



Sustainable Retrofitting Of Fire Damaged Cement And Geopolymer Concrete Slabs Using Hybrid Basalt And Carbon Fiber Reinforced Polymers.

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Abstract: This experimental study evaluates the structural performance of M25-grade cement concrete and M40-grade geopolymer concrete slabs subjected to fire damage and retrofitted using various Fiber Reinforced Polymer (FRP) systems. A total of 14 slab specimens (610 × 380 × 80 mm) were prepared—two control slabs and twelve fire-damaged and repaired slabs (six each for cement and geopolymer). The fire-damaged slabs were exposed to 800°C for one hour and subsequently repaired using polymer-modified mortar (Sika Monotop 122F) followed by 14 days of curing. Post-repair, the slabs were retrofitted using six FRP configurations involving Basalt FRP (BFRP), Carbon FRP (CFRP), and hybrid CFRP–BFRP combinations in different sequences. All specimens were tested under two-point loading to determine their load-bearing capacity. The control cement slab withstood a maximum load of 32 kN, while the control geopolymer slab sustained 40 kN. Fire damage significantly reduced the strength of both types: cement slabs dropped to 12.0–16.0 kN, and geopolymer slabs to 17.5–22.0 kN. After retrofitting, all slabs showed improved strength. Notably, the CFRP–BFRP–CFRP (Configuration 5) performed the best, restoring cement slabs up to 27.8 kN and geopolymer slabs up to 33.8 kN—a recovery of over 85% and 84%, respectively. Geopolymer slabs consistently exhibited superior post-fire performance compared to cement slabs, both before and after retrofitting.

This research emphasizes the potential of geopolymer concrete as a sustainable and fire-resilient material and establishes CFRP–BFRP–CFRP hybrid retrofitting as the most effective technique for enhancing the structural performance of fire-damaged concrete elements.

Index Terms - Geopolymer concrete, Fire damage, Retrofitting, Fiber Reinforced Polymer (FRP), Hybrid CFRP–BFRP, Load-bearing capacity, Sustainable construction.

I. INTRODUCTION

Over the last two decades, the utilization of fiber-reinforced polymers (FRP) in structural engineering has evolved significantly, driven by the need to address challenges associated with aging infrastructure, material degradation, and increased loading demands. FRP composites have proven to be highly effective in retrofitting and reinforcing structural elements such as beams, slabs, and columns. Their lightweight nature, coupled with high tensile strength and corrosion resistance, makes them particularly advantageous for extending the service life of reinforced concrete (RC) structures. Additionally, the flexibility of FRP materials enables customized solutions for strengthening complex structural geometries, making them suitable for a wide range of applications. Emerging research focuses on enhancing the bond strength between FRP and concrete, optimizing adhesive formulations, and improving surface preparation techniques to ensure durable and efficient performance. Moreover, advanced computational models and finite element simulations are being increasingly

utilized to predict the behavior of FRP-reinforced structures under various loading conditions, enabling more precise and reliable designs.

One of the primary reasons for the growing preference for FRP in structural rehabilitation is its ability to mitigate common issues faced by conventional materials like steel. Unlike steel, FRP does not suffer from electrochemical corrosion, making it an ideal choice for structures exposed to harsh environmental conditions, such as marine and industrial applications. In addition to their corrosion resistance, FRP materials have demonstrated superior fatigue performance under cyclic loading, an essential property for elements like bridge decks and highway pavements that experience repetitive traffic loads. Furthermore, the ease of installation and the potential to minimize downtime during retrofitting projects significantly reduce labor and operational costs, making FRP solutions both practical and economically attractive. Recent studies have also explored hybrid FRP systems, combining carbon fiber-reinforced polymers (CFRP) and basalt fiber-reinforced polymers (BFRP), to optimize performance while balancing cost-effectiveness. These hybrid systems offer enhanced mechanical properties, making them particularly effective in applications requiring high strength and resilience.

The integration of FRP in construction has also contributed to advancements in sustainable engineering practices. FRP materials require less energy during manufacturing compared to traditional materials and result in lighter structural elements, reducing transportation and installation costs. Moreover, FRP-based retrofitting extends the lifespan of existing structures, delaying the need for demolition and reconstruction, thereby reducing waste and environmental impact. As research continues to focus on developing new types of FRP with improved thermal stability, fire resistance, and recyclability, the potential applications of these materials in modern construction will likely expand further. The ability to address both structural and sustainability challenges positions FRP as a transformative solution for the future of engineering and infrastructure development.

II. RESEARCH GAP

- There is a lack of comprehensive studies comparing the fire damage resistance and retrofitting performance of geopolymer concrete and traditional cement concrete under similar experimental conditions.
- While BFRP and CFRP systems have been studied individually, limited research exists on the synergistic effects of combining these two materials for retrofitting fire-damaged slabs.
- The optimal configuration and layering techniques for hybrid systems remain unexplored.
- There is insufficient data on how geopolymer concrete interacts with BFRP and CFRP systems, particularly in terms of bond strength and long-term durability after retrofitting.

III. OBJECTIVES

- To evaluate the structural performance of fire-damaged cement and geopolymer concrete slabs after repair and retrofitting using hybrid CFRP and BFRP laminates.
- To compare the effectiveness of ambient-cured M40 geopolymer concrete slabs with conventional M25 cement concrete slabs in terms of load-bearing capacity and post-fire recovery.
- To assess the effectiveness of various CFRP and BFRP laminate configurations in enhancing the post-fire structural strength of repaired cement and geopolymer concrete slabs.

IV. METHODOLOGY

The subsequent section delineates the methodology employed to conduct the research under discussion.

- Selection of materials and preliminary tests

The selection of materials and conducting preliminary tests are essential steps in achieving the desired quality and durability of concrete structures. Tests are performed on various components such as cement, fly ash, ground granulated blast furnace slag (GGBS), fine aggregates, and coarse aggregates to ensure their suitability for research purpose.

- Mix Design

For this purpose, the design calculations are carried out for M25 grade concrete for cement slabs and M40 grade concrete for Geopolymer slabs, and Fe500 reinforcement is utilized.

- Casting of slab specimens

Cement and geopolymer slab specimens, including controlled slabs, are prepared in accordance with the specified designs and requirements.

- Selection of Fibers and Polymer Resin for FRP sheets

In this project, carbon and basalt fibers are chosen as the materials for retrofitting, with epoxy used as the resin.

- Fire Exposure

A high-speed burner was used to burn both cement and geopolymer slabs.

- Application of FRP sheets on the Loaded Beam Specimens

For various combination cases, FRP sheets are applied at the soffit of the slabs. The surface of the slab specimens is cleaned before performing the FRP wrapping. Once the wrapping is completed, the specimens are cured.

- Load tests on the FRP wrapped Slab Specimens

The same loading test is performed on the FRP-wrapped specimens until failure, and the failure load is recorded.

- Results and Discussions

The recorded results are compared and presented in a tabular format.

- Conclusions

Based on the comparison of results and discussions, conclusions are drawn from the conducted experiment.

3. SELECTION OF MATERIALS AND PRELIMINARY TEST RESULTS

3.1 Cement

Cement plays a vital role in construction by acting as the binding agent that holds concrete and mortar together. It imparts strength, durability, and stability to structures, making it essential for applications like foundations, walls, bridges, and more. The quality of cement significantly affects the overall strength and lifespan of construction projects. Key characteristics, including fineness, setting time, and compressive strength, determine how cement performs in various construction scenarios. Standards such as IS 12269-2013 for 53-grade OPC and IS 1489 for Portland Pozzolana Cement ensure that the cement used meets the required quality standards, thereby ensuring the structural integrity of the project.

Table 1: Properties of cement

Test	Method	Result	Limit
Fineness	Sieve test (is 4031 part-2) 1988	7%	<10%
Normal consistency	Vicat apparatus (is 4031 part-4) 1988	30%	30-35%
Initial setting time	Vicat apparatus (is 4031 part-5) 1988	40 min	>30 min
Specific gravity	Sp.gravity bottle (is 4031 part-4) 1988	3.13	<3.15

3.2 Fine aggregates

Fine aggregates are essential in construction, especially in the production of concrete and mortar. Composed mainly of small particles like sand, they fill the gaps between larger aggregates, helping to create a dense and compact mixture. Fine aggregates improve the strength, durability, and overall performance of concrete by enhancing the bond between cement and other materials. They also contribute to a smooth surface finish and prevent segregation in the concrete mix. The quality of fine aggregates is crucial to ensuring the desired performance of the concrete, with proper grading and purity being key factors in achieving the intended strength and longevity of the material. In this investigation, M-sand was utilized as a fine aggregate, conforming to Zone II grading requirements as specified by IS: 383-1970. The M-sand, which was sourced from a local supplier, was carefully selected to ensure compliance with the necessary standards for use in concrete production.

Table 2: Properties of fine aggregates

Test	Method	Result	Limit
Fineness modulus	Sieve analysis (IS 2386 part-3) 1963	3.15	2.2-3.2
Specific gravity	Pycnometer (IS 2386 part-3) 1963	2.64	2.5-3.0

3.3 Coarse aggregate

Coarse aggregates are crucial in construction, serving as a key component in concrete that influences its strength, durability, and volume stability. They add bulk to the concrete, reducing the amount of cement needed and improving the overall structural integrity. The size, shape, and texture of the aggregates affect both the workability and strength of the concrete mix. Larger aggregates help reduce the water-cement ratio, boosting strength, while angular aggregates improve the bond with the cement paste, enhancing the overall performance of the concrete. Crushed stone aggregates of 20 mm nominal size, conforming to IS: 383-1970 specifications, were used in the investigation. These aggregates were tested for gradation using IS: 480 sieves to ensure compliance with standard size distribution requirements.

Table 3: properties of coarse aggregates

Test	Result	Limit
Water absorption (is 2386 part-3) 1963	2.70%	< 3.0%
Specific gravity (is 2386 part-3) 1963	2.74	2.5-3.0

Table 4: Mechanical Properties of Conventional concrete

Property	Age	Strength (MPa)
Compression Strength	7 days	19.62
	28 days	25
Split Tensile Strength	7 days	1.94
	28 days	2.72
Flexural Strength	7 days	4.25
	28 days	4.85

3.4 Steel

Steel is a crucial construction material recognized for its exceptional strength, flexibility, and resilience, making it indispensable in reinforced concrete structures. It provides tensile strength and enhances the load-bearing capacity of concrete. In this investigation, 8 mm diameter steel bars conforming to IS: 1786-2008 specifications were used. These bars are classified as high-strength deformed steel reinforcement, ensuring compliance with the required standards for mechanical properties such as yield strength, tensile strength, and elongation.

3.5 Ground Granulated Blast Furnace Slag (GGBS)

Ground Granulated Blast Furnace Slag (GGBS) is a by-product derived from blast furnaces used in iron production. During its formation, the molten slag is rapidly cooled by quenching it in large quantities of water. This rapid cooling process enhances its cementitious properties and transforms it into granules resembling coarse sand. When incorporated into concrete, GGBS reacts during the setting and hardening process with significantly less heat generation compared to ordinary Portland cement. This characteristic helps minimize temperature rises, reducing the risk of thermal cracking commonly associated with Portland cement.

3.6 Fly Ash

Fly ash is a fine powder produced as a by-product from the combustion of pulverized coal in thermal power plants. It is primarily composed of silica, alumina, and other oxides, making it a valuable supplementary cementitious material in concrete. Fly ash improves the workability, durability, and strength of concrete while reducing the overall cement content, making it an environmentally friendly option. In this experiment, Class F fly ash, which is characterized by its low calcium content and pozzolanic properties, is used. Class F fly ash enhances the long-term strength and durability of concrete, particularly in aggressive environments, by reacting with calcium hydroxide to form additional cementitious compounds.

3.7 Sodium Hydroxide (NaOH)

Sodium hydroxide (NaOH), commonly known as caustic soda, is a highly alkaline and corrosive chemical widely used in industrial applications. It is often utilized in geopolymer concrete as an activator to dissolve aluminosilicates and initiate the geopolymerization process. Sodium hydroxide flakes used in this investigation is of commercial grade with 97% purity.

3.8 Sodium Silicate Solution (Na₂SiO₃)

Sodium silicate, often referred to as water glass, is a versatile chemical composed of sodium oxide (Na₂O) and silica (SiO₂) in varying ratios. It is commonly used in geopolymer concrete as an activator to enhance the binding properties and strength development of the material.

3.9 Molarity

In this investigation, an 8M concentration of sodium hydroxide solution was used in conjunction with sodium silicate as alkaline activators to initiate the geopolymerization process. Sodium hydroxide (NaOH) was prepared by dissolving pellets in water to achieve the desired molarity, while sodium silicate, consisting of sodium oxide (Na₂O) and silica (SiO₂) in aqueous form, was used to provide the necessary silicate ions for the reaction. The combination of these activators was selected based on extensive literature, as it is known to effectively dissolve aluminosilicate materials, promote polymeric gel formation, and enhance the binding and strength properties of geopolymer concrete.

Table 5: Mechanical properties of geopolymer concrete

Property	Age	Strength (MPa)
Compression Strength	7 days	28.24
	28 days	40.72
Split Tensile Strength	7 days	3.28
	28 days	4.60
Flexural Strength	7 days	6.10
	28 days	6.86

3.10 Adhesive

Araldite LY 556 epoxy resin and Aradur HY 951 hardener was used as adhesive in application of FRP laminates.

Table 5: Properties of Araldite LY 556

Property	Range	Unit
Epoxy content	5.30-5.45	eq/kg
Viscosity	10000-12000	mPas
Density	1.15-1.20	g/cm

Table 6: Properties of Aradur HY 951

Property	Range	Unit
Viscosity	50-100	mPas
Density	1.20-1.25	g/cm

Table 7: Physical properties of epoxy and hardner mix

Property	Range	Unit
Tensile strength	83-93	MPa
Ultimate Strength	80-90	MPa
Tensile modulus	3100-3300	MPa

3.11 Fiber Reinforced Polymer Laminate

The repair materials used for both cement concrete and geopolymer concrete are Basalt Fiber Reinforced Polymer (BFRP) and Carbon Fiber Reinforced Polymer (CFRP).

Table 8: Properties of basalt FRP

Property	Value
Weight of Fiber (g/m ²)	380
Fiber Thickness (mm)	0.40
Nominal Thickness per Layer (Cured) (mm)	1.0
Fibre Tensile Strength (MPa)	3000
Tensile Modulus (GPa)	95

Table 9: Properties of Carbon FRP

Property	Value
Weight of Fiber (g/m ²)	400
Fiber Thickness (mm)	0.38
Nominal Thickness per Layer (Cured) (mm)	1.0
Fibre Tensile Strength (MPa)	4500
Tensile Modulus (GPa)	240

I. MIX DESIGN

In this study, the mix design was prepared in accordance with the guidelines specified in the Indian Standard IS:10262-2009, and the mix ratio used for the experimental investigation is as follows,

- **Conventional Concrete:**
The mix ratio for the M20 grade concrete is **1: 1.63: 2.65 :0.45**
- **Geopolymer Concrete:**
The mix ratio for the M40 grade concrete is **1: 0.04: 0.05: 0.31: 1.17: 0.78**

3.1 Slab design Reinforcement

. The slab was designed and cast with a mold dimension of 610 mm × 380 mm × 80 mm and a clear cover of 10 mm. Reinforcement consisted of six 8 mm diameter bars placed along the length at a spacing of 118 mm and four 8 mm diameter bars placed along the breadth at a spacing of 120 mm. Bar bending, cutting, and placement of reinforcement were carried out at the casting site to ensure accuracy and proper alignment before concreting.

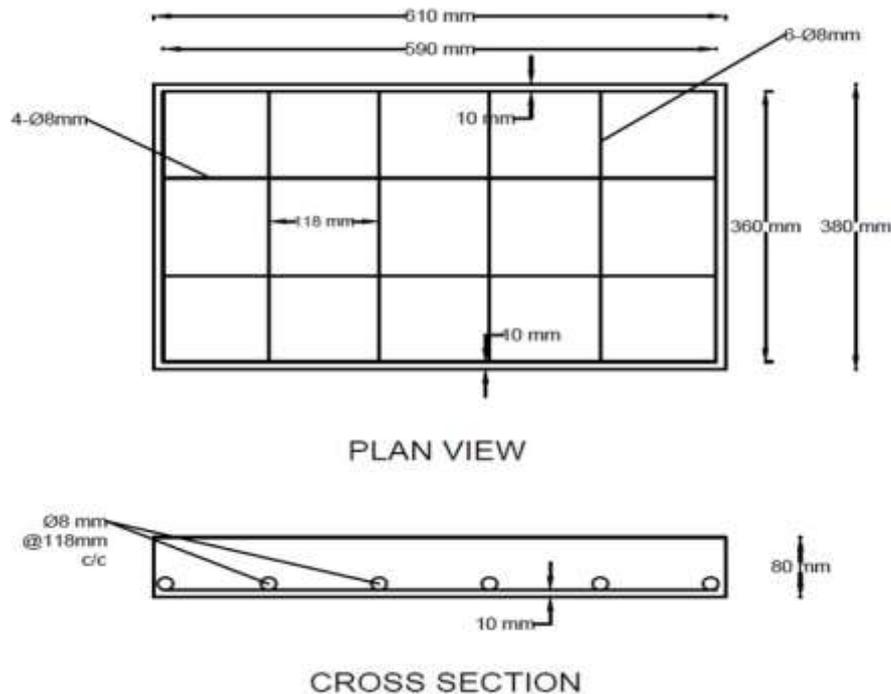


Fig 1: Slab reinforcement Schedule

3.2 Casting of Slabs

The casting of both cement and geopolymer concrete slabs was carried out following standard laboratory procedures. For cement concrete slabs, an M25 grade mix was prepared using the weight-batching method to ensure accurate proportioning of materials. A slump test was performed, resulting in a true slump of 80 mm, confirming the desired workability. For geopolymer concrete slabs, an M40 grade mix was prepared with a 50:50 ratio of Class F fly ash and GGBS, activated using sodium hydroxide and sodium silicate solutions, with the alkaline activator solution prepared 24 hours prior to casting. In both cases, the molds were cleaned and oiled before placing the reinforcement and pouring the mix. The prepared mix was placed into the slab molds in layers, with manual tamping carried out to ensure compaction and uniformity. Care was taken to avoid segregation and honeycombing.



Fig 2: Casting of Slabs

3.3 Curing of Slabs

Both cement concrete and geopolymer concrete slabs were cured for 28 days water curing for cement concrete and ambient curing for geopolymer concrete. After curing, all slabs were demolded and stored under ambient conditions until testing.



Fig 3: Pond curing of Cement concrete slabs



Fig 4: Ambient curing of Geopolymer concrete slabs

3.4 Fire Damage Simulation and Temperature Monitoring in Slabs

All slabs, both conventional cement concrete and geopolymer concrete, were subjected to controlled fire exposure to evaluate their behavior under elevated temperatures. Each slab was exposed to a temperature of 800 °C for a duration of 1 hour, replicating severe fire conditions. To ensure uniform heating and avoid heat loss, the fire setup was closed from all sides, creating a controlled furnace like environment around the slab. For internal thermal monitoring, a small hole was drilled at the center of each slab up to half of its thickness, into which the EUROLAB Digital Thermometer TM-902C with K-type thermocouple (−50 °C to +1300 °C range) was inserted. This arrangement allowed continuous and accurate measurement of the internal temperature of the slabs, while the external surface temperature was simultaneously observed to verify uniform heating. After completion of the heating cycle, all slabs were allowed to cool naturally under ambient conditions, replicating post-fire exposure scenarios.



Fig 5: Fire set up



Fig 6: Thermocouple

3.4.1 Impact of Fire exposure on Cement and Geopolymer Concrete Slabs

3.4.1.1 Visual assessment

After exposure to fire, the cement concrete slab exhibited very extensive cracking across the surface, with cracks forming in multiple directions, indicating severe thermal stress. There was pronounced spalling, with pieces of the surface layer detaching, sometimes accompanied by a distinct loud cracking sound. The slab's color changed significantly, turning dark grey, which indicates decomposition of hydrated cement phases and surface dehydration. Some portions of the slab showed minor surface powdering due to intense heat. Overall, the damage was severe, with large areas of the slab losing structural integrity.

The geopolymer slab also developed substantial cracks, though they were relatively less extensive than in the cement slab. Slight spalling occurred, primarily near the edges, but the overall slab maintained better surface integrity. The slab turned dark grey as well, indicating surface thermal effects, but there was less fragmentation and no loud sounds, reflecting higher thermal stability. The geopolymer slab’s surface remained more cohesive, demonstrating better resistance to high-temperature damage compared to cement concrete.



Fig 7: Fire Damaged Cement and Geopolymer Slabs

3.4.1.2 Reduction in Mass

After exposure to elevated temperature of 800°C for 1 hour, both cement concrete and geopolymer concrete slabs exhibited significant reduction in mass due to evaporation of free water, dehydration of bound water, and thermal decomposition of hydration products. The cement concrete slabs recorded a higher mass loss of up to 18%, which can be attributed to severe spalling, cracking, and decomposition of calcium hydroxide (Ca(OH)₂) and calcium silicate hydrate (C-S-H) phases at high temperature. The escape of moisture from pores caused internal vapor pressure, leading to surface scaling and disintegration, thereby accelerating weight reduction. In contrast, the geopolymer slabs showed a comparatively lower mass loss of up to 14%, demonstrating better thermal stability. This behavior can be explained by the absence of portlandite in geopolymer matrices and the presence of aluminosilicate gel, which provides greater resistance against dehydration and thermal decomposition. The reduced weight loss of geopolymer slabs highlights their superior fire resistance, reduced spalling tendency, and enhanced structural integrity compared to conventional cement concrete under identical fire conditions.

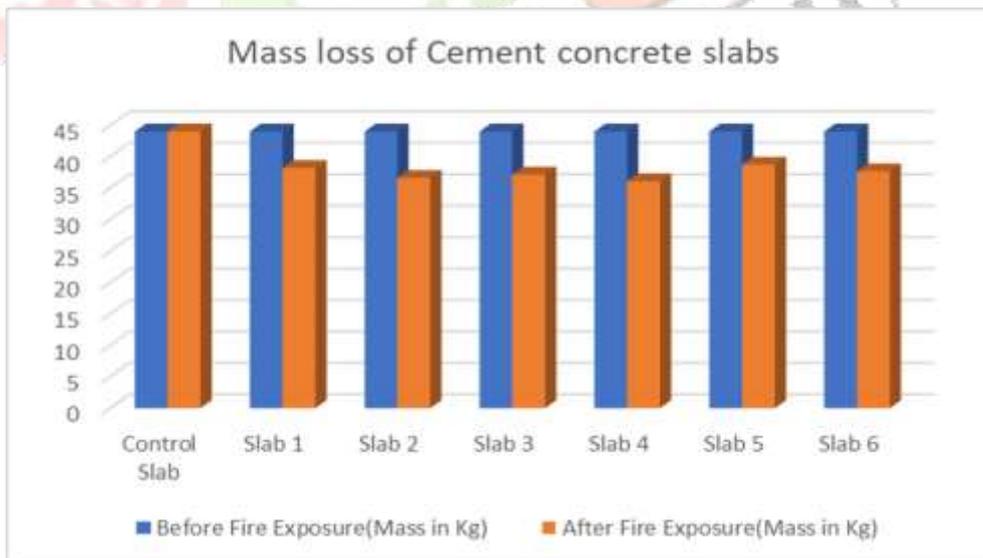


Fig 8: Mass loss of Cement concrete slabs

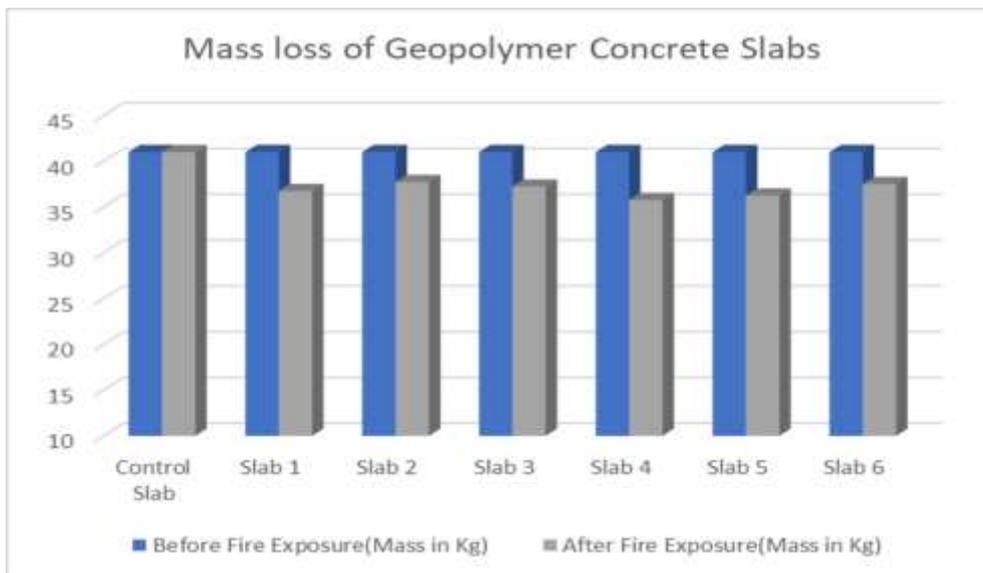


Fig 9: Mass loss of Geopolymer concrete slabs

3.4.2 Repair of Fire damaged Slabs

After the completion of fire exposure, the deteriorated cement and geopolymer concrete slabs were subjected to a repair process to restore their structural integrity prior to retrofitting. The damaged and weakened concrete surface layers were first cleaned thoroughly to remove all loose particles, dust, and charred material generated due to fire. Edges of the cracks and spalled regions were carefully trimmed to achieve a sound substrate and improve the bonding efficiency of the repair mortar. A polymer-modified repair mortar (Sika Monotop 122F) was then applied to the damaged regions of both cement and geopolymer slabs. This repair mortar was selected due to its superior adhesion, shrinkage control, and enhanced mechanical performance compared to conventional mortars, making it suitable for repairing thermally degraded concrete surfaces. The mortar was carefully packed into the prepared cavities and over the affected surfaces in successive layers to ensure full coverage and void-free compaction. After application, the repaired slabs were kept under moist curing for 14 days to facilitate proper hydration of the polymer-modified mortar and achieve the required strength gain. This repair phase effectively restored the surface profile, reduced crack widths, and provided a uniform substrate for the subsequent retrofitting process, thereby enhancing the durability and load-bearing capacity of the fire-damaged slabs.



Fig 10: Repaired Slabs

3.4.3 Load test on fire damaged slabs before retrofitting

To evaluate the residual strength and behavior of the slabs after exposure to elevated temperatures, a four-point static load test was carried out on the fire-damaged cement and geopolymer concrete slabs. The test aimed to determine their ultimate load-carrying capacity, stiffness, and deflection characteristics before undertaking any retrofitting measures. This assessment provided a baseline for understanding the extent of strength loss due to fire damage and for comparing the effectiveness of subsequent repair and strengthening techniques.



Fig 11: Testing of fire damaged before retrofitting

3.4.4 Surface preparation of slabs for FRP application

. After completion of the load testing, the slabs were subjected to surface preparation prior to retrofitting with FRP laminates. The concrete surface was treated using a angle grinder to remove any laitance, loose particles, and irregularities, thereby ensuring a smooth and uniform bonding surface. Following grinding, the accumulated dust and fine particles were completely removed using an electric air blower to achieve a clean and dry surface. This process ensured proper adhesion of the epoxy resin and enhanced the bond strength between the FRP laminates and the concrete substrate.



Fig 12: Surface preparation of slab by grinding method

3.4.5 Combinations of FRP laminate

Table 10: FRP combinations

Slabs	FRP Combinations (2 layer - Bidirectional)
Slab 1	Basalt FRP
Slab 2	Carbon FRP
Slab 3	Basalt FRP - Carbon FRP
Slab 4	Carbon FRP - Basalt FRP
Slab 5	Carbon FRP - Basalt FRP - Carbon FRP
Slab 6	Basalt FRP - Carbon FRP - Basalt FRP

3.4.6 Application of FRP laminates

For retrofitting, Araldite LY 556 epoxy resin and Aradur HY 951 hardener were prepared in the recommended ratio of 100:10 by weight. The two components were thoroughly mixed in a clean container until a homogenous and consistent blend was achieved, ensuring no air entrapment during stirring. The prepared epoxy adhesive was applied uniformly only on the soffit (bottom surface) of the slabs as well as on the bonding face of the FRP laminate. The laminate was then carefully positioned on the soffit and pressed firmly against the surface to achieve full contact and to expel any air pockets. A roller was used to provide uniform pressure, thereby improving the adhesive distribution and bond quality. After placement, the slabs were kept undisturbed under ambient conditions for a curing period of 14 days to allow complete development of adhesive strength. This ensured a durable bond between the soffit surface of the concrete slabs and the FRP laminates, which is essential for enhancing the load-carrying capacity and overall performance of the retrofitted slabs.



Fig 13: Application of FRP on slab surface with the use of Epoxy adhesive

3.4.7 Testing of FRP strengthened slabs

The strengthened slabs were tested under two-point loading to evaluate their ultimate load bearing capacity. The load–deflection behavior was carefully recorded to assess the effectiveness of FRP retrofitting in enhancing strength and stiffness.



Fig 14: Testing of FRP strengthened slab

3.4.8 Debonding in FRP strengthened Slabs

Debonding in FRP-strengthened slabs refers to the separation of the FRP laminate from the soffit of the slab, which can severely affect the efficiency of the retrofitting system. This phenomenon may occur due to insufficient surface preparation, air entrapment during epoxy application, or bond failure when the slab is subjected to increasing stress. The problem becomes more critical when multiple layers of FRP are applied, as higher interfacial stresses may accelerate debonding. Similarly, thicker laminates are more prone to stress concentration, making them vulnerable to premature detachment.

In slabs, debonding generally initiates at the edges of the laminate or near areas with higher stress intensity, such as cracks or loading points. What often begins as a small local separation can progressively spread along the interface, reducing the composite action between FRP and concrete. As a result, the slab's flexural strength and stiffness are significantly compromised. The mechanism of debonding involves a combination of shear and tensile stresses, and its progression is influenced by factors such as epoxy type, slab surface roughness, and FRP thickness and orientation.

Preventive measures include thorough grinding of the soffit to achieve a clean, rough bonding surface, ensuring uniform adhesive application, and selecting a compatible epoxy resin system. In some cases, anchorage techniques such as FRP U-wraps or additional mechanical fasteners are used to delay or restrict debonding. Environmental factors like moisture, temperature variations, and long-term loading must also be considered, as they can weaken the adhesive bond over time. Regular inspection and non-destructive evaluation methods, such as ultrasonic pulse velocity or acoustic emission monitoring, help in detecting early signs of debonding in strengthened slabs. Proper installation practices and continuous monitoring are therefore essential to maintain the long-term effectiveness and safety of FRP-retrofitted slabs.

IV. RESULTS AND DISCUSSION

4.1 Performance of retrofitted Cement concrete slabs

The fire-damaged cement slabs showed a considerable improvement in load-bearing capacity after retrofitting with different FRP configurations. Before retrofitting, the maximum load values ranged from 12.0 kN to 16.0 kN, depending on the type of strengthening system. After retrofitting, the values increased significantly, reaching up to 27.8 kN in the case of the CFRP–BFRP–CFRP configuration. The percentage increase in load capacity varied between 25% and 73%, with the highest gain observed in multi-layer hybrid systems. This clearly demonstrates that retrofitting with hybrid FRP laminates is highly effective in restoring and even enhancing the strength of damaged cement concrete slabs, providing them with a renewed structural capacity.

Table 11: Performance of retrofitted Cement concrete slabs

Slab No.	Retrofitting Type	Before (kN)	After (kN)	% Increase
1	BFRP	14.0	17.5	25.0%
2	CFRP	12.0	16.8	40.0%
3	BFRP – CFRP	13.5	20.9	54.8%
4	CFRP – BFRP	13.2	21.2	60.6%
5	CFRP – BFRP – CFRP	16.0	27.8	73.8%
6	BFRP – CFRP – BFRP	12.5	22.0	76.0%

4.2 Performance of retrofitted Geopolymer concrete slabs

In the case of geopolymer slabs, the effect of retrofitting was even more pronounced compared to cement slabs. The initial load-bearing capacity of the fire-damaged slabs ranged from 17.5 kN to 22.0 kN, which increased substantially after strengthening, with the highest value reaching 33.8 kN under the CFRP–BFRP–CFRP arrangement. The percentage increase in strength was observed between 20% and 73%, with the maximum enhancement again found in hybrid multi-layer systems. These results confirm that geopolymer concrete not only withstands fire exposure better than cement concrete but also responds more effectively to FRP retrofitting, making it a superior alternative for sustainable structural rehabilitation.

Table 12: Performance of retrofitted Geopolymer concrete slabs

Slab No.	Retrofitting Type	Before (kN)	After (kN)	% Increase
1	BFRP	22.0	26.5	20.5%
2	CFRP	18.0	25.2	40.0%
3	BFRP – CFRP	20.0	31.0	55.0%
4	CFRP – BFRP	17.5	28.0	60.0%
5	CFRP – BFRP – CFRP	19.0	33.8	77.9%
6	BFRP – CFRP – BFRP	18.5	32.2	74.0%

4.3 Comparison of Retrofitted Cement and Geopolymer Concrete Slabs

The experimental results clearly indicate that geopolymer concrete slabs exhibited superior performance compared to cement concrete slabs under retrofitting. While both slab types showed a noticeable increase in ultimate load capacity after the application of different FRP systems, the percentage increase was consistently higher in geopolymer slabs. For instance, in hybrid configurations such as CFRP–BFRP and BFRP–CFRP, geopolymer slabs achieved ultimate loads exceeding 30 kN, whereas cement slabs remained below this range even after retrofitting. This difference highlights the inherent strength and durability of geopolymer concrete, which provided a better bonding surface and enhanced composite action with FRP laminates. Overall, the results demonstrate that geopolymer slabs not only retained higher initial capacities before retrofitting but also benefited more effectively from strengthening, making them a more sustainable and resilient alternative to conventional cement concrete slabs.

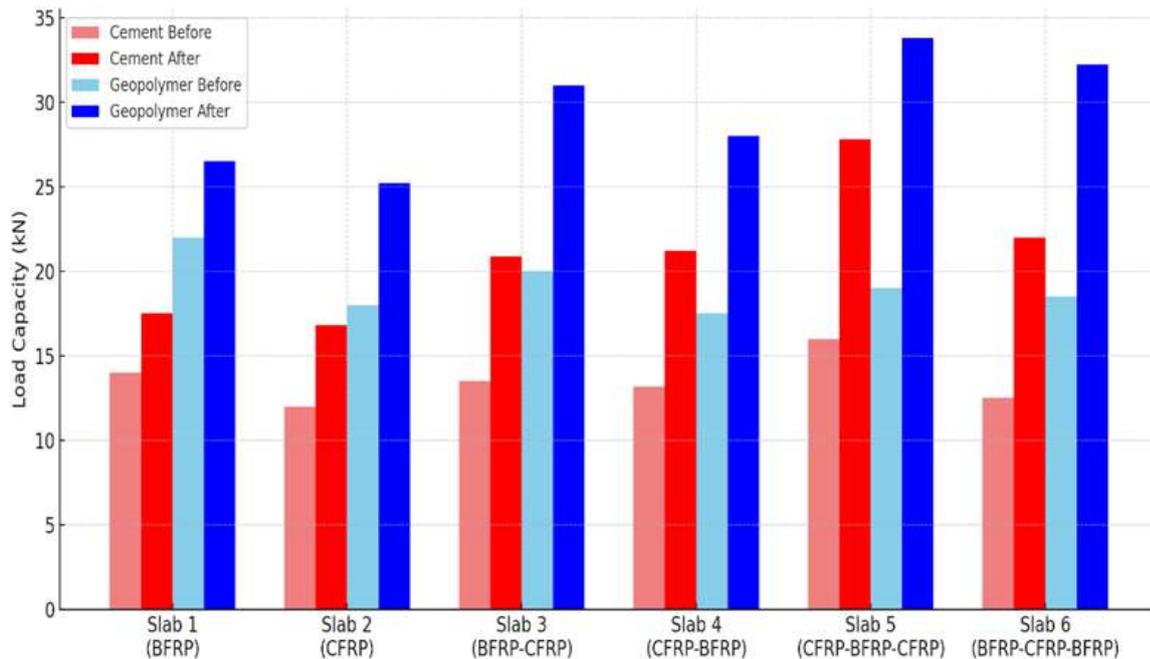


Fig 15: Load bearing capacity of cement and geopolymer concrete slabs before and after retrofitting

4.4 Conclusion

- Retrofitting significantly enhanced the load-carrying capacity of both fire-damaged cement and geopolymer slabs.
- Geopolymer concrete slabs exhibited higher load-carrying capacity compared to cement concrete slabs, both before and after retrofitting, indicating superior performance under high-temperature conditions.
- All FRP retrofit configurations improved strength, with the best-performing retrofitting observed in the CFRP–BFRP–CFRP configuration, which gave the highest enhancement in both slab types.
- The increase in load capacity of retrofitted slabs compared to their respective control slabs confirms the effectiveness of FRP systems in restoring and enhancing structural integrity.
- The use of Sika Monotop 122F after fire exposure improved surface strength, enabling better bonding of the FRP laminates.
- The M40 grade ambient-cured geopolymer concrete slabs (28 days) demonstrated sufficient strength and are suitable for structural applications even under fire exposure.
- Use of fly ash and GGBS in geopolymer concrete and fiber-reinforced polymers contributes to eco-friendly and sustainable construction practices.
- Successful restoration using FRP systems supports rehabilitation over replacement, saving cost and resources.
- Both cement and geopolymer slabs showed marked improvement in flexural strength after retrofitting, proving the viability of FRP systems in structural rehabilitation projects.

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