sieve size in micron	Weight retained (grams)	Percentage passing (%)
90	95	92%
75	122	83%
45	704	62%
Specific gravity	2.1	
Fineness (Blain’s air permeability)	516 m^2 /kg	

Fig. 2 Metakaolin

2.3 Fine aggregates

Locally available river sand belonging to zone II of IS: 383–1970 was used for the research work. The sieve analysis data and physical properties of fine aggregates used are shown in Table 4 [4] and Fig. 3.

Table 4 Sieve analysis and physical properties of fine aggregate

IS sieve size	Cumulative percentage passing of fine aggregates	Specifications for Zone II as per IS:383–1970
4.75 mm	100	90–100
2.36 mm	98	75–100
1.18 mm	83	55–90
600 microns	55	35–59
300 microns	16	8–30
150 microns	2	0–10
Pan	0	0
Specific gravity = 2.26		
Bulk density = 1752 kg/m^3		
Water absorption = 1.0%		

Fig. 3 Fine aggregates

2.4 Coarse aggregates

Locally available crushed aggregates confirming to IS: 383–1970 was used in this work. The sieve analysis data and physical properties of coarse aggregates are given in Table 5 and Fig. 4.

Table 5. Sieve analysis and physical properties of coarse aggregate

IS sieve size (mm)	Percentage passing of coarse aggregates		Percentage passing of different fractions			Specifications as per IS: 383 – 1970		
	I	II	I	II	Combined 100%	Graded	Single sized	
	(20 mm)	(12.5 mm)	60%	40%			I	II
20	100	100	60	40	100	95–100	85–100	—
12.5	0	98.5	0	0	0	—	—	85–100
10	0	35.2	0	29.5	29.5	25–55	0–20	0–45
4.75	0	8.4	0	4.1	4.1	0–10	0–5	0–10
Specific gravity = 2.65								
Bulk density = 1782 kg/m^3								
Water absorption = 0.6%								

Fig. 4. Coarse aggregates

2.5 Water

Water fit for drinking is generally considered fit for making concrete. Water used for mixing concrete was free from acids, oils, alkalies, vegetables or other organic impurities. Water has two functions in a concrete mix. Firstly, it reacts chemically with the cement to form a cement paste in which the inert aggregates are held in suspension until the cement paste has hardened. Secondly, it serves as a vehicle or lubricant in the mixture of fine aggregates and cement.

2.6 Steel fibres (SF)

In the present work steel fibres of 1mm thickness and 50mm length giving an aspect ratio of 50 were used (Fig. 5). Fibres of crimped shape were found suitable from literature studies. The density and ultimate tensile strength was found to be 7850 kg/m^3 and 395 MPa respectively. Steel fibres were obtained from Stewools India (P) Ltd. Nagpur.

Fig. 5 Steel fibres

2. 7 Galvanized iron fibres (GIF)

Round GI wire of 1mm diameter was cut to the required length of 50 mm giving an aspect ratio of 50 (Fig. 6). The ultimate strength and density of fibres was found to be 395 MPa and 7850 kg/m^3 respectively. These low tensile strength wires are commercially available and are generally used for electrical work.

Fig. 6 Galvanized iron (GI) fibres

2.8 Waste coiled steel fibre (WCSF)

Waste coiled steel fibres were obtained from lathe machine shops. The coiled steel wires were cut in lengths of 50mm (Fig. 7). Average thickness was found to be 1mm so that the aspect ratio is 50.

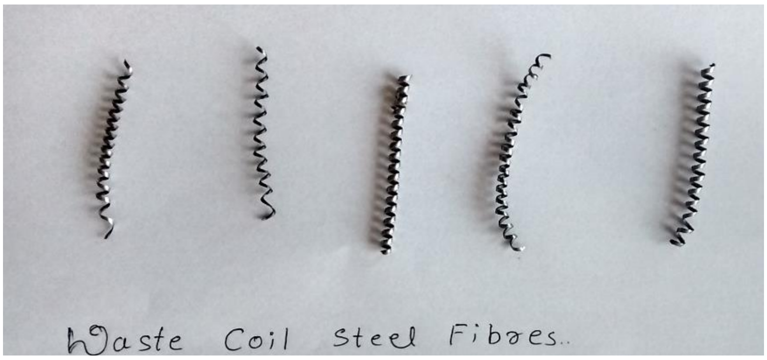

Fig. 7 Waste coiled steel fibre

2.9 High density polyethylene fibres (HDPEF)

High density polyethylene fibres were procured from cutting HDPE oil cans. Fibres were cut to a length of 50 mm and width of 2mm (Fig. 8). Thickness was found to be 1 mm, so that the aspect ratio is 50. Density of HDPE fibre was found to be 900 kg/m$^{3.}$

Fig. 8 High density polyethylene fibres

2.10 Waste plastic fibre (WPF)

Waste plastic fibres were procured from cutting waste plastic buckets. Fibres were cut to a length of 50 mm and width of 2mm.Thickness was found to be 1mm, so that aspect ratio is 50. Density of waste plastic fibre was found to be 230 kg/m$^{3.}$

2.11 Polypropylene fibre (PPF)

Polypropylene fibre is high density fibrillated mesh fibres with chemical treatment to the surface for uniform dispersion in wet concrete. Length of the polypropylene fibre is found to be 12mm. The specific gravity is found to be 0.92 (Fig. 9).

Fig. 9 Polypropylene fibres

3.4 Mixing and casting of specimens

The mixing procedure was done according to following steps:

- Replace 20% cement by metakaolin [9].
- Separately mix the cementitious materials (cement and metakaolin)
- Dry mix the sand and cementitious materials and fibres. The monofibres are added at 1% by volume fraction and hybrid fibres are added (0.5% + 0.5%) by volume fraction.
- Add coarse aggregate to it and mix it thoroughly to achieve a homogeneous mix.
- Add the calculated quantity of water to the dry mix and mix thoroughly to get homogeneous wet mix.
- Fig. 10 and Fig. 11 shows the mix ingredient in dry form and wet form respectively.

Fig. 10 Mix ingredients in dry form

Fig. 11 Wet mix

3.5 The following procedure is adopted to cast the specimens.

- Place the moulds on the vibrating table and put the wet concrete mix inside the moulds in three layers.
- Vibrate the concrete both through table vibrator and by hand compaction using tamping rod.
- Vibration should not be more, otherwise segregation will take place.
- After filling the moulds with wet concrete, level the surface and give the designation to each specimen.
- Demould the specimen after 24 hours.
- Transfer the specimens to curing tank wherein they are allowed to cure in water for 28 days or 90 days.

3.5 Testing Procedure

The slump test was conducted for the different combinations of the design mix (Fig. 12). The slump mould was cleaned and oiled properly with all the initial adjustments. The mix was placed and filled in to four equal layers by tamping each layer with 25 blows **[11]**. The extra material was trimmed off and the initial reading was noted. Then the mould was lifted vertically without disturbing the mix and the final reading was noted. The difference in the height was noted as slump value in terms of mm.

Fig. 12 Slump test

Compaction factor test was conducted to determine the compaction factor for the design mix and for different combinations (Fig. 13). The mould assembly consists of upper hopper A having top internal diameter of 254mm,bottom internal diameter of 127mm internal height of 279mm,hopper B having top internal diameter 229mm,bottom internal diameter 127mm and height 229mm, Cylinder C having internal diameter of 152 mm internal height of 305mmand distance between the hopper A,B and cylinder C is 203mm.

Initially the hoppers and cylinders were oiled and the shutter doors were clamped properly. The material to be tested was filled in to the top hopper and the trap door of the hopper A was opened and the material was allowed to fall freely and fill the hopper B, then the trap door was opened to fill the material in to the cylinder. The weight was noted as partially compacted cement concrete. The material was emptied from the cylinder and the material to be tested was filled in to four equal layers with 25 blows from the tamping rod. The weight was noted as fully compacted cement concrete. The ratio of the above weights is known as compaction factor.

$$\textbf{Compaction factor} = \frac{\mathit{Weightofpartiallycompactedcementconcrete}}{\mathit{Weightoffullycompactedcementconcrete}} \qquad (2)$$

Fig. 13 Compaction factor test

Vee-bee consistometer test This test was conducted to know the consistency of the concrete for the design mix and for different combinations (Fig. 14). All the initial arrangements were made before starting the experiment. Concrete was placed in to the slump cone and filled into four equal layers by 25 tamping blows. Initial reading was noted. By lifting the cone final slump value was recorded. The glass disc attached and the motor was started. Simultaneously the stop watch was also started. The time interval was noted for the remoulding of the concrete. The time interval is expressed in terms of Vee-Bee degree.

Fig. 14 Vee-bee consistometer

Flow table test was conducted to know the fluidity of the freshly prepared concrete for design mix and for different combinations (Fig. 15). The instrument consists of the table and mould having the base diameter of 250 mm, upper diameter of 170 mm and the height of 120 mm. It is attached to the drop handle. Before starting the test all the necessary initial arrangements were made. The concrete to be tested was filled in to the mould in to three equal layers with 25 tamping blows. Then 15 blows were given to the mix. The spread diameter in six directions was measured. Percentage of flow is determined by the following equation.

$$\textbf{Percentage flow} = \left(\frac{\textit{Spread dia} - \textit{Initial dia}}{\textit{Initial dia}}\right) \textbf{X 100} \qquad \textbf{(5)}$$

Fig. 15 Flow table

The size of the specimen is 150 X 150 X 150 mm. The compressive strength test was conducted after the concrete specimens were cured after 28 days and 90 days (Fig. 16). The specimens were kept centrally on the compression testing machine and load was applied continuously and uniformly on the surface perpendicular to the direction of the tamping. The failure load was recorded.

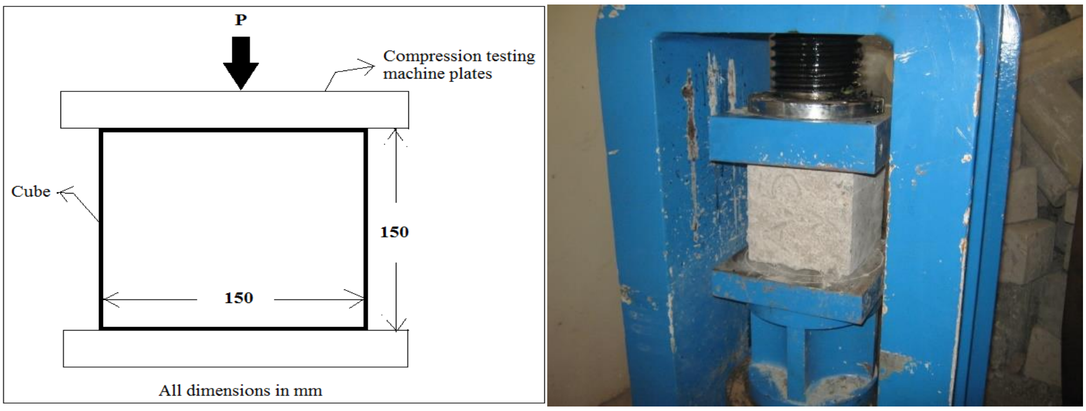

Fig. 16 Line diagram and photograph of compression test on cubes

Compressive strength is calculated as: **Compressive strength = P / A × 1000**

Where, P = Load in kN, A = Area of cube surface = 150 x 150 mm^2

Tensile strength was tested as shown in Fig. 17. The size of the cylindrical specimen is of 150 mm diameter and 300 mm length. The specimens were placed with its axis horizontal, between the plattens of compression testing machine. 6 mm plywood strips were introduced on the top and bottom of specimen. Load was applied continuously and uniformly until the specimen failed in its vertical diameter.

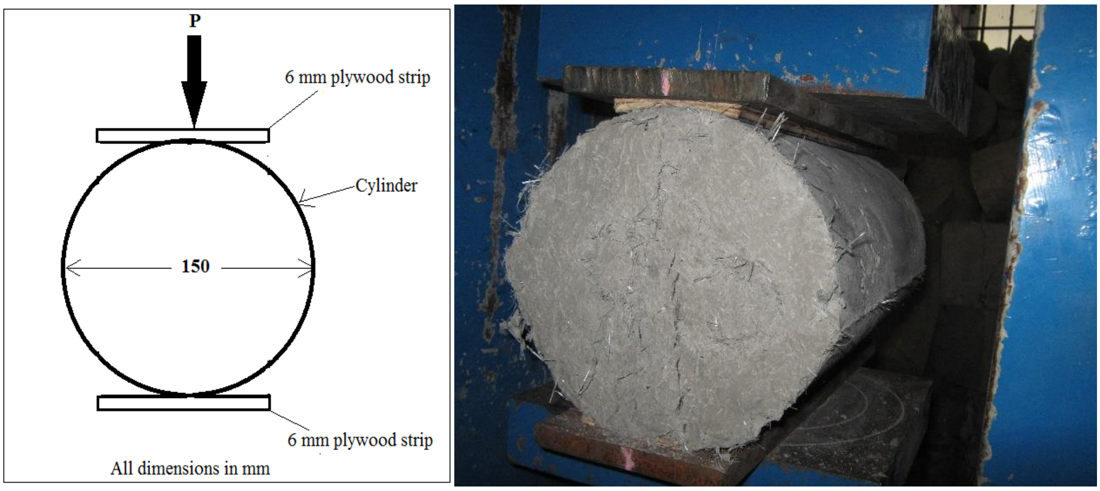

Fig. 17 Line diagram and photograph of split tensile test on cylinders

Split tensile strength is calculated as follows:

Split tensile strength = 2P / (3.142 × dL) × 1000

Where, P = Load in kN, d = Diameter of cylinder = 150 mm, L = Length of cylinder = 300 mm

The size of the beam for flexural strength is 500 X 100 X 100 mm (Fig. 18). The specimen was subjected to bending, using two point loading until it failed. The distance of the loading point is 133 mm and the supporting point is 400 mm. The test was carried out under controlled conditions. The failure load was recorded.

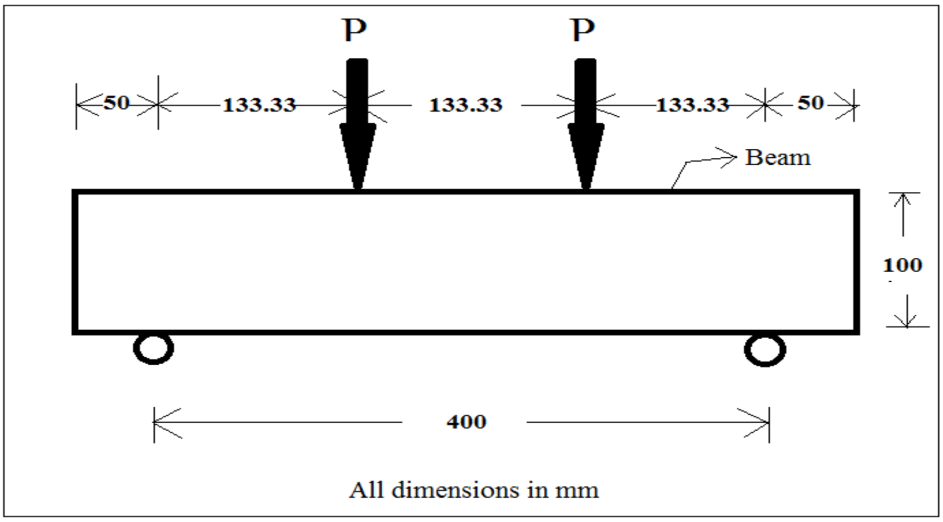

Fig. 18 Line diagram of flexural test on beams

The flexural strength of the specimen is expressed as the modulus of rupture and is calculated using following formula. **Flexural strength = PL / bd^2 × 1000**

Where, P = Load in kN, L = Effective length of beam = 400 mm, b = Width of the beam = 100 mm, d = Depth of the beam = 100 mm

3.6 Test for resistance to sustained elevated temperature

In order to study the effect of sustained elevated temperatures on the strength characteristics of metakaolin based hybrid fibre reinforced concrete, after 28 days and 90 days of curing, the specimens were kept in oven at sustained elevated temperatures of 200˚C for 3 hours as required (Fig. 19). The specimens were tested for their respective strengths after they were cooled to room temperature. The facilities at Laxmi foundries, Harihar were used for this purpose.

Fig. 19 Specimen subjected to elevated temperature

4. Results

The mix proportion for M 30 grade concrete as per mix design is found to be 1:1.38:2.75 with w/c ratio 0.45. Then the required quantity of cement, fine aggregates, coarse aggregates were dry mixed. Before dry mixing, 20% of cement was replaced with metakolin. To this dry mix required quantity of water was added and thoroughly mixed. Then the combination of admixtures such as superplasticizer and accerlator (SP+ACC), superplasticizer and retarder (SP+RET) and superplasticizer and air entraining agent (SP+AEA) are added in concrete with specified dosages and mixed thoroughly. This green concrete was placed in three different layers in the moulds which were thoroughly oiled. The moulds were vibrated by keeping them on table vibrator. Hand compaction was also adopted simultaneously. After compaction, the specimens were covered by wet gunny bags. After 15 hours, the specimens were demoulded and transferred to curing tank. They were allowed to cure in water for 28 days and 90 days as the case may be.

4.1 Compressive strength test results when subjected to 200˚C

Following tables give the compressive strength test results of metakaoline based hybrid fibre reinforced concrete without subjecting to temperature and when subjected to 200˚C for 3 hours after 28 days and 90 days curing.

Table 6 Results of 28 days compressive strength without subjecting to temperature

Description of concrete	Specimen identification	Weight of the specimen (N)	Density (N/cum)	Average density (N/cum)	Failure load (kN)	Compressive strength (MPa)	Average compressive strength (MPa)
Without fibres (REF)	POY	83.39	24706.67	24706.67	760.00	33.78	34.22
	POY	82.40	24416.00		780.00	34.67	
	POY	84.37	24997.33		770.00	34.22	
(SF+GIF)	P1Y	81.47	24139.87	24149.56	1060.00	47.11	47.11
	P1Y	81.62	24183.47		1050.00	46.67	
	P1Y	81.42	24125.33		1070.00	47.56	
(SF+WCSF)	P2Y	81.62	24183.47	24154.40	1035.00	46.00	46.44
	P2Y	81.52	24154.40		1050.00	46.67	
	P2Y	81.42	24125.33		1050.00	46.67	
(SF+HDPEF)	P3Y	80.93	23980.00	24033.29	1000.00	44.44	44.44
	P3Y	80.98	23994.53		1000.00	44.44	
	P3Y	81.42	24125.33		1000.00	44.44	
(SF+WPF)	P4Y	81.37	24110.80	24178.62	950.00	42.22	42.44
	P4Y	82.01	24299.73		950.00	42.22	
	P4Y	81.42	24125.33		965.00	42.89	
(SF+PPF)	P5Y	81.62	24183.47	24420.84	895.00	39.78	39.56
	P5Y	84.22	24953.73		880.00	39.11	
	P5Y	81.42	24125.33		895.00	39.78	
SF	P6Y	82.06	24314.27	24430.53	1045.00	46.44	46.67
	P6Y	83.88	24852.00		1055.00	46.89	
	P6Y	81.42	24125.33		1050.00	46.67	
GIF	P7Y	83.24	24663.07	24202.84	950.00	42.22	44.44
	P7Y	80.39	23820.13		1025.00	45.56	
	P7Y	81.42	24125.33		1025.00	45.56	
WCSF	P8Y	80.64	23892.80	24130.18	960.00	42.67	43.11
	P8Y	82.26	24372.40		970.00	43.11	
	P8Y	81.42	24125.33		980.00	43.56	
HDPEF	P9Y	79.71	23616.67	23839.51	950.00	42.22	41.56
	P9Y	80.25	23776.53		935.00	41.56	
	P9Y	81.42	24125.33		920.00	40.89	

WPF	P10Y	79.66	23602.13	23950.93	870.00	38.67	39.11
	P10Y	81.42	24125.33		885.00	39.33	
	P10Y	81.42	24125.33		885.00	39.33	
PPF	P11Y	81.77	24227.07	24139.87	840.00	37.33	36.89
	P11Y	81.23	24067.20		825.00	36.67	
	P11Y	81.42	24125.33		825.00	36.67	

Table 7 Results of 90 days compressive strength without subjecting to temperature

Description of concrete	Specimen identification	Weight of the specimen (N)	Density (N/cum)	Average density (N/cum)	Failure load (kN)	Compressive strength (MPa)	Average compressive strength (MPa)
Without fibres (REF)	POZ	83.39	24706.67	24619.47	820.00	36.44	36.74
	POZ	83.48	24735.73		830.00	36.89	
	POZ	82.40	24416.00		830.00	36.89	
(SF+GIF)	P1Z	83.34	24692.13	24600.09	1200.00	53.33	51.11
	P1Z	84.32	24982.80		1100.00	48.89	
	P1Z	81.42	24125.33		1150.00	51.11	
(SF+WCSF)	P2Z	82.21	24357.87	24275.51	1150.00	51.11	50.44
	P2Z	82.16	24343.33		1135.00	50.44	
	P2Z	81.42	24125.33		1120.00	49.78	
(SF+HDPEF)	P3Z	83.73	24808.40	24377.24	1050.00	46.67	46.22
	P3Z	81.67	24198.00		1030.00	45.78	
	P3Z	81.42	24125.33		1040.00	46.22	
(SF+WPF)	P4Z	81.52	24154.40	24435.38	975.00	43.33	44.44
	P4Z	84.46	25026.40		1000.00	44.44	
	P4Z	81.42	24125.33		1025.00	45.56	
(SF+PPF)	P5Z	80.34	23805.60	23980.00	920.00	40.89	41.33
	P5Z	81.03	24009.07		940.00	41.78	
	P5Z	81.42	24125.33		930.00	41.33	
SF	P6Z	83.34	24692.13	24600.09	1110.00	49.33	48.89
	P6Z	84.32	24982.80		1090.00	48.44	
	P6Z	81.42	24125.33		1100.00	48.89	
GIF	P7Z	85.10	25215.33	24537.11	1070.00	47.56	47.56
	P7Z	81.91	24270.67		1065.00	47.33	

	P7Z	81.42	24125.33		1075.00	47.78	
WCSF	P8Z	82.45	24430.53	24164.09	1025.00	45.56	45.11
	P8Z	80.79	23936.40		1000.00	44.44	
	P8Z	81.42	24125.33		1020.00	45.33	
HDPEF	P9Z	81.03	24009.07	24125.33	1000.00	44.44	44.00
	P9Z	81.82	24241.60		1000.00	44.44	
	P9Z	81.42	24125.33		970.00	43.11	
WPF	P10Z	83.88	24852.00	24333.64	900.00	40.00	41.33
	P10Z	81.08	24023.60		900.00	40.00	
	P10Z	81.42	24125.33		990.00	44.00	
PPF	P11Z	78.14	23151.60	23597.29	850.00	37.78	38.67
	P11Z	79.36	23514.93		860.00	38.22	
	P11Z	81.42	24125.33		900.00	40.00	

Table 8 Results of 28 days compressive strength when subjected to 200˚C

Description of concrete	Specimen identification	Weight of the specimen (N)	Density (N/cum)	Average density (N/cum)	Failure load (kN)	Compressive strength (MPa)	Average compressive strength (MPa)
Without fibres (REF)	GOY	82.40	24416.00	24609.78	760.00	33.78	33.33
	GOY	82.40	24416.00		740.00	32.89	
	GOY	84.37	24997.33		750.00	33.33	
(SF+GIF)	G1Y	81.96	24285.20	24246.44	1000.00	44.44	44.44
	G1Y	82.11	24328.80		1000.00	44.44	
	G1Y	81.42	24125.33		1000.00	44.44	
(SF+WCSF)	G2Y	84.66	25084.53	24798.71	1000.00	44.44	44.00
	G2Y	85.00	25186.27		1000.00	44.44	
	G2Y	81.42	24125.33		970.00	43.11	
(SF+HDPEF)	G3Y	82.11	24328.80	24304.58	920.00	40.89	40.00
	G3Y	82.55	24459.60		900.00	40.00	
	G3Y	81.42	24125.33		880.00	39.11	
(SF+WPF)	G4Y	83.09	24619.47	24537.11	880.00	39.11	39.56
	G4Y	83.92	24866.53		930.00	41.33	
	G4Y	81.42	24125.33		860.00	38.22	
(SF+PPF)	G5Y	81.91	24270.67	24028.44	820.00	36.44	37.33
	G5Y	79.95	23689.33		850.00	37.78	
	G5Y	81.42	24125.33		850.00	37.78	
SF	G6Y	81.77	24227.07	24222.22	1000.00	44.44	44.00
	G6Y	82.06	24314.27		1000.00	44.44	
	G6Y	81.42	24125.33		970.00	43.11	
GIF	G7Y	84.02	24895.60	24445.07	955.00	42.44	43.33

	G7Y	82.06	24314.27		970.00	43.11	
	G7Y	81.42	24125.33		1000.00	44.44	
WCSF	G8Y	82.55	24459.60	24459.60	960.00	42.67	41.78
	G8Y	83.68	24793.87		930.00	41.33	
	G8Y	81.42	24125.33		930.00	41.33	
HDPEF	G9Y	81.57	24168.93	24139.87	860.00	38.22	38.67
	G9Y	81.42	24125.33		875.00	38.89	
	G9Y	81.42	24125.33		875.00	38.89	
WPF	G10Y	82.31	24386.93	24173.78	850.00	37.78	35.56
	G10Y	81.03	24009.07		775.00	34.44	
	G10Y	81.42	24125.33		775.00	34.44	
PPF	G11Y	82.26	24372.40	23902.49	785.00	34.89	35.11
	G11Y	78.33	23209.73		785.00	34.89	
	G11Y	81.42	24125.33		800.00	35.56	

Table 9 Results of 90 days compressive strength when subjected to 200˚C

Description of concrete	Specimen identification	Weight of the specimen (N)	Density (N/cum)	Average density (N/cum)	Failure load (kN)	Compressive strength (MPa)	Average compressive strength (MPa)
Without fibres (REF)	GOZ	83.39	24706.67	24609.78	780.00	34.67	34.67
	GOZ	83.39	24706.67		770.00	34.22	
	GOZ	82.40	24416.00		790.00	35.11	
(SF+GIF)	G1Z	83.09	24619.47	24396.62	1120.00	49.78	48.89
	G1Z	82.50	24445.07		1100.00	48.89	
	G1Z	81.42	24125.33		1080.00	48.00	
(SF+WCSF)	G2Z	80.74	23921.87	24057.51	1000.00	44.44	44.89
	G2Z	81.42	24125.33		1030.00	45.78	
	G2Z	81.42	24125.33		1000.00	44.44	
(SF+HDPEF)	G3Z	82.99	24590.40	24353.02	910.00	40.44	41.78
	G3Z	82.16	24343.33		950.00	42.22	
	G3Z	81.42	24125.33		960.00	42.67	
(SF+WPF)	G4Z	82.89	24561.33	24139.87	920.00	40.89	40.89
	G4Z	80.10	23732.93		910.00	40.44	
	G4Z	81.42	24125.33		930.00	41.33	
(SF+PPF)	G5Z	82.01	24299.73	24294.89	885.00	39.33	39.56
	G5Z	81.96	24285.20		900.00	40.00	

	G5Z	82.01	24299.73		885.00	39.33	
SF	G6Z	81.72	24212.53	24125.33	1060.00	47.11	47.85
	G6Z	81.13	24038.13		1090.00	48.44	
	G6Z	81.42	24125.33		1080.00	48.00	
GIF	G7Z	81.96	24285.20	24081.73	1030.00	45.78	46.96
	G7Z	80.44	23834.67		1090.00	48.44	
	G7Z	81.42	24125.33		1050.00	46.67	
WCSF	G8Z	81.42	24125.33	24377.24	975.00	43.33	43.56
	G8Z	83.97	24881.07		970.00	43.11	
	G8Z	81.42	24125.33		995.00	44.22	
HDPEF	G9Z	82.40	24416.00	24246.44	800.00	35.56	40.00
	G9Z	81.67	24198.00		900.00	40.00	
	G9Z	81.42	24125.33		1000.00	44.44	
WPF	G10Z	84.42	25011.87	24648.53	880.00	39.11	39.19
	G10Z	82.75	24517.73		885.00	39.33	
	G10Z	82.40	24416.00		880.00	39.11	
PPF	G11Z	78.58	23282.40	23544.00	810.00	36.00	36.07
	G11Z	78.38	23224.27		810.00	36.00	
	G11Z	81.42	24125.33		815.00	36.22	

Table 10 gives the overall results of compressive strength of metakaoline based hybrid fiber reinforced concrete, when subjected to 200˚C for 3 hours. Table also gives the percentage increase of compressive strength of hybrid fiber reinforced concrete with respect to respective monofibre reinforced concrete. Table also indicates the percentage increase of compressive strength of hybrid fiber reinforced concrete and monofibre reinforced concrete with respect to reference mix. Residual compressive strengths are also indicated in the table. The variation of compressive strength is shown graphically in the Figure 20 and residual compressive strength in Figure 21.

Table 10 Overall results of compressive strength when subjected to 200˚C

Description of concrete	28 days compressive strength without subjecting to temperature (MPa)	28 days compressive strength when subjected to200˚C (MPa)	Percentage increase of 28 days compressive strength (when subjected to 200˚C) for HFRC with respect to corresponding mono fibre reinforced concrete	Percentage increase of 28 days compressive strength (when subjected to 200˚C) with respect to reference concrete	28 days residual compressive strength (%)	90 days compressive strength without subjecting to temperature (MPa)	90 days compressive strength when subjected to 200˚C (MPa)	Percentage increase of 90 days compressive strength (when subjected to 200˚C) for HFRC with respect to corresponding mono fibre reinforced concrete	Percentage increase of 90 days compressive strength (when subjected to 200˚C) with respect to reference concrete	90 days residual compressive strength (%)
Without fibres (REF)	34.22	33.33			97	36.74	34.67			94.35
(SF+GIF)	47.11	44.44	3	33	94	51.11	48.89	4	41	95.65
(SF+WCSF)	46.44	44.00	5	32	95	50.44	44.89	3	29	88.99
(SF+HDPEF)	44.44	40.00	3	20	90	46.22	41.78	4	21	90.38
(SF+WPF)	42.44	39.56	11	19	93	44.44	40.89	4	18	92.00
(SF+PPF)	39.56	37.33	6	12	94	41.33	39.56	10	14	95.70
SF	46.67	44.00	--------	32	94	48.89	47.85	--------	38	97.88
GIF	44.44	43.33	--------	30	98	47.56	46.96	--------	35	98.75
WCSF	43.11	41.78	--------	25	97	45.11	43.56	--------	26	96.55
HDPEF	41.56	38.67	--------	16	93	44.00	40.00	--------	15	90.91
WPF	39.11	35.56	--------	7	91	41.33	39.19	--------	13	94.80

PPF	36.89	35.11	--------	5	95	38.67	36.07	--------	4	93.30

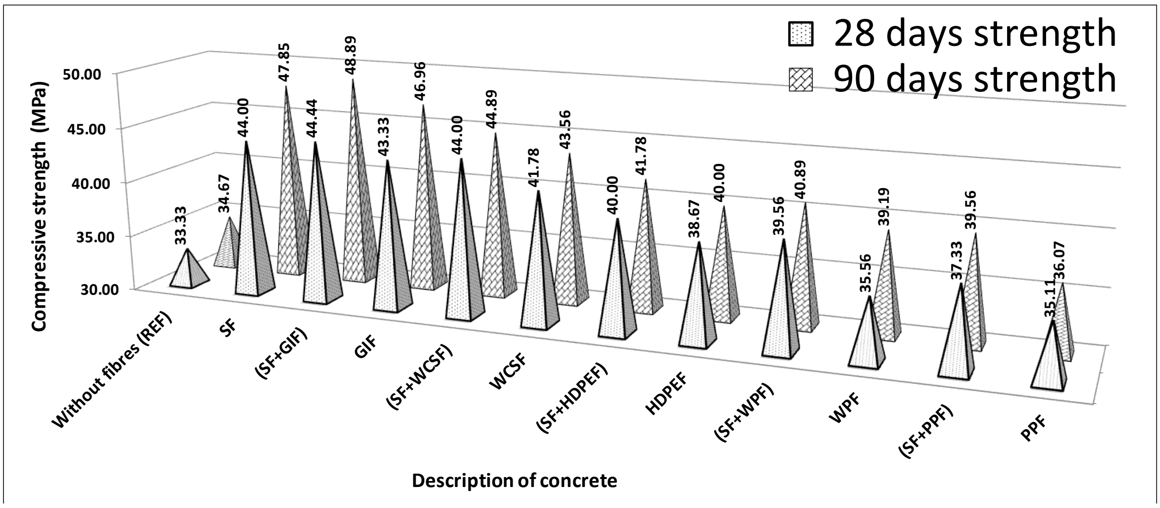

Fig. 20 Variation in the compressive strength at 200°C

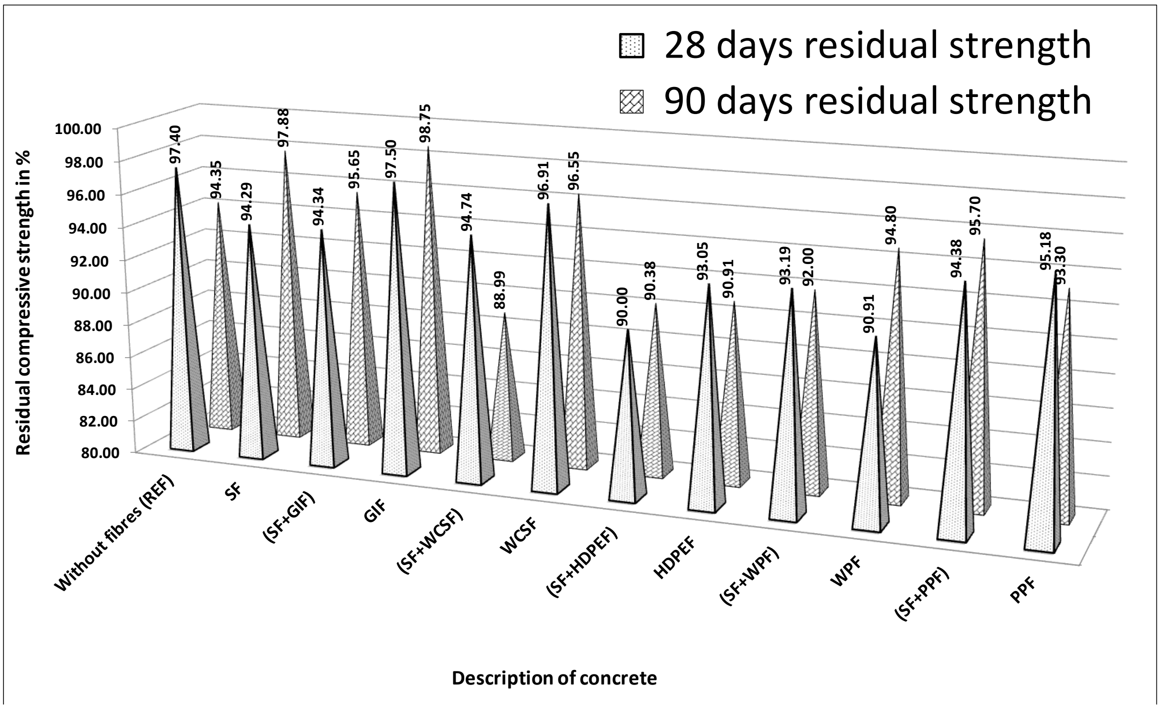

Fig. 21 Variation in the residual compressive strength at 200°C

4.2 Tensile strength test results when subjected to 200˚C

Following tables give the tensile strength test results of metakaoline based hybrid fibre reinforced concrete without subjecting to temperature and when subjected to 200˚C for 3 hours after 28 days and 90 days curing.

Table 11 Results of 28 days tensile strength without subjecting to temperature

Description of concrete	Specimen identification	Failure load (kN)	Tensile strength (MPa)	Average tensile strength (MPa)
Without fibres (REF)	POY	180.00	2.55	2.40
	POY	170.00	2.40	
	POY	160.00	2.26	
(SF+GIF)	P1Y	300.00	4.24	4.31
	P1Y	310.00	4.39	
	P1Y	305.00	4.31	
(SF+WCSF)	P2Y	250.00	3.54	3.82
	P2Y	280.00	3.96	
	P2Y	280.00	3.96	
(SF+HDPEF)	P3Y	240.00	3.39	3.54
	P3Y	240.00	3.39	
	P3Y	270.00	3.82	
(SF+WPF)	P4Y	220.00	3.11	3.23
	P4Y	230.00	3.25	
	P4Y	235.00	3.32	
(SF+PPF)	P5Y	200.00	2.83	3.09
	P5Y	230.00	3.25	
	P5Y	225.00	3.18	
SF	P6Y	290.00	4.10	4.24
	P6Y	290.00	4.10	
	P6Y	320.00	4.53	
GIF	P7Y	280.00	3.96	4.24
	P7Y	300.00	4.24	
	P7Y	320.00	4.53	
WCSF	P8Y	280.00	3.96	3.68
	P8Y	250.00	3.54	
	P8Y	250.00	3.54	
HDPEF	P9Y	225.00	3.18	3.32
	P9Y	230.00	3.25	
	P9Y	250.00	3.54	
WPF	P10Y	200.00	2.83	2.97
	P10Y	210.00	2.97	

	P10Y	220.00	3.11	
PPF	P11Y	205.00	2.90	2.81
	P11Y	190.00	2.69	
	P11Y	200.00	2.83	

Table 12. Results of 90 days tensile strength without subjecting to temperature

Description of concrete	Specimen identification	Failure load (kN)	Tensile strength (MPa)	Average tensile strength (MPa)
Without fibres (REF)	POZ	175.00	2.48	2.50
	POZ	180.00	2.55	
	POZ	175.00	2.48	
(SF+GIF)	P1Z	340.00	4.81	4.67
	P1Z	340.00	4.81	
	P1Z	310.00	4.39	
(SF+WCSF)	P2Z	300.00	4.24	4.39
	P2Z	330.00	4.67	
	P2Z	300.00	4.24	
(SF+HDPEF)	P3Z	285.00	4.03	4.10
	P3Z	285.00	4.03	
	P3Z	300.00	4.24	
(SF+WPF)	P4Z	270.00	3.82	3.68
	P4Z	270.00	3.82	
	P4Z	240.00	3.39	
(SF+PPF)	P5Z	260.00	3.68	3.54
	P5Z	245.00	3.47	
	P5Z	245.00	3.47	
SF	P6Z	330.00	4.67	4.53
	P6Z	300.00	4.24	
	P6Z	330.00	4.67	
GIF	P7Z	325.00	4.60	4.46
	P7Z	300.00	4.24	
	P7Z	320.00	4.53	
WCSF	P8Z	305.00	4.31	4.24
	P8Z	305.00	4.31	
	P8Z	290.00	4.10	
HDPEF	P9Z	290.00	4.10	3.96
	P9Z	275.00	3.89	
	P9Z	275.00	3.89	

WPF	P10Z	265.00	3.75	3.54
	P10Z	225.00	3.18	
	P10Z	260.00	3.68	
PPF	P11Z	200.00	2.83	2.83
	P11Z	210.00	2.97	
	P11Z	190.00	2.69	

Table 13 Results of 28 days tensile strength when subjected to 200˚C

Description of concrete	Specimen identification	Failure load (kN)	Tensile strength (MPa)	Average tensile strength (MPa)
Without fibres (REF)	GOY	150.00	2.12	2.17
	GOY	155.00	2.19	
	GOY	155.00	2.19	
(SF+GIF)	G1Y	300.00	4.24	3.54
	G1Y	225.00	3.18	
	G1Y	225.00	3.18	
(SF+WCSF)	G2Y	250.00	3.54	3.25
	G2Y	220.00	3.11	
	G2Y	220.00	3.11	
(SF+HDPEF)	G3Y	200.00	2.83	3.11
	G3Y	230.00	3.25	
	G3Y	230.00	3.25	
(SF+WPF)	G4Y	200.00	2.83	2.97
	G4Y	210.00	2.97	
	G4Y	220.00	3.11	
(SF+PPF)	G5Y	205.00	2.90	2.83
	G5Y	205.00	2.90	
	G5Y	190.00	2.69	
SF	G6Y	250.00	3.54	3.51
	G6Y	245.00	3.47	
	G6Y	250.00	3.54	
GIF	G7Y	255.00	3.61	3.47
	G7Y	240.00	3.39	
	G7Y	240.00	3.39	
WCSF	G8Y	230.00	3.25	3.23
	G8Y	225.00	3.18	
	G8Y	230.00	3.25	
HDPEF	G9Y	225.00	3.18	3.04
	G9Y	200.00	2.83	
	G9Y	220.00	3.11	
WPF	G10Y	185.00	2.62	2.76

	G10Y	200.00	2.83	
	G10Y	200.00	2.83	
PPF	G11Y	180.00	2.55	2.66
	G11Y	190.00	2.69	
	G11Y	195.00	2.76	

Table 14 Results of 90 days tensile strength when subjected to 200˚C

Description of concrete	Specimen identification	Failure load (kN)	Tensile strength (MPa)	Average tensile strength (MPa)
Without fibres (REF)	GOZ	170.00	2.40	2.36
	GOZ	170.00	2.40	
	GOZ	160.00	2.26	
(SF+GIF)	G1Z	250.00	3.54	3.68
	G1Z	250.00	3.54	
	G1Z	280.00	3.96	
(SF+WCSF)	G2Z	240.00	3.39	3.32
	G2Z	265.00	3.75	
	G2Z	200.00	2.83	
(SF+HDPEF)	G3Z	225.00	3.18	3.21
	G3Z	225.00	3.18	
	G3Z	230.00	3.25	
(SF+WPF)	G4Z	210.00	2.97	3.25
	G4Z	240.00	3.39	
	G4Z	240.00	3.39	
(SF+PPF)	G5Z	210.00	2.97	2.95
	G5Z	210.00	2.97	
	G5Z	205.00	2.90	
SF	G6Z	250.00	3.54	3.63
	G6Z	260.00	3.68	
	G6Z	260.00	3.68	
GIF	G7Z	260.00	3.68	3.58
	G7Z	240.00	3.39	
	G7Z	260.00	3.68	
WCSF	G8Z	230.00	3.25	3.23
	G8Z	230.00	3.25	
	G8Z	225.00	3.18	

HDPEF	G9Z	200.00	2.83	3.11
	G9Z	230.00	3.25	
	G9Z	230.00	3.25	
WPF	G10Z	190.00	2.69	2.78
	G10Z	200.00	2.83	
	G10Z	200.00	2.83	
PPF	G11Z	200.00	2.83	2.73
	G11Z	190.00	2.69	
	G11Z	190.00	2.69	

The overall results of tensile strength when subjected to 200˚C corresponding gives the overall results of tensile strength of metakaoline based hybrid fiber reinforced concrete when subjected to 200˚C for 3 hours. Table also gives the percentage increase of tensile strength of hybrid fiber reinforced concrete with respect to respective monofibre reinforced concrete. Table also indicates the percentage increase of tensile strength of hybrid fiber reinforced concrete and monofibre reinforced concrete with respect to reference mix. Residual tensile strengths are also indicated in the table. The variation of tensile strength is shown graphically in the Figure 22 and residual tensile strength in Figure 23.

Table 15 Overall results of tensile strength when subjected to 200˚C

Description of concrete	28 days tensile strength without subjecting to temperature (MPa)	28 days tensile strength when subjected to200˚C (MPa)	Percentage increase of 28 days tensile strength (when subjected to 200˚C) for HFRC with respect to corresponding mono fibre reinforced	Percentage increase of 28 days tensile strength (when subjected to 200˚C) with respect to reference concrete	28 days residual tensile strength (%)	90 days tensile strength without subjecting to temperature (MPa)	90 days tensile strength when subjected to 200˚C (MPa)	Percentage increase of 90 days tensile strength (when subjected to 200˚C) for HFRC with respect to corresponding mono fibre reinforced	Percentage increase of 90 days tensile strength (when subjected to 200˚C) with respect to reference concrete	90 days residual tensile strength (%)
Without fibres (REF)	2.40	2.17			90	2.50	2.36			94.34
(SF+GIF)	4.31	3.54	2	63	82	4.67	3.68	3	56	78.79
(SF+WCSF)	3.82	3.25	1	50	85	4.39	3.32	3	41	75.81
(SF+HDPEF)	3.54	3.11	2	43	88	4.10	3.21	3	36	78.16
(SF+WPF)	3.23	2.97	8	37	92	3.68	3.25	17	38	88.46
(SF+PPF)	3.09	2.83	6	30	92	3.54	2.95	8	25	83.33
SF	4.24	3.51	--------	62	83	4.53	3.63	--------	54	80.21
GIF	4.24	3.47	--------	60	82	4.46	3.58	--------	52	80.42
WCSF	3.68	3.23	--------	49	88	4.24	3.23	--------	37	76.11
HDPEF	3.32	3.04	--------	40	91	3.96	3.11	--------	32	78.57
WPF	2.97	2.76	--------	27	93	3.54	2.78	--------	18	78.67

PPF	2.81	2.66	--------	23	95	2.83	2.73	--------	16	96.67

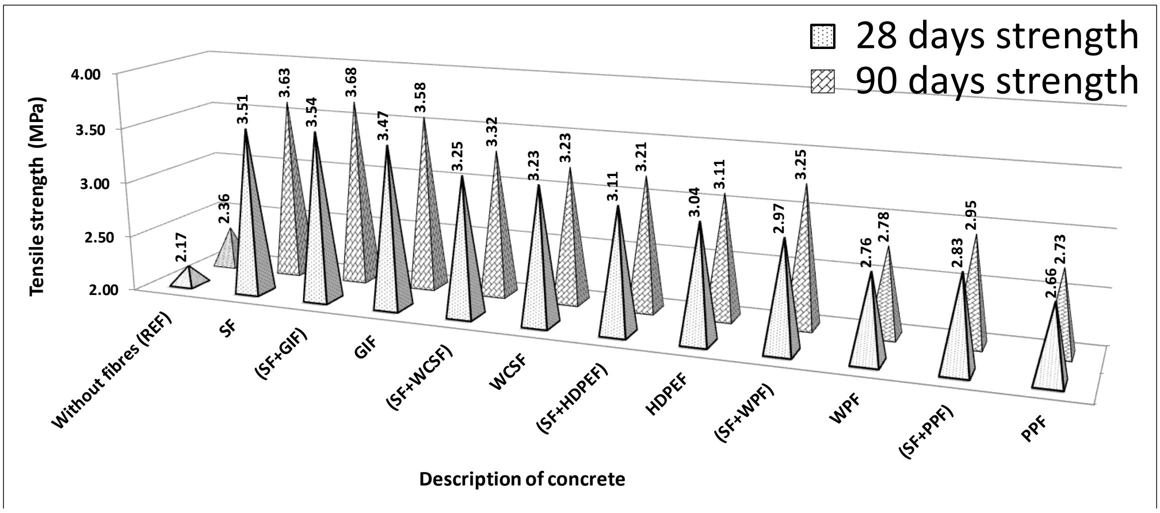

Fig. 22 Variation in the tensile strength

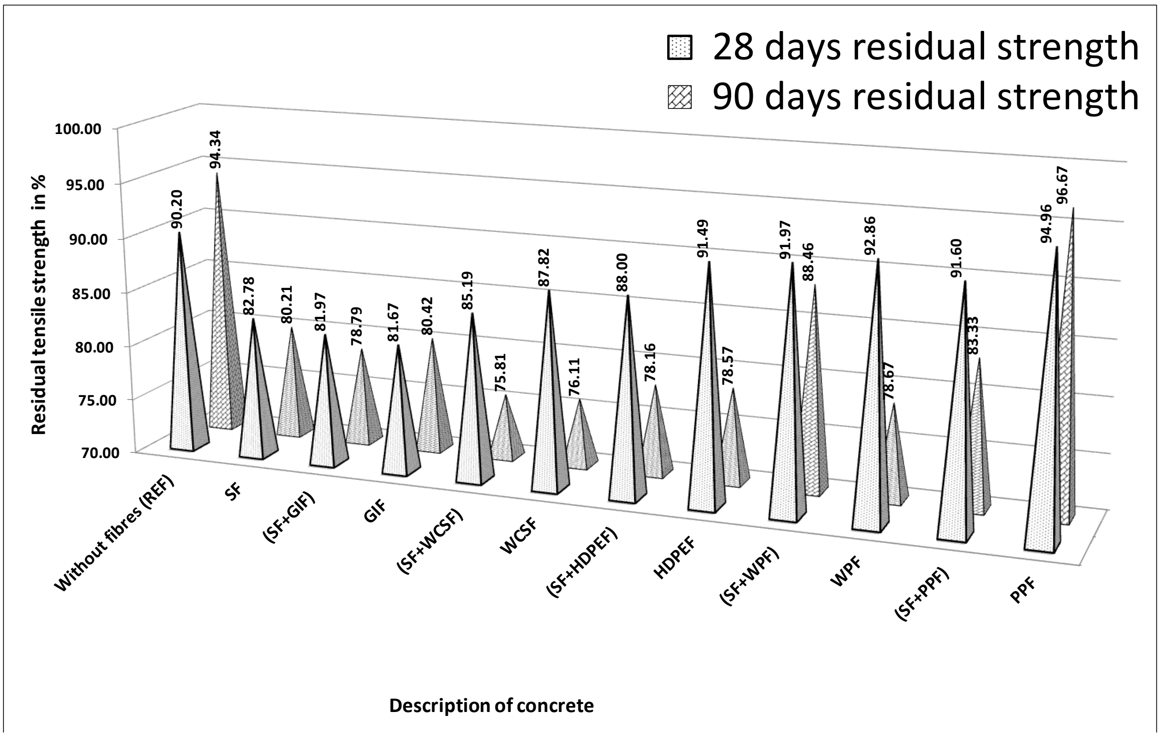

Fig. 23 Variation in the residual tensile strength

5. Observations and discussion

The compressive strength test results for metakaoline based hybrid fibre reinforced concrete when subjected to a sustained elevated temperature of 200ºC for 3 hours are presented in table 9.5. It is evident from the table that metakaoline based hybrid fibre reinforced concrete and mono fibre reinforced concrete under-go a small loss of compressive strength when subjected to 200ºC. Also it is seen that the performance of metakaoline based hybrid fibre reinforced concretes are certainly good as compared to corresponding mono fiber reinforced concrete. Metakaoline based hybrid fibre reinforced concrete with combination of fibres (SF+GIF), (SF+WCSF), (SF+HDPEF), (SF+WPF) and (SF+PPF) show 3%, 5%, 3%, 11% and 6% increase in the compressive strength when subjected to 200ºC. This is further supported by the observation of residual compressive strength of 94%, 95%, 90%, 93% and 94% for metakaoline based hybrid fibre reinforced concretes.

Tensile strength test results for metakaoline based hybrid fibre reinforced concrete when subjected to a sustained elevated temperature of 200ºC for 3 hours are presented in table 9.10. It is evident from the table that metakaoline based hybrid fibre reinforced concrete and mono fibre reinforced concrete under-go a small loss of tensile strength when subjected to 200ºC. Also, it is seen that the performance of metakaoline based hybrid fibre reinforced concretes are certainly good as compared to corresponding mono fiber reinforced concrete. Metakaoline based hybrid fibre reinforced concrete with combination of fibres (SF+GIF), (SF+WCSF), (SF+HDPEF), (SF+WPF) and (SF+PPF) show 2%, 1%, 2%, 8% and 6% increase in the tensile strength when subjected to 200ºC. This is further supported by the observation of residual tensile strength of 82%, 85%, 88%, 92% and 92% for metakaoline based hybrid fibre reinforced concretes.

This is attributed to the fact that the hybrid fibres used will help in distributing the temperature evenly in the concrete mass. Also, the synergistic effect of hybrid fibres can effectively resist the temperature stresses produced at 200ºC.

Thus, it can be concluded that the metakaoline based hybrid fibre reinforced concretes exhibit better resistive properties at 200ºC as compared to corresponding mono fibre reinforced concretes.

6. Conclusions

Following conclusions are made based on the experimentations conducted on the behavior of metakaoline based hybrid fibre reinforced concrete when subjected to sustained elevated temperatures.

1) Metakaoline based hybrid fibre reinforced concretes exhibit better resistive properties at 200ºC as compared to corresponding mono fibre reinforced concretes. At 200ºC the specimens have exhibited minor hairy cracks which are sometimes invisible to the naked eye.
2) Metakaoline based hybrid fibre reinforced concrete with combination of fibres (SF+GIF) has shown better performance over other combination of fibres such as

(SF+WCSF), (SF+HDPEF), (SF+WPF) and (SF+PPF) when subjected to sustained elevated temperatures of 200°C for 3 hours.

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