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EFFECT OF FIBRE REINFORCED POLYMER WRAPPING ON MECHANICAL PROPERTIES OF CONCRETE SUBJECTED TO FIRE

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Abstract.
This study aims to get a better understanding on the behaviour of fibre reinforced polymer (FRP) laminates at higher temperatures. Also, this article summarises the discoveries of an experimental investigation into the mechanical behaviour of specimens retrofitted with Glass FRP (GFRP), Aramid FRP (AFRP), and Basalt FRP (BFRP) confinements after being damaged by fire. The fire-damaged specimens were first subjected to a range of increased temperatures of 250ºC, 500ºC, and 750ºC for durations of 1 hour, 2 hours and 3 hours and then allowed to cool down to the ambient temperature. Tests on tensile strength, flexural strength, and elastic modulus were conducted on fire-damaged specimens to determine the effectiveness of GFRP, AFRP, and BFRP confinements for restoration purposes. Based on the analysis of test data, it was possible to draw the conclusion that the fire-damaged concrete was strengthened when retrofitted with different FRP jackets.

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

Introduction

Numerous instances of fire occurred. Since the occurrence of multiple fires in various structures such as high-rise buildings, tunnels, and drilling platforms, the performance of concrete at higher temperatures has become a topic of interest. A fire may reach temperatures of up to 1100°C in buildings and even 1350°C in tunnels, which can significantly affect concrete structures. In incredibly rare circumstances when even very low temperatures might cause explosive disintegration of concrete, the load-carrying capability of the concrete may be affected. However, concrete is regarded as a building material that satisfactorily retains its characteristics under extreme temperatures. Since heat is transferred through concrete slowly because of its relatively low coefficient of thermal conductivity, reinforced steel which is susceptible to high heat is protected for a good length of time. When concrete is heated under fire conditions, the temperature intensification in the deeper layers of the material is progressive. Due to the slowness of the process, large heat gradients are developed between the structural member's surface and its interior, further damaging the elements. Identification of the intricate changes that occur in concrete while heated is a fundamental aspect of the stimulus of high temperature on concrete. This relates to the processes accompanying mass movement along with the physical and chemical properties changes occurring in an adhesive binder. The examination is complex since cement adhesive and aggregates are two different ingredients that are combined to form cement concrete. Liquid vanishing, C-S-H gel dryness, calcium hydroxide and calcium aluminates breakdown, etc are all characterized by the rise in temperature. The structural integrity and elastic modulus of concrete gradually deteriorate as a result of these changes. Various criteria, such as the exposed temperature, exposed time, or exposed area, can be used to estimate the extent of fire damage to concrete structures.

The splitting tensile strength of concrete is a critical mechanical characteristic that has a significant impact on the amount and extent of cracking in concrete structures. The split-tensile strength of concrete must first be determined because of the material's inherent weakness under tension. In addition, flexural strength is an essential consideration to make as it affects the brittleness ratio, flexural cracking, shear strength, and deflection features of the concrete.

Concrete gradually loses volumetric mass density as temperature increases (Novak and Kohoutkova 2018) [1]. Chowdhury (2014) reported that the remaining compressive strengths decreased with increasing exposure duration and highest temperature. [2]. Xiao and Konig (2004) stated that the tensile property loss is substantially more pronounced at raised degrees [3]. Hager (2013) stated that understanding how spalling affects tensile strength at maximum degrees is essential. [4]. Krishna et al. (2019) revealed that once concrete was subjected to 600^{o}C, its splitting tensile strength considerably dropped [5]. The temperature's effect on concrete's elastic modulus must be taken into account while analysing the deformation of a fire-damaged concrete structure (Chang et al. 2006) [6]. Excessive thermal stresses and physical and chemical changes in the concrete microstructure were responsible for the deprivation of elastic modulus (Kodur 2014) [7]. However, the elasticity values heavily depend on whether the concrete is loaded while it is being heated (Hager 2013) [4].

To restore the structural performance of the reinforced concrete structural members after a fire, precise repairs must be done. The investigation of post-fire structural member repair in recent years employs a wide range of repairing approaches. Section enlargement is a simple, inexpensive way to repair fire-damaged members. But it is acknowledged that there are limitations, such as increased structural self-weight and less indoor space. Because of its superior strength-to-weight ratio, strong corrosion resistance, ease of installation and excellent compatibility with several different structural geometries, Fiber-Reinforced Polymer (FRP) is becoming an alternate measure (Qiu et al. 2021) [8]. Neeladharan et al. (2018) stated that carbon fibre sheets are more efficient at improving the flexural property and eventual carrying capacity of beams [9]. Usman et al. (2021) stated that When exposed to extreme heat, the CFRP composite wrapping technique enhanced the burnt concrete specimens' load-carrying ability. Additionally, post-heated concrete specimens repaired using only CFRP confinement repairing techniques demonstrated higher levels of deformability than those repaired using cement slurry injected CFRP confinement composites [10]. Ouyang et al. (2021) revealed that BFRP jackets have been shown to be effective in increasing the strength under compression and maximum axial strain of thermally damaged concrete. [11] .

Despite the fact that constructions made of concrete reinforced with FRP operate satisfactorily when exposed to typical temperatures, there is a research gap in the experimentation and study of the efficiency of fire damaged concrete that has been retrofitted with FRP covers. Therefore, the purpose of the present study is to evaluate the effectiveness of concrete specimens that were covered in glass FRP, basalt FRP, and aramid FRP sheets and subjected to fire at different degrees and for varying periods of time.

Research significance:

Rendering to the literatures reviewed, the research gap in the direct comparison of GFRP, AFRP and BFRP in the retrofitting of fire spoiled cylinders. Consequently, the current research sought to govern the efficacy of various FRPs in retrofitting thermally damaged specimens. The following are the highlights of this research investigation.

- To investigate how the temperature of a fire affects the structural and stiffness attributes of concrete.
- To experimenting with the properties of various fire durations on concrete pieces.
- To examine the retrofitting consequence of fibre laminates (viz, glass, basalt and aramid) on fire-damaged specimens.

2. Experimental design:

Experimental design is the process of planning and conducting experiments to test a hypothesis or answer a research question. In the case of concrete elements, experimental design involves the systematic and standardized testing of concrete specimens to evaluate their properties and behavior under different conditions

2.1 Materials:

The specification of the materials used to make the samples. This includes the type and proportions of the raw resources, namely cement, aggregates, water, and any supplementary materials or admixtures used.

2.1.1 Cement:

OPC 53 grade cement used with properties confirming to IS 12269-2013 was pretested before concreting. Table 1 lists the stuffs of binder material which has been tested, along with the values recommended by IS 12269-2013 [10].

Table 1 - Properties of cement

Properties	**Experimented values**	**Requirements as per IS 12269-2013**
Specific gravity	3.15	-
Standard consistency (%)	30	-
Initial setting time (min)	55	Not less than 30
Final setting time (min)	285	Not more than 600
Fineness (m^2/Kg)	230	Not less than 225

2.1.2 Fine aggregate

M-sand, graded according to IS 383-2016, was utilised in the mixtures and mixing under saturated surface dry conditions. Table 2 displays the features of fine aggregate. [11].

2.1.3 Coarse aggregate

Under saturated surface dry conditions, coarse aggregate of nominal size 20 mm with gradation according to IS 383-2016 was added in the mixes[11]. Table 2 lists the properties of coarse aggregate.

Table 2 - Physical properties of aggregate

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

2.1.4 Water

For concreting and curing, potable water that met the IS 456-2000 standard was used[12].

2.1.5 Fibre reinforced polymer (FRP)

Unidirectional FRP laminates accustomed to retrofit the thermally damaged specimens. Table 3 lists the features of the FRPs utilized in this investigation. Figure 1 depicts the different FRPs used such as GFRP, BFRP, and AFRP one-to-one.

Table 3 - 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

Fig. 1 - FRP laminates (a) GFRP; (b) AFRP; (c) BFRP

2.2 Resin

The surfaces of the concrete samples had been treated with epoxy for the intent of adhering the FRP sheets to them. The features of the resin used are listed in Table 4.

Table 4 - 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

2.3 Concrete mix design

According to IS 8142-1976, a fresh concrete test was carried out. With a slump value of 100mm, exposed to moderate condition and a target strength of 33.25 MPa, the mix design for M25 grade concrete was designed in accord with IS 10262-2019. Table 5 lists the final mix proportion.

Table 5 - The concrete's mix ratio.

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

2.4 Casting and Curing

After being subjected to extreme temperatures, concrete's mechanical properties were evaluated for varying lengths of time, standard size cylinders of 150 mm diameter and 300 mm height and standard size prisms of 100 x 100 x 500 mm were cast. The specimens were air dried in the laboratory for 24 hours after being cured for 28 days. Finally, the specimens were heated to

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temperatures of 250°C, 500°C and 750°C. After that, the specimen were air cooled before being placed to the examination. Figure 2 shows concrete specimens after curing.

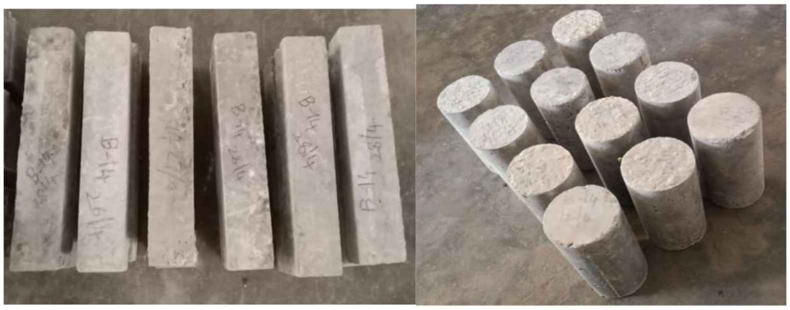

Fig. 2 – Concrete specimens after curing

2.5 Fire exposure

The heat was set in accordance through the fire curve [ISO 834-1:1999(E)][15]. For evaluating concrete's mechanical properties, two cooling methods are normally used: (1) air cooling, which involves exposing hot specimens to normal temperature, and (2) water cooling, which involves after being showing to a maximum temperature, submerging the specimens in waters [19]. The former scenario is preferred for this study (i.e., air cooling at normal temperature).

Fig. 3 – Fire exposure on concrete specimens

Fig. 4 – Thermocouple

2.6 Fire temperature

All reseaches were done in furnace made of refractory bricks that met ISO 834 standard[15]. A high-speed burner was assigned to burn cylindrical specimens as exposed in figure 3. The degree range was monitored using a K-type thermocouple (as shown in figure 4) and a temperature control device (UTC4202 model) to maintain the fire temperature. After being showing to fire for various periods of time (1h, 2h, and 3h), the heat range was observed before the cylindrical specimens were permitted to cool inside the furnace.

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Fig. 5 – FRP wrapped specimens

2.7 Wrapping of FRP laminate

The FRP laminates were bonded in accordance with the ISIS manual and ACI440-2R guidelines. The FRP laminates were wrapped around the specimens in a direction perpendicular to the load application [14]. The air-cooled specimens were removed from the furnace and roughened on all sides before being wrapped. The required amount of epoxy and hardener were mixed and applied uniformly around the cylinder. The FRP has adhered to the specimen using rollers to prevent air pockets. Allowed up to 48 hours for the adhesive to dry. Once they had dried, the required tests were performed. The specimens with fire damage are encased in FRP laminates in Figure 5.

3. Test results and discussion

When showing to fire, concrete undergoes hydrothermal, physical property, and chemical property changes that contribute to the loss of strength. Once the degree reaches 200ºC, the hydrothermal conditions begin to change, causing an escape of free and adsorbed water. (Khoury 1992)[16]. Once the degree of heat reaches 200ºC, the hydrothermal conditions start to change, allowing both free and adsorbed water to escape. This also entails the Vander Waals forces being disturbed by the initial weakening of the bonding forces in the calcium silicate hydrate (C-S-H) gel caused by dehydration. At temperatures above 400ºC, physical and chemical deterioration begins, leading to the disintegration of C-S-H gel, as the shrinkage of C-S-H gel is brought by the evaporation of moisture and the expansion of aggregates at this temperature. The aggregate-paste bond is damaged because of this simultaneous shrinkage and expansion (Behnood and Ghandehari 2009), (Georgali and Tsakiridis 2005)[3] [8]. The disintegration of calcium hydroxide ($Ca(OH)_2$) occurs at heat between 400 and 600ºC. Calcium carbonate (CaCO3) decarbonates mainly in the fire range among 600 and 800ºC, while calcium hydroxide ($Ca(OH)_2$) decomposes primarily between 400 and 600ºC. The disintegration of hydrates causes a further loss in mechanical characteristics amid 600 and 800ºC (Castillo and Durrani 1990)[4]. The micropattern of concrete degrades and disintegrates at elevated degrees, which also causes excessive micro-cracking and strength loss.

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Split-tensile and flexural strength tests were performed on fire-damaged specimens wrapped in and without FRP to examine the mechanical behaviour of the specimens. Also, the modulus of elasticity fire-damaged aged specimens with and without FRP was studied. The test results showed that the fire damaged specimens wrapped with basalt FRP showed greater strength than glass and aramid FRP laminates.

3.1 Visual observation

A physical property of concrete that may be utilised as a tool for evaluating the condition of fire-damaged concrete has changed colour. The visual inspection of fire-damaged concrete indicated that an extensive range of colours comes in contact with flames of various temperatures. The concrete was light grey in tone at normal degree. However, the surface colour changed to dark grey at 250°C, brownish grey at 500ºC, and whitish-grey at 750ºC. The progressive loss and dryness of the grouting paste and changes occurring inside the aggregateas well as changes occurring inside the aggregate, are the primary sources of colour variation in hot concrete. Furthermore, there were no noticeable surface cracks at 250ºC.However, the face of the concrete samples had numerous irregular cracks at 500ºC and 750ºC. The differential thermal enlargement of cement sealant and coarse aggregate may be the cause of this.

At different exposure temperatures and durations, there was absolutely no explosive spalling seen in the samples during fire exposure. However, It is important to note that after cooling to ambient temperature, a thin exterior covering of the post-heated concrete specimens (which were exposed to the fire for 750ºC) spalled in forms of powdery whitish material, which is consistent with the outcomes that were formerly reported (Usman et al. 2021)[23].

3.2 Mass loss

Figure 6 and 7 shows the outcomes of the weight loss in concrete specimens after being reveal to the fire of different degrees and time. The result illustrates that the initial mass loss was brought on by evaporation and the decrease of free water. The weight loss of the specimen when it was disclosed to fire at different degrees (250ºC, 500ºC, and 750ºC) for an hour was approximately 2.45%, 8.43%, and 13.16%. 3.61%, 9.86%, and 14.85%, respectively, were determined to the mass losses for specimen subjected to fire for two hours at temperatures of 250°C, 500°C, and 750°C. The weight reduction during three hours of sample exposure to fire at various temperatures (250ºC, 500ºC, and 750ºC) was reported to be 6.18%, 12.66%, and 16.46%. The dryness of hydrated chemical components in concrete was the cause of the reduction in the mass of sample at elevated temperatures.

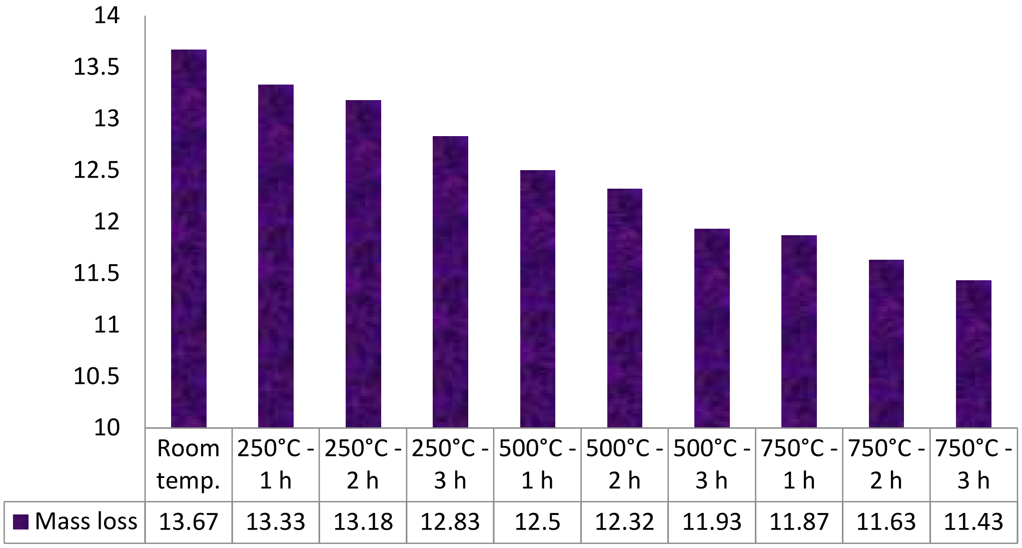

Fig. 6 – Mass of concrete cylinder exposed to different temperatures and durations

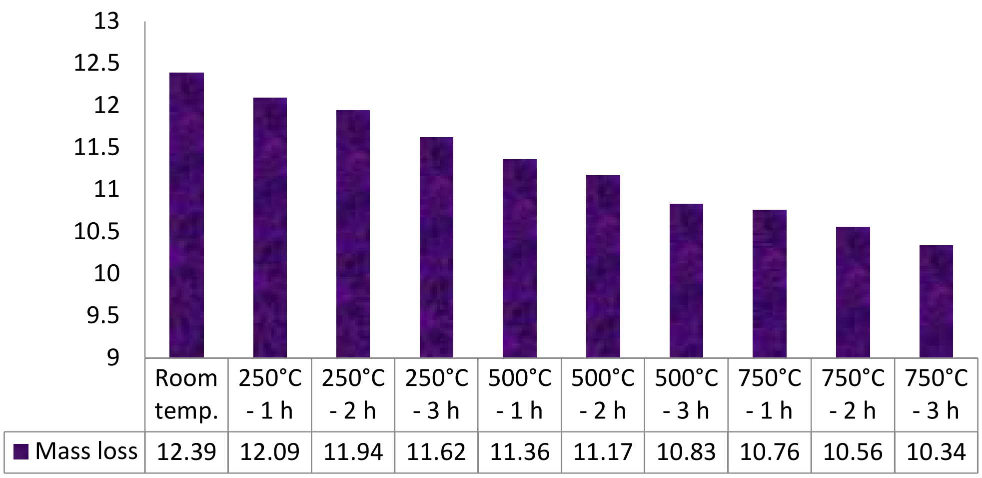

Fig. 7 – Mass of concrete prism exposed to different temperatures and durations.

3.3 Split-tensile strength:

When assessing strength, the tensile toughness of the specimen is frequently disregarded because it is substantially lower than the strength at compression. However, it is a significant attribute in terms of fire resistance since cracking in concrete is usually induced by tensile strains, and structural damage to tension members is frequently caused by micro-cracking propagation. To evaluate split tensile strength, a typical cylinder with a diameter of 150 mm and a length of 300 mm was employed. The test was carried out with a consistent loading rate of 1.2 MPa/min after the specimens were kept in the center of the universal testing machine. The specimen was loaded until failure. Table 6 summarizes the ductile property of cylinders exposed to raised degrees.

Table 6 - Tensile strength of concrete specimens exposed to elevated temperatures**.**

Exposure temperature (ºC)	Exposure time (hour)	Retrofit Material	Tensile strength of samples (Mpa)
Room temperature	-	-	4.05
Room temperature	-	GFRP	6.52
Room temperature	-	AFRP	7.32
Room temperature	-	BFRP	8.14
250	1	-	4.45
250	1	GFRP	7.13
250	1	AFRP	8.04
250	1	BFRP	8.89
250	2	-	3.85
250	2	GFRP	6.19
250	2	AFRP	6.94
250	2	BFRP	7.72
250	3	-	3.65
250	3	GFRP	5.83
250	3	AFRP	6.56
250	3	BFRP	7.27
500	1	-	3.52
500	1	GFRP	5.65
500	1	AFRP	6.32
500	1	BFRP	7.09
500	2	-	3.32
500	2	GFRP	5.31
500	2	AFRP	5.98
500	2	BFRP	6.65
500	3	-	2.96
500	3	GFRP	4.73
500	3	AFRP	5.32
500	3	BFRP	5.91
750	1	-	3.31
750	1	GFRP	5.31
750	1	AFRP	5.98
750	1	BFRP	6.63
750	2	-	2.55
750	2	GFRP	4.07
750	2	AFRP	4.57
750	2	BFRP	5.11
750	3	-	1.82
750	3	GFRP	2.92

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750	3	AFRP	3.28
750	3	BFRP	3.65

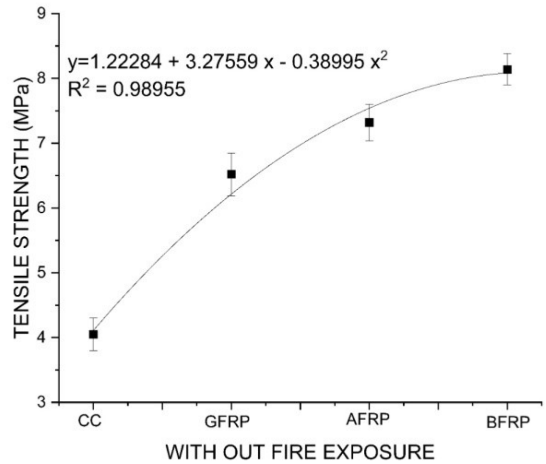

Fig. 8 – Tensile strength of concrete without fire exposure strengthened with FRPs

Figure 8 shows the split tensile property of concrete at normal degree for both unwrapped and wrapped specimens. From the trial outcomes, it is evident that the specimens wrapped with GFRP, AFRP and BFRP showed improved strength of about 60.98%, 80.74% and 100.98% respectively. The improvement in resilience of FRP strengthened specimen was because of the fibre's tensile strength. The bonding of the FRP wrap to the concrete's surface has an impact on the strength of FRP-enhanced concrete as well.

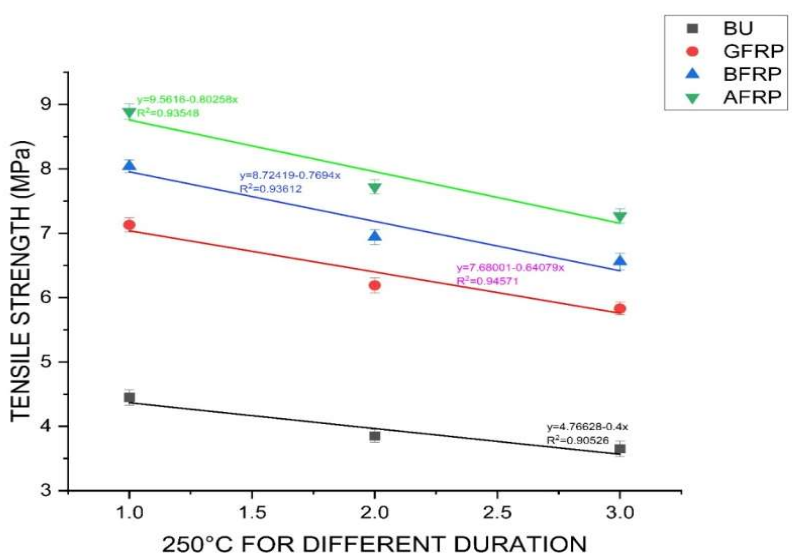

Fig. 9 – Tensile strength of concrete exposed to 250ºC unwrapped and wrapped with different FRPs

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The ductile property of fire exposed specimens to different temperature and duration was plotted in figure 9 – 11. It also provides the tensile strength of specimen that has been retrofitted with various FRPs after being damaged by fire. When the concrete is subjected to 250ºC for 1 hour, the tensile strength of the specimen increased by 9.87%. The escalation in strength was due to the dryness of pore water. Further, the tensile strength cylinder decreases by 5.19% and 10.95% after 2 hours and 3 hours of revelation to heat at 250ºC. The reduction in strength was due to the difference in thermal development of cement glue and aggregate. Further, by retrofitting the fire damaged specimens with GFRP, AFRP and BFRP the tensile property increased by 60.23%, 80.21% and 99.81% respectively. The improvement in the tensile property because of fibre's tensile modulus. among the three fibres, the basalt fibre laminate outperformed the other two fibre laminates used in this investigation, because of its high tensile strength than GFRP and AFRP laminates.

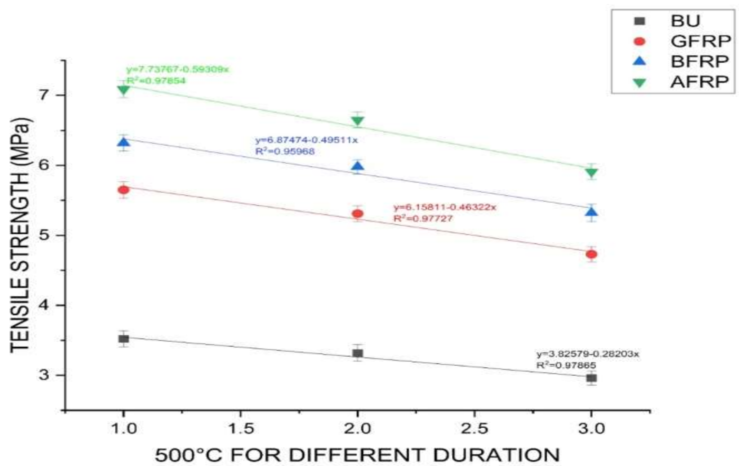

Fig. 10 – Tensile strength of concrete exposed to 500ºC unwrapped and wrapped with different FRPs

When the specimen is subjected to 500ºC for 1 hour, 2 hours and 3 hours, the loss in strength of the specimens was witnessed to be 15.05%, 21.98% and 36.82% which confirms the results reported previously (Kodur 2014)[17]. Similar observations were reported previously (Kodur et al. 2019)[2]. The alterations among the thermal enlargement rates of cement glue and aggregate were responsible for the loss in concrete's tensile strength. Wrapping of fire spoiled specimens with FRP increases the tensile property of the cylinder. After being retrofitted with GFRP, AFRP, and BFRP, the percentage surge in the tensile property of the fire-damaged cylinder was 60.07%, 79.79%, and 100.46%, respectively.

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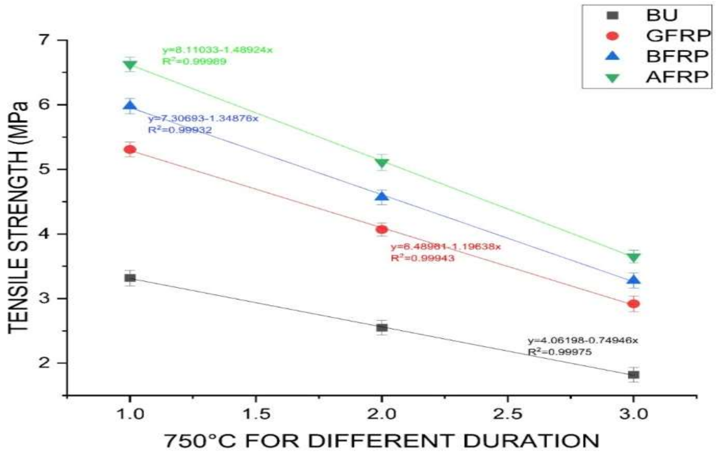

Fig. 11 – Tensile strength of concrete exposed to 750ºC unwrapped and wrapped with different FRPs

The toughness of the specimens was detected to drop by 22.35%, 58.82%, and 122.52% when the specimen was showing to 750ºC for 1, 2, and 3 hours, respectively. Moreover, the tensile property of the fire-damaged cylinders was enhanced by 59.98%, 79.84%, and 100.20%, respectively, by retrofitting the fire damaged cylinders with GFRP, AFRP, and BFRP.

3.4 Flexural strength test:

In compliance with IS: 516 – 1959(Reaffirmed 1999), the test has carried out[13]. For this study, concrete prisms with a standard size of 100 x 100 x 500 mm are used. At points along its one-third span, the concrete prism was loaded. The supporting span of prism was maintained at 400 mm. The equation below was used to analyze the flexural property of the specimen. The flexural property of the heat damaged prism and retrofitting of them with different FRPs were displayed in the table 7.

Flexural strength of the specimen is given as,

Modulus of rupture (f_b) = $\frac{PL}{bd^2}$

Where, P = applied load

L = length of the specimen

b = breadth of the beam

d = depth of the beam

Table 7 - Flexural strength of unwrapped and wrapped specimens**.**

Exposure temperature (ºC)	**Exposure time (hour)**	**Retrofit Material**	**Flexural strength of samples (MPa)**
Room temperature	-	-	4.07
Room temperature	-	GFRP	6.49
Room temperature	-	AFRP	7.36
Room temperature	-	BFRP	8.15

250	1	-	4.47
250	1	GFRP	7.15
250	1	AFRP	8.06
250	1	BFRP	8.93
250	2	-	3.87
250	2	GFRP	6.21
250	2	AFRP	6.99
250	2	BFRP	7.75
250	3	-	3.67
250	3	GFRP	5.83
250	3	AFRP	6.65
250	3	BFRP	7.32
500	1	-	3.54
500	1	GFRP	5.66
500	1	AFRP	6.39
500	1	BFRP	7.12
500	2	-	3.35
500	2	GFRP	5.39
500	2	AFRP	6.04
500	2	BFRP	6.71
500	3	-	2.99
500	3	GFRP	4.78
500	3	AFRP	5.41
500	3	BFRP	5.98
750	1	-	3.34
750	1	GFRP	5.35
750	1	AFRP	6.01
750	1	BFRP	6.71
750	2	-	2.60
750	2	GFRP	4.16
750	2	AFRP	4.69
750	2	BFRP	5.23
750	3	-	1.83
750	3	GFRP	2.93
750	3	AFRP	3.29
750	3	BFRP	3.67

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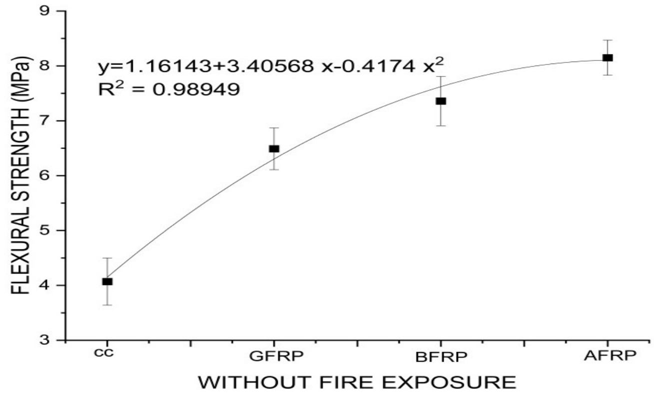

Fig. 12 – Flexural strength of concrete without fire exposure strengthened with FRPs

Flexural behaviour of specimen at normal temperature for specimens wrapped in FRP and for specimens not wrapped in FRP was plotted in figure 12. The test findings clearly reveal that concrete specimens wrapped with GFRP, AFRP, and BFRP had enhanced strengths of about 60.98%, 80.74%, and 100.98%, respectively.

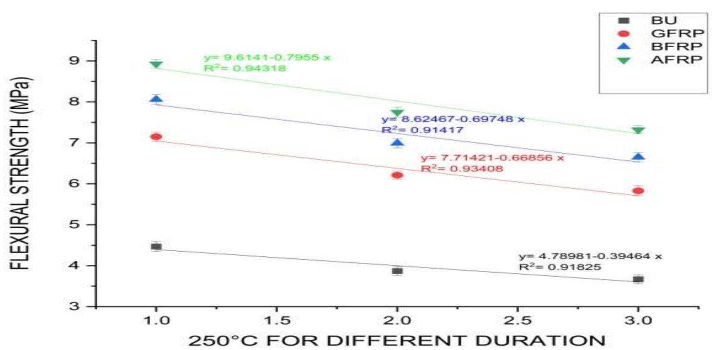

Fig. 13 – Flexural strength of concrete exposed to 250ºC unwrapped and wrapped with different FRPs

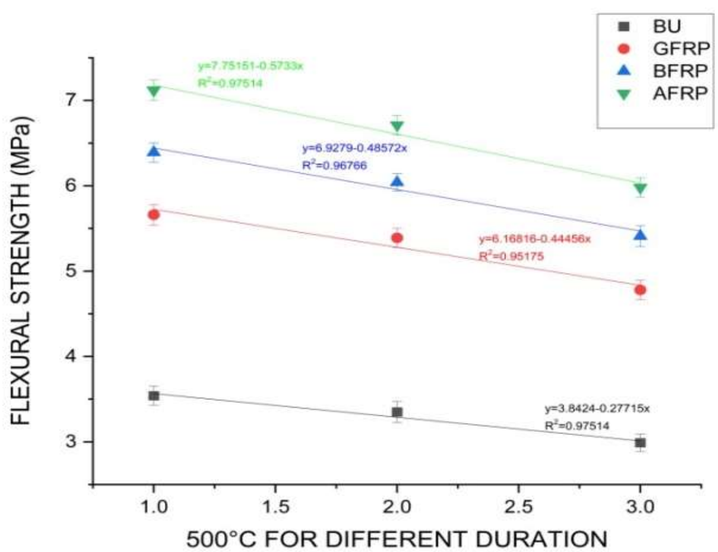

Fig. 14 – Flexural strength of concrete exposed to 500ºC unwrapped and wrapped with different FRPs

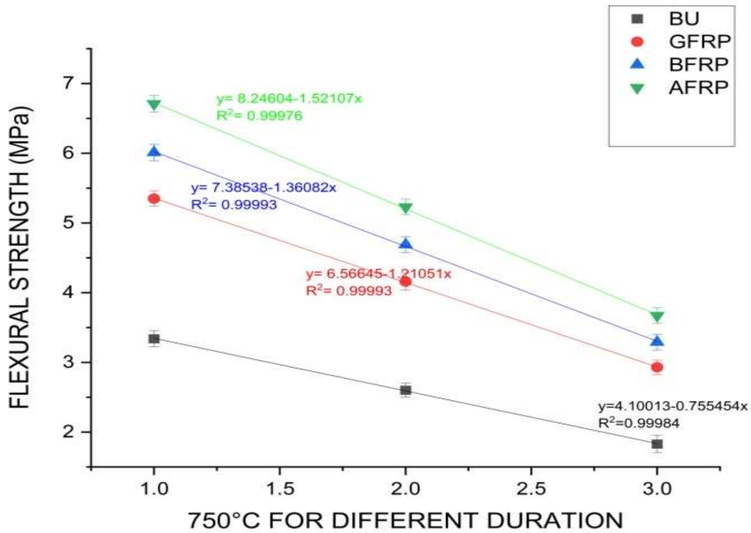

Fig. 15 – Flexural strength of concrete exposed to 750ºC unwrapped and wrapped with different FRPs

The flexural property of specimens showing to fire at different degrees and for varying lengths of time was plotted in figure 13 – 15. Additionally, it gives the flexural strength of fire-harm concrete that has been retrofitted with different FRPs. From this study, it is evident that as the fire degree amplifying the flexural strength decreases. The amount of damage depends on temperature, exposure time, nature of aggregate used etc. Similar observations as that of tensile strength were attained for flexural strengths of the specimens after disclosure to diverse temperatures and for different durations.

3.5 Stress – Strain response:

The characteristics of concrete is typically expressed as stress-strain relations, which are regularly used as input data in mathematical models to estimate the flammability of concrete structural components. The slope of the stress-strain curve tends to fall with temperature due to a fall in the compressive strength and an intensification in ductility of concrete. The properties of concrete has a significant influence on the stress-strain response at both low and high degrees.

Figures 16 show the stress-strain actions of the specimen at various temperatures and exposure times. Specimen shows a linear response at all fire exposure temperatures and durations. As with the amount of temperature rise, the stress-strain behaviour of specimen is strongly influenced by temperature.

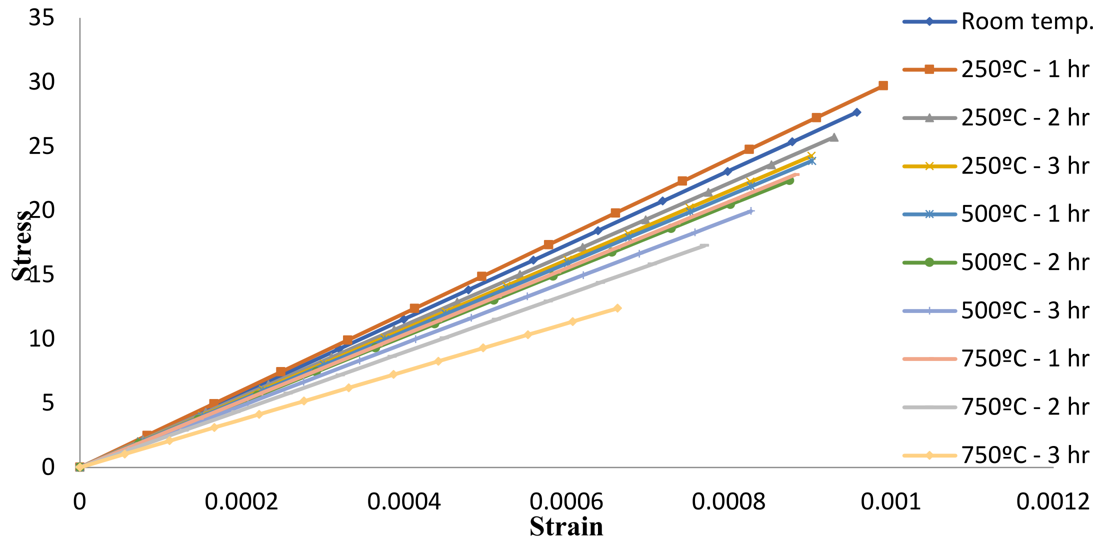

Fig. 16 - Stress vs Strain response of concrete cylinders under axial compression subjected to fire of different temperature and duration

3.6 Young's modulus

Modulus of elasticity, a measurement of its stiffness or resistance to deformation, is frequently utilised while analysing reinforced concrete constructions to pinpoint the stresses that develop in simple components and the stresses, moments, and deflections that occur in more complicated structures. Since the stress-strain curve of concrete is nonlinear, the initial tangent modulus, secant modulus, or tangent modulus methods are practiced to calculate the modulus of elasticity.

Table 8 - Elastic modulus of fire damaged cylinders wrapped with and without FRP

Exposure temperature	Exposure time	Retrofit material	Young's modulus (GPa)
Room temperature	-	-	28.879
Room temperature	-	GFRP	32.935
Room temperature	-	AFRP	35.270
Room temperature	-	BFRP	37.393
250	1	-	30.012
250	1	GFRP	34.223
250	1	AFRP	36.820
250	1	BFRP	39.099
250	2	-	27.667
250	2	GFRP	32.042
250	2	AFRP	33.952
250	2	BFRP	35.940
250	3	-	26.911
250	3	GFRP	30.915
250	3	AFRP	33.237
250	3	BFRP	35.376

500	1	-	26.462
500	1	GFRP	30.045
500	1	AFRP	32.526
500	1	BFRP	34.633
500	2	-	25.539
500	2	GFRP	29.321
500	2	AFRP	31.630
500	2	BFRP	33.715
500	3	-	24.140
500	3	GFRP	27.590
500	3	AFRP	29.533
500	3	BFRP	31.705
750	1	-	25.860
750	1	GFRP	29.308
750	1	AFRP	31.626
750	1	BFRP	33.604
750	2	-	22.438
750	2	GFRP	25.504
750	2	AFRP	27.577
750	2	BFRP	29.116
750	3	-	18.701
750	3	GFRP	21.289
750	3	AFRP	22.934
750	3	BFRP	24.351

Young's modulus is the characteristics that affect the ability of concrete to resist fire. It decreases with escalation in degree. The extent of the decline in elastic modulus at developed degrees be subject to moisture loss, high temperature, creep and aggregate type. At maximum temperatures, hydrated cement products disintegrate and linkages in the micropattern of cement glue break down, reducing elastic modulus which confirms the results reported previously (Khaliq and Taimur 2018, Xiao and Konig 2004)[24]. The elasticity modulus of concrete at high heats is listed in the table 8 along with its effect of FRP retrofitting on fire-damaged concrete.

3.7 Scatter plot

Based on temperature (X_1) and exposure time (X_2), a regression equation for tensile strength ($\check{T}$), flexural strength ($\hat{y}$), and young's modulus ($\check{E}$) was developed, as given below.

$\check{T} = 5.64333 - 0.00285\ X_1 - 0.475\ X_2$ (A)

$\hat{y} = 5.66222 - 0.00283\ X_1 - 0.4766\ X_2$ (B)

$\check{E} = 35.361 - 0.01173\ X_1 - 2.097\ X_2$ (C)

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The above-mentioned equations (A), (B) & (C) have justifications, specifically temperature ranges of 250ºC to 750ºC and duration of up to 3 hours.

A scatter plot was plotted against experimented values and observed values of tensile strength, flexural strength and Young's modulus. The observed tensile strength, flexural strength and Young's modulus values were compared with their corresponding predicted values which gives an R^2 value of 0.95466, 0.9 and 0.9 respectively as shown in figure 17, 18 and 19.

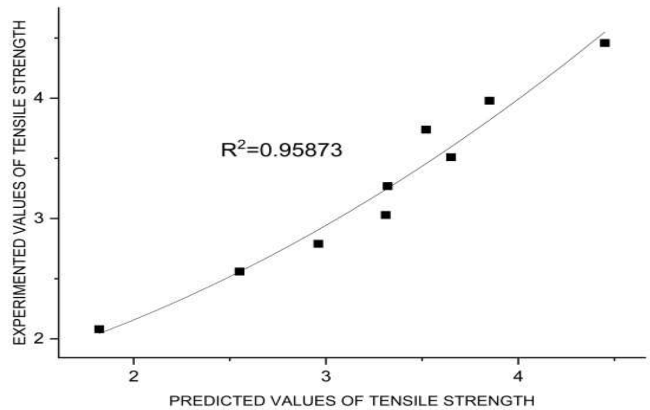

Fig. 17 - Scatter Plot for Tensile Strength.

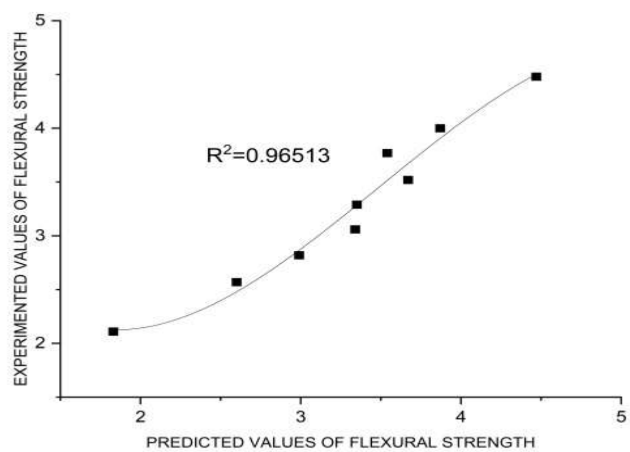

Fig. 18 - Scatter Plot for Flexural Strength.

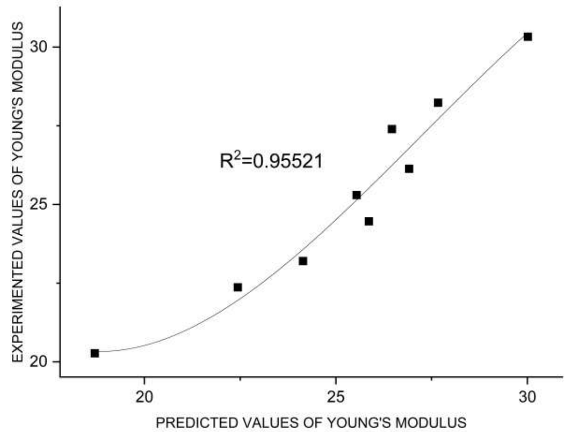

Fig. 19 - Scatter Plot for Young's modulus.

4 Conclusion

- Visual examination of the fire-damaged specimens reveals that those exposed to 500ºC show only moderate crack formation, whereas at 750ºC the cracks become dominant. For specimens exposed to various temperatures for various lengths of time, there was no evidence of concrete spalling. Also, it exhibited wide range of colours when showing to dissimilar heat and period.
- At developed temperatures, concrete's mechanical qualities are impacted. Generally speaking, qualities like strength, elastic modulus, peak strain, etc., degrade with cumulative temperature.
- Except for the specimens subjected to the fire of 250ºC for one hour, the split tensile property and flexural strength tests on specimens showing to the fire of 250ºC, 500ºC, and 750ºC for a time of 1, 2, and 3 hours revealed a decrease in strength. The dryness of moisture from the concrete resulted in an rise in the tensile strength of the specimens exposed to 250ºC for 1 hour.
- After disclosure to fire for different temperatures and duration, a decline in elastic modulus was noted. It has observed that there is an approximately linear association among the rise in heating temperature and the decline in elasticity modulus.
- Wrapping fire-damaged specimens with different FRPs showed that the split-tensile and flexural properties of concrete was improved.
- The tensile and flexural property of concrete was amplified when the fire-damaged specimens were retrofitted with glass FRP. Thermally damaged specimens were found to have a 60.1% increase in tensile strength after being retrofitted with GFRP.
- After being retrofitted with aramid FRP, the retrofit efficiency of fire-damaged specimens was found to be 79.95%.
- Wrapping fire-damaged specimens with basalt FRP increased the tensile and flexural strength of concrete by 100.16%.
- The rupture of the FRP laminate is the failure mechanism for all specimens wrapped in FRP.
- When specimens were exposed to 750ºC for 3 hours, a substantial loss of tensile and flexural strength was observed.

- The basalt fibre laminate outperformed the glass fibre laminate and the aramid fibre laminate in this investigate because the basalt FRP had greater tensile strength than the glass and aramid fibre laminates.
- The equation proposed in the study [eq.(1), (2) & (3)] for split-tensile strength, flexural strength and young's modulus based on temperature and time are more precise for the temperature range of 250 to 750ºC and duration up to 3 hours.

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