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Effectiveness of Concrete Retrofitted with FRP Wrapping Subjected to Higher Temperature

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Abstract

This work aims to provide additional insight into the behavior of fiber-reinforced polymer (FRP) laminates at high temperatures. The compressive properties of concrete coated in fiber-reinforced polymer (FRP) under elevated heat levels. The study addresses the important issue of assessing the performance of structural elements, specifically concrete columns, in the event of a fire. Recently, there has been increased interest in fiber-reinforced polymer (FRP) composite materials as a possible concrete structural rehabilitation solution. The purpose of this study was to ascertain, using both destructive and non-destructive methods, how fire damage affected concrete specimens retrofitted with Aramid FRP, Carbon FRP, and Glass FRP laminates. After being exposed to 250, 500, and 750°C for one, two, and three hours, the cube specimens were retrofitted with FRP laminates. In order to maximize the performance of concrete structures under harsh circumstances, the research highlights the significance of taking into account both the mechanical and fire-resistant qualities of retrofitting materials. The concrete's compressive strength increased for one hour at 250ºC, after which it fell, according to the results. Nonetheless, a decrease in compressive strength was noted at higher temperature and fire duration ranges. The compressive strength improved as compared to standard concrete, regardless of the type of fiber-reinforced polymer wraps utilized.

Keywords: Carbon FRP, fiber-reinforced polymer (FRP) wrapping, aramid FRP, Glass FRP, retrofitting, elevated temperature

INTRODUCTION

In recent years, there has been a rise in interest in the investigation of lightweight composite materials. Glass (GF), aramid (AF), and carbon (CF) fibers are widely used in advanced polymer matrix composites due to their special properties and tunable features (high strength, flexibility, and stiffness). When concrete cylinders are damaged by intense heat, the carbon fiber composite restores them exceptionally effectively. The CFRP fabric's layer count and the type of reinforcement were among the experimental conditions [1]. FRP, or fiber-reinforced polymer, is a productive way to give concrete columns more durability and strength, as evidenced by a multitude of research. Testing fiber-reinforced polymer (FRP) wrapped in the hoop direction in solid cross-section columns was the subject of numerous research [2]. Both carbon fiber reinforced polymer (CFRP) concrete and glass fiber reinforced polymer (GFRP) types were utilized in this work to extend the concrete portion in order to repair the damaged concrete [3]. With the exception of two specimens that were not burned, an investigation of the efficacy of CFRP wrapping jackets was carried out experimentally on twelve square specimens of reinforced concrete (CR) columns were burned at three hundred, five hundred and seven hundred degrees Celsius in order to make repairs to them [4].

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The strength models that are currently accessible in the scientific literature for fiber-reinforced polymer wrapped columns were created at room temperature. There is currently neither analytical nor experimental data on the behavior of circular columns made of reinforced concrete that are loaded, heated, and cooled before being wrapped in textiles reinforced with carbon fiber [5]. Eight were subsequently imprisoned using textiles made of carbon fiber reinforced polymer (CFRP) [6]. Flexural strength can be increased in beams, columns, and plates by bonding fiber-reinforced polymer (FRP) to the tension zone using epoxy, common glue. The use of FRP is growing in popularity because it offers a number of benefits over traditional methods for strengthening and repairing structures [7]. The correct application of the CFRP system requires compatible CFRP, a clean concrete surface, and a strong adhesive like epoxy resins. Nonetheless, the limited resilience of CFRP systems to high temperatures and fire is one of the things impeding their wider use [8]. The flexural, shear, and axial load carrying capacities of these elements are increased by using FRP material, which is sold as sheets or laminates. The suggested method entails wrapping glass fiber-reinforced polymer composite mats on the RC beam's shear and flexural zones and examining their properties [9]. Provided that the FRP level temperature stays below the epoxy resin's breakdown limit, FRP composites have been shown to be successful in increasing the axial load capacity of exposed columns. The columns underwent axial compression testing until they failed during cooling [10].

RELATED WORK

Kolkar et al. (2017) [11]. have described the high-level overview of the behavior of concrete elements and systems at a better temperature [12]. A comparison is made between the characteristics of regular concrete and high-strength concrete that has been heated. Li et al. (2017) [13]. have described the attempts to shed light on how high temperatures affect the mechanical characteristics of concrete strengthened with fiber-reinforced plastic (FRP) and bonded with modified epoxy resin (MER) adhesive. This study by Hadi et al. (2018) [14]. presents the experimental results of sixteen circular reinforced concrete (RC) column specimens. It also looks at the flexural and axial behavior of these columns that have fiber-reinforced polymer wrapping and a reactive powder concrete (RPC) jacket added to them. While the fire application has been covered by Nguyen et al. (2018) [15]. this article specifically addresses the second type of CFRP's thermo-mechanical efficiency. The mechanical properties of the material at temperatures ranging from twenty degrees Celsius to 600 degrees Celsius is assessed in addition to its heat resistance for tensile stress ratios ranging from 10% to 75% of the maximum tensile stress at room temperature. Hassan et al. (2019) [16]. examined the behavior of twenty-eight beams under indirect fire circumstances, for 60 minutes and 120 minutes, respectively, they were heated to 400°C and 600°C. Joined steel plates, carbon fiber reinforced polymer (CFRP) laminates, and concrete jacketing have all been used in beam capacity retrofitting. Alanazi et al. (2019) [17]. conducted an experiment whose goal is to assess the stress-strain behavior and residual strength of partially damaged concrete columns that have undergone external modification utilizing CFRP strips. Oprişan et al. (2019) [18]. have described the way short columns of rubberized concrete enclosed in aramid fiber reinforced polymer (AFRP) behaved when compressed is examined experimentally and numerically in this work. For the emergency restoration of severely damaged reinforced concrete columns subjected to coupled axial compression stresses and fire, Chinthapalli et al. (2020) [19]. have reported the efficacy of retrofitting with hybrid fiber reinforced polymer (FRP). In order to provide lateral confinement, the hybrid FRP retrofitting technology combines externally bonded (EB) CFRP wrapping with near-surface mounted (NSM) CFRRP reinforcement. Research has been done by Bengar et al. (2020) [20] on how well heat-damaged concrete can be wrapped in carbon fiber-reinforced polymer (CFRP) to be repaired to preserve and reinforce the steel rebar link. The goal of BP, Sachin et al. (2021) [21]. is to investigate how high temperatures affect the reinforcement self-compacting concrete beams' ability to support loads as well as how degraded beams behave after GFRP sheet retrofitting. Qureshi et al. (2022) [22] have described the structures are now exposed to higher than normal temperatures due to climate change [23]. thus it's critical to comprehend how these anchored FRP sheets behave in these conditions. Koppula et al. (2022) [24]. examined the test results and discovered that when the load that was applied ratio was raised, columns wrapped in two separate layers of CFRP sheets and subjected to a longer fire duration than 2 hours showed a higher drop in post-fire

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residual compressive strength. In order to replicate a real-world situation, the study used one instead of two sheets of CFRP wrapping paper to retrofit concrete columns that had previously been subjected carrying service loads of twenty percent and forty percent of the column's ultimate capacity at design, respectively, to one- and two-hour typical fires. Kharmale et al. (2023) [25] have described the regardless of cooling regime, CFRP laminate retrofitting to heat-damaged concrete samples offered the containment to stop the spread of cracks and severely damage spalling. Consequently, the CFRP retrofitting method shows to be a practical and successful way to rebuild the concrete's strength after being destroyed by fire. Abadel et al. (2023) [26] examined potential enhancements in the deep beams' shear strength when exposed to extreme temperatures by experimentally examining the shear capacity of UHPFC deep beams reinforced with carbon fiber-reinforced polymer (CFRP) sheets. Revanna et al. (2024) [27] examined the fiber-reinforced polymer epoxies at high temperatures can be mitigated using Textile Reinforced Mortars (TRMs). This study looks at the thermo mechanical behavior of reinforced concrete beams at high temperatures that are reinforced with mortar reinforced with textile fibers. In order to strengthen and assess reinforced concrete beams, basalt and carbon textiles were used while the specimens were stored in a heated environment.

MATERIAL AND METHOD

Fiber-reinforced plastic (FRP) is a composite material made of a matrix of fiber-reinforced polymer. The most prevalent fiber kinds are glass (found in fiberglass), carbon (found in carbon-fibre-reinforced polymer), and aramid. In order to increase the plastic's elasticity and mechanical strength, a polymer matrix is carefully combined with a supporting material or fiber to create fiber-reinforced polymers, or FRPs.

Material

The details of the materials that were utilized to create the samples. This covers the kind and amounts of the raw ingredients, which are water, cement, aggregates, and any additional materials or admixtures that are utilized.

Cement

The material utilized was ordinary Portland cement (OPC) of 53 grade, satisfying IS 12269-2013 standard standards, having a fineness value of 230 m^2/kg and a specific gravity of 3.15. 55 minutes was the first setting time and 285 minutes was the last setting time.

Fine Aggregate

Under saturated surface dry circumstances, M-sand, graded in accordance with IS 383-2016, was used in the mixes and mixing. Table 1 displays the attributes of fine aggregate.

Coarse Aggregate

The details of the materials that were utilized to create the samples. This covers the kind and amounts of the raw ingredients, which are water, cement, aggregates, and any additional materials or admixtures that are utilized.

Table 1. Physical properties.

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

Water

Potable water that complied with IS 456-2000 standards was utilized for concreting and curing.

Fiber Reinforced Polymer

FRP laminates that are unidirectional and used to retrofit specimens that have been thermally damaged. Table 2 enumerates the attributes of the FRPs utilized in this investigation. The many FRPs that are employed, including GFRP, CFRP, and AFRP one-to-one, are displayed in Figure 1.

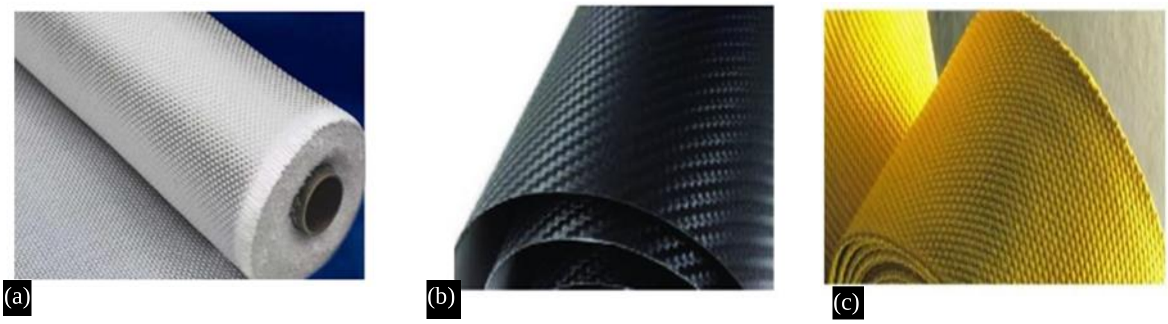

Figure 1. FRP laminates (a) GFRP; (b) CFRP; (c) AFRP

Table 2. FRP Laminate Properties

Properties	**GFRP**	**CFRP**	**AFRP**
Material	Glass	Carbon	Aramid
Colour	White	Black	Yellow
Weight of fibre(g/m^2)	920	380	280
Fibre thickness (mm)	0.9	0.3	0.4
Fibre tensile strength (N/mm^2)	3400	4000	2900
Nominal thickness per layer (mm)	1.5	1.3	1.6

Resin

In order to attach the FRP sheets to the concrete samples, their surfaces were coated with epoxy. Table 3 lists the characteristics of the resin that was used.

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

Concrete Mixed Design

As per IS 8142-1976, a new concrete test was conducted. According to IS 10262-2019, the design mix was created to produce concrete with an M25 grade and a slump value of 100 mm. Before deciding on the mix ratio mentioned above, several tests were conducted to ensure the consistency and compressive strength that were anticipated. Table 4 presents the design mix ratio that was used in this investigation. Every specimen that is evaluated and cast for this investigation is made using the same mixture.

Table 4. Incorporate the concrete by mixing the proportions.

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

Specimen Preparation and Testing

In accordance with IS456-2000 specification, the concrete elements were mixed for at least two minutes in a tilting drum mixer with a 0.15 m3 capacity to guarantee homogeneity in the concrete mix. After measurement, the droop was found to be 100 mm. Before filling them with wet concrete mix, the molds were greased. In order to mesh the various levels, the concrete was also put in three layers and tamped with 25 blows before being set on a vibrating table. After a day, the cubes were taken out of the mold and allowed to cure in water for a total of 28 days. After that, they were placed in an open area to await fire treatment.

Fire Exposure and Temperature

The fire curve [ISO 834-1:1999(E)] was used to determine the appropriate temperature. When evaluating the mechanical properties of concrete, two cooling methods are frequently used: (1) air cooling, which involves bringing heated specimens down to room temperature, and (2) water cooling, which involves submerging the specimens in water once they have achieved their highest temperature.

Figure 2. Thermocouple.

Figure 3. Exposure of fire on concrete cubes

For this investigation, the first case (air cooling at room temperature) is favored. Refractory bricks were used to build a furnace for fire treatment. Figure 3 illustrates how cube specimens were burned (ISO 834, standard fire curve) with a high-speed burner. As seen in figure 2, a 'K'-type thermocouple was utilized to measure temperature using a UTC-4202 model temperature controller device. Specimens were subjected to fire for one, two, and three hours at a time. Before the cube specimens were cooled, the temperature range was measured.

FRP Wrapping

After being taken out of the furnace and let to cool, the specimens were roughened all over before being cleaned and wrapped. On the matching sides of each cube, an adequate amount of epoxy resin was metered out and applied uniformly. The FRP wraps are cut to the necessary cube dimensions. While wrapping, air pockets are prevented with the use of rollers. Figure 4 shows how FRP is wrapped around a concrete cube. The cyanoacrylate glue is left undisturbed to dry for a maximum of 48 hours. The necessary tests are run when the material has dried. The FRP sheets were wrapped in compliance with the ACI440-2R and ISIS manuals, perpendicular to the direction of the load.

Figure 4. Wrapping of FRP

TESTING RESULT AND DISCUSSION

Fire is one of the worst dangers that structures can face. The thermal and mechanical properties of materials are deteriorated in such a fire accident because temperature variations in the structural members cause physical and chemical changes in the constituent materials. The main design factors, such as the cement quantity and w/c ratio, were held constant in order to comprehend the impact of fiber wrapping on fire-damaged concrete. The fire resistance of conventional concrete has been studied for a longer period of time, and building codes (EN 1992-1-2: 2004) outline typical strength loss models.

Visual Observation

In general, damage from exposure to elevated temperatures can be determined by looking at the concrete's surface. As a result, the first step in evaluating fire-damaged concrete is usually a visual examination for color changes, fracture formation, and surface spalling. Upon visual inspection of the concrete damaged by fire, it was discovered that distinct concrete components displayed varying color ranges. At 300–600 degrees Celsius, the color changes to red; at 600–900 degrees Celsius, it turns whitish grey; and at 900–1000 degrees Celsius, it turns buff. Red color results from the oxidation of iron hydroxides in cement paste and aggregates. The light gray color of the concrete is caused by the breakdown of the calcareous components of the aggregate and cement paste. The kind of aggregates utilized also had an impact on how the concrete behaved when burned. Moreover, popouts, crazing, and cracking are caused by the aggregate particles of quartz or chert. Heating causes the aggregate volume in concrete to rise. It also causes the cement paste surrounding the aggregate to compress, which results in microcracks in the microstructure of the concrete. Additionally, tiny cracks start to show when the temperature reaches 500°C, and prominent cracks start to show when the temperature reaches 750°C.

Mass Loss

Mass loss occurs in concrete as temperature rises virtually continuously. It was demonstrated that mass loss is higher at first up to 250ºC, which can be related to evaporation and the loss of free water because of the hydrothermal conditions in the beginning. It was discovered that the mass loss at 250oC for varying times ranged from 2.24% to 6.18%. At 500ºC, however, it rose between 8.49% and 12.34% for varying exposure times. At 750ºC, it increases further by 13.19% to 16.32% depending on how long the fire is exposed to. The impact of higher temperatures on concrete, as previously stated, is confirmed by the mass loss data in Figure 5. The dehydration of hydrated chemical components in the concrete was the cause of the specimen's mass loss.

Compressive Strength by Destructive Testing

A standard cube specimen measuring 150 mm by 150 mm by 150 mm was used for the compression test. The specimens were held in the center of the testing machine, and tests were conducted with uniform stress of 140 kg/cm2/min until the specimen failed.

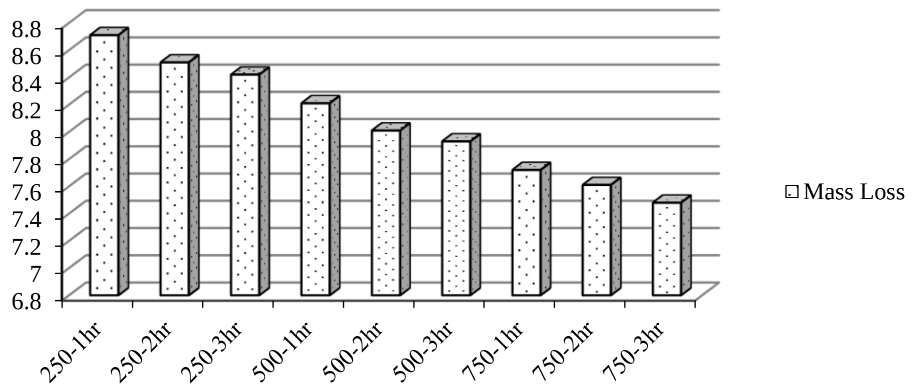

Figure 5. Mass loss of concrete cubes subjected to different temperature and duration.

Table 5. 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		34.3	
	GFRP	41.32	32%
	AFRP	50.21	50.72%
	CFRP	58.72	72.37%

As a result of the experiment, the maximum load applied to the appropriate cross-sectional area was divided to provide the maximum compressive strength and maximum compressive load. Three specimens were tested in order to determine the average strength value, with variations of ±15% of the mean value (IS 516-1959). The compressive strength increased at temperatures between 200 and 250ºC. At 300ºC, strength was reduced by 15–40%, and at 700ºC, it was reduced by 55–72%.

The average compressive strength of specimens that are wrapped in FRP and that are not exposed to fire is tested, and the findings are displayed in Figure 6. The results of the testing were similar. Table 5 indicates that the concrete specimens wrapped with GFRP, AFRP, and CFRP exhibited increases in strength of 34%, 50.72%, and 72.37%, respectively. Specimen strength varies according on the characteristics of FRPs.

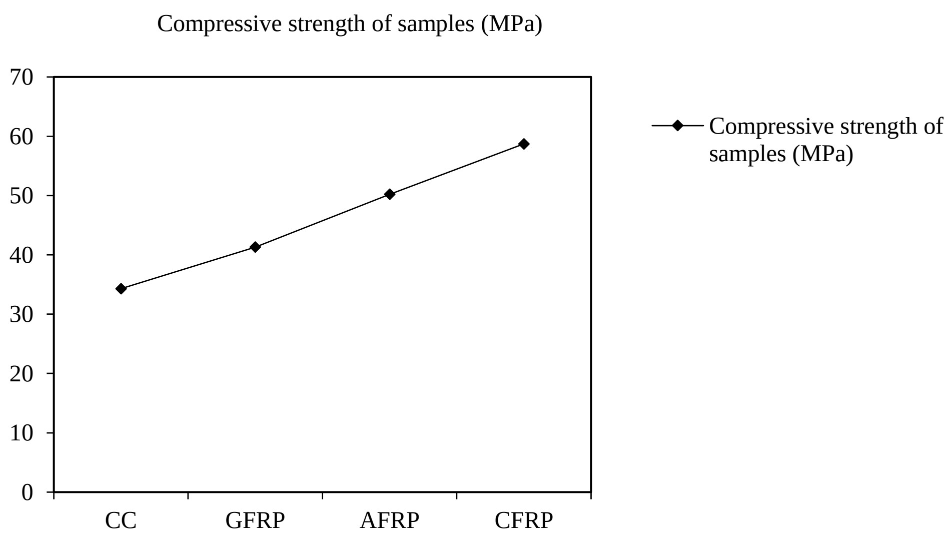

Figure 6. Without fire exposure.

Concrete exposed to fire for one, two, and three hours at 250oC, 500°C, and 750°C was measured and its compressive strength is summarized in Figures 7–9. It is shown graphically in figures 7 through 9.

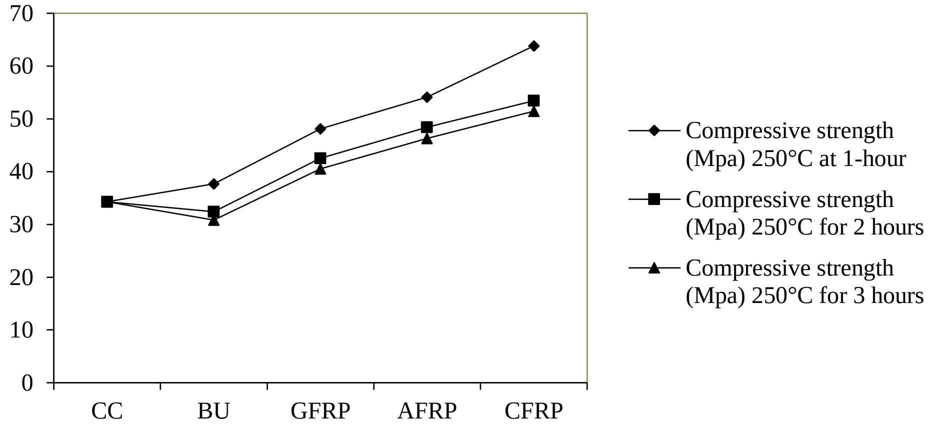

Figure 7. Test results for compressive strength of unwrapped and wrapped specimens exposed to the fire of 250ºc for 1hr, 2hr and 3hr duration

The variance in concrete's compressive strength exposed to a fire at roughly 250°C for one, two, and three hours is depicted in Figures 7. The dehydration of the pore water caused the charred cubes' compressive strength to increase by 10% after an hour in the fire. Because the aggregate and cement paste had different rates of thermal expansion, the compressive strength decreased by 10.61% and 5.16% after two and three hours of fire exposure, respectively. Similar to previous findings, it was discovered that the higher temperature of 250°C used in this investigation had very little impact on the unwrapped cubes' compressive strength. Moreover, the compressive strength of the burnt cube was increased by wrapping it in GFRP, AFRP, and BFRP. The average strength increase was found to be 32.21%, 50.94% and 70.93% respectively.

The variation in compressive strength of fire-exposed concrete at 500°C for one, two, and three hours is shown in Figure 8. Burnt cubes had a decrease in compressive strength of 15.83%, 23.85%, and 37.88%. The association between exposure temperature and compressive strength was found to be comparable to earlier published studies. Different fiber-reinforced polymers (FRPs) such as GFRP, AFRP, and BFRP were wrapped around charred cubes, and the average strength increase was 30.91%, 49.94%, and 71.97%, respectively. All wrapped specimens demonstrated higher compressive strength than unwrapped specimens, regardless of the temperature period or level. After being exposed to 500°C for three hours, compressive strength dramatically dropped.

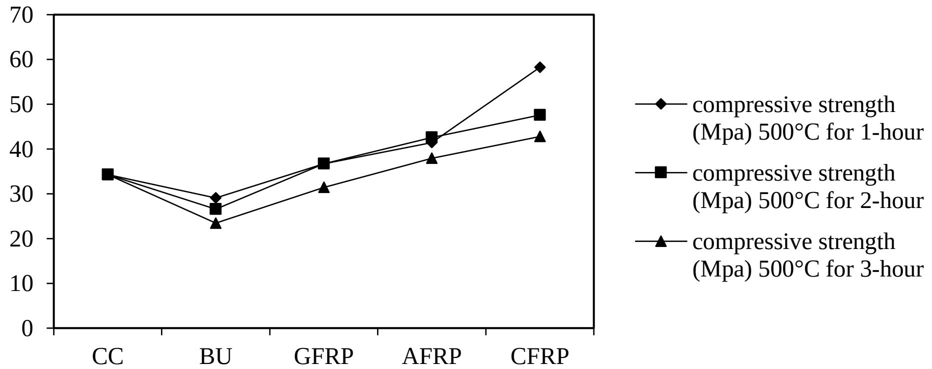

Figure 8. Test results for compressive strength of unwrapped and wrapped specimens exposed to the fire of 500ºc for 1hr, 2hr and 3hr duration.

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The variation in compressive strength of fire-exposed concrete at 750°C for one, two, and three hours is shown in Figure 9. Burnt cubes lose compressive strength by 18.79%, 59.43%, and 121.5%, in that order. There was a noticeable loss of strength after three hours at 750°C. When the charred cube is wrapped in various fiber-reinforced polymers (FRPs) like GFRP, AFRP, and BFRP, the compressive strength improves by 29.73%, 48.49%, and 68.94%, respectively.

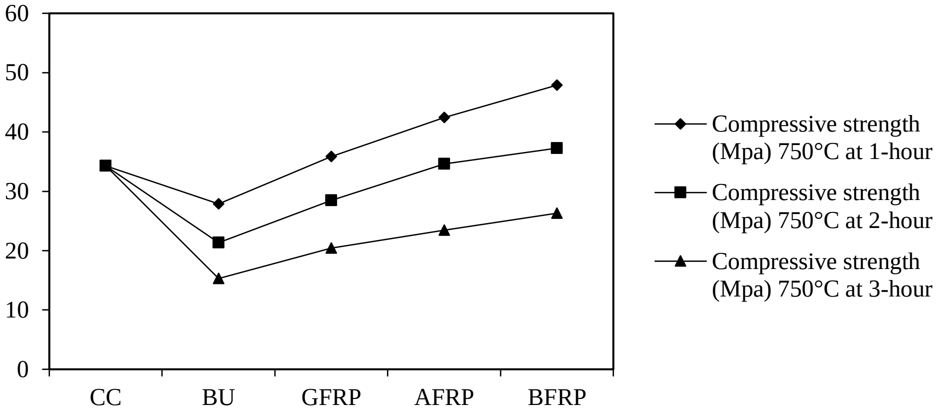

Figure 9. Test results for compressive strength of unwrapped and wrapped specimens exposed to the fire of 750ºc for 1hr, 2hr and 3hr duration.

To ascertain the extent of harm and the durability of the damaged concrete components, NDTs are frequently used to evaluate structures that have been destroyed by fire. The results of the controlled and hammer test's destructive and non-destructive tests revealed lower compressive strength than those of the destructive tests.

Scatter Plot

Using multiple regression, an equation for compressive strength was put out that took temperature and exposure time into account. Additionally, a scatter plot was created and plotted against projected compressive strength values derived from destructive testing as well as experimental compressive strength values. We looked at how compressive strength ($\hat{y}$) changed with temperature (X_1) and time (X_2).

$$\hat{y} = 46.43 - 0.02305x_1 - 4.03467x_2 \quad (1)$$

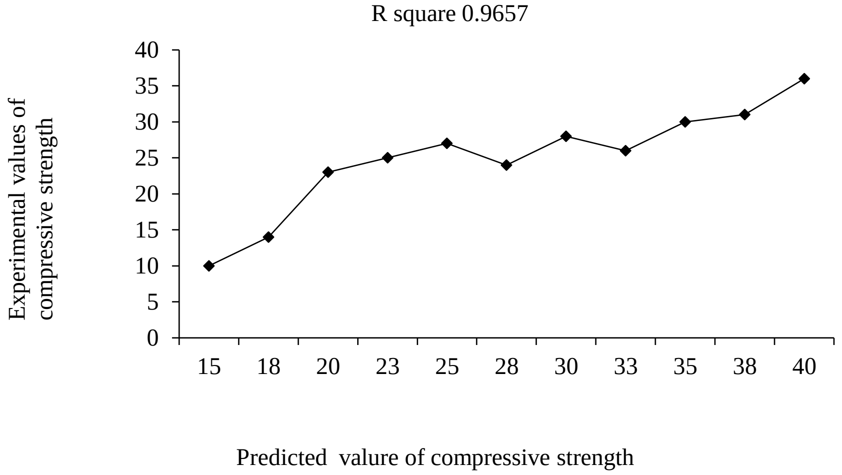

Figure 10. Scatter plot.

To determine the compressive strength of concrete that has been burned, use the formula below, taking into account temperature and time. When the expected and measured compressive strength values were compared, figure 10's R^2 value was 0.96457. Note that the temperature range of 250ºC to 750ºC and time of up to 3 hours are justifications for the preceding equation.

CONCLUSIONS

This study evaluated the compressive strength of concrete that has been burned and reconstructed using fiber-reinforced polymers (FRP) made of glass, carbon, and aramid materials. Applying temperatures of 250°C, 500°C, and 750°C to 128 cube specimens takes one hour, two hours, and three hours, respectively. The compressive strength of unwrapped and wrapped concrete cubes with FRP sheets was evaluated under identical conditions. It is possible to conclude the following: Visual examination of the fire-damaged specimens revealed that, for specimens exposed to 500°C, little fracture formation had occurred, and that, at 750°C, the cracks were prominent. No concrete spalling was seen in specimens that were exposed to various temperatures for varied lengths of time. According to the test results, concrete loses strength after being exposed to 250ºC for an hour. After that, the strength increases. A decrease in compressive strength was noted for greater temperature ranges and extended exposure times. A comparison was made between the compressive strengths derived from destructive and non-destructive approaches. The elevated temperature investigated in this study had an impact on the unwrapped specimens' compressive strength. Following a 3-hour exposure to 750°C, a maximum strength loss of around 121.5% was noted.The compressive strength of all GFRP, AFRP, and BFRP wrapped specimens was higher than that of unwrapped cubes. For GFRP, AFRP, and CFRP, the increase in strength was roughly 31.68%, 50.89%, and 72.19%, respectively. Ruptures in the FRP sheet caused all wrapped specimens to fail. Because carbon fiber laminate has a higher tensile strength than the other two fibers employed in this research, the test results showed that it has a higher retrofitting efficiency than glass and aramid fiber laminate. For the temperature range of 250 to 750ºC and duration up to 3 hours, the suggested for compressive strength depending on temperature and duration is more accurate.

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