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Flexural Behavior of TBSFRC Subjected to Sustained Elevated Temperature

KEYWORDS: Flexural strength, ternary blended steel fibre reinforced concrete, fly ash, silica fume, metakaolin, ground granulated blast furnace slag.

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ABSTRACT *A detailed investigation is made to study the flexural behaviour of steel fibre reinforced concrete with ternary blends on the beam specimen when subjected to sustained elevated temperature of 200°C, 400°C, 600°C, 800°C and 1000°C for 3 hours and then allowed to cool. The mix design was carried out for M30 grade concrete which yielded a proportion of 1:1.86: 2.41 with a w/c ratio of 0.45. Before mixing, 30% of cement was replaced by (FA + SF) or (FA+GGBFS) or (FA+MK) according to the proportions such as (0+0), (30+0), (25+5), (20+10), (15+15), (10+20), (5+25) and (0+30) respectively. It has been found that the TBSFRC containing (FA+GGBFS) and (FA+MK) offer higher resistance to sustained elevated temperatures upto 600°C and 800°C, where as the blend containing (FA+SF) offers resistance only upto 400°C.*

INTRODUCTION

Concrete is a composite material that consists mainly of mineral aggregates bound by a matrix of hydrated cement paste. The matrix is highly porous and contains a relatively large amount of free water unless artificially dried. When exposed to high temperatures, concrete undergoes changes in its chemical composition, physical structure and water content. These changes occur primarily in the hardened cement paste in unsealed conditions. Such changes are reflected by changes in the physical and mechanical properties of concrete that are associated with temperature increase. A number of factors will enter into a decision regarding the type of concrete to use under conditions of elevated temperature. These include the following: length of exposure, rate of temperature rise, temperature to which the concrete mass will be raised, temperature of concrete at initiation of exposure to high temperature, degree of water saturation of the concrete, age of the concrete , type of aggregate used, type of cement used, aggregate / cement ratio, and loading conditions at time of exposure. [(1), (2)]

These failure behaviours are due to:

(a) Thermal stresses induced by thermal gradients.
(b) Decomposition of calcium hydroxide (CH) in the cement paste.
(c) Calcination or phase transformation of aggregates.
(d) Vaporization of free moisture.

RESEARCH SIGNIFICANCE

In case of unexpected fire, the concrete elements such as columns, beams, etc will be subjected to extreme temperatures and needs assessment of their performance after fire. The behavior of concrete exposed at elevated temperature is important to facilitate the concrete use for new applications like in gasification and liquification tanks and vessels subjected to high temperature in the field of metallurgical, chemical, power, glass and cement industries.[(3)] They are also useful in nuclear reactors, concrete chimneys, in airports, runways of jet aircrafts, where localised area of concrete are subjected to the effect of exhaust gases of jet. [(4)]

EXPERIMENTAL INVESTIGATION

Main objective of this experimental investigation is to study the flexural strength [(5)] of ternary blended steel fibre reinforced concrete when subjected to different sustained elevated temperatures such as 200°C , 400°C, 600°C , 800°C and 1000°C for 3 hours. 30% of cement is replaced by ternary blend combinations such as (FA+SF), (FA+GGBFS) and (FA+MK). The proportions of (FA+SF) or (FA+GGBFS) or (FA+MK) are (0+0), (30+0), (25+5), (20+10), (15+15), (10+20), (5+25) and (0+30). The residual flexural strength characteristics are studied. The mix design was carried out for M30 grade concrete as per IS: 10262-2009 which yielded a proportion of 1:1.86: 2.41 with a w/c ratio of 0.45. The dosage of superplasticizer used was 0.78% (by weight of cement). 1% steel fibres by volume was added to the mix and the entire concrete was agitated thoroughly to get a homogeneous mix. For assessing flexural strength of ternary blended steel fibre reinforced concrete at elevated temperatures, standard beam specimen [100mm] width, [100mm] depth and [500mm] length were cast.

The specimens were finished smooth and kept under wet gunny bags for 24 hours after which they were cured for 90 days. After 90 days curing, the specimens were placed in the heating chamber, where in they were subjected to 200°C or 400°C or 600°C or 800°C or 1000°C as the case may be for 3 hours. An electrical furnace or the heating chamber consisting of 14 elements of canthol wire giving electrical load of 14KW (kilo watt) was used for sustained elevated temperature test of concrete specimens. Furnace was cubical in shape of size 2x2x2 feets with a volume of 8 cubic feet with temperature indicator, temperature sensor, and ampere rating. There is a knob to set the desired oven temperature. The rate of temperature rise was 3°C/minute. The figure 1 shows the furnace used for heating the samples. Specimens were maintained in the specified temperature for 3 hours. After removing from the heating chamber, they were allowed to cool sufficiently.

The specimen for flexural strength [(5)] is subjected to bending, using two point loading until it fails and shall be expressed as the modulus of rupture using the formula:

$$f = PL / bd^2 \qquad (1)$$

P = Maximum load applied to the specimen
L = Length of the specimen
b = Width of the specimen
d = Depth of the specimen

EXPERIMENTAL RESULTS

Tables 6 and 7 give the overall results of flexural strength for ternary blended steel fibre reinforced concrete when subjected to different sustained elevated temperature such as 200°C 400°C, 600°C, 800°C, & 1000°C for 3 hours.

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OBSERVATIONS AND DISCUSSIONS

(1) It was observed that at sustained exposure to 200°C (392°F) the ternary blended mixes gave better residual strength than the reference mix. It was observed that the reference mix returned 82.91% residual strength and the ternary blended mixes returned a very healthy residual strength as follows: (FA+SF) combination with (10+20) gave 90.9% (FA+GGBFS) with (10+20) returned with 89.3% and (FA+MK) with (15+15) returned with 86% . Further all the specimens did not show any discoloration or surface cracks.

Also it was observed at sustained exposure to 400°C the ternary blended mixes again gave better residual strength than the reference mix. It was observed that the reference mix returned around 80.4% residual strength that is the decrease in strength was almost 20%, but the blended mixes returned a slightly high residual strength as follows: (FA+SF) combination with (10+20) gave 82.7% , (FA+GGBFS) with (10+20) returned with 85% and (FA+MK) with (15+15) returned with 80.7% , further all the specimens did not show any discoloration or surface cracks.

Thus upto 400°C all the ternary blended steel fibre reinforced concrete show much better performance than the reference concrete, with combination (FA+GGBFS) showing the best resistance followed by (FA+SF) and then (FA+MK).

This may be attributed to the fact that the synergistic effect of the ternary blended combination can change the morphological structure of concrete by densifying the cement paste matrix and improving the interfacial zone. Also the replacement level of (10+20) with (FA+SF) and (FA+GGBFS) and replacement level of (15+15) with (FA+MK) probably have the higher pozzolanic reaction which can convert calcium hydroxide to calcium silicate hydrate gel. In addition, the physical effect of fine grains allows denser packing within the cement matrix and reduces the wall effect in the transition zone between the paste and aggregates thus returning higher strength.

(2) It is observed from the experimental results that the ternary blended steel fibre reinforced concrete with the combination of (FA+SF) when subjected to a sustained elevated temperature of 600°C for 3 hours shows a decreasing trend of flexural strength as silica fume content in it increases. At 600°C, the specimens with the combination of (FA+SF) have shown sufficient surface cracks with a color change from pink to deep red. The residual strength is also observed to decrease as the silica fume content increases.

This can be attributed to the fact that silica fume being very fine makes the concrete dense and brittle at 600°C. Higher susceptibility of concrete with (FA+SF) combination to explosive spalling and cracking is due in parts to its lower permeability which limits the ability of water vapour to escape from the pores. This results in buildup of pore pressure within the cement paste.

Thus it can be concluded that the ternary blended steel fibre reinforced concrete with the combination of (FA+SF) when subjected to sustained elevated temperature of 600°C shows poor performance.

(3) It is observed that the ternary blended steel fibre reinforced concrete with the combination of (FA+GGBFS) and (FA+MK) when subjected to sustained elevated temperature of 600°C for 3 hours shows higher flexural strength at a cement replacement level of (10+20) and (15+15) respectively. Beyond this replacement the flexural strength shows a decreasing trend. No surface cracks were observed at 600°C. But there was a color change from grey to pink. The residual strength also shows peak of 63.71% and 60% at a replacement level of (10+20) and (15+15). This may be due to the fact of synergistic action of the combinations of (FA+GGBFS) and (FA+MK) at a cement replacement level of (10+20) and(15+15). Since ground granulated blast furnace slag has a rough textured surface, small pores are left within the concrete which can accommodate the vapour pressure due to rise in temperature and there by inducing resistance to concrete to sustain the temperature. And also since metakaolin is a good pozzolanic material it can change the morphological structure of concrete thus improving the interfacial zone.

(5) It is observed that the ternary blended steel fibre reinforced concrete with (FA+GGBFS) has shown more residual strength at sustained elevated temperature of 600°C as compared to the combinations of (FA+SF) and (FA+MK). The order of preference can be given as (FA+GGBFS), (FA+MK) and finally (FA+SF).

This may be due to the fact of the rough textured nature of GGBFS which results in small pores in concrete within which the pore pressure can be accommodated due to rise in temperature.

Thus it can be concluded that the ternary blended steel fibre reinforced concrete with the combination of (FA+GGBFS) shows higher resistance to sustained elevated temperature of 600°C as compared to the combinations of (FA+SF) and (FA+MK).

(6) It is observed from the experimental results that the ternary blended steel fibre reinforced concrete with the combination of (FA+SF) when subjected to a sustained elevated temperature a 800°C for 3 hours shows a decreasing trend of flexural strength as silica fume content in it increases. The specimens have shown severe cracks. The residual strength is also observed to decrease as the silica fume content increases. This can be attributed to the fact that silica fume being very fine makes the concrete dense and brittle at 800°C. Higher susceptibility of concrete with (FA+SF) combination to explosive spalling and cracking is due in parts to its lower permeability which limits the ability of water vapour to escape from the pores. This results in buildup of pore pressure within the cement paste.

Thus it can be concluded that the ternary blended steel fibre reinforced concrete with the combination of (FA+SF) when subjected to sustained elevated temperature of 800°C shows poor performance.

(7) It is observed that the ternary blended steel fibre reinforced concrete with the combination of (FA+GGBFS) when subjected to sustained elevated temperature of 800°C for 3 hours shows higher flexural strength at a cement replacement level of (10+20). Beyond this replacement, the flexural strength shows a decreasing trend. Minor cracks were observed at 800°C . But there was a color change from grey to whitish. The residual strength also shows peak of 26.75% at a replacement level of (10+20). This may be due to the fact of synergistic action of the combinations of (FA+GGBFS) at a cement replacement level of (10+20). Since ground granulated blast furnace slag has a rough textured surface, small pores are left within the concrete which can accommodate the vapour pressure due to rise in temperature and there by inducing resistance to concrete to sustain the temperature.

Thus it can be concluded that the ternary blended steel fibre reinforced concrete with the combination of (FA+GGBFS) when subjected to sustained elevated temperature of 800°C shows better performance.

(8) It is observed that the ternary blended steel fibre reinforced concrete with the combination of (FA+MK) when subjected to sustained elevated temperature of 800°C for 3 hours shows higher flexural strength at a cement replacement level of (15+15). Beyond this replacement, the flexural strength shows a decreasing trend. Minor sur-

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face cracks were observed . But there was a color change from gray to whitish. The residual strength also shows peak of 19.43% at a replacement level of (15+15).

This may be due to the fact of synergistic action of the combinations of (FA+MK) at a cement replacement level of (15+15). Since metakaolin is a good pozzolanic material it can change the morphological structure of concrete thus improving the inter facial zone.

Thus it can be concluded that the ternary blended steel fibre reinforced concrete with the combination of (FA+MK) when subjected to sustained elevated temperature of 800°C shows better performance.

(9) It is observed that the ternary blended steel fibre reinforced concrete with (FA+GGBFS) has shown more residual strength at sustained elevated temperature of 800°C as compared to the combinations of (FA+SF) and (FA+MK). The order of preference can be given as (FA+GGBFS), (FA+MK) and finally (FA+SF).

This may be due to the rough textured nature of GGBFS which results in small pores in concrete within which the pore pressure can be accommodated due to rise in temperature.

Thus it can be concluded that the ternary blended steel fibre reinforced concrete with the combination of (FA+GGBFS) shows higher resistance to sustained elevated temperature of 800°C as compared to the combinations of (FA+SF) and (FA+MK).

(10) It is observed that the ternary blended steel fibre reinforced concrete with the combinations (FA+SF) and (FA+MK) when subjected to 1000°C have shown a crumbling effect and disintegration with severe cracks and spalling. Even these specimens could not be replaced from the oven to a safer place. The color was changed to total white. The specimens with the combination of (FA+GGBFS) have not crumbled much. This may be due to the fact that GGBFS being more reactive in pozzolanic action have not allowed the serious cracks to appear. Thus it can be concluded that ternary blended steel fibre reinforced concrete with the combination of (FA+GGBFS) can sustain to a little extent the sustained elevated temperature of 1000°C where as the combination of (FA+SF) and (FA+MK) show very poor performance at 1000°C.

CONCLUSIONS

Based on the results of this experimental investigation of ternary blended steel fibre reinforced concrete at sustained elevated temperature the following conclusions are drawn:

(1) Ternary blended steel fibre reinforced concrete with (FA+SF) combination and with a cement replacement level of (10+20) shows better flexural strength resistance to a sustained elevated temperature of 200°C and 400°C.
(2) Ternary blended steel fibre reinforced concrete with (FA+GGBFS) combination and with cement replacement level of (10+20) shows better flexural strength resistance to a sustained elevated temperature of 200°C and 400°C.
(3) Ternary blended steel fibre reinforced concrete with (FA+MK) combination and with cement replacement level of (15+15) shows better flexural strength resistance to a sustained elevated temperature of 200°C and 400°C.
(4) It has been found that the ternary blended steel fibre reinforced concrete containing (FA+GGBFS) and (FA+MK) offer higher flexural strength to sustained elevated temperatures upto 600°C and 800°C, where as the blend containing (FA+SF) offers resistance only upto 400°C also (FA+GGBFS) shows higher flexural strength and flexural toughness resistance to sustained elevated temperature of 600°C and 800°C than the combination of (FA+MK).
(5) Ternary blended steel fibre reinforced concrete with the combination of (FA+GGBFS) can sustain to a little extent of sustained elevated temperature of 1000°C where as the combination of (FA+SF) and (FA+MK) show very poor performance at 1000°C.

Table 1 Physical properties of Wanakbori fly ash

Properties	Results	Requirement as per IS 3812-2003
Fineness, specific surface area (m^2/kg)	333	>320
Particles retained on 45-□m (No. 325). IS sieve (Wet sieving) in %	3.5	<34
Lime reactivity, average compressive strength	4.58 MPa (0.664 ksi)	>4.5 MPa (0.652 ksi)
Compressive strength at 28 days	17.3 MPa, (2.515 ksi)	>80% of the strength of corresponding plain cement mortar works

Table 2 Chemical properties of fly ash

Properties	Results obtained	Requirement as per IS 3812-2003
Silicon dioxide (SiO_2) + Aluminum Oxide ($A1_2O_3$) + Iron Oxide (Fe_2O_3) present by mass Min.	95.0	> 70 Min.
Silicon dioxide (SiO_2), percent by mass Min.	62	> 35 Min.
Total Sulphur as Sulphur trioxide (SO_3), percent by mass Max.	31	< 3.0 Max.
Available Alkalis as sodium Oxide (Na_2O) in percent by mass Max.	NIL	> 1.5 Max.
Loss on ignition, in percent by mass Max.	0.87	< 5.0 Max.
Moisture content %	0.132	3.0 Max.

Table 3 Physical and chemical properties of silica fume

Sr. No.	Particulars	Test results	Requirement as per ASTM C-1240-03
Physical properties			
1	Particles retained on 45-□m (No. 325)Sieve (%)	0.4%	Max 10%
2	Bulk density kg/m^3	640	500 to 700
3	Specific gravity	2.2	2.2 to 2.4
4	Surface area (m^2/gm)	20	Min. 15
Chemical properties			
1	SiO_2	90.3%	Min 85%
2	Moisture content	0.6%	Max 3%
3	Loss of ignition @ 975°C [1787 °F]	2.1%	Max 6%
4	Carbon	0.8%	Max 2.5%

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Table 4 Physical and chemical properties of GGBFS

Characteristics	Test result	Requirements as per BS-6699
Fineness m^2/kg	380	275(Min)
Soundness, Le-Chatelier Expansion(mm)	0	10(max)
Initial setting time (min)	210	Not less than IST of OPC
Insoluble residual (%)	0.11	1.5(max)
Magnesia content (%)	8.06	14(Max)
Sulphide content (%)	0.9	2.0 (Max)
Sulphite content (%)	0.28	2.5(Max)
Loss on ignition (%)	0.68	3.0 (Max)
Manganese content (%)	0.24	2.0(Max)
Chloride content (%)	0.001	0.10 (Max)
Moisture content (%)	0.01	1.0 (Max)
Glass content (%)	95.34	67(Min)
Compressive Strength		
After 7 days	30.66 MPa	12 MPa (Min)
28 days	48.6 MPa	32.5 MPa (Min)
Chemical Module		
$CaO+MgO+SiO_2$	76.41	66.66(Min)
$CaO+MgO+SiO_2$	1.33	>1.0
CaO/SiO_2	1.08	<1.4

Table 5 Physical properties of Metakaolin

Physical properties	Results
Average particle size	1.5 mm
Residue 325 mesh, 45-□m (No. 325)	0.5 %
B.E.T. Surface area,	15 m^2/gm
Pozzolanic reactivity,	1050 mg
Specific gravity	2.5
Bulk density,	300 ± 30 gm/lt
Brightness	80 ± 2
Physical form	Off-white power

Table 6 (a) Overall results of flexural strength for ternary blended steel fibre reinforced concrete without subjecting to temperature and when subjected to sustained elevated temperature 200°Cand 400°C.

Percentage replacement of cement byTernary Blends	Without subjecting to temperature			Subjected to 200°C						Subjected to 400°C					
	(FA+SF)	(FA+GGBFS)	(FA+MK)	(FA+SF)		(FA+GGBFS)		(FA+MK)		(FA+SF)		(FA+GGBFS)		(FA+MK)	
	Flexural strength (MPa)	Flexural strength (MPa)	Flexural strength (MPa)	Flexural strength (MPa)	Resi. strength(%)	Flexural strength (MPa)	Resi. strength (%)	Flexural strength (MPa)	Resi. strength (%)	Flexural strength (MPa)	Resi. strength (%)	Flexural strength (MPa)	Resi. strength (%)	Flexural strength ((MPa)	Resi. strength (%)
(0+0)	5.39	5.39	5.39	4.47	82.91	4.47	82.91	4.47	82.91	4.33	80.40	4.33	80.31	4.33	80.40
(30+0)	6.14	6.14	6.14	5.28	86.09	5.28	86.09	5.28	86.09	4.74	77.26	4.74	77.26	4.74	77.26
(25+5)	6.64	6.80	6.64	5.55	83.61	5.77	84.85	5.69	85.71	5.15	77.59	5.42	79.70	5.15	77.55
(20+10)	7.18	7.42	7.45	6.10	84.91	6.42	86.50	6.50	87.27	5.55	77.30	6.01	80.96	5.83	78.18
(15+15)	7.60	7.79	7.72	6.64	87.37	6.83	87.65	6.64	85.96	6.10	80.21	6.60	84.73	6.23	80.70
(10+20)	7.90	8.51	7.59	7.18	90.91	7.60	89.33	6.50	85.71	6.53	82.68	7.23	85.03	6.10	80.36
(5+25)	7.69	7.52	7.18	6.64	86.30	6.58	87.57	6.10	84.91	5.93	77.11	6.22	82.70	5.42	75.47
(0+30)	7.29	7.14	6.91	6.23	85.48	6.18	86.53	5.69	82.35	5.36	73.61	5.73	80.27	5.28	76.42

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Table 7(a) Overall results of flexural strength for ternary blended steel fibre reinforced concrete when subjected to sustained elevated temperature 600°C , 800°C and 1000°C.

Percentage replacement of cement by Ternary blends	Subjected to 600°C						Subjected to 800°C						Subjected to 1000°C					
	(FA+SF)		(FA+GGBFS)		(FA+MK)		(FA+SF)		(FA+GGBFS)		(FA+MK)		(FA+SF)		(FA+GGBFS)		(FA+MK)	
	Flexural strength (MPa)	Resi. strength (%)	Flexural strength (MPa)	Resi. strength (%)	Flexural strength (MPa)	Resi. strength (%)	Flexural strength (MPa)	Resi. strength (%)	Flexural strength (MPa)	Resi. strength (%)	Flexural strength (MPa)	Resi. strength (%)	Flexural strength (MPa)	Resi. strength (%)	Flexural strength (MPa)	Resi. strength (%)	Flexural strength (MPa)	Resi. strength (%)
(0+0)	3.52	65.33	3.52	65.33	3.52	65.33	1.22	22.61	1.22	22.61	1.22	22.61	0.00	0.00	0.00	0.00	0.00	0.00
(30+0)	3.93	64.02	3.93	64.02	3.93	64.02	1.30	21.19	1.30	21.19	1.30	21.19	0.00	0.00	0.00	0.00	0.00	0.00
(25+5)	3.66	55.10	4.47	65.74	4.20	63.27	1.38	20.82	1.58	23.31	1.50	22.65	0.00	0.00	0.00	0.00	0.00	0.00
(20+10)	3.52	49.06	4.97	66.95	4.47	60.00	1.34	18.68	1.83	24.64	1.46	19.64	0.00	0.00	0.00	0.00	0.00	0.00
(15+15)	3.25	42.78	5.28	67.79	4.61	59.65	1.26	16.58	2.15	27.65	1.50	19.43	0.00	0.00	0.00	0.00	0.00	0.00
(10+20)	3.12	39.45	5.42	63.71	4.33	57.14	0.79	10.00	2.28	26.75	1.14	15.03	0.00	0.00	0.00	0.00	0.00	0.00
(5+25)	2.84	36.97	4.94	65.71	4.20	58.49	0.77	10.04	2.07	27.57	1.10	15.32	0.00	0.00	0.00	0.00	0.00	0.00
(0+30)	2.71	37.17	4.67	65.46	4.33	62.67	0.72	9.88	2.03	28.43	0.93	13.46	0.00	0.00	0.00	0.00	0.00	0.00

Fig. 1 Furnace for heating the samples

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