Compressive Behaviour of Concrete Retrofitted with Fibre Reinforced Polymer Wrapping Subjected to Elevated Temperature

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Abstract: Concrete structures often collapse in fire due to material degradation and thermal expansion. The compressive behaviour of concrete retrofitted with fiber-reinforced polymer (FRP) wrapping under elevated temperature conditions. The study addresses the critical issue of assessing the performance of structural elements, particularly concrete columns, when subjected to fire events. The composite material made of fibre-reinforced polymer (FRP) has recently gained attention as a potential repair method for damaged concrete structures. This study aimed at determining the influence of fire damage on concrete specimens retrofitted with Glass FRP, Aramid FRP, and Basalt FRP laminates by destructive and non-destructive methods. The cube specimens were subjected to temperatures of 250, 500, and 750°C for a period of 1, 2, and 3 hours followed by retrofitting with FRP laminates. The research emphasizes the importance of considering not only the mechanical properties but also the fire-resistant characteristics of retrofitting materials in optimizing the performance of concrete structures under extreme conditions.The results indicated an increase in compressive strength of concrete when subjected to 250ºC for 1 hour beyond which it decreased. However, a fall in compressive strength was observed for higher ranges of temperature and duration of the fire. Irrespective of the FRP wraps used, the compressive strength increased in comparison with the conventional concrete.

Keywords: Glass fibre**,** Aramid fibre, Basalt fibre, Elevated temperature, Retrofitting.

1. Introduction

Concrete is one of the most extensively used materials in the construction industry. Concrete has inherent fire-resistant qualities. However, this benefit cannot be achieved without taking into account, the fire damage while designing concrete structures. When concrete is subjected to fire, it affects its physical and mechanical characteristics. As a result, the properties of concrete exposed to fire are still important for assessing load carrying capacity and restoring fire-damaged structures. Dehydration of the Calcium Silicate Hydrate (CSH) releases chemically bonded water at temperatures exceeding 110°C. Internal stresses are increased by dehydration of the hydrated calcium silicate and thermal expansion of the aggregate. Micro-cracks are generated beyond 300 °C. One of the most essential components in cement paste is calcium hydroxide [$Ca(OH)_2$] which dissociates at around 530°C, possibly causing the concrete to shrink. Water generally extinguishes the fire, and CaO gets converted to [$Ca(OH)_2$], causing concrete cracking and crumbling. As a result, the effects of high temperature are commonly visible as surface cracking and spalling.

The effect of fire has been investigated on concrete [1], [2]. Assessment of fire damage by Schmidt rebound hammer was proved to be useful to determine the extent of fire damage on concrete [3],[4] stated that most changes experienced by concrete at temperatures above 500°C are considered irreversible and the relative strength of concrete is reduced with an increase in exposure temperature. FahedAlrshoudi[5] reported that most damaged structural elements were identified as slabs based on the case study conducted on the main control building of the thermal power plant,[6,7] stated that sufficient cover thickness has a significant effect on fire resistance,Georgia E. Thermou[8] reported that the residual strength of concrete after cooling is lower than the strength at elevated temperature. Furthermore, the compressive strength not only depends on its constituents but also on other factors such as external loading, heating and moisture conditions.

Over the last two decades, research initiatives around the world have documented the behaviour of externally bonded Fibre Reinforced Polymers (FRP) for strengthening reinforced concrete (RC) structures. FRPs are bonded to the exterior of RC structures in these applications, typically using an epoxy resin saturant/adhesive, to provide additional tensile or confining reinforcement. FRP jackets perform the best for confining members with circular cross sections. Numerous studies have shown that wrapping reinforced concrete columns with FRP can significantly improve their strength and ductility. The use of FRP jackets in building and bridge columns is one of the most common applications of FRPs. FRP sheets have been used to strengthen columns, slabs, beams, and other structural members.

According to C.S. Poon[9], regaining ultimate strength is possible, but regaining stiffness is more challenging, CaiJianguo[10] reported that the use of CFRP, GFRP and steel fibrous grout layer is effective in retrofitting heat damaged RC slabs. For the restoration of fire-damaged concrete members, [11] observed that FRP jacketing was more effective than steel jacketing and concrete enlargement, Drzymala[12] stated that FRP strengthened specimens showed an increase in flexural strength and ductility of T beams to a great extent. According to [13,14] the increase in strength caused by FRP confinement appears to be independent of the unconfined concrete strength and instead depends on the fundamental physical characteristics of the concrete. The GFRP laminates have a substantial structural global deformation capability without compromising their strength [15,16]. The compressive strength and ultimate axial stresses of the thermally damaged concrete wrapped in BFRP jackets improved as the concrete core and layers of BFRP jackets were exposed to higher temperatures[17,18].

Although it was discovered that the behaviour of FRP strengthened concrete structures at normal temperatures is satisfactory, there is a research gap that exists in experimentation and analysis of the behaviour of fire burnt concrete retrofitted with FRP laminates. Hence, the novelty of the current research lies in determining the performance of concrete cubes subjected to fire in different temperatures and durations followed by wrapping with glass FRP (GFRP), basalt FRP (BFRP), and aramid FRP (AFRP) sheets.

1.1. Research Significance

Following are the main objectives formulated towards the research gap based on the literature study,

- To investigate the effect of fire temperature on the compressive strength of concrete.
- To experiment the effect of different duration of fire on the compressive strength of concrete.
- To analyse the retrofitting effect of fibre laminates (namely glass, basalt and aramid) on fire damaged concrete specimens.

2. Materials and Methods:

Fiber-reinforced plastic (FRP), sometimes known as fiber-reinforced polymer or fiber in American English, is a composite material consisting of a fiber-reinforced polymer matrix. Glass (in fiberglass), carbon (in carbon-fibre-reinforced polymer), aramid, or basalt are the most common types of fibers. Fiber-reinforced polymers, or FRPs, are composite materials that are made of a polymer matrix that has been carefully mixed with a supporting material or fiber to improve the plastic's elasticity and mechanical strength.

2.1 Materials:

For casting of specimens, raw materials that satisfy Indian standard codes were chosen

Cement: Ordinary Portland cement (OPC) of 53 grade with a specific gravity of 3.15 and a fineness value of 230 m^2/kg meeting IS 12269-2013 standard requirements were used. The initial and final setting time were 55 and 285 minutes respectively.

Fine aggregate: Manufactured sand obtained from local source satisfying zone II warrants (IS 383-2016)[21] were used as fine aggregate. The properties of fine aggregate are provided in table 1.

Coarse aggregate: Crushed stone aggregate of maximum nominal size of 20mm was used as coarse aggregate under the saturated surface dry condition to avoid the influence of moisture content. The physical properties of coarse aggregate are tabulated in table1.[16]

Water: For concreting and water curing, potable water with a pH of 7.1 that satisfies IS456 -2000 requirements were used[17].

Fibre laminates: Unidirectional FRP laminates made of glass, aramid, and basalt were used as retrofit materials in fire damaged concrete specimens. [18]Figure 1 shows different FRPs used in this study whose properties are listed in table 2.

Resin: For bonding FRP sheets to concrete surface, a resin coat was applied to the surface of concrete specimens.[19] The properties of resin used are provided in table 3.

Table 1 (a) - Physical Properties of Aggregates.

Properties	4.75 mm aggregate	20 mm aggregate
Specific gravity	2.65	2.74
Fineness modulus	3.06	6.95
Bulk density (kg/m^3)	1685	1760
Water absorption (%)	0.54	0.201
Flakiness index (%)	-	12
Elongation index (%)	-	16

Table 1(b) - Mechanical Properties of Aggregates.

Properties	Results
Specific gravity	2.65
Fineness modulus	3.66
Bulk density (kg/m^3)	1585
Water absorption (%)	2.56
Flakiness index (%)	3.68
Elongation index (%)	9.6

Table 2 - Properties of FRP Laminates.

Properties	GFRP	AFRP	BFRP
Material	Glass	Aramid	Basalt
Colour	White	Yellow	Black
Weight of fibre (g/m^2)	920	280	330
Fibre thickness (mm)	0.9	0.4	0.6
Nominal thickness per layer (mm)	1.5	1.6	1.0
Fibre tensile strength (N/mm^2)	3400	2900	4840

Table 3 - Properties of Resin

Properties	Resin
Tensile strength (MPa)	30
Strain at failure (%)	1.5
Flexural modulus of elasticity (GPa)	3.8
Recommended dosage (kg/m^2)	0.7 – 1.2

2.2 Concrete Mix Design

The design mix was developed to achieve an M25 grade of concrete with a slump value of 100mm. Various trials were made before finalising the above mix ratio for obtaining the expected compressive strength and consistency. The design mix ratio adopted in this study is provided in table 4. The same mix is used for all the specimens casted and tested in this study

Table 4 - Mix proportion for the concrete.

Ingredients	Cement (Kg/m^3)	Fine aggregate (Kg/m^3)	Coarse aggregate (Kg/m^3)	Water (Kg/m^3)
Quantity	350	636	1140	168

Fig. 1 - Casting of cubes.

2.3 Specimen Preparation and Testing

The concrete materials were mixed in a tilting drum mixer with a capacity of $0.15m^3$ for not less than 2 minutes as per IS456-2000 specification in order to ensure homogeneity of the concrete mix. The slump was measured and determined to be 100mm. The moulds were oiled before placing wet concrete mix. Further, the concrete was laid in 3 layers along with tamping of 25 blows and placed on a vibrating table for meshing of different layers. The cubes were demoulded after 24 hours and subjected to 28 days of water curing before being brought to an open environment to await fire treatment.

Fig. 2 - Thermocouple **Fig. 3- Exposure of fire on concrete cubes**

2.4 Fire Exposure

For fire treatment, refractory bricks were used to construct a furnace. Cube specimens were subjected to fire treatment (ISO 834 – standard fire curve) using a high-speed burner as shown in figure 4. A UTC-4202 model temperature controller device was used for measuring temperature with a 'K'-type thermocouple as shown in figure 2. Specimens were exposed to fire for different time periods of 1hour, 2hours and 3hours. The temperature range was measured before the cube specimens were cooled.

Fig. 4 - Wrapping of FRP.

2.5 FRP Wrapping

Cooled specimens were removed from the furnace and roughened on all sides followed by cleaning of surfaces before wrapping. A sufficient quantity of epoxy resin was measured out and evenly applied to the cubes' corresponding sides. The FRP wraps are cut to the cube dimensions that are required. Rollers are used to avoid air pockets while wrapping. Figure 5 represents the wrapping of FRP around concrete cube. TheCyanoacrylate glue is allowed to dry for up to 48 hours without disturbance. Once dried, the essential tests are carried out. The FRP sheets were wrapped perpendicular to load direction in accordance with the ISIS manual and the ACI440-2R guidelines.

3. Results and Discussion

One of the most serious risks that buildings might encounter is fire. Under such fire accident, structural members undergo temperature changes causing physical and chemical changes in the constituent materials, thereby degrading the thermal and mechanical properties of materials. With the aim of understanding the effect of fibre wrapping on fire damaged concrete, the major design parameters namely w/c ratio, cement content, etc. were kept constant. Conventional concrete's resistance to fire has been studied for a longer time, and building codes describe typical strength loss models (EN 1992-1-2: 2004).

3.1 Visual Observation

Damages caused by exposure to higher temperature can be generally identified by examining the surface of concrete. Therefore, evaluation of fire-damaged concrete typically begins with visual inspection for changes in colour, formation of cracks and spalling of the concrete surface. Visual inspection of fire damaged concrete indicated that different components of concrete exhibited a different range of colours. According to [19,20,22], colour changes from red at a temperature between 300 - 600ºC, whitish grey around 600 - 900ºC and buff at 900 - 1000ºC. The oxidation of iron hydroxides in aggregates and cement paste causes crimson colour. The disintegration of calcareous constituents of aggregate and cement paste are responsible for whitish grey colouring of the concrete.

According to [23,24] high temperatures may induce spalling in concrete, which will significantly degrade mechanical properties of the building and even result in structure collapse. Vapour pressure in pores and thermal stresses are two main factors that influence mechanisms of spalling of concrete at higher temperatures. If the pore structure of the concrete is sufficiently dense and/or heating rate is high enough, the escape of vapour layer would be too slow, leading to a significant increase in pore pressure in the concrete. Concrete would spall if the tensile stress of the material could not resist the pore pressure. When concrete is heated to a higher temperature, a thermal gradient will also occur between the heated surface and the inner core of the concrete. Compressive stress is produced parallel to the heated concrete surface as temperature rises quicker at the surface, while tensile stress is produced perpendicularly to the interior of concrete. Spalling of concrete will occur when the compressive stress is greater than tensile stress.

The behaviour of concrete under fire was also influenced by type of aggregates used. Furthermore, the quartz or chert aggregate particles induce crazing, cracking and popouts[25,26]. The volume of aggregate in concrete increases as a result of heating, which also causes the cement paste that surrounds the aggregate to contract causing cracks in micro structure of concrete. Furthermore, when the temperature hits 500°C, minor cracks appear and when the temperature reaches 750°C, the cracks become dominant [27].

3.2 Mass Loss

Concrete experiences mass loss as temperature rises almost constantly. It was shown that mass loss is higher initially up to 250ºC, which is attributable to evaporation and loss of free water as a result of the initial hydrothermal conditions. The mass loss at 250ºC for different duration was found to be 2.34% to 6.08%. However, it increased between 8.59% and 12.64% at 500ºC for different exposure time. Further it rises between 13.09% and 16.42% at 750ºC for different duration of fire exposure. The mass loss data in figure 5 confirms the impact of higher temperatures on concrete that was previously reported [27,28,29]. The reduction in mass of specimen was due to dehydration of hydrated chemical compounds in concrete.

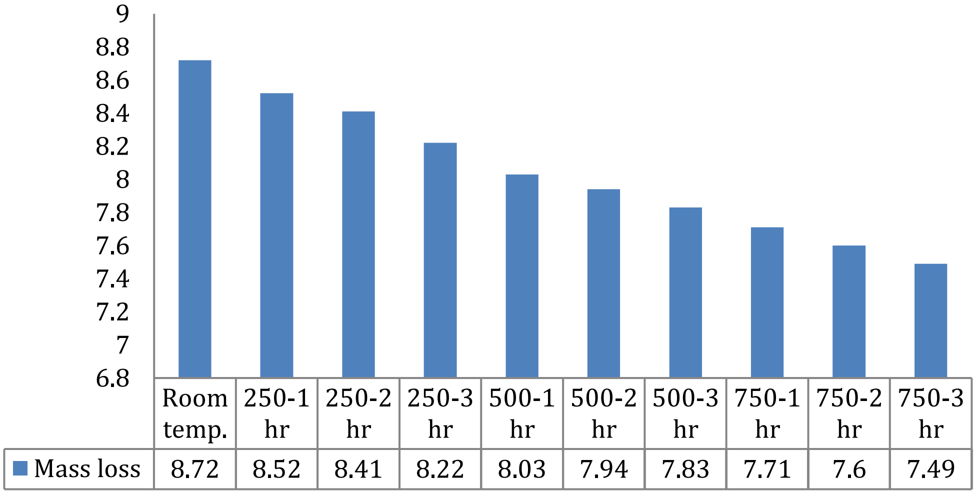

Fig. 5 - Mass Loss of Concrete Cubes Subjected to Different Temperature and Duration

3.3 Compressive Strength by Rebound Hammer Test

Schmidt rebound hammer is used worldwide to detect the surface hardness of a material. BS 811: Part 202, ASTM C805, and NBN EN 12504-2 provide recommendations for the use of the rebound method. The working principle is simple: a spring is tensioned when a plunger with a hammer is pressed against the concrete surface. The spring is automatically released at full tension, causing the hammer mass to impact the concrete. The exhibited rebound value of the mass is a measure of the investigated material's surface hardness. Table 5 lists the rebound hammer measurement of the fire damaged concrete.

Table 5 - Schmidt rebound hammer measurement.

Exposure Condition		**Rebound Hammer Number**	**Compressive Strength (MPa)**
Temperature(ºC)	**Duration (hour)**		
Room temperature	-	65	32.04
250	1	71	35.003
250	2	60.5	29.826
250	3	57	28.101
500	1	55.5	27.361
500	2	52.5	25.882
500	3	48	23.664
750	1	53.5	26.375
750	2	40.5	19.966
750	3	29	14.297

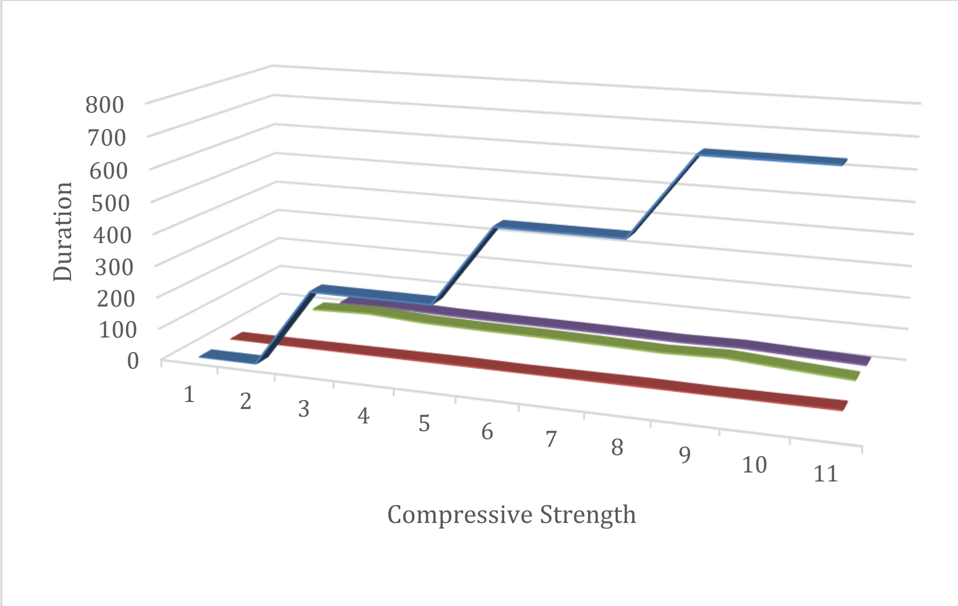

Fig 6: Compressive strength result for rebound hammer

3.4 Compressive Strength by Destructive Testing

A compression test was carried out in a standard cube specimen of size 150 mm X 150 mm X 150 mm. After the specimens were held at the centre of the testing machine, the tests were performed with uniform stress of 140 kg/cm^2/min. The loading was continued until the specimen failed. Based on the experiment, maximum compressive load and maximum compressive strength were determined by the ratio of maximum load applied to the corresponding cross-sectional area. Three specimens were tested to determine the average strength value, with variations of ±15% of the mean value (IS 516-1959). Compressive strength increases at temperature between 200 and 250ºC. At 300ºC, strength was reduced by 15–40%, while at 700ºC, it was reduced by 55–70% [30].

Table 6. Test Results of Unwrapped and Wrapped Specimens Without Fire Exposure

Exposure condition	Retrofit material	Compressive strength of samples (MPa)	% increase/decrease in strength
Without Fire Exposure	-	33.4	-
Without Fire Exposure	GFRP	43.42	30% (+)
Without Fire Exposure	AFRP	49.99	49.67% (+)
Without Fire Exposure	BFRP	56.87	70.26% (+)

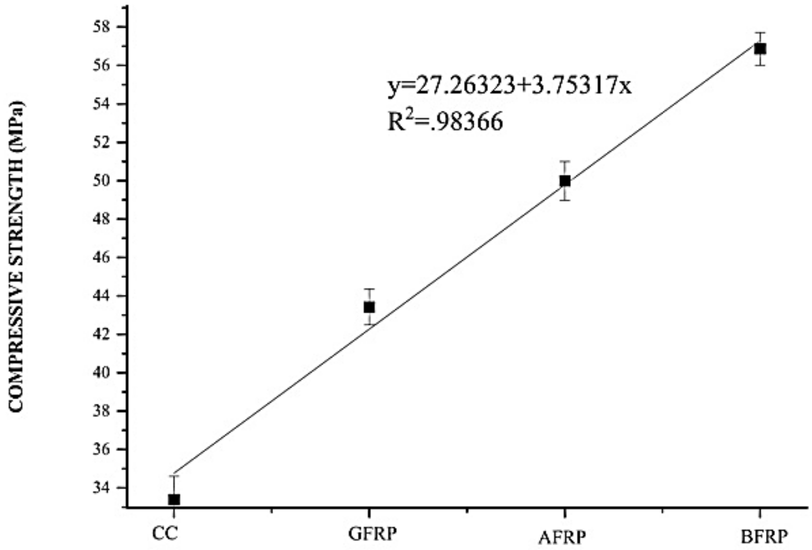

Fig. 7 - Without Fire Exposure

Figure 6 shows test results of the average compressive strength of unwrapped and FRP wrapped specimens which are not exposed to fire. The outcomes of tests were comparable. The concrete specimens wrapped with GFRP, AFRP and BFRP showed an increase in strength of 30%, 49.67% and 70.26% respectively which referred in table 6. Based on the properties of FRPs, specimen strength varies.

The compressive strength of concrete exposed to fire of 250ºC, 500°C and 750°C for 1 hour, 2 hours and 3 hours are summarised in tables 7 – 9. The graphical representation is shown in figures 7 – 16.

Table 7 - Test Results of Unwrapped and Wrapped Specimens Exposed to The Fire of 250ºC.

Exposure condition		Retrofit material	Compressive strength of samples (MPa)	% increase/decrease in strength
Temperature (ºC)	Duration (hour)			
Room temperature	-	-	33.4	-
250	1	-	36.74	10% (+)
250	1	GFRP	47.7	29.8% (+)
250	1	AFRP	55.1	49.97% (+)
250	1	BFRP	62.45	69.97% (+)
250	2	-	31.73	5.26% (-)
250	2	GFRP	41.249	30% (+)
250	2	AFRP	47.15	48.59% (+)
250	2	BFRP	52.941	66.84% (+)
250	3	-	30.06	11.11% (-)
250	3	GFRP	39.33	30.83% (+)
250	3	AFRP	45.47	51.26% (+)
250	3	BFRP	51.102	70% (+)

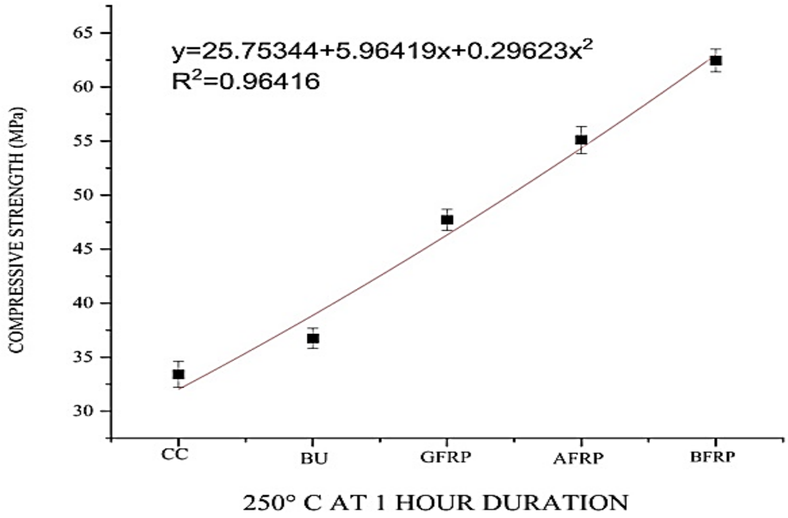

Fig. 8 - 250°C at 1-hour duration.

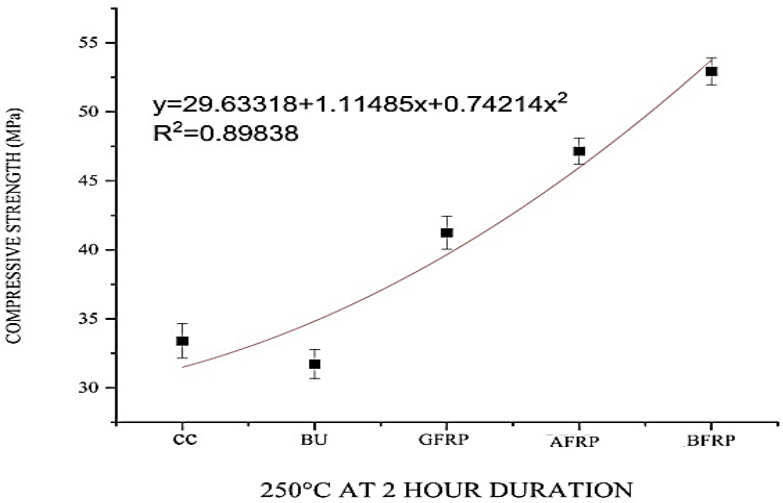

Fig. 9 - 250°C for 2 hours' duration.

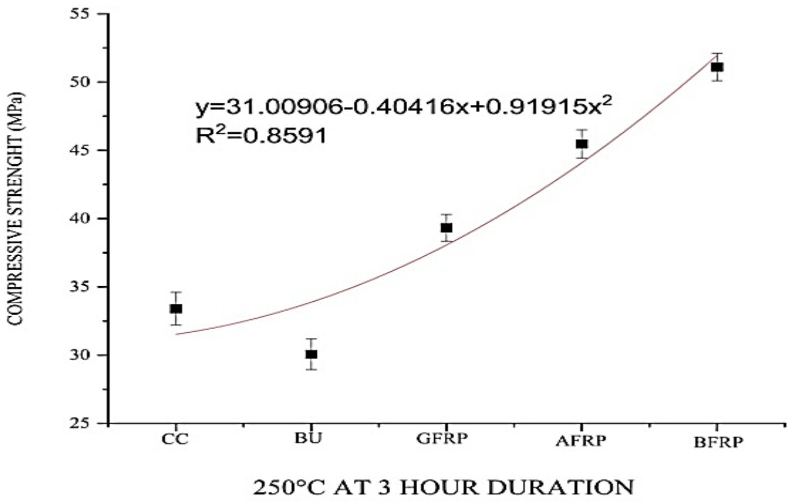

Fig. 10 - 250°C for 3 hours' duration

The compressive strength variation of concrete subjected to fire of about 250°C for 1 hour, 2 hours and 3-hour exposure time is represented in Figures 7, 8, and 9. Due to dehydration of pore water, compressive strength of burnt cubes increased by 10% after 1 hour of fire exposure. The compressive strength reduced by 5.26% and 11.11% after 2 hours and 3 hours of fire exposure due to differences in thermal expansion of cement paste and aggregate. It was found that the increased temperature of 250°C used in this investigation had virtually minor influence on the compressive strength of unwrapped cubes which is similar to the findings of furthermore, by wrapping the burnt cube with GFRP, AFRP and BFRP, the compressive strength of the cube was improved. The average strength increase was found to be 30.21%, 49.94% and 68.93% respectively.

Table 8 - Test Results of Unwrapped and Wrapped Specimens Exposed to The Fire of 500ºC.

Exposure condition		Retrofit material	Compressive strength of samples (MPa)	% increase/decrease in strength
Temperature (ºC)	Duration (hour)			
Without fire exposure	-	-	33.4	-
500	1	-	29.06	14.93% (-)
500	1	GFRP	37.078	27.59% (+)
500	1	AFRP	43.24	48.79% (+)
500	1	BFRP	49.1	68.96% (+)
500	2	-	27.388	21.95% (-)
500	2	GFRP	35.6%	29.98% (+)
500	2	AFRP	41.08	49.99% (+)
500	2	BFRP	46.78	70.8% (+)
500	3	-	24.382	36.98% (-)
500	3	GFRP	31.495	29.17% (+)
500	3	AFRP	36.1	48.06% (+)
500	3	BFRP	41.49	70.16% (+)

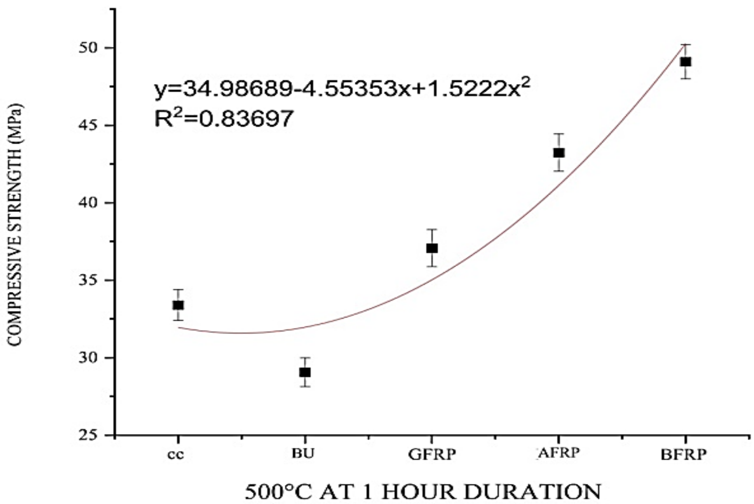

Fig. 11 - 500°C for 1-hour duration.

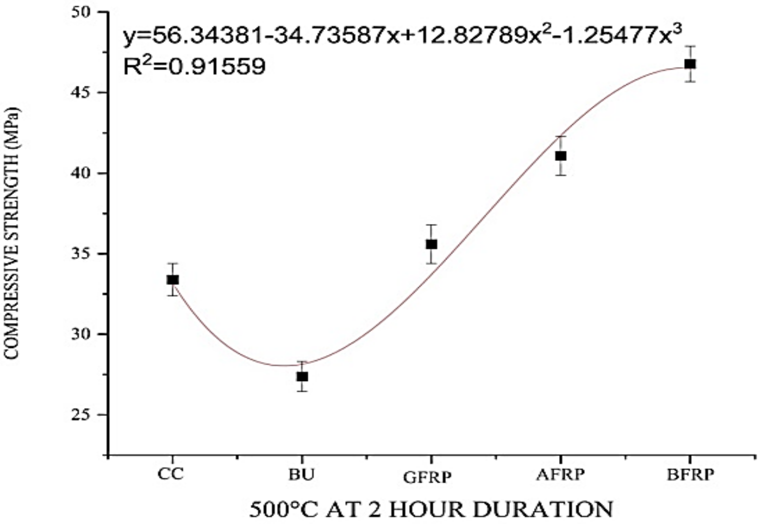

Fig. 12 - 500°C for 2-hours' duration.

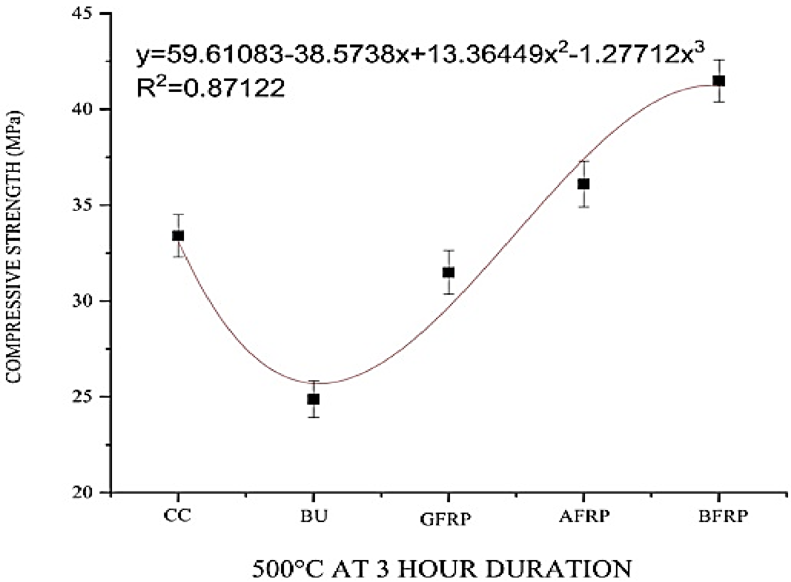

Fig. 13 - 500°C at 3-hours' duration.

Figure 11,12 and 13 represents the compressive strength variation of concrete subjected to 500°C fire for 1 hour, 2 hours and 3 hours. The compressive strength of burnt cubes were reduced by 14.93%, 21.95% and 36.98%. It was observed that the relationship between compressive strength and exposure temperature were similar to those previously reported. Wrapping burnt cubes with different FRPs such as GFRP, AFRP and BFRP resulted in an average increase in strength of 28.91%, 48.94% and 69.97%, respectively. Regardless of temperature period or temperature level, all wrapped specimens exhibited greater compressive strength than unwrapped ones. After 3 hours of exposure to 500°C, compressive strength decreased significantly.

Table 9 - Test Results of Unwrapped and Wrapped Specimens Exposed to The Fire of 750ºC.

Exposure condition		Retrofit material	Compressive strength of samples (MPa)	% increase/decrease in strength
Temperature (°C)	Duration (hour)			
Without fire exposure	-	-	33.4	-
750	1	-	27.88	19.79% (-)
750	1	GFRP	35.60	27.69% (+)
750	1	AFRP	41.082	47.35% (+)
750	1	BFRP	46.559	66.99% (+)
750	2	-	21.042	58.73% (-)
750	2	GFRP	27.05	28.55% (+)
750	2	AFRP	31.96	51.88% (+)
750	2	BFRP	35.37	68.09% (+)
750	3	-	15.03	122.2% (-)
750	3	GFRP	19.03	26.61% (+)
750	3	AFRP	22.249	48.03% (+)
750	3	BFRP	25.35	68.66% (+)

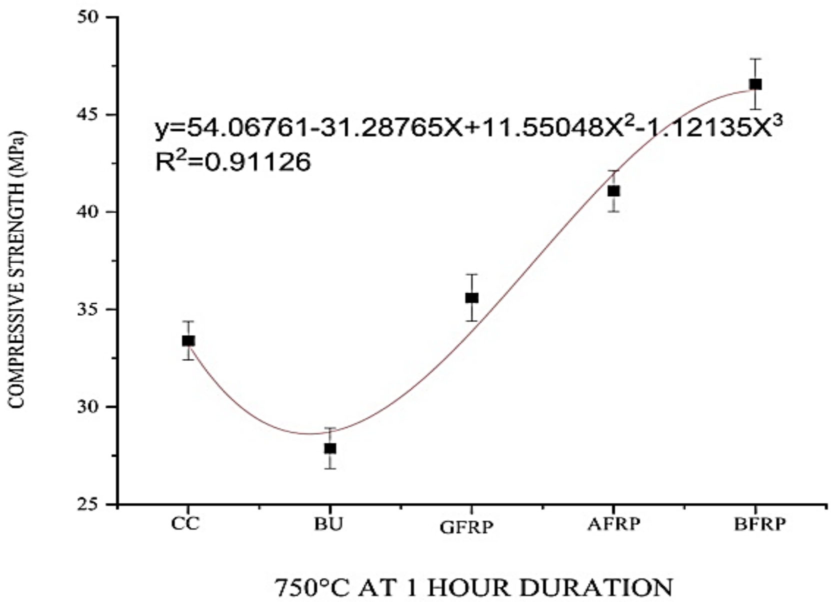

Fig. 14 - 750°C at 1-hour duration.

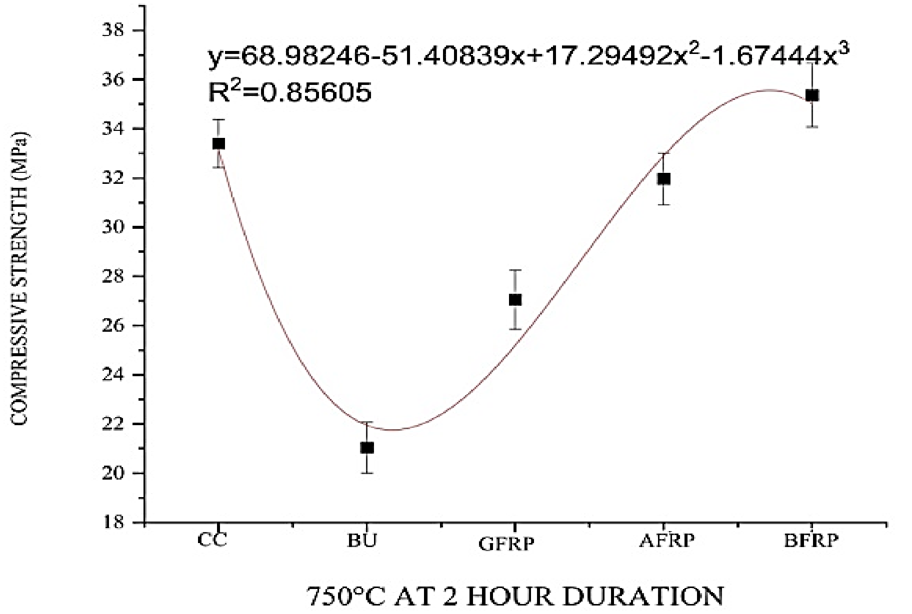

Fig. 15- 750°C at 2-hour duration.

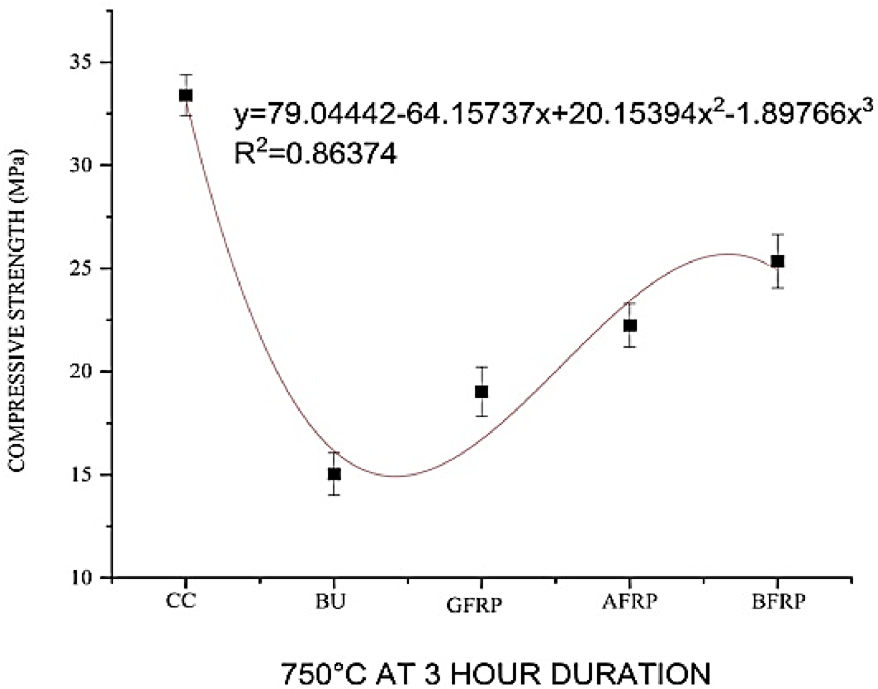

Fig. 16 - 750°C at 3-hour duration.

Figure 14, 15 and 16 depicts compressive strength variation of concrete exposed to 750°C fire for 1 hour, 2 hours and 3 hours. The compressive strength of burnt cube decreases by 19.79%, 58.73% and 122.2% respectively. At 750°C for 3 hours, significant strength loss was observed. Wrapping of the burnt cube with different FRPs such as GFRP, AFRP and BFRP increases the compressive strength by 27.69%, 47.35% and 66.99%, respectively.

NDTs are commonly used to assess fire-damaged structures in order to identify the extent of damage and the strength of damaged concrete members. Destructive and non-destructive tests carried out for controlled and fire-damaged samples indicate that rebound hammer test showed less compressive strength than destructive testing.

4.5 Scatter plot

An equation was proposed for compressive strength based on temperature and duration of exposure through multiple-regression. And a scatter plot was plotted against experimented values of compressive strength and predicted values of compressive strength obtained by destructive testing.

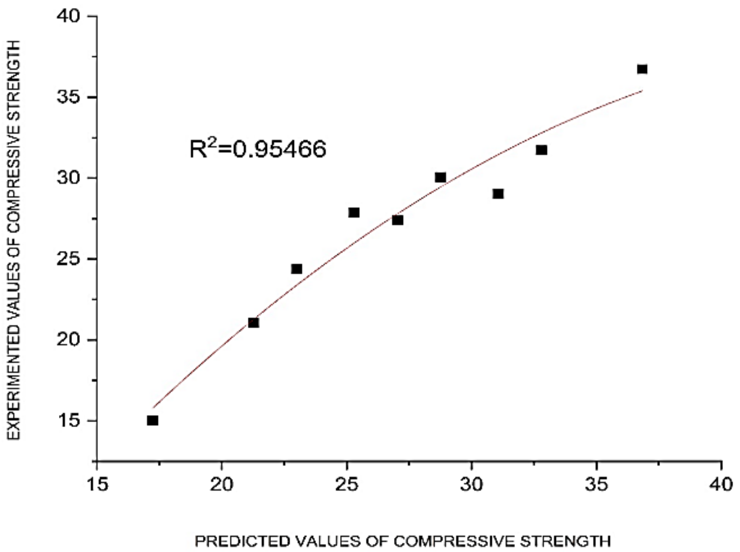

Fig. 17 - Scatter Plot

The dependence of compressive strength (ŷ) on temperature (X_1) and time(X_2) were examined. An equation to determine the compressive strength of fire damaged concrete based on temperature and time is proposed, as given below. The observed compressive strength values were compared with predicted values which gave an R^2 value of 0.95466 as shown in figure 17.

$\hat{y} = 46.63 - 0.02305X_1 - 4.03467X_2$------------ (1)

It is to be noted that the above equation possesses warrants, namely temperature ranging from 250ºC to 750ºC and duration up to 3 hours.

5. Conclusion

The objective of this study was to evaluate the compressive strength of fire damaged concrete retrofitted with glass, basalt and aramid FRP. The experimental programme included 120 concrete cubes, of which 30 were unwrapped, 30 were wrapped with GFRP sheets, 30 were wrapped with AFRP sheets and another 30 were wrapped with BFRP sheets. One hundred and eight cube specimens are subjected to temperature of 250°C, 500°C and 750°C for one hour, two hours and three hours, respectively. Under the same conditions, the compressive strength of wrapped concrete cubes with FRP sheets were compared to that of unwrapped concrete cubes. The following conclusions can be drawn:Visual inspection of the fire damaged specimens showed minor crack development for specimens subjected to 500ºC and cracks were dominant at 750ºC. There was no spalling of concrete observed for specimens subjected to different temperatures for varying time periods. The test results indicated that the strength of concrete increases after being exposed to 250ºC for an hour beyond which the strength decreases. For higher temperature ranges and a longer period of exposure, a decline in compressive strength was observed.The compressive strength obtained from destructive and non-destructive methods was compared. The results indicated that the rebound hammer test showed a loss in compressive strength than destructive testing as the rebound hammer gives only the surface hardness of the specimens. The compressive strength of the unwrapped specimens was affected by the increased temperature examined in this investigation. After 3 hours of exposure to 750°C, the highest strength loss was observed at around 122.2%.When compared to unwrapped cubes, all GFRP, AFRP and BFRP wrapped specimens had superior compressive strength. Strength increased by approximately 29.98%, 49.99% and 70.8% for GFRP, AFRP and BFRP, respectively. All wrapped specimens failed due to FRP sheet rupture.The test results indicated that basalt fibre laminate has high retrofitting efficiency than glass and aramid fibre laminate because of its high tensile strength than the other two fibres used in this research.The proposed equation (1) for compressive strength based on temperature and duration is more accurate for the temperature range of 250 to 750ºC and duration up to 3 hours.

References

[1] Albert N. Noumowe a, RafatSiddique b, G. Debicki c, "Permeability of high-performance concrete subjected to elevated temperature (600 °C)" Construction and Building Materials, Volume 23, Issue 5, May 2009, Pages 1855-1861, https://doi.org/10.1016/j.conbuildmat.2008.09.023

[2] A.N. Noumowe a, P. Clastres a, G. Debicki a, J.-L. Costaz b, "Transient heating effect on high strength concrete" Nuclear Engineering and Design Volume 166, Issue 1, 1 October 1996, Pages 99-108, https://doi.org/10.1016/0029-5493(96)01235-6.

[3] Bernardo A. Lejano (2014) "Confinement effects of different retrofitting materials on the axial strength of reinforced concrete columns" Published in: 2014 International Conference on Humanoid, Nanotechnology, Information Technology, Communication and Control, Environment and Management (HNICEM) DOI: 10.1109/HNICEM.2014.7016219

[4] C.S. Poon, Z.H. Shui, L. Lam 2004 "Compressive behavior of fiber reinforced high-performance concrete subjected to elevated temperatures" Cement and Concrete Research Volume 34, Issue 12, December 2004, Pages 2215-2222 doi.org/10.1016/j.cemconres.2004.02.011

[5] FahedAlrshoudi, Husain Abbas, ArefAbadel, AbdulrahmanAlbidah, Ali Altheeb, Yousef Al-Salloum, "Compression behavior and modeling of FRP-confined high strength geopolymer concrete" Construction and Building Materials Volume 283, 10 May 2021, 122759, https://doi.org/10.1016/j.conbuildmat.2021.122759

[6] FariborSharifianjazi ,ParhamZeydi ,MiladBazli,ORCID,AmirhosseinEsmaeil khanian 5ORCID,Roozbeh Rahmani, "Fibre-Reinforced Polymer Reinforced Concrete Members under Elevated Temperatures: A Review on Structural Performance" Polymers 2022, 14(3), 472; https://doi.org/10.3390/polym14030472.

[7] Georgali, B., &Tsakiridis.P.E. (2005). "Microstructure of fire – damaged concrete - A case study". Cement & concrete composites, 27, 255 – 259, Cement and Concrete Composites Volume 27, Issue 2, February 2005, Pages 255-259https://doi.org/10.1016/j.cemconcomp.2004.02.022

[8] Georgia E. Thermou, ImanHajirasouliha, "Compressive behaviour of concrete columns confined with steel-reinforced grout jackets" Composites Part B: Engineering Volume 138, 1 April 2018, Pages 222-231, https://doi.org/10.1016/j.compositesb.2017.11.041.

[9] Haddad, R.H., Al-mekhlafy, N., &Ashteyat, A.M., (2011). "Repair of heat damaged reinforced concrete slabs using fibrous composite materials". Construction and Building Materials, 25,

1213 – 1221, Construction and Building Materials
Volume 25, Issue 3, March 2011, Pages 1213-1221https://doi.org/10.1016/j.conbuildmat.2010.09.033

[10] Hammad Ahmad, Rashid Hameed, Muhammad RizwanRiaz and Asad Ali Gillani. "Strengthening of concrete damaged by mechanical loading and elevated temperature Advances in Concrete Construction, Vol. 6, No. 6 (2018) 645-658 DOI: https://doi.org/10.12989/acc.2018.6.6.645

[11] HafidaBouchelaghem a, AbderrezakBezazi a, FabrizioScarpa, "Compressive behaviour of concrete cylindrical FRP-confined columns subjected to a new sequential loading technique" Composites Part B: Engineering Volume 42, Issue 7, October 2011, Pages 1987-1993, https://doi.org/10.1016/j.compositesb.2011.05.045.

[12] J Xu1, C Tan1 and R Aboutaha1, "Experimental investigation of high strength reinforced concrete columns damaged by fire and retrofitted with CFRP jackets" Published under licence by IOP Publishing Ltd IOP Conference Series: Earth and Environmental Science, Volume 358, Issue 4, DOI 10.1088/1755-1315/358/4/042009.

[13] Weiqiang Wang a, Chengqing Wu a, Zhongxian Liu b, Honglan Si, "Compressive behavior of ultra-high performance fiber-reinforced concrete (UHPFRC) confined with FRP" Composite Structures Volume 204, 15 November 2018, Pages 419-437, https://doi.org/10.1016/j.compstruct.2018.07.102.

[14] Khaliq, W. (2018) "Mechanical and physical response of recycled aggregates high-strength concrete at elevated temperatures" Fire safety journal, 96, 203-214, Fire Safety Journal Volume 96, March 2018, Pages 203-214 https://doi.org/10.1016/j.firesaf.2018.01.009

[15] Khalifa Al-Jabri,1Ahmed Al-Mahri,1and Saud Al-Mahrouqi1, "Effects of Elevated Temperatures on the Compressive Strength Capacity of Concrete Cylinders Confined with FRP Sheets: An Experimental Investigation" Volume 2015 | Article ID 549187 | https://doi.org/10.1155/2015/549187.

[16] Ojha, P. N., Suresh Kumar, Abhishek Singh, Brijesh Singh, and B. N. Mohapatra. "Alkali-Aggregate Reactivity Evaluation of Aggregates for Application in Indian Concrete Dams." *DAM ENGINEERING* 31, no. 3.

[17] Khalid, Bisma, and Abdullah Alodah. "Multivariate Analysis of Harvested Rainwater Quality Utilizing Sustainable Solar-Energy-Driven Water Treatment." *Sustainability* 15, no. 19 (2023): 14568.

[18] Bazli, Milad. "Mechanical and microstructural properties of different FRP composites under various environmental conditions." PhD diss., Monash University, 2020.

[19] Toutanji, Houssam, and Gerardo Ortiz. "The effect of surface preparation on the bond interface between FRP sheets and concrete members." *Composite structures* 53, no. 4 (2001): 457-462.

[20] KommaHemanth Kumar Reddy, Ruben Nerella, Sri Rama Chand Madduru, "Different temperature effects on CFRP wrapped concrete" Volume 27, Part 2, 2020, Pages 1127-1131, https://doi.org/10.1016/j.matpr.2020.01.582.

[21] Standard, Indian. "IS: 383 (2016) Coarse and fine aggregate for concrete-specification." *Bureau of Indian Standards, New Delhi* (2016).

[22] Krzysztof Ostrowski a, Mateusz Dudek b, ŁukaszSadowski c, "Compressive behaviour of concrete-filled carbon fiber-reinforced polymer steel composite tube columns made of high performance concrete" Composite Structures Volume 234, 15 February 2020, 111668,

https://doi.org/10.1016/j.compstruct.2019.111668.

[23] Ma, Q., Guo, R., Zhao, Z., Lin, Z., & He, K. (2015) "Mechanical properties of concrete at high temperature – a review" Construction & building materials, 93, 371 – 383, Construction and Building Materials, Volume 93, 15 September 2015, Pages 371-383https://doi.org/10.1016/j.conbuildmat.2015.05.131

[24] Mahdi Nematzadeh a, FaridHasan-Nattaj a, AliakbarGholampour b, Hassan Sabetifar a, Tuan D. Ngo c, "Strengthening of heat-damaged steel fiber-reinforced concrete using CFRP composites: Experimental study and analytical modeling" Structures Volume 32, August 2021, Pages 1856-1870, https://doi.org/10.1016/j.istruc.2021.03.084.

[25] Ouyang, L.J., Chai, M.X., Song, J., Hu, L.L., &Gao, W.Y. (2021) "Repair of thermally damaged concrete cylinders with basalt fibre reinforced polymer jackets" Building Engineering, 44, 01 – 13, Nano Energy Volume 85, July 2021, 105878https://doi.org/10.1016/j.jobe.2021.102673

[26] Prasad V. Bahekar, Sangeeta S. Gadve, V. Sumanth, "EFFECT OF FIBER REINFORCED POLYMER WRAPPING ON STRUCTURAL BEHAVIOUR OF COLUMNS WITH DIFFERENT CROSS-SECTIONS" Volume 9, Issue 10, October 2018, pp. 378–387, Article ID: IJCIET_09_10_039, DOI: https://doi.org/10.17605/OSF.IO/X78WV.

[27] Qinghai Xiea b, Haijin Zhang a, Jianzhuang Xiao b, ZhonglingZong a, "Mechanical behavior and its variability analysis of fiber reinforced polymer rebars after high temperatures" Construction and Building Materials Volume 380, 30 May 2023, 131266, https://doi.org/10.1016/j.conbuildmat.2023.131266

[28] Rousan, R.A. (2020) "Optimum endurance time of reinforced concrete one-way slab subjected to fire". Procedia Manufacturing, 44, 520 – 527, Procedia Manufacturing Volume 44, 2020, Pages 520-527https://doi.org/10.1016/j.promfg.2020.02.260.

[29] Steven D. Thomalla; James D. Van de Ven (2018) "Modeling and Implementation of the McKibben Actuator in Hydraulic Systems" Journals & Magazines >IEEE Transactions on Robotics >Volume: 34 Issue: 6, DOI: 10.1109/TRO.2018.2864780

[30] Schneider, U. (1988) "Concrete at high temperatures – a general review". Fire Safety Journal, 13, 55 – 68, Fire Safety Journal Volume 13, Issue 1, 7 April 1988, Pages 55-68,https://doi.org/10.1016/0379-7112(88)90033-1

[31] A. M. Vasumathi,K. Rajkumar, G. Ganesh Prabhu, "Compressive Behaviour of RC Column with Fibre Reinforced Concrete Confined by CFRP Strips" Volume 2014 | Article ID 601915 | https://doi.org/10.1155/2014/601915.

[32] VikramJadhav, Dr.RosalinSahoo, "Behaviour of Reinforced and Unreinforced Circular Concrete Columns Retrofitted By Microconcrete& CFRP Confinement" Volume V, Issue VII, July 2016 | ISSN 2278-2540, https://doi.org/10.1016/j.engstruct.2023.117155.

[33] Xu Yang, Bing Zhang, Ao Zhou, Huinan Wei, Tiejun Liu, "Axial compressive behaviour of corroded steel reinforced concrete columns retrofitted with a basalt fibre reinforced polymer-ultrahigh performance concrete jacket" Composite Structures Volume 304, Part 2, 15 January 2023, 116447, https://doi.org/10.1016/j.compstruct.2022.116447.

[34] Yang Wei, Chao Zhu, Kunting Miao, Jile Chai, KaiqiZheng, "Compressive behavior of rectangular concrete-filled fiber-reinforced polymer and steel composite tube columns with stress-release grooves" Composite Structures Volume 281, 1 February 2022, 114984,

https://doi.org/10.1016/j.compstruct.2021.114984

[35] Yu-Lei Bai, Shi-Zhu Liu, Shi-Jie Mei, "Compressive behavior and modeling of concrete wrapped by hybrid low-high elongation capacities FRP" Engineering Structures Volume 300, 1 February 2024, 117155 https://doi.org/10.1016/j.engstruct.2023.117155.