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Performance of fire damaged cement and geopolymer concrete slabs retrofitted with BFRP laminates under static loading

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ABSTRACT

Many of the existing reinforced concrete structures throughout the world are in urgent need of rehabilitation, repair, or reconstruction. Because of deterioration due to various factors like corrosion, lack of detailing the failure of bonding between beam, column joints, accidental fire, loss of strength, deflection, etc. Use of externally bonded FRP for strengthening the structures has received considerable attention in recent years. This study exclusively focuses on assessing the load-carrying capacity of fire-damaged Cement and Geopolymer Concrete structural elements wrapped with BFRP laminates. And the scope of this study is expected to provide cost-effective and retrofit solutions that can be implemented in the concrete industry. The slab specimens were subjected to temperatures of 200, 400, 600 and 800°C for a period of 1, 2, and 3 hours followed by retrofitting with BFRP laminate. The results showed that the ultimate load-carrying capacity of both cement and geopolymer concrete slabs increased when exposed to 200ºC for 1 hour. However, beyond this point, the capacity started to decrease. Nevertheless, a decline in ultimate load capacity was noted for higher temperature ranges and prolonged fire exposure durations.

The application of Basalt FRP wrapping to the soffit of slabs led to an 80% increase in the ultimate load capacity of both cement and geopolymer concrete slabs that had been damaged by fire. The analysis of test data led to the conclusion that retrofitting with Basalt FRP Laminates achieved a strengthening effect on the fire-damaged cement and geopolymer concrete slabs.

Keywords: Geopolymer; Concrete; Elevated temperature; Retrofitting; Basalt fibre.

1. INTRODUCTION

In recent decades, Fiber-Reinforced Polymer (FRP) composites have emerged as a promising solution for enhancing the structural performance of various civil engineering structures. In response to these challenges, researchers and engineers have turned to FRP composites as a viable solution for improving the performance and extending the service life of existing structures. Repair and strengthening of existing RC structures is of great interest not only for extending their service life, but also and rather often for their retrofitting after being damaged during exceptional events such as accidental fire, earthquake, etc. Due to the usually high cost of new construction there is an increasing need for repair, strengthening, or retrofit of RC structures. To effectively reuse an old and impaired structure, the initial crucial step involves assessing the extent of repair needed and determining the retrofitting or strengthening strategies that can be applied. So, a new structure composite technology that uses FRP has recently emerged as a very practical tool for strengthening and /or retrofitting of concrete structures. FRP composites find extensive application in fortifying deteriorated civil structures and serving as components in new structural construction. Common instances include the external bonding of FRP sheets to the tensile soffit of structures and the use of FRP profiles, bars, and cables in bridge engineering. FRP laminates bring forth several advantages inherent to composite materials, including a high strength-to-weight ratio, resistance to damping, corrosion resistance, and more. Various types of FRPs, including CFRP, GFRP, BFRP, and AFRP, offer diverse options for this purpose. The application of externally bonded FRP for strengthening of RC structures has garnered significant attention in recent years. This approach involves applying FRP laminates to the exterior surface of existing concrete elements, providing an additional layer of strength and durability. The use of FRP in this manner proves to be a cost-effective and efficient solution, allowing for the enhancement of structural performance without resorting to complete reconstruction.

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The impact of fire in buildings extends to the loss of life, structural damage, and repercussions on the broader economy and environment. In recent years, there has been a renewed interest in understanding how building structures respond to fires. Fires can compromise the load-bearing capacity, stiffness, and overall performance of structural members, leading to potential structural collapse and life safety risks. Statistical surveys consistently show a rising trend in the frequency of fire incidents across nearly all countries worldwide. In the context of contemporary advancements in structural safety, fire is now regarded as a risk alongside other factors like overcrowding and extreme wind loads. As such, the aftermath of fire incidents necessitates prompt and effective measures to assess, repair, and retrofit fire-damaged structural elements. Understanding the consequences of fire damage is paramount in ensuring the reliability and longevity of built environments. Fire-induced effects such as loss of material strength, thermal degradation, spalling of concrete, and buckling of steel components can significantly compromise the structural stability and functionality of buildings and bridges. Moreover, the residual effects of fire, including residual stresses, residual deformations, and residual displacements, can further exacerbate the structural vulnerabilities and necessitate comprehensive rehabilitation strategies. The need for retrofitting fire-damaged members arises from the imperative to restore structural integrity, mitigate risks, and enhance the fire resistance of affected structures. From an economic efficiency standpoint, opting to retrofit damaged structural components may prove more advantageous than partial or complete demolition.

Concrete stands as the second most utilized construction material globally, surpassed only by water. Ordinary Portland cement (OPC) plays a pivotal role as the primary component in concrete. However, the production of cement is a major contributor to greenhouse gas emissions, releasing substantial amounts of carbon dioxide (CO2) into the atmosphere. It is estimated that one ton of CO2 is released into the atmosphere for every ton of OPC produced. Given this environmental impact, there is a pressing necessity to explore sustainable alternatives to traditional cement. This involves harnessing the cementitious properties of industrial by-products like fly ash and ground granulated blast furnace slag. Geopolymer concrete holds the potential to significantly diminish global carbon emissions, contributing to sustainable development and playing a crucial role in the environmentally friendly construction and building products industry. It is envisioned as a more eco-friendly substitute for Portland cement.

The presence of plaster significantly effect on the fire resistance because it played a role similar to that of concrete cover in protecting the steel reinforcement. Increasing the cover thickness led to almost a linear increase in fire resistance [1]. The geopolymer concrete retained higher percentage of strength than OPC concrete specimens up to 650^{o}C. The geopolymer microstructure remained stable and compact after exposure to high temperature fire [2]. GGBS blended FA based GPC mixes attained enhanced mechanical properties at ambient room temperature curing itself without the need of heat curing as in the case of only FA based GPC mixes. The increase in GGBS replacement in GPC mixes enhanced the mechanical properties at ambient room temperature curing at all ages [3]. Sisal fiber and chicken mesh wrapping were employed as external strengthening reinforcement in geopolymer concrete (GPC). The use of sisal fiber and chicken mesh wrapping as an external strengthening reinforcement in geopolymer concrete (GPC). Through experimental analysis of three categories – geopolymer (GPC), GPC retrofitted without cracks, and GPC retrofitted with cracks – it was determined that retrofitted GPC without cracks exhibited superior failure resistance and overall efficiency [4]. The feasibility of production of GPC using red mud and fly ash are evaluated. Geopolymer concrete based on red mud gives less compressive and flexural strength as compared to geopolymer based on fly ash at different mix [5]. The characteristics of fire-resistant concrete are explored through the incorporation of mineral admixture. Traditional concrete strength experiences a decline when subjected to temperatures surpassing 600°C. To counteract the effects of elevated temperatures, increasing the proportion of nano silica fume in the concrete proves to be an effective strategy for enhancing compressive strength [6]. Thermal shrinkage or expansion occurs as a result of increased temperature exposure, which leads to macro cracking. Optimizing the amount of water in a geopolymer mix is crucial for regulating strength, spalling resistance, and thermal deformation [7]. The basalt fiber was found to provide better resistance than the glass fiber. However, the basalt fiber kept about 90% of the normal temperature strength after exposure at 600°C for 2h whereas the carbon and the glass fibers did not maintain their volumetric integrity [8]. BFRP was bonded with concrete with the help of epoxy resin. Basalt fibers were applied in two forms either fully or partially wrapping. BFRP increases in confinement of RC specimens with a little increase in strain and also strain softening behavior exhibited [9]. The energy and ductility dissipation capacities of retrofitted predamaged RC columns with fiber reinforced polymer were improved greatly after BFRP wrapping. The flexural strength of the moderate predamaged RC column was restored fully while it was partially restored for the severe predamaged columns [10].

Premature debonding of the FRP, which could occur at load values much less than the strength of the FRP material used in the retrofitted system, is one of these brittle failures. As a result, a better understanding of the various failure modes of FRP reinforced concrete structures is required as the foundation for a reliable retrofit design [11]. RC shear walls strengthened with basalt FRP (BFRP) is restricted in comparison to RC shear walls strengthened with carbon FRP or glass FRP one of them was tested without any strengthening, while the other five were strengthened with BFRP strips of various configurations. In addition, the theoretical load carrying capability was estimated and compared to the test findings [12]. The data suggest that a 45-degree wrapping pattern was more successful than 90-degree wrapping and no wrapping. The RC T-beam was then modelled in ABAQUS to confirm the experimental and analytical results. The analytical results agree fairly with the experimental results after a series of comparison examinations [13]. The new epoxy anchors have the benefit of a simple installation technique that includes pre-drilling holes and then bonding FRP. Totally, five RC beams containing one control specimen and four anchored ones were tested. Compared to the control specimen, the load-carrying capacity and ductility of anchored beams enhanced by up to 13.12% and 53.31%, respectively, and the strain utilisation of FRP improved by 43.48% [14]. The use of fibrous composite materials such as CFRP and GFRP in the repair of heat damaged reinforced concrete slabs has shown promising results in restoring flexural capacity, stiffness, and load carrying capacity. External bonding of CFRP, GFRP, and steel fibrous grout layer is done on heat-damaged RC slabs. The slabs repaired with CFRP, GFRP, and steel fibrous grout layers gained strength up to 158%, 125%, and 84% of the control slab's ultimate load capacity [15]. BFRP sheets in single and double layers with varied configurations were used to bond the columns. Two of the fourteen columns were control columns, with the remaining columns reinforced with BFRP. The experimental results showed that BFRP-enhanced columns have a good load carrying capability and ductility index [16]. Accelerated corrosion with NaCl solutions is preferred, while FRP and ECC methods emerge as effective for restoring capacity in corrosion-damaged RC members. Further research is needed to assess the long-term durability of these strengthening techniques for sustainable infrastructure solutions [17]. The-art review on repairing and strengthening severely damaged RC members under static and seismic loads, analyzing repair methods for various damage mechanisms such as core concrete damage, cover concrete spalling, tie rupture, and longitudinal reinforcement yielding and buckling [18]. Experimental findings suggest epoxy as the optimal bonding material for NSM FRP laminates, significantly enhancing peak load capacity. Geopolymer mortar also shows promise, offering substantial improvements in peak shear strength and ultimate displacement, warranting consideration alongside high strength cement grout for NSM shear strengthening [19]. The study demonstrates that both NSM and Hybrid FRP systems effectively restore the load-carrying capacity of pre-damaged columns. Additionally, analytical predictions and staged FE modeling validate the reliability of these strengthening techniques, with hybrid FRP systems showing promising results in restoring strength and displacement [20]. This paper investigates the performance of severely damaged RC columns under axial compression, evaluating the efficacy of diverse strengthening techniques through strength, stiffness, and ductility indices. Techniques such as concrete cover replacement with high strength cementitious grout, NSM strengthening, and hybrid strengthening are employed to enhance column performance [21].

The tensile fatigue behavior of FRP and hybrid FRP sheets, including carbon, glass, PBO, and basalt fibers are explored. The hybrid composites of carbon-basalt significantly improve the fatigue resistance in comparison to the homogeneous basalt composite, whereas the resistance of the carbon-glass hybrid composites does not provide such effects [22]. Increasing the bottom layer of GFRP can enhance the dynamic performance of RC slabs under impact loads, resulting in better performance compared to steel fibres. Numerical simulations based on LS-DYNA program were validated through experimental data, showing good agreement for maximum displacement, acceleration, and failure pattern [23]. The geopolymer concrete had a better spalling resistance to rapidly rising temperature exposure than Portland cement concrete by conducting the surface exposure test and standard gas furnace fire test [24]. The research revealed that a blend comprising 80% Ground Granulated Blast Furnace Slag (GGBS) and 20% fly ash yielded the most favorable results, despite achieving the highest strength when using 100% GGBS. The optimized blend demonstrated notably enhanced strength compared to control samples across various curing conditions. However, employing 100% GGBS led to minor surface cracks on the cubes, rendering it unsuitable for slab applications [25]. Considering the variability of the input variables, a low-reliability index is determined for buildings with no basic firefighting measures, and adding intervention measures, sprinkler systems, and detection systems will increase the reliability index by 53%, 85%, and 89%, respectively [26]. The hybrid CG laminate maintain its stiffness up to 250°C and it shows better fire resistance at service load as its elasticity modulus showed less degradation at elevated temperature as compared to the commonly used C and G sheets in strengthening reinforced concrete structural members [27].

This research is dedicated to examining the impact of BFRP laminates on the retrofitting of fire-damaged cement and geopolymer concrete slabs. The primary objective is to compare the load-carrying capacity of cement and geopolymer concrete slabs wrapped with BFRP laminates under static loading conditions. Basalt fibre is a material made from extremely fine fibres of basalt, which is composed of the minerals plagioclase, pyroxene, and olivine. It is similar to fiberglass, having better physico mechanical properties than fiberglass, but being significantly cheaper than carbon fibre.

1.1. Research significance

This research aims to investigate the impact of various FRP laminates on retrofitting fire-damaged reinforced structures. The study involves casting cement concrete and geopolymer slabs and comparing their load-carrying capacity with those wrapped in Basalt FRP laminates under static loading. Indeed, existing research predominantly addresses the enhancement of fire-damaged cement concrete slabs, with limited attention given to the behaviour of geopolymer concrete under fire exposure. The scarcity of studies on geopolymer concrete in fire-related contexts underscores the need for a more comprehensive understanding of its performance and response to fire damage.

This study uniquely concentrates on identifying suitable retrofitting techniques for geopolymer structures damaged by fire. Consequently, this endeavour proves highly valuable in assessing the feasibility of retrofitting techniques, particularly with FRP laminates, for both fire-damaged cement and geopolymer concrete structures. The objective is to enhance the performance of fire-damaged reinforced concrete structures by utilizing Basalt FRP laminates to restore strength and durability. Additionally, the aim is to enhance the ductility properties of reinforced concrete structures through the application of various FRP laminates.

2. MATERIALS AND METHODS

2.1. Cement

The specimens were prepared using OPC 53 grade cement, adhering to properties outlined in IS 12269-2013. Pretests were conducted on the cement to ensure compliance before the actual concreting process. Table 1 provides a comprehensive overview of the tested properties of the cement, alongside the corresponding values recommended by IS 12269-2013.

2.2. Fly ash (FA)

Fly ash is a finely powdered, grey substance predominantly composed of spherical, glassy particles. It is generated as a by-product in coal-fired power stations. Indeed, fly ash possesses pozzolanic properties, engaging in a chemical reaction with lime to create cementitious compounds. Class F fly ash was utilized in the preparation of specimens.

2.3. Ground granulated blast furnace slag (GGBS)

GGBS is indeed an environmentally friendly product crafted from a by-product of iron manufacturing, specifically the blast furnace process. Moreover, GGBS is recognized for its high quality and is considered a low CO_2 material, contributing to efforts aimed at reducing carbon emissions in construction practices.

The important properties of geopolymer binder (FA80: GGBS20) determined are given in Table 2.

Table 1: Properties of cement.

S.NO	TESTS PERFORMED	EXPERIMENTED VALUES	REQUIREMENTS AS PER IS 12269-2013
1	Standard consistency	31%	28-32
2	Initial setting time	55 minutes	Not less than 30
3	Final setting time	285 minutes	Not more than 600
4	Specific gravity	3.11	3.15
5	Fineness (<90 microns)	2.5%	<10%
6	3rd day compressive strength of cement	30.0 N/mm^2	Greater than 27.0 N/mm^2
7	7th day compressive strength of cement	42.0 N/mm^2	Greater than 37.0 N/mm^2
8	28th day compressive strength of cement	56.5 N/mm^2	Greater than 53.0 N/mm^2

2.4. Aggregate

Using M-sand (manufactured sand) conforming to IS: 383 – 1970 as the fine aggregate and crushed granite stone aggregate with maximum sizes of 20 mm and 12.5 mm as the coarse aggregate aligns with standard specifications. This selection is in accordance with established standards, ensuring the quality and suitability of the aggregates for the concrete mix. The properties of fine and coarse aggregates are presented in Table 3.

2.5. Steel

Selecting the size and diameter of reinforcement with reference to IS: 1786 – 1985 indicates adherence to the Indian Standard specifications for high-strength deformed steel bars for concrete reinforcement. Testing the 8 mm diameter rebars for tensile stress using a universal testing machine is a crucial step in quality assurance and structural integrity. Tensile testing helps assess the material's strength and performance under tension, providing valuable information about its mechanical properties.

2.6. Alkaline solution

The use of sodium hydroxide (NaOH) and sodium silicate (Na_2SiO_3) as an alkaline solution in geopolymer concrete is a common practice. These substances play key roles in the geopolymerization process, where aluminosilicate materials (such as fly ash or metakaolin) react with the alkaline solution to form a geopolymer binder.

In the preparation of the alkaline solution for the geopolymer concrete mix, 320 grams of sodium hydroxide (NaOH) pellets were dissolved in potable water to create a concentrated 8M sodium hydroxide solution with a total volume of one liter. To attain the desired strength, a carefully determined ratio of 2.5 was established between the sodium silicate solution and the sodium hydroxide solution. This meticulously proportioned mixture was then left to mature, undergoing a 24-hour storage period before its application in the casting process. This comprehensive procedure ensures the precise formulation of the alkaline solution, a critical component in the geopolymerization reaction for the subsequent production of high-performance geopolymer concrete.

2.7. Molarity

The achievement of high strength in geopolymer concrete, particularly based on an 8M concentration, is a recurring observation supported by various literature sources. Notably, the maximum strength of the 8M concrete formulation is consistently observed after a curing period of 28 days under ambient conditions. However, it is noteworthy that beyond this critical period, a discernible and consistent decline in strength becomes evident. The correlation between the compressive strength of Geopolymer Concrete and the molarity of sodium hydroxide is typically positive, indicating that higher molarity solutions often result in increased compressive strength. A study conducted by Sasi Rekha M. and Sumathy S.R. in 2021 further supports this trend. According to their findings, an 8M Geopolymer Concrete formulation is expected to achieve an ultimate strength of 57.53 MPa after 28 days of curing.

Table 2: Properties of geopolymer binder (FA80: GGBS20).

S.NO	TESTS PERFORMED	EXPERIMENTED VALUES
1	Consistency test	30%
2	Initial setting time	76 minutes
3	Final setting time	285 minutes

Table 3: Properties of fine and coarse aggregate.

S.NO	PROPERTY	FINE AGGREGATE	COARSE AGGREGATE	
			20 mm	12.5 mm
1	Specific gravity	2.61	2.89	2.81
2	Fineness modulus	2.75	6.8	6
3	Density	1685 kg/m^3	1760 kg/m^3	1710 kg/m^3
4	Water absorption	0.54%	0.211%	0.203%

Table 4: Properties of basalt FRP.

PROPERTIES	WEIGHT OF FIBRE (G/M^2)	FIBRE THICKNESS (MM)	NOMINAL THICKNESS PER LAYER (MM)	FIBRE TENSILE STRENGTH (N/MM^2)	TENSILE MODULUS (N/MM^2)
BFRP (Bidirectional)	330	0.60	1.0	4840	86000

2.8. Fibre reinforced polymer laminate

The repair material chosen for the fire-damaged cement and geopolymer reinforced concrete (RC) slab is a Basalt Fiber Reinforced Polymer (BFRP) laminate. Specific details regarding the properties of the BFRP laminate utilized in this context can be found in Table 4.

2.9. Mix design for conventional concrete

In the course of this study, the mix design adhered to the guidelines outlined in the Indian Standard IS:10262-2009.

Mix ratio has taken for the experimental study is **1: 2.02 : 2.14 : 1.44 : 0.48**

2.10. Mix design for geopolymer concrete

Mix ratio has taken for the experimental study is **0.8 : 0.2 : 2.09 : 2.22 : 1.50 : 0.48**

3. CASTING AND TESTING OF REINFORCED SLABS

3.1. Design

The slabs were designed according to the Indian design code IS456-2000. The slabs measured 450 × 600 × 50 mm, with a clear cover of 10mm provided on all sides.

3.2. Casting of reinforced slabs

Plywood moulds measuring 600 × 450 × 50mm were prepared, and necessary reinforcements were assembled before the casting process. To facilitate demoulding, the sides of the moulds were greased before placing cover blocks and positioning the reinforcements. Concrete casting was completed, and the specimen was carefully surfaced. After 24 hours, demoulding took place, followed by a curing period of 28 days in water for cement concrete slabs. For geopolymer concrete slabs, curing took place under ambient conditions during the same period. Figures 1 and 2 illustrate the sequential steps involved in casting a RC slab specimen, encompassing the placement of reinforcement within the mould. Figures 3 and 4 visually depict the curing process for both conventional and geopolymer concrete.

3.3. Fire exposure

A high-speed burner, as depicted in Figure 5, was utilized to burn both cement and geopolymer slabs. To maintain the fire temperature, the temperature range was monitored employing a K-type thermocouple (Utc4202 model), as illustrated in Figure 6. Following exposure to fire for different durations (1h, 2h, and 3h), the temperature range was continuously monitored using the specified time intervals before allowing the specimens to cool inside the furnace. Figures 7 and 8 visually represent the firing process and the resulting fire-damaged slabs.

3.4. Wrapping of FRP

The FRP laminates were wrapped to the bottom of the slabs, with the fiber orientation positioned perpendicular to the load application. The air-cooled specimens were taken out of the furnace and smoothened on all sides before the wrapping process. The necessary quantity of epoxy and hardener was blended and uniformly applied to the bottom of the slab. Figure 9a illustrates the process of surface cleaning, followed by the depiction of the slab wrapped with BFRP laminates in Figure 9b.

3.5. Testing of specimens

All slabs were tested under uniform loading conditions, experiencing a point load at the mid-span. The Leaf Spring Testing Machine, employed for testing, possesses a loading accuracy well within ± 1%, conforming to IS

Figure 1: Placing of reinforcement.

Figure 2: Casting of specimens.

Figure 3: Water curing of cement concrete slabs.

Figure 4: Ambient curing of geopolymer concrete slabs.

Figure 5: Set up for firing.

Figure 6: Thermocouple.

Figure 7: Exposure of fire on concrete slab.

Figure 8: Fire damaged slabs.

1828/BS1610 standards. Figure 10 illustrates the schematic diagram depicting the supporting condition of the slab. Figure 11a depicts the test setup for fire-damaged slabs without wrapping, while Figure 11b illustrates the test setup for fire-damaged slabs wrapped with BFRP Laminates.

Figure 9: a) Surface cleaning process. b) Slab wrapped with BFRP laminates.

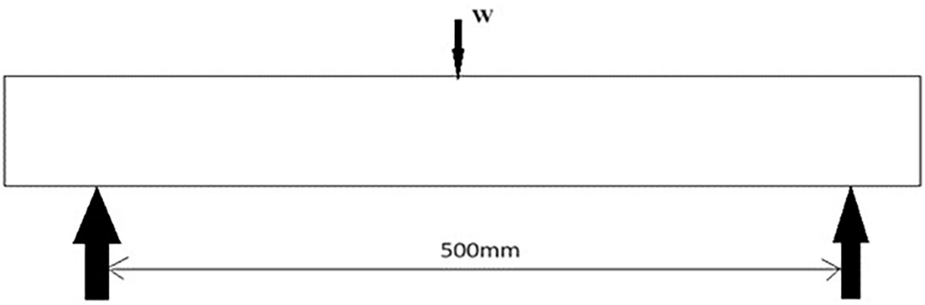

Figure 10: Schematic representation of supporting condition of slab.

Figure 11: a) Testing of fire damaged slab without wrapping. b) Testing of fire damaged slab retrofitted with BFRP laminates.

3.6. Effect of fire on cement and geopolymer concrete

3.6.1. Visual observation

Examination of the cement concrete surface is generally employed for identifying damages caused by exposure to high temperatures. Hence, the assessment of fire-damaged cement concrete commonly initiates with a visual inspection, looking for alterations in colour, the presence of cracks, and any spalling on the concrete surface. Temperatures reaching 200ºC and beyond result in significant alterations in colour observation. The color transformation progresses as follows: from light gray at 200ºC to gray at 400ºC, shifting to light pink at 600ºC, and ultimately adopting a Boro Gray hue at 800ºC. Up to 400ºC, no thermal cracks are visibly apparent on the surface of the exposed concrete. Nevertheless, when exposed to temperatures above 600ºC, minor cracks and surface crazing become perceptible. Upon reaching 800ºC, increased surface cracking and crazing are evident. This phenomenon is linked to the dense microstructure of cement concrete, impeding the free movement of water vapours and causing pore pressure, ultimately resulting in cracks in the specimens. The absence of fire-induced spalling in cement concrete is ascribed to two factors: the low heating rate and the intrinsic porosity inherent in cement concrete.

The damage resulting from exposure to high temperatures is generally identifiable through surface examination of the geopolymer concrete. Hence, the assessment of fire-damaged geopolymer concrete typically initiates with a visual inspection to detect alterations in colour, cracks, and spalling on the geopolymer concrete surface. After exposure to fire, noticeable discoloration was observed in the geopolymer concrete slabs. Following exposure to 800ºC for different durations, cracks were observed, although they were not prominently visible. The cracks in geopolymer concrete resulted from post-burning shrinkage, as the matrix of the geopolymer concrete remained stable at elevated temperatures. No spalling was observed in the geopolymer concrete. Visual observations indicate that the geopolymer concrete exhibited greater resistance to fire, showcasing higher endurance.

3.6.2. Mass loss

The weight of all cement concrete slabs was measured both before and after exposure to heating. As temperature increases, concrete consistently undergoes a gradual loss of mass. Observations revealed that the initial mass loss is higher, up to 200ºC, and can be attributed to the evaporation and loss of free water due to the initial hydrothermal conditions. The mass loss at 200ºC varied between 2% and 3.7% for different durations. Nevertheless, it increases to a range of 4.4% to 6% at 400ºC and between 7.8% and 11% at 600ºC for varying exposure times. Furthermore, it further increases, ranging between 12.1% and 17.2% at 800ºC for varying durations of fire exposure. The decrease in specimen mass can be attributed to the dehydration of hydrated chemical compounds within the concrete.

Figure 12 provides a summary of the mass loss observed in cement concrete slabs exposed to elevated temperatures for varying durations.

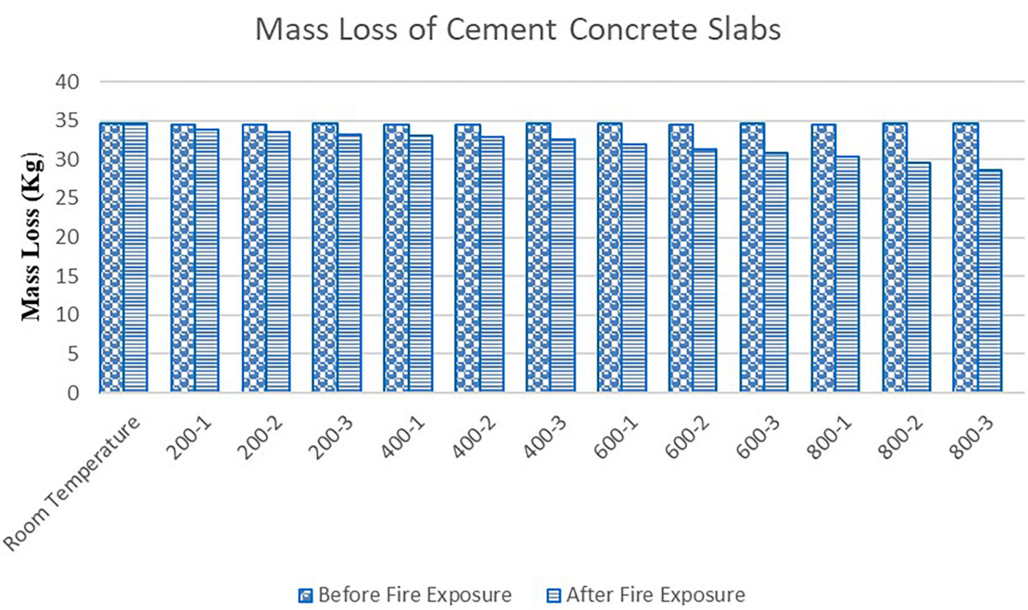

Figure 12: Mass loss of cement concrete slabs subjected to different temperature and duration.

The weights of all geopolymer concrete samples were measured both before and after exposure to heating. As temperature increases, concrete consistently undergoes a nearly constant mass loss. Observations indicate that the initial mass loss is notably higher, up to 200ºC, and is primarily due to evaporation and the loss of free water resulting from the initial hydrothermal conditions. The percentage of mass loss at a specific temperature is determined by dividing the difference between the final and initial mass by the initial mass of the test specimen. The mass loss at 200ºC varied between 1.5% and 3.9% for different durations. However, it increases, ranging between 4.3% and 7.2% at 400ºC and between 8.4% and 11% at 600ºC for different exposure times. Furthermore, it further increases, ranging between 12.1% and 18.8% at 800ºC for varying durations of fire exposure. Figure 13 illustrates the mass loss of geopolymer concrete specimens exposed to elevated temperatures for varying durations.

3.7. Load carrying capacity of fire damaged cement and geopolymer concrete slabs under static loading

Table 5 provides the ultimate loads sustained by the fire-damaged cement concrete slabs under static loading.

Figure 14 offers a comprehensive comparison of the ultimate load-carrying capacity between fire-damaged cement and geopolymer slabs, considering both wrapped and unwrapped conditions. The illustration emphasizes the performance of both cement and geopolymer slabs across various temperatures and durations under diverse loading conditions.

4. RESULTS AND DISCUSSIONS

4.1. Effect of temperature

Identifying damages resulting from exposure to high temperatures can generally be accomplished through surface examination of the concrete. Hence, the assessment of fire-damaged concrete typically initiates with a visual inspection for alterations in colour, cracks, and spalling of the concrete surface, encompassing both conventional and geopolymer concrete. Major changes in colour are observed at temperatures of 200ºC and above. Here are some common signs of damage caused by high temperatures in concrete: Here are some common signs of damage caused by high temperatures in concrete is given in Table 6. The physical and chemical reactions in response to fire, as outlined in Table 7.

Temperature plays a pivotal role in influencing the structural integrity and durability of concrete. In this regard, a comparison between conventional concrete and geopolymer concrete underscores the superior temperature resistance of the latter. At 200ºC, conventional concrete can endure the heat without spalling, which is the breaking or chipping of the concrete surface. In contrast, geopolymer concrete not only prevents spalling but also remains entirely free of cracks, showcasing its capacity to sustain structural stability even under elevated temperatures.

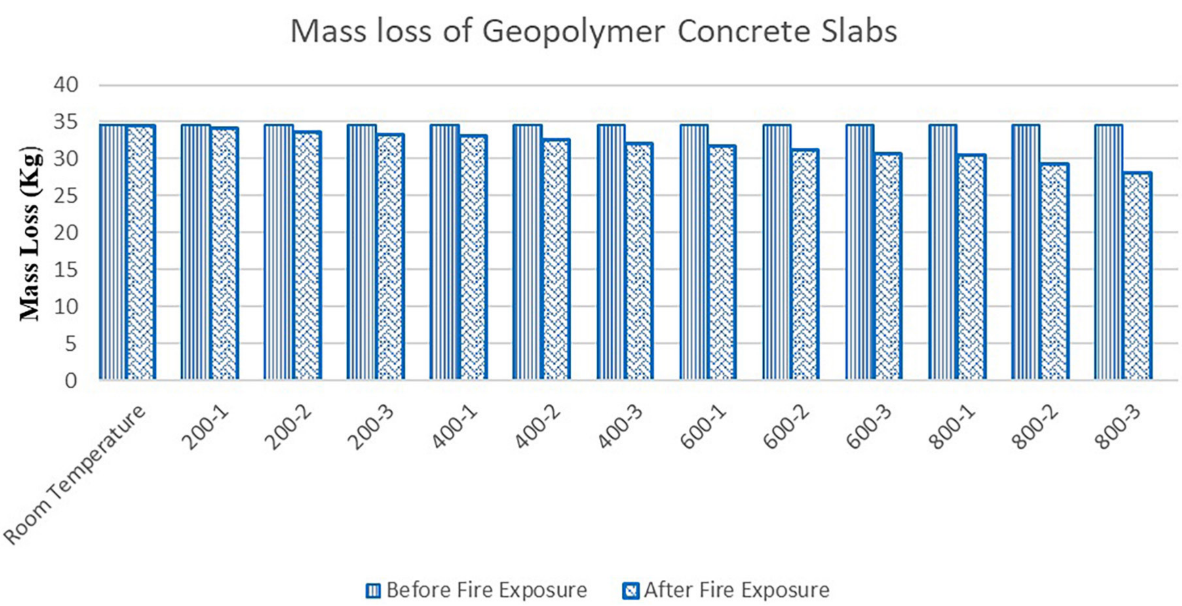

Figure 13: Mass loss of geopolymer concrete slabs subjected to different temperature and duration.

Table 5: Ultimate load carrying capacity of cement and geopolymer concrete slabs subjected to different temperature and duration under static loading. Retrofit material: BFRP laminates.

EXPOSURE CONDITION		TYPE OF CONCRETE	LOAD CARRYING CAPACITY OF SLAB BEFORE RETROFIT (KN)	LOAD CARRYING CAPACITY OF SLAB (KN) AFTER RETROFIT	% OF INCREASE IN LOAD CARRYING
TEMPERATURE (ºC)	DURATION (HOUR)				
Room temperature	–	Cement	34	61.20	80.00
Room temperature	–	Geopolymer	40	72.40	81.00
200	1	Cement	37.4	67.32	80.00
	1	Geopolymer	47.2	84.96	80.00
	2	Cement	33.32	59.64	78.99
	2	Geopolymer	43.2	77.33	79.00
	3	Cement	32.3	58.46	80.99
	3	Geopolymer	38.8	69.06	77.99
400	1	Cement	31.62`	56.92	80.01
	1	Geopolymer	39.2	70.56	80.00
	2	Cement	29.24	52.92	80.98
	2	Geopolymer	36.8	65.87	78.99
	3	Cement	27.2	48.42	78.01
	3	Geopolymer	34.4	61.23	77.99
600	1	Cement	28.9	52.02	80.00
	1	Geopolymer	36	64.44	79.00
	2	Cement	25.5	46.16	81.02
	2	Geopolymer	33.2	59.76	80.00
	3	Cement	22.1	39.34	78.01
	3	Geopolymer	30	53.70	79.00
800	1	Cement	22.78	40.78	79.02
	1	Geopolymer	28.8	51.84	80.00
	2	Cement	17.68	31.47	78.00
	2	Geopolymer	24.0	42.96	79.00
	3	Cement	13.6	24.21	78.01
	3	Geopolymer	20.4	36.72	80.00

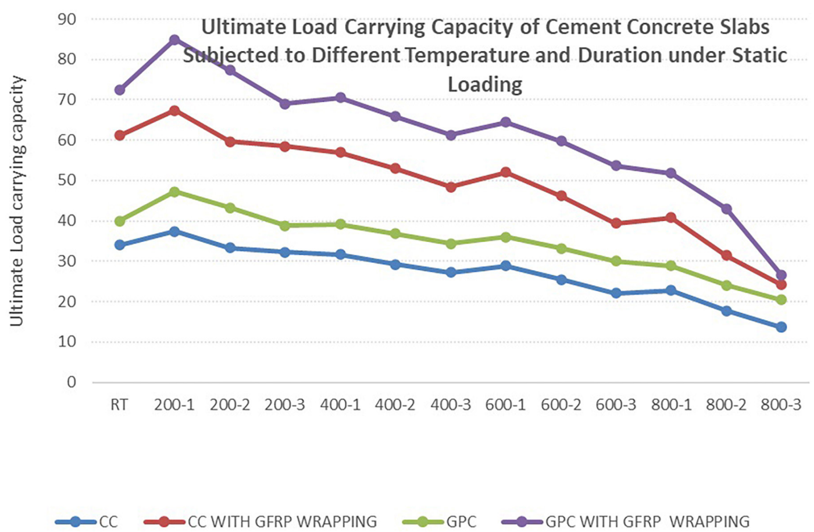

Figure 14: Overall comparison of Ultimate load carrying capacity of Cement and Geopolymer slabs at various temperatures and various durations.

Table 6: Visual observation.

TEMPERATURE (°C)	WHAT HAPPENS
200	The color transitions to light gray.
400	The color further changes to gray, and up to 400ºC, there are no visible thermal cracks on the surface of the exposed concrete.
600	As the temperature increases, the color shifts to light pink, and at this stage, minor cracks and surface crazing become visible.
800	The color transforms to Gainsboro gray, and at this point, higher surface cracking and crazing become observable.

Table 7: Physical and chemical response to fire.

TEMPERATURE (°C)	DURATION (HOUR)	WHAT HAPPENS	
		IN CEMENT CONCRETE SLABS	IN GEOPOLYMER CONCRETE SLABS
For 200	1	No cracks are observed	Geopolymer concrete exhibits no formation of cracks.
For 200	2	Very minor cracks formation was observed	No crack formation
For 200	3	Minor crack formation was identified.	There is no formation of cracks.
For 400	1	Some Minor cracks have formed.	Very minor cracks formation was noted.
For 400	2	Moderate cracks formation was observed	Minor cracks formation was observed.
For 400	3	Extensive cracks formation was noted.	Moderate Crack formation was noticed.
For 600	1	Cracks of medium size were observed.	Observations revealed the formation of minor cracks.
For 600	2	Extensive cracks were observed.	Moderate cracks formation without any spalling of the concrete.
For 600	3	Cracks of medium size appeared within the first hour, followed by substantial spalling starting 1at 2:30 hr. Beyond this temperature threshold, Concrete loses its full structural capacity	Large cracks have formed, and there is no occurrence of concrete spalling.
For 800 – 1 Hr	1	The surface of the concrete exhibited the formation of extensive cracks.	Moderate Crack formation was noticed.
For 800 – 2 Hrs	2	65% of very extensive cracks and spalling occur, accompanied by a distinct and heavy sound.	Substantial cracks, accompanied by slight spalling of the concrete, occur.
For 800 – 3Hrs	3	Nearly 90% of the concrete undergoes complete damage, characterized by extensive cracks and spalling, accompanied by a pronounced and heavy sound.	Extensive formation of large cracks is accompanied by concrete spalling.

The increase in load carrying capacity of concrete and geopolymer concrete slabs when subjected to 200ºC for 1 hour can be attributed to several factors related to the behaviour of cement and geopolymer materials at elevated temperatures:

- Densification and Dehydration: The exposure to high temperatures can lead to the removal of excess water from the concrete. The dehydration process reduces the volume of pores and void spaces within the concrete matrix, contributing to a denser structure. A denser matrix typically correlates with increased strength due to enhanced load transfer mechanisms.

- Enhanced Geopolymerization: The high-temperature exposure may accelerate or enhance the geopolymerization reactions. The activation of aluminosilicate materials in the presence of an alkaline activator at elevated temperatures can lead to the formation of a more robust geopolymer gel, contributing to increased strength.
- Minimization of Microcracking: The evaporation of excess water and reduction in void spaces can minimize the potential for internal microcracking. Water vapor pressure can contribute to the development of internal pressures within the pores, leading to cracking. By reducing excess pore water, the risk of thermal-induced microcracking is minimized, contributing to the overall integrity and strength of the concrete.
- Changes in Microstructure: The exposure to elevated temperatures may induce changes in the microstructure of the concrete. In geopolymer concrete, these changes can include the refinement of pore structures, reduction in voids, and improvements in the bond between geopolymer gel and aggregates, all of which can contribute to increased strength.

As the temperature increases to 400ºC, conventional concrete exhibits the emergence of minor cracks, signifying a diminished resistance to thermal stress. Conversely, geopolymer concrete maintains outstanding performance, displaying no discernible formation of cracks at the same temperature. This remarkable behavior highlights the superior thermal properties and strength of geopolymer concrete, positioning it as an attractive alternative in environments where temperature fluctuations are frequent.

Nevertheless, when exposed to a temperature of 600ºC, both conventional and geopolymer concrete begin to exhibit signs of vulnerability. Conventional concrete starts to spall after approximately 30 minutes at 600ºC, signifying significant deterioration and a loss of structural integrity. Although there is no mention of spalling in geopolymer concrete, it begins to develop cracks, implying that its performance may not be as robust as at lower temperatures. Nevertheless, the ability of geopolymer concrete to resist spalling remains advantageous when compared to conventional concrete. At 800ºC, conventional concrete undergoes large cracks and spalling, severely compromising its structural stability and rendering it unsuitable for use in high-temperature applications. Although the specific behavior of geopolymer concrete at this temperature is not explicitly mentioned, it can be inferred that its performance remains relatively superior to that of conventional concrete, as there is no specific mention of spalling or crack formation.

In summary, the findings emphasize the potential of geopolymer concrete as a more durable and resilient alternative in high-temperature environments. Its demonstrated ability to resist spalling and maintain structural integrity at elevated temperatures, observed up to 600ºC, positions it as an appealing option for applications in industrial settings, fire-resistant structures, and infrastructure exposed to extreme heat condition.

4.2. Effect of duration

In conclusion, the duration has a significant impact on the performance of both conventional concrete and geopolymer concrete under various temperature conditions.

When conventional concrete is subjected to a temperature of 200ºC, a one-hour duration led to a 10% rise in load carrying capacity, attributed to the dehydration of pore water. However, with prolonged durations of two and three hours, the load carrying capacity declined by 2% and 5%, respectively. Likewise, geopolymer concrete demonstrated an increase of 18% and 8% augmentation in load carrying capacity following one hour and two hours of exposure at 200ºC, but encountered a decrease of 3% after three hours.

At 400ºC, 600ºC, and 800ºC, the load carrying capacity of both types of concrete experienced a notable decrease with prolonged duration. For instance, at 400ºC, the reduction in load carrying capacity was noted to be 7%, 14%, and 20% for durations of 1 hour, 2 hours, and 3 hours, respectively. In the case of geopolymer concrete, at this temperature, the strength diminished by 2% after one hour, 8% after two hours, and experienced a slight reduction of 14% after three hours. When subjected to 600ºC for 1 hour, 2 hours, and 3 hours, the load carrying capacity of cement concrete slabs exhibited losses of 15%, 25%, and 35%. The variations in thermal expansion rates between the cement paste and aggregate were identified as the cause for the decline in the load capacity of the concrete. Whereas geopolymer concrete, exposed to 600ºC, the strength exhibited a reduction of 10% after one hour, 17% after two hours, and 25% after three hours.

At 800ºC, the most significant reduction occurred in conventional concrete, with load carrying capacity decreasing by 33% after one hour, 48% after two hours, and 60% after three hours. These capacity decreases were attributed to the differential thermal expansion between the cement paste and aggregate. In the end, at

800ºC, the strength of geopolymer concrete diminished by 28% after one hour, 40% after two hours, and 49% after three hours.

These results illustrate how extended exposure to elevated temperatures negatively impacts the load-carrying capacity of both conventional concrete and geopolymer concrete. It emphasizes the significance of factoring in the duration of exposure when designing concrete structures for fire or high-temperature environments. Additionally, it highlights the potential benefits of geopolymer concrete, particularly in terms of enhanced load-carrying capacity and strength retention in such conditions. In summary, the duration of exposure emerges as a crucial factor influencing the behavior and performance of concrete.

When conventional concrete is exposed to high temperatures for an extended period, minor cracks become evident. This suggests that as the duration of exposure increases, conventional concrete becomes more vulnerable to thermal stress and the possibility of structural damage. Conversely, the specific reaction of geopolymer concrete to prolonged exposure is not explicitly discussed. However, given its superior performance in high-temperature environments, a reasonable inference can be drawn that it would demonstrate enhanced durability and resistance to cracking compared to conventional concrete.

4.3. Effect of retrofitting

The retrofitting of fire-damaged slabs wrapping with BFRP laminates has proven effective in enhancing their load-carrying capacity. The application of these materials in the retrofitting process has shown promising outcomes, contributing to an increased load-carrying capacity and overall improved performance of fire-damaged slabs. This approach offers a practical and viable solution for rehabilitating concrete structures that have sustained damage.

The application of BFRP wrapping to fire-damaged specimens has been found to significantly enhance the load capacity of the slabs. Following the retrofitting with BFRP, there was an observed 80% increase in the load carrying capacity of the fire-damaged slabs.

4.4. Mode of failure

Typically, the majority of tested slabs exhibited failure through concrete crushing at the mid-span. In both cement concrete and geopolymer concrete slabs exposed to a temperature of 200ºC, initial flexural cracks emerged at the constant moment region. Additionally, a few diagonal cracks near the supports were observed. As the applied load increased, one of these cracks extended diagonally towards the nearest loading point. In both Cement Concrete and Geopolymer Concrete slabs retrofitted with BFRP Laminates, failure occurred due to concrete crushing in the high-moment region on the top surface.

In all slabs exposed to temperatures of 400ºC and 600ºC, cracking initiated in the concrete layer between the BFRP and the embedded longitudinal steel reinforcement. The failure of the slab occurred through the crushing of the concrete on the top surface, and no BFRP debonding was observed. The failure was highly brittle and localized at one end of the slab, originating from the support, for slabs exposed to fire for varying durations. This mode of collapse has been previously documented as a failure mechanism for externally bonded FRP on RC one-way slab systems, as reported by [28]. Figures 15, 16, 17 and 18, demonstrate the failure modes observed in fire-damaged conventional concrete and geopolymer slabs both before and after being wrapped with BFRP laminates.

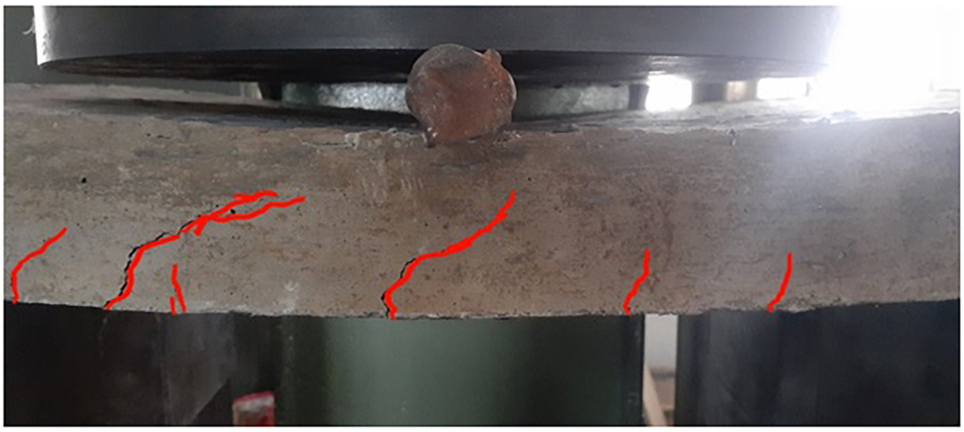

Figure 15: Failure mode of fire damaged cement concrete slab.

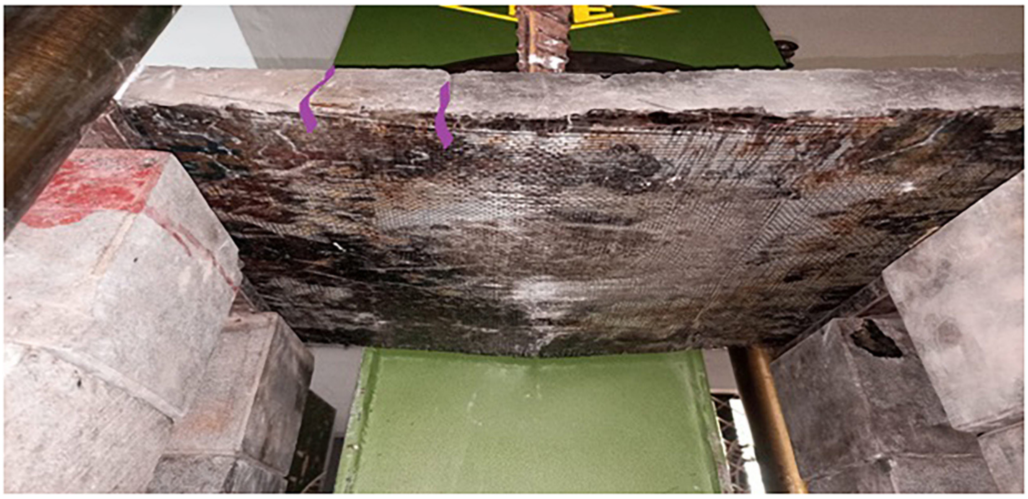

Figure 16: Failure mode of fire damaged geopolymer concrete slab.

Figure 17: Failure mode of fire damaged CC slabs wrapping with BFRP laminates.

Figure 18: Failure mode of fire damaged GPC slabs wrapping with BFRP laminates.

4.5. Predicting potential degradation

Furthermore, the investigation into the material's degradation involves an analysis of both pre- and post-fire mechanical test results, specifically focusing on compressive, split tensile, and flexural strength. The findings of these tests are thoroughly discussed in this paper. Additionally, a microstructure study utilizing X-ray Electron Microscopy (XEM) is carried out to anticipate any structural changes that might indicate degradation.

5. CONCLUSION

The following conclusions can be drawn from the results and discussions presented in this study.

- When comparing fire-damaged cement concrete and geopolymer concrete slabs, visual inspections indicated minor crack development at 200ºC for cement concrete and at 400ºC for geopolymer concrete. No spalling was observed in either case.
- No spalling was observed in geopolymer concrete slabs subjected to different temperatures, including 200ºC, 400ºC, and 600ºC, for varying time periods.
- Regarding load-carrying capacity, the ultimate load of cement concrete slabs initially increased after exposure to 200ºC for an hour but decreased with higher temperatures and longer exposure durations.
- Likewise, geopolymer concrete slabs exhibited a similar trend with crack development at 400ºC, no spalling, and a decrease in ultimate load capacity with higher temperatures and extended exposure.
- The initial increase in the ultimate load-carrying capacity of geopolymer concrete slabs was noted after being subjected to 200ºC for one and two hours. However, this capacity declined with higher temperatures and extended exposure durations.
- When compared to fire-damaged cement and geopolymer concrete slabs that were not retrofitted, those slabs retrofitted with BFRP laminates exhibited superior strength capacity. The strength increased by approximately 80%.
- These findings emphasize the effectiveness of BFRP retrofitting in enhancing the load carrying capacity of both cement concrete and geopolymer concrete slabs after fire damage.

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