SSRG International Journal of Civil Engineering
ISSN: 2348-8352/ https://doi.org/10.14445/23488352/IJCE-V11I7P104

Volume 11 Issue 7, 36-42, July 2024

Original Article

Effect of Fibre Reinforced Polymer Wrapping on Mechanical Properties of Concrete Subjected to Fire

John Thangam[1], Ilango Sivakumar[2]

[1,2]*Department of Civil and Structural Engineering, Annamalai University, Tamilnadu, India,*

[1]*Corresponding Author : johnthangam2014@gmail.com*

Received: 09 May 2024 Revised: 08 June 2024 Accepted: 08 July 2024 Published: 31 July 2024

Abstract - *Concrete buildings often fare rather well in a fire and can usually be restored after one has occurred. The concrete cover has a very low thermal conductivity, which, if it stays intact, keeps the interior reinforcing steel and the concrete at relatively low temperatures over extended periods of intense heat. This work reports on an extension of the application of fibre-reinforced polymer confinement technology for reinforcing burned concrete columns. Following a four-hour heating cycle to gradually higher temperatures and a cooling period to room temperature, in order to investigate the compressive strength and stress-strain behaviour of plain concrete, both unconfined and FRP confined, an experimental program was started. The outcomes demonstrate how well FRP confinement works to increase even badly fire-damaged concrete columns' ability to support loads. The findings also shed light on the mechanics of FRP confinement of concretes with different compressive strengths but similar compositions.*

Keywords - *Fibre reinforced polymer concrete, FRP laminates, Fire exposure, Tensile strength test, Stress-strain response.*

1. Introduction

Fibre reinforced polymers, or FRPs for short, are becoming more and more popular in a variety of building applications, particularly in the restoration of wood, steel, and concrete structures. The restoration of damaged reinforced concrete structural sections has become more common than the use of steel plates because Fibre Reinforced Polymers (FRPs) have so many advantages over steel, including excellent strength to resistance to electrochemical corrosion, weight ratios, speed and ease of application explained by Zhou et al. (2022). During structural repair, Fibre Reinforced Polymer (FRP) sheets or plates are attached to the outside of reinforced concrete components to give them external strength.

Fire Resistant Polymers (FRPs) have been extensively employed in the restoration of bridges. Wang et al. (2007) have explained about the fire safety issues continue to impede the use of the FRPs in parking garages and buildings, mostly because of the vulnerability in mechanical and property degradation bonds at high temperatures.

In high temperatures, Bazli et al. (2020) have discussed that all polymer resins have the potential to melt and finally catch fire. This weakens the resin matrix and raises concerns about the structural stability of the FRP-stimulated concrete in the event of a fire.

As interest in environmentally friendly materials has grown over the past few years, a variety of fibre types, including inorganic and organic fibres, have been added to compounds containing carbon fibre. Liu et al. (2020) have discussed a new and more competitive type of reinforcing fibre that outperforms glass fibres that have been introduced recently: basalt fibre. Basalt fibres are essentially naturally occurring fibres that are created from melting basalt volcanic rock.

Bai et al. (2008) have concluded that for design purposes, it is standard procedure to assume that a concrete element's load demand in the fire limit condition is between 40% and 60% of its ultimate design load. This means that during a fire, large member capacity losses brought on by heating are permitted. As a matter of fact, very few buildings are ever filled to capacity; in the case of buildings designed to endure seismic pressures, this percentage is much lower.

1.1. Research Gap

The key benefits of basalt fibre are its outstanding mechanical properties, no flammability, high-temperature resistance, nontoxicity, and superior chemical stability. It is feasible from an environmental and economic standpoint. According to much research, basalt fibres have the potential to be used as reinforcement materials to enhance the characteristics of fibre-reinforced composites. Flexure can be reinforced by adding FRP strips at the soffit portion of beams and slabs along the axis of bending. A robust, lightweight, corrosion-resistant building material is fibre glass-reinforced polymer. Due to its composite nature, which is achieved by the combining of many elements, FRP is sometimes referred to as composite material.

The goal of this study is to determine the FRPs that are most effective for retrofitting specimens which have been thermally damaged. The research investigation's highlights are listed below.

- To examine how the temperature of the fire affected the structural characteristics and stiffness of concrete.
- To investigate the retrofitting effects of fibre laminates on fire-damaged specimens.
- To evaluate the tensile strength value using a split tensile strength test of the normal and FRP-wrapped concrete.
- To investigate the FRP laminates wrapped concrete's stress-strain response. It is mandatory to submit your original work in Microsoft Word format (.doc) or (.docx). We will do only minor corrections and the final formatting of your paper.

2. Literature Review

Bisby et al. (2011) have established the axial/lateral stress-strain response and residual strength; exposed to elevated temperatures, when tested under uniaxial compression, all plain concrete cylinders show decreased rigidity. The effectiveness of externally attached Fibre Reinforced Polymer (FRP) hoop wraps for repairing and fortifying the compressive strength of concrete elements damaged by fire at exposure temperatures up to a manageable maximum of 700 °C. An extension of the FRP confinement model enables a quantitative evaluation of the efficacy of FRP wraps applied to reinforce concrete columns damaged by fire.

Chowdhury et al. (2007) have explained the properties of mechanical, thermal, and fibre-reinforced composites at high temperatures. The many FRP composite kinds and their corresponding thermal properties are currently available for application in infrastructure. Among these characteristics are thermal conductivity, specific heat, mass loss with temperature, and glass transition temperature. The degree of adhesion between the two parts is assessed, as well as the stress-strain behaviour of steel, concrete, and fibre-reinforced polymer composites at high temperatures. Preliminary findings from thermal tests of insulating materials and carbon/epoxy fibre reinforced polymer composites.

Sharifianjazi et al. (2022) have examined the Fibre-Reinforced Polymer (FRP)-stimulated reinforced concrete members' structural performance. Although FRP-reinforced/strengthened concrete components have many benefits, one disadvantage is that they are susceptible to high temperatures. It is unclear how well FRP-reinforced concrete operates at elevated temperatures. Analytical models have been developed to predict the tensile strength losses of the FRPs at elevated temperatures.

Bisby et al. (2004) have examined how many factors affected the way plastic-coated and fibre-bolstered reinforced concrete columns behaved in a fire. It has been demonstrated that, with the right planning and safety precautions, columns clad with Fibre Reinforced Polymer (FRP) can reach fire endurances that are comparable to those of conventional reinforced concrete columns. Furthermore, this study suggests that the fire design of FRP-wrapped members requires a complete strategy rather than one that only considers the special performance of the FRP materials. A demonstration and discussion of fire-safe design options for concrete columns coated with fibre-reinforced polymer.

Bisby et al. (2005) have investigated the fire performance of three types of circular reinforced concrete columns: those wrapped in Fibre Reinforced Polymer (FRP), those wrapped in fibre glass, and those wrapped in insulated FRP. Preliminary model predictions are presented and discussed, and the model is tested against data from full-scale fire endurance studies on conventionally reinforced concrete columns that are accessible in the literature. According to the model that most nearly matches experimental data from tests conducted on circular reinforced concrete columns, should a fire occur, a larger concentration of Fibre Reinforced Polymer (FRP) can help maintain the materials' structural integrity.

3. Materials

The details of the materials that were utilized are shown below. The raw ingredients are water, cement, aggregates, and any additional materials or admixtures that are utilized.

3.1. Cement

OPC is a general-purpose Portland cement appropriate for all applications in which the unique qualities of other varieties are not required when cement or concrete is not exposed to certain conditions, such as sulphate assault from soil or water or an increase in temperature causing heat production by hydration. Tables 1 and 2 list the cement's qualities.

Table 1. Cement's characteristics

Sl.No.	Property	Value
1	Grade	53
2	Normal consistency	30%
3	Particle size range	50µm
4	Initial setting time	50 min
5	Final setting time	390 min
6	Specific gravity	3.12

Table 2. Chemical composition for cement

Sl. No.	Chemical Composition	Quantity (%)
1	Iron Oxide (Fe_2O_3)	0.4
2	Calcium Oxide (CaO)	65.45
3	Magnesium Oxide (MgO)	0.4
4	Silicon Dioxide (SiO_2) + Grays	5.50
5	Sulphur Trioxide (SO_3)	0.5

Table 3. FRP laminate properties

Property	Material Type	Property
	BFRP	CFRP
Coefficient of Linear Expansion (10^{-6}/°C)	–9.0–0	Coefficient of Linear Expansion (10^{-6}/°C)
Tensile Strength (MPa)	600-1200	Tensile Strength (MPa)
Young's Modulus (GPa)	50–65	Young's Modulus (GPa)
Density (gm/cm^3)	1.5-2	Density (gm/cm^3)

3.2. Fine Aggregate

In compliance with IS 2386, the properties of both physical and chemical are investigated. In this experimental investigation, river sand is used as the fine aggregate, and the sieve analysis test findings indicate that it complies with Zone II.

3.3. Coarse Aggregate

Coarse aggregates, or granular and uneven materials used to build concrete, include crushed stone, sand, and gravel. You can use crushers, blast quarries, or crush them yourself to obtain coarse material. The maximum size of the coarse aggregate's component parts is 63 mm, and the sieve size is 4.75 mm. It is suggested that foreign materials should not comprise more than 5% of the weight of the coarse aggregate. Examples of these components include coal, lignite, soft bits, and lumps of clay.

3.4. Water

Since hydration is started when water reacts with cement to generate the hydration product, water is a crucial component of concrete. The cement concrete's strength is determined by the hydrated cement paste gel's binding action.

3.5. Fibre Reinforced Polymer

Fibre Reinforced Polymers (FRP) composite materials consist of robust fibres embedded in a resin matrix. The fibres usually supply most of the applied loads as well as the composite's strength and stiffness. Bars made of Basalt Fibre Reinforced Polymer (BFRP) are incredibly strong, lightweight, corrosion-resistant, and have superior dielectric properties. Furthermore, bars made of Basalt Fibre-Reinforced Polymer (BFRP) are a novel class of eco-friendly alternative materials. One composite material used to reinforce and repair reinforced concrete structures is carbon fibre reinforced polymer or CFRP.

3.6. Resin

The surfaces of the concrete samples had been treated with epoxy for the intent of adhering the FRP sheets to them.

- Resins can be solid, semisolid, translucent, or transparent.
- They also have a specific gravity that is higher than that of water.
- Generally speaking, they soften when heated.
- The majority of the time, resins are amorphous.
- They don't dissolve in water.

3.7. Mix Design

BIS: 10262-2019 is used in this study to design the M25 grade concrete mix. The cement mortar mix ratio for M25 grade concrete is 1:1:2, which combines two parts aggregate, one part sand, and one part cement. The mix proportions for concrete of grade M25 are specified between A-I and A-ll, where s is the standard deviation. Standard Deviation for IS 10262:2009 Table 1 is s = 4 N/mm^2.

Table 4. Test results for the concrete material

Specific Gravity	Specific Gravity
Cement	2.88
Coarse Aggregate	2.74
Fine Aggregate	2.63

3.8. Casting and Curing

After casting standard-sized 150 mm diameter by 300 mm height cylinders and 100 x 100 x 500 mm prisms, the mechanical characteristics of the concrete were assessed over a period of time. After a 28-day curing period, the specimens were let to air dry in the laboratory for a full day. The samples were eventually heated to 250°C, 500°C, and 750°C. After that, the specimens were let to cool naturally before being examined.

Fig. 1 Concrete specimens after curing

3.9. Fire Exposure

The fire's temperature and duration influence concrete fire resistance. A longer length of exposure enhances the effect at lower heating temperatures. The high heat of a fire can cause chemical and mechanical changes in concrete. Among the mechanical changes that could occur is spalling, a process that causes pieces of concrete to separate from the top layer. External cracking in concrete is caused by dehydration and thermal expansion.

When evaluating the mechanical properties of concrete, two popular cooling methods are used: water cooling, which involves submerging hot specimens in water once they have achieved their maximum temperature, and air cooling, which involves exposing hot specimens to room temperature.

Fig. 2 Fire exposure on concrete specimens

Fig. 3 K Type thermocouple

A K-type thermocouple and a temperature control device (UTC4202 model) were employed to monitor the degree range in order to maintain the fire temperature. Following varying times of fire exposure, the specimens of cylinders were set free to cool within the furnace before the heat range was measured.

Fig. 4 FRP-wrapped specimens of CFRP and BFRP

The sheets of high-strength carbon and basalt fibres are impregnated with a two-part epoxy-based adhesive to join them to structural elements. The combination of fibre and resin material's deformability may conform to almost any complex or geometric shape, which makes the method adaptable and useful in a range of contexts. FRP sheets are typically supplied in rolls, which can be cut to exact sizes using fabric scissors or a sharp utility knife. In order to prevent air pockets and allow the resin to fully dry, rollers were employed to connect the FRP to the specimen. The tests were carried out after they had dried.

3.10. Thermomechanical Properties of Fibres / Matrix / Composite Elements

Materials with a basic chemical makeup have a higher thermal conductivity than those with a complex chemical composition. Materials with a crystal structure have a higher thermal conductivity than those with an amorphous or mixed structure. Porous materials transfer heat through both the pore space and the continuous substance. When the pores are filled with air, porous materials have lower heat conductivity than continuous materials.

3.11. Behavior of Concrete Reinforced with FRP at High-Temperature Conditions

Even at 250 °C, 500 °C, and 750 °C, CFRP bars exhibited elastic behavior; nevertheless, there was a progressive decrease in displacement and, thus, a decrease in the load required to cause rupture. When exposed to high temperatures, CFRP bars' tensile strength dramatically reduced; the key temperature at which the polymer matrix broke down and released harmful volatiles and heat was 250 °C. The CFRP bar specimens' bond strength declined by 7.19–14.4%, and the BFRP bar specimens' bond strength decreased by 2.45–7.11% at temperatures between 70 and 220 degrees Celsius, respectively, as compared to the bond strength at room temperature.

The CFRP and BFRP bar specimens' binding strengths decreased by around 31% at 370°C. The CFRP and BFRP bar specimens' bond strengths dramatically dropped at 350 °C; at that point, the specimens' bond strengths were 12.0% and 23.4% of their initial values, respectively.

3.12. Effect of Fire on the Concrete Strength

The way structural concrete fails in a fire depends on the kind of fire, the loading system, and the type of structure. Possible causes of failure include spalling, bending or tensile strength, bond strength, compressive strength, and shear or torsional strength loss in the concrete.

Severe flames can cause the chemical composition of concrete to break down. Spalling, or the deterioration of the structural integrity of the concrete, is another possibility. Concrete will lose some of its structural strength when the temperature rises above one thousand degrees Fahrenheit.

3.13. Effect of Fire Exposure on FRPs Mechanical Properties

Rebar that is exposed to temperatures higher than 260°C (500°F) may fracture (sometimes referred to as "blue brittleness"). Up to 704°C (1300°F), rebar may lose up to 20% of its design strength. Reinforced concrete often fails structurally when heating reduces the effective tensile strength of the steel reinforcement.

In a temperature range of 250–750 C, the changes in mechanical characteristics of concrete exposed to actual standard fire were examined. At increased temperatures up to 350°C, properties like compressive strength, ultrasonic pulse velocity values, and mass loss in concrete specimens did not exhibit any negative effects. Marble concrete blends absorbed less water than control mixes did. Overall, it was determined that after being exposed to fires up to 400 degrees Celsius, the mechanical qualities of concrete mixes made from leftover marble were found to be satisfactory.

4. Literature Results and Discussion

When concrete comes into touch with fire, it undergoes hydrothermal, physical, and chemical changes that cause it to lose strength. At 200 degrees Celsius, the hydrothermal conditions begin to change, allowing both adsorbed and free water to escape. Once the temperature reaches 200 °C, the hydrothermal conditions start to change, enabling both adsorbed and free water to escape. This indicates that the Vander Waals forces are also disturbed by the early weakening of the bonding forces caused by dehydration in the calcium silicate hydrate (C-S-H) gel. When temperatures rise above 400ºC, physical and chemical degradation begins, which in turn causes C-S-H gel to disintegrate.

This is because, at this temperature, the gel shrinks due to the expansion of aggregates and the evaporation of moisture. Concrete that can be utilized to determine the extent of burned-in damage is the change in colour. A visual inspection of the fire-damaged concrete showed that flames of varying temperatures react with a rainbow of hues. The concrete's tone was a consistent light grey. However, the surface turned dark grey at 250°C, brownish grey at 500°C, and whitish-grey at 750°C. The primary reasons for colour variation in hot concrete are the aggregate's internal alterations as well as the grouting paste's growing loss and drying out.

The result indicates that the initial mass loss was driven by evaporation and a decrease in free water. The specimen lost approximately 2.5%, 8.3%, and 13.6% of its weight after being subjected to fire for an hour at three different temperatures 250, 500, and 750 degrees Celsius. The mass losses were determined to be 3.1%, 9.6%, and 14.5%, respectively, for specimens subjected to fire for two hours at 250°C, 500°C, and 750°C. The sample was exposed to fire for three hours at three different temperatures, and the weight loss was reported to be 6.8%, 12.6%, and 16.6%. To investigate the mechanical behaviour of fire-damaged specimens wrapped in and without FRP, split-tensile strength tests were conducted. Also examined was the modulus of elasticity in aged, fire-damaged specimens with and without FRP. The test findings demonstrated that Basalt Fibre Reinforced Polymer (BFRP)-wrapped fire-damaged specimens exhibited higher strength compared to carbon and amaranth FRP laminates.

4.1. Split Tensile Strength Test

A method for measuring concrete's tensile strength involves dividing a cylinder along its vertical diameter. It is an indirect technique for determining the concrete's tensile strength. It is not possible to apply actual axial load in a direct tensile strength test. There's going to be some strangeness around. An additional issue is the strains brought on by grips. The specimen has a propensity to shatter at the ends due to gripping. For the tensile strength test, the specimens underwent compression testing using a machine. Three cylinders with and without wrapped FRP were tested in each category, and the average value was given. The tensile strength was computed using the split tensile strength.

Table 5. Tensile strength of fire-damaged cylinders wrapped with and without FRP

Exposure Temperature (^{0}C)	Material Type	Tensile Strength (MPa)
Room Temperature	-	4.5
	BFRP	8.9
	CFRP	4.5
250	-	4.3
	BFRP	8.5
	CFRP	3.8
500	-	3.9
	BFRP	7.3
	CFRP	3.5
750	-	3.5
	BFRP	6.4
	CFRP	3.2

4.2. Stress-Strain Response

Concrete properties are often explained by stress-strain relations, which are commonly used as input data in mathematical models to evaluate the flammability of concrete structural components. The stress-strain curve's slope tends to decrease with temperature due to a drop in concrete's compressive strength and an increase in its ductility. At low and high degrees, concrete characteristics are important in the stress-strain response. As with the rate of temperature increase, temperature significantly affects the stress-strain behaviour of the specimen.

BFRP and CFRP shared the load during the initial loading. The curves showed an inflection point at roughly 0.23% tensile strain, indicating that the CFRP had given way. The stress would increase slower and more steadily with the same increment once the steel plate reached the yield point, meaning that the FRP would have a stable stiffness. The CFRP could only withstand so much loading before yielding, hence the majority of the load was carried by the outside of the BFRP. The outer BFRP split in the centre zone along the specimen's length as the load grew and the FRP's bearing capacity approached its limit. Only CFRP was able to handle the load, and the specimen's remaining bearing capacity stayed largely unchanged. A failure mechanism was demonstrated by the CFRP specimen, wherein the steel plate yielded initially, then the BFRP broke second, and ultimately, the steel plate would attain tensile failure in the vicinity of the cracked BFRP.

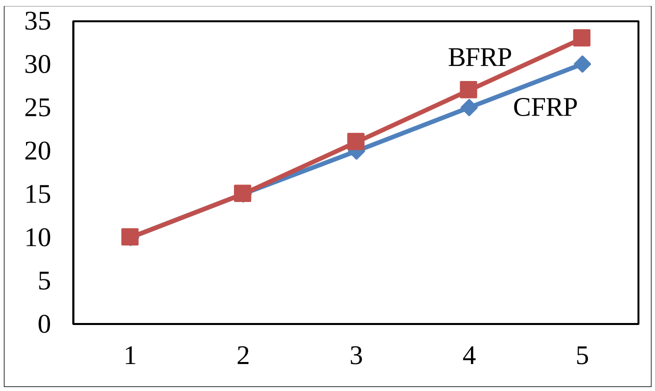

Fig. 5 Stress vs. Strain response of concrete cylinders

4.3. Young's Modulus

In order to identify the stresses that form in basic parts and the stresses, moments, and deflections that occur in more complex structures, a common tool for analysing reinforced concrete structures is the modulus of elasticity, which measures a material's stiffness or resistance to deformation.

Table 6. Elastic modulus of fire-damaged cylinders wrapped with and without FRP

Exposure Temperature (^{0}C)	Material Type	Young's Modulus (GPa)
Room Temperature	-	28.5
	BFRP	38.9
	CFRP	24.5
250	-	25.3
	BFRP	28.5
	CFRP	23.8
500	-	30.9
	BFRP	37.3
	CFRP	33.5
750	-	23.5
	BFRP	36.4
	CFRP	23.2

Concrete's nonlinear stress-strain curve can be obtained using the initial tangent modulus, secant modulus, or tangent modulus methods to determine the modulus of elasticity. Young's modulus is a property that influences how resistant concrete is to fire; it diminishes as the degree increases. Aggregate type, moisture loss, high temperatures, and creep all have an impact on how much the elastic modulus declines at higher degrees.

Table 7. Comparision table for BFRP and CFRP

Literature Review	Characteristics	CFRP	BFRP
Garbacz et al. (2015)	Tensile Strength (Mpa)	6.0	10.35
	Young's Modulus (GPa)	35	25
Li et al. (2016)	Tensile Strength (MPa)	2.8	5.9
	Young's Modulus (GPa)	35	31
This Research	Tensile Strength (MPa)	4.5	8.9
	Young's Modulus (GPa)	24.5	38.9

For tensile strength and Young's modulus, the comparison table is shown above it shows that, in this research, the BFRP and CFRP give better results.

5. Conclusion

Visual examination of the fire-damaged specimens reveals that, at 500ºC, only moderate crack formation is observed, but at 750ºC, dominating crack production takes place. When specimens were exposed to varying temperatures for varying durations of time, there was no indication of concrete spalling. Wrapping fire-damaged specimens with different FRPs demonstrated that the split-tensile properties of concrete were improved.

A decline in elastic modulus was noted after exposure to fire for varying temperatures and durations. It has been observed that there is an approximately linear association between the rise in heating temperature and the decline in elasticity modulus. The basalt fibre laminate outperformed the carbon fibre laminate in this investigation because the basalt FRP had greater tensile strength than the carbon fibre laminates.

Funding Statement

The research activities received no external funding. This study has also formed part of a PhD thesis.

Acknowledgements

We, the authors, thank the staff and the participants of the study.

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