REVISTA MATÉRIA V.29 N.2
ISSN 1517-7076 articles e20240033, 2024

Behaviour of fire damaged cement and geopolymer concrete slabs under static and impact loading

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ABSTRACT

Fire is considered one of the most serious potential risks for buildings and structures, as was demonstrated in the 9/11 twin tower failure. If a structure is damaged by fire, it is necessary to investigate the cause of the fire and evaluate the reusability of the damaged structure. Concrete structures often collapse in fire due to material degradation and thermal expansion. Geopolymer concrete has the potential to reduce carbon emission globally and lead to sustainable development to form an important contributor towards environmentally sustainable construction and building products industry. It proposed to be a more eco-friendly replacement to Portland cement. The experimental results of Cement and Geopolymer concrete slabs subjected to high temperatures are presented in this study. This study exclusively focuses on assessing the load-carrying capacity of fire-damaged Cement and Geopolymer Concrete structural elements. The slab specimens were subjected to temperatures of 200, 400, 600 and 800°C for a period of 1, 2, and 3 hours. 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. When exposed to high temperature, the chemical composition and physical structure of the geopolymer concrete change considerably.

Keywords: Geopolymer; Concrete; Elevated temperature; static loading; impact loading.

1. INTRODUCTION

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. 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. From an economic efficiency standpoint, opting to retrofit damaged structural components may prove more advantageous than partial or complete demolition. 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. 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. 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. This research is dedicated to examining the performance of fire-damaged cement and geopolymer concrete slabs. The primary objective is to compare the load-carrying capacity of cement and geopolymer concrete slabs under static and impact loading conditions.

Corresponding Author: Ulagambika Patchirajan Received on 02/02/2024 Accepted on 28/02/2024

DOI: https://doi.org/10.1590/1517-7076-RMAT-2024-0033

The strength of conventional concrete decreases when exposed to temperatures beyond 600°C, but by adding a higher percentage of nano silica fume, the strength of the concrete can be increased at high temperatures, improving its durability and performance [1]. Concrete undergoes changes in physical and chemical properties when subjected to high temperatures [2]. The environmental challenges posed by the disposal of waste from industries, particularly fly ash from thermal power plants, and suggests the use of fly ash as a raw material in geopolymer concretes as a sustainable solution [3]. Geopolymer concrete (GPC) made with red mud and fly ash is a more economical and eco-friendly alternative to OPC-based concrete. The study found that geopolymer concrete based on fly ash had higher compressive and flexural strength than geopolymer based on red mud at different mix ratios [4]. 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 [5]. 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 [6]. The fly ash geopolymer concrete shows better resistance to spalling and cracking than ordinary cement concrete in the fire. It also retained a higher percentage of strength than cement concrete specimen [7]. 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 [8]. The GPC has less embodied energy compared to the OPC concrete. The cost of the GPC at a bulk level reduced the cost of up to 40% of the OPC concrete [9]. Strength developed in geopolymer concrete is high when compared to normal concrete. Early strength developed (90% strength will be gain in 3 to 7 days) which helps in removing scaffolding early. Resistance to temperature and spalling is high compared to normal concrete. Economical in large scale usage. Sustainable use of waste materials helps to overcome problem of land filling [10].

The main limitations of fly ash based geopolymer concrete are slow setting of concrete at ambient temperature and the necessity of heat curing are eliminated by addition of Ground Granulated Blast Furnace Slag (GGBS) powder which shows considerable gain in strength. In this research, the mix design M30 is designed in this research work and various percentage 10, 25, 50, 75% GGBS is replaced with fly ash [11]. The embodied energy of fly ash- GGBS based geopolymer concrete is 40% less than that of OPC based concrete. Sodium hydroxide (39%) and sodium silicate (49%) together contributes a lion's share to embodied energy of geopolymer concrete while in OPC cement contributes nearly 94% of the total embodied energy [12]. Uniaxial compression tests were conducted to measure the strength of the geopolymer paste specimens. X-ray diffraction (XRD), scanning electron microscopy/energy dispersive X-ray spectroscopy (SEM/EDX), and Fourier transform infrared spectroscopy (FTIR) analyses were performed to investigate the micro/nano-structure, morphology and phase/surface elemental compositions of the geopolymer paste and the effect of calcium (Ca) on them [13]. Geopolymer concrete is well-suited to manufacture precast concrete products that can be used in infrastructure developments [14]. The coupled effect of temperature and duration on the mechanical properties of self compacting concrete were studied. Further, the load at first crack and load carrying capacity of reinforced concrete beams was found to be decreasing with the rise in temperature for both 2hrs and 4hrs duration [15]. Beam shows flexural cracks in the pure bending region at temperature of 100°C and 300°C and shear flexure cracks in the shear region at temperature of 600°C and 900°C [16]. In transient test the specimens were preloaded to a certain stress level and heated up to failure. In non- transient tests, the specimens were first heated up to a set temperature and then compressed until failure [17]. The polypropylene fibres is a good alternative to traditional concrete, since it improves its strength and its behaviour in case of fire. Also, the addition of steel fibres presents advantages compared to traditional concrete, although the former is not able to achieve the performance obtained when adding polypropylene fibres [18]. The findings highlight the significant influence of lightweight aggregates on the workability, density, and mechanical properties of LWGPC. TAA-based GPC exhibited improved workability and higher compressive, split tensile, and flexural strengths owing to its increased density. Conversely, LECA-based GPC demonstrated enhanced workability but reduced density and mechanical strength [19]. The study found that a mix containing 80% GGBS (Ground Granulated Blast Furnace Slag) and 20% fly ash was the best blend, even though using 100% GGBS resulted in the highest strength. The optimized mix showed significantly increased strength compared to control samples under different curing conditions. However, using 100% GGBS caused minor surface cracks on the cubes, making it unsuitable for slabs [20].

The ideal substitution is determined to be the M27 mix, a geopolymer concrete where 5% of the coarse aggregate is replaced with coconut shell and 5% with palm shell at a molarity of 16M. This indicates that these organic solid wastes can be efficiently used in concrete. The use of coconut shell aggregate is particularly promising due to its excellent impact resistance. The study will be expanded to assess impact and bond characteristics in further detail [21]. Low calcium fly ash-based geopolymer concrete and demonstrated improved performance in terms of load carrying capacity, deflection, and crack propagation compared to conventional concrete [22]. The combination of geopolymer concrete and bamboo reinforcement presents a promising solution for sustainable construction practices. Geopolymer concrete, with its rapid settling and impressive compressive strength, offers a viable alternative to traditional cement-based concrete, reducing environmental impact. Although bamboo requires treatment for durability, bamboo-reinforced geopolymer concrete (BRGC) showcases enhanced flexural strength compared to conventional reinforced concrete (RCC) [23]. The workability and compressive strength of low-calcium fly ash-based SCGC, meticulously investigating the impacts of additional water, curing duration, and temperature variations. Their findings highlight the necessity of meticulous control over these factors to attain desired self-compacting behaviour. Collectively, these studies contribute nuanced perspectives to the evolving understanding of SCGC, encompassing mechanical enhancement, environmental sustainability, and the intricate interdependencies between constituent materials and resultant properties [24]. The impact resistance of fiber-reinforced concrete using polypropylene fibers and GFRP (Glass Fiber Reinforced Polymer) wrapping. Notably, GFRP wrapping had a more significant impact, improving resistance by about 150%. Moreover, GFRP-wrapped specimens exhibited reduced cracks and damage intensity, suggesting a substantial improvement in performance [25]. The primary objective of the project is to assess the mechanical characteristics of cement and geopolymer concrete slabs when subjected to varying durations of fire exposure, comprehensively examining the impact of fire on these slabs. Beyond the fire-related aspects, the project also seeks to evaluate the response of cement and geopolymer slabs to static loading. Additionally, the study intends to determine the load-carrying capacity of fire-damaged cement and geopolymer concrete slab specimens, both in their original state and after exposed to fire, under static and impact loading conditions.

1.1. Research significance

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.

2. MATERIALS AND METHODS

2.1. Cement

The specimens were prepared using OPC 53 grade cement, adhering to properties outlined in IS 12269-2013. The properties of tested cement, along with the values recommended by IS 12269-2013 [26], are presented in Table 1.

2.2. Fly ash (FA)

Fly ash is a finely grained grey powder comprised predominantly of spherical, glassy particles, generated as a byproduct in coal-fired power stations. Possessing pozzolanic properties, fly ash reacts with lime to create cementitious compounds, earning its common designation as a supplementary cementitious material. Specimens were prepared using Class F fly ash.

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

2.3. Ground granulated blast furnace slag (GGBS)

GGBS (Ground Granulated Blast Furnace Slag) is an environmentally beneficial product derived from a by-product of the iron industry. It stands out as a premium, low-CO2 substance. Due to its low embodied CO2, GGBS enables the design of concrete mixes for sustainable construction. The determined essential properties of the geopolymer binder (FA80: GGBS20) are provided in Table 2.

2.4. Aggregate

M-sand, adhering to IS: 383-1970 [27] specifications, serves as the fine aggregate, while crushed granite stone aggregates with maximum sizes of 20 mm and 12.5 mm are employed as the coarse aggregate. The properties of both fine and coarse aggregates are detailed in Table 3. Particle size distribution curve of fine aggregate and coarse aggregates are shown in Figure 1 and 2.

2.5. Steel

The size and diameter of reinforcement was selected with references to IS: 1786-1985 [28]. The 8 mm diameter rebars used has been tested for its tensile stress in a universal testing machine.

2.6. Water

The water employed in this mixing process should be fresh and devoid of any organic or harmful solutions that might compromise the properties of the mortar. The use of saltwater is prohibited. Potable water is suitable for both mixing and curing slabs.

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%

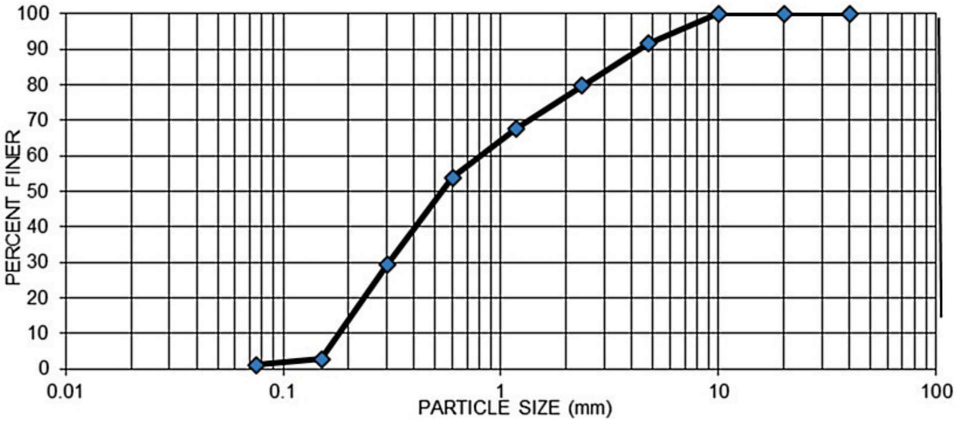

Figure 1: Gradation curve of fine aggregate.

2.7. Alkaline solution

In the preparation of geopolymer concrete, sodium hydroxide (NaOH) and sodium silicate (Na_2SiO_3) serve as the alkaline solution. To prepare one liter of 8M sodium hydroxide solution, 320 g of NaOH pellets were dissolved in potable water. In order to attain the desired strength, the ratio of sodium silicate solution to sodium hydroxide solution was established at 2.5. The combined solution was then stored for 24 hours before being utilized for casting.

2.8. Molarity

High strength in Geopolymer concrete is achieved with an 8M concentration, as indicated by various literature sources. The maximum strength of 8M concrete is typically observed after 28 days of ambient curing. Following this duration, a gradual decrease in strength becomes noticeable. The heightened strength of geopolymer concrete is primarily attributed to the presence of soluble alumino-silicates. The compressive strength of Geopolymer Concrete generally demonstrates a positive correlation with the molarity of sodium hydroxide.

2.9. Mix design for conventional concrete

In this study, the mix design adhered to the Indian Standard guidelines outlined in IS:10262-2009. The characteristic compressive strength of concrete used for the study was 25N/mm^2. The mix proportions for Conventional concrete are provided in Table 4.

2.10. Mix design for geopolymer concrete

The mix proportion chosen for the 8M geopolymer concrete in this study has been specifically determined to achieve a target compressive strength of 25 N/mm^2. Table 5 presents the mix proportions for Geopolymer concrete.

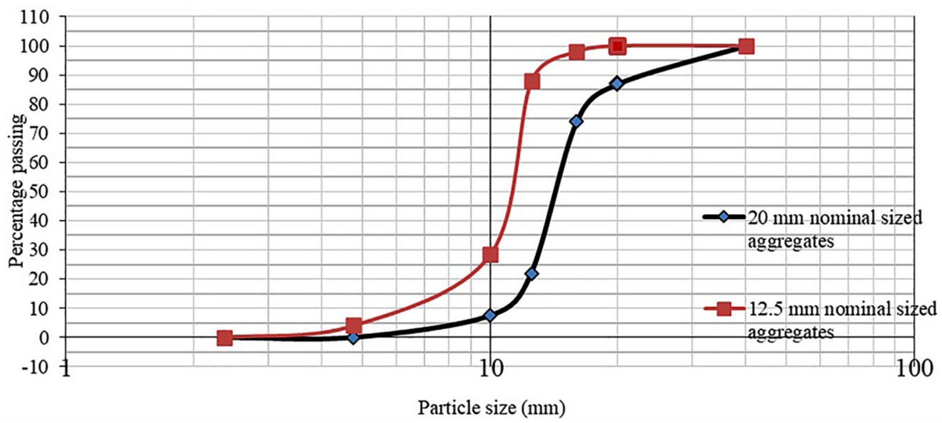

Figure 2: Gradation curve of coarse aggregate.

Table 4: Mix proportion for conventional concrete.

CEMENT (kg/m^3)	M – SAND (kg/m^3)	COARSE AGGREGATE (kg/m^3)		WATER-CEMENT RATIO
		20 mm	12.5 mm	
350.0	705.60	747.56	505.09	0.48

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

Table 5: Mix proportion for geopolymer concrete.

FLYASH (kg/m^3)	GGBS (kg/m^3)	M – SAND (kg/m^3)	COARSE AGGREGATE (kg/m^3)		ALKALINE-BINDER RATIO
			20 mm	12.5 mm	
280	70	732.09	775.63	524.07	0.48

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 in accordance with the Indian design code IS456-2000, with dimensions measuring 450 × 600 × 50 mm. A clear cover of 10 mm was uniformly provided on all sides of the slabs.

3.2. Casting of reinforced slabs

Plywood moulds measuring 600 × 450 × 50 mm were fabricated. Necessary reinforcements were prepared and the casting process was completed. Cover blocks were then installed, and the reinforcements were positioned after applying grease to the mould sides to facilitate easier demoulding. Concrete casting was carried out, and the specimen was surfaced. Demoulding took place after 24 hours, followed by curing for 28 days in water for cement concrete slabs and ambient curing for geopolymer concrete slabs. Figure 3 and Figure 4 depict the stages involved in casting the RC slab specimen, including the placement of reinforcement in the mould. Figure 5 and Figure 6 illustrate the curing processes for both Conventional and Geopolymer concrete.

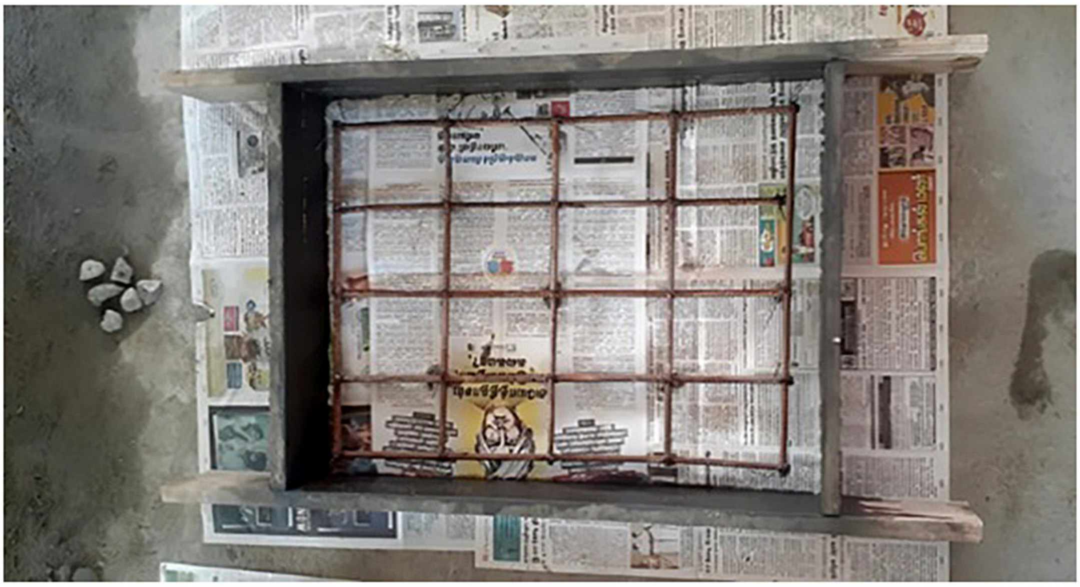

Figure 3: Placing of reinforcement.

Figure 4: Casting of specimens.

Figure 5: Water curing of cement concrete slabs.

Figure 6: Ambient curing of geopolymer concrete slabs.

3.3. Fire exposure

A high-speed burner (depicted in Figure 7) was employed for the combustion of both cement and geopolymer slabs. The temperature range was closely monitored with a K-type thermocouple (Utc4202 model, as shown in Figure 8) to ensure precise control of the fire temperature.

Following exposure to fire for different durations (1h, 2h, and 3h), the temperature range was continually monitored before allowing the specimens to cool inside the furnace. Figure 9 and 10 illustrate the firing process and the resulting damage to the slabs caused by the fire.

3.4. Testing of specimens

All the slabs underwent testing under identical loading conditions, subject to a point load at the mid-span. The Leaf Spring Testing Machine was employed for the testing process, boasting a loading accuracy well within ± 1%, in accordance with IS 1828/ BS1610 standards. The test setup for reinforced slabs is depicted in Figure 11.

Figure 7: Set up for firing.

Figure 8: Thermocouple.

Figure 9: Exposure of fire on concrete slab.

Figure 10: Fire damaged slabs.

Figure 11: Load set up for static load test on slabs.

3.5. Mode of failure

In general, the majority of tested slabs experienced failure due to concrete crushing at the mid-span. In both cement concrete and geopolymer concrete slabs exposed to a temperature of 200ºC, initial flexural cracks were observed primarily in the constant moment region. Additionally, a few diagonal cracks near the supports were noticed. As the applied load increased, one of these cracks progressed diagonally towards the nearest loading point.

For both Cement Concrete and Geopolymer Concrete slabs failed by crushing of the concrete in high moment region on the top surface as shown in Figure 12. Similar failure pattern was observed by [29], who noted that failure was characterized by compression failure of the concrete in the constant moment region on the top surface of slabs which should be expected for a section having a short effective depth. The failure exhibited extreme brittleness, manifesting at one end of the slab and originating from the support. This pattern was observed in slabs exposed to fire for varying durations.

3.6. Effect of fire on cement and geopolymer concrete

3.6.1. Mass loss

Both the cement concrete and geopolymer concrete slabs underwent weighing both before and after exposure to heating. The concrete exhibited a nearly constant increase in mass loss as temperatures rose. It was observed that the mass loss was more pronounced initially, up to 200ºC. This higher mass loss is attributed to the evaporation and loss of free water, a consequence of the initial hydrothermal conditions. The percentage of mass loss at any given temperature was calculated by dividing the difference between the final and initial mass by the initial mass of the test specimen. Table 6 provides a summary of the mass loss observed in cement and geopolymer concrete slabs exposed to elevated temperatures for various durations which is graphically represented in Figures 13 and 14.

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

The ultimate loads sustained by the fire-damaged cement concrete slabs under static loading are provided in Table 7. For a visual representation, Figure 15 illustrates the evaluation of the ultimate load-carrying capacity of the fire-damaged slabs at different temperatures and durations under static loading conditions.

3.7. Impact load test

An impact load test involves the application of a sudden and dynamic force, typically generated by dropping a heavy weight, to a structure or component. This test is conducted to assess the structure's ability to withstand

Figure 12: Failure mode of fire damaged slab.

Table 6: Mass loss of cement concrete and geopolymer slabs subjected to different temperature and duration.

EXPOSURE CONDITION		MASS OF CEMENT CONCRETE SLAB (KG)			MASS OF GEOPOLYMER CONCRETE SLAB (KG)		
TEMPERATURE (ºC)	DURATION (HOUR)	BEFORE	AFTER	% OF MASS LOSS	BEFORE	AFTER	% OF MASS LOSS
Room temperature	–	34.58	–	–	34.56	–	–
200	1	34.55	33.86	2	34. 62	34.10	1.5
	2	34.55	33.58	2.8	34.58	33.65	2.7
	3	34.56	33.28	3.7	34.60	33.25	3.9
400	1	34.54	33.02	4.4	34.54	33.05	4.3
	2	34.54	32.85	4.9	34.62	32.65	5.7
	3	34.58	32.51	6	34.55	32.06	7.2
600	1	34.60	31.90	7.8	34.60	31.69	8.4
	2	34.55	31.37	9.2	34.62	31.26	9.7
	3	34.62	30.81	11	34.55	30.75	11
800	1	34.55	30.37	12.1	34.62	30.43	12.1
	2	34.62	29.53	14.7	34.58	29.25	15.4
	3	34.58	28.63	17.2	34.56	28.06	18.8

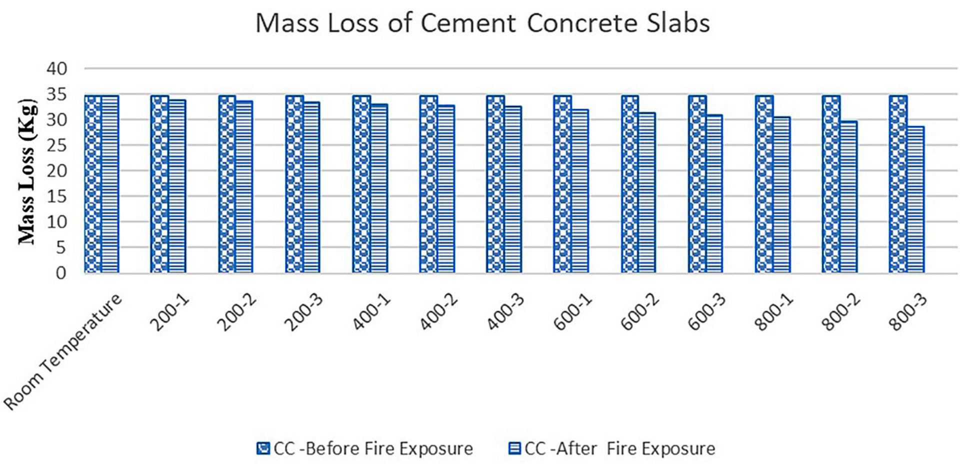

Figure 13: Mass loss of cement concrete slabs subjected to different temperature and duration.

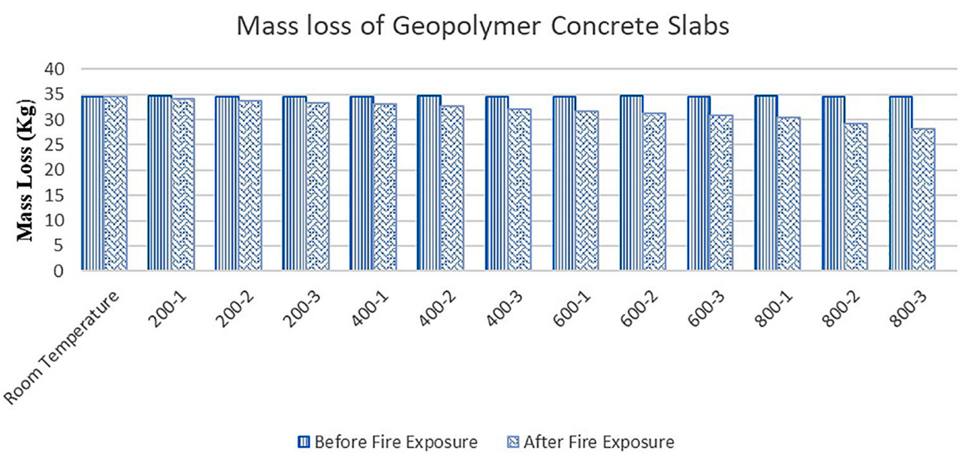

Figure 14: Mass loss of geopolymer concrete slabs subjected to different temperature and duration.

Table 7: Ultimate load carrying capacity of cement and geopolymer concrete slabs subjected to different temperature and duration under static loading.

EXPOSURE CONDITION		LOAD CARRYING CAPACITY OF CC SLAB (KN)	LOAD CARRYING CAPACITY OF GPC SLAB (KN)	% OF INCREASE IN LOAD CARRYING (COMPARING TO CC)
TEMPERATURE (ºC)	DURATION (HOUR)			
Room temperature	–	34	40	17.65
200	1	37.4	47.2	26.20
	2	33.32	43.2	29.65
	3	32.3	38.8	20.12
400	1	31.62	39.2	23.97
	2	29.24	36.8	25.85
	3	27.2	34.4	26.47
600	1	28.9	36	24.57
	2	25.5	33.2	30.20
	3	22.1	30	35.75
800	1	22.78	28.8	26.43
	2	17.68	24.0	35.75
	3	13.6	20.4	50.00

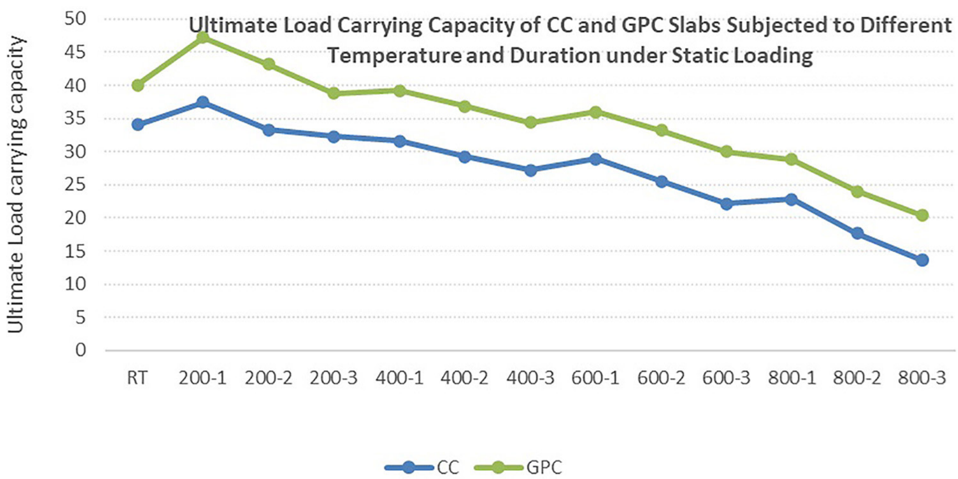

Figure 15: Overall comparison of Ultimate load carrying capacity of Cement and Geopolymer slabs at various temperatures and various durations.

sudden loads, such as those caused by falling objects, seismic events, or other dynamic forces. Drop weight test was used to simulate impact load on the Steel reinforced concrete slabs of 600 mm size and test set up was shown in Figure 16 a. It consists of a steel tripod with steel hammer of mass 63.5 kg was used for impact on the specimen. The height of fall was kept as 760 mm. The free fall of the hammer at the centre of slab applied the impact load on the slabs and the slab damaged by impact loading was shown in Figure 16 b. The no. of blows required to achieve ultimate failure was noted and recorded in Table 8.

The energy absorption of the Steel reinforced conventional as well as geopolymer concrete slabs can be calculated using the formula:

$$E = N \times (w \times h) \text{ joules}$$

Where,

E is the energy absorbed in joules,

w is weight of hammer in Newton,

h is the height of drop in meter and

N is the no. of impact blows.

Figure 16: a) Impact load test set up. b) Punching failure of slabs by impact load test.

Table 8: Load carrying capacity of steel reinforced cement concrete and geopolymer concrete slabs under impact loading condition.

FIRE EXPOSURE CONDITION		IMPACT STRENGTH			
TEMPERATURE (ºC)	DURATION (HOUR)	CONVENTIONAL CONCRETE		GEOPOLYMER CONCRETE	
		NO. OF BLOWS	IMPACT STRENGTH IN JOULES	NO. OF BLOWS	IMPACT STRENGTH IN JOULES
Room temperature	–	16	9182.16	12	6886.62
200	1	17	9756.05	13	7460.51
200	2	14	8034.39	11	6312.74
200	3	13	7460.51	10	5738.85
400	1	15	8608.28	12	6886.62
400	2	14	8034.39	11	6312.74
400	3	12	6886.62	9	5164.97
600	1	13	7460.51	10	5738.85
600	2	12	6886.62	9	5164.97
600	3	8	4591.08	5	2869.43
800	1	9	5164.97	6	3443.31
800	2	7	4017.12	4	2295.54
800	3	5	2869.43	3	1721.66

4. RESULTS AND DISCUSSIONS

4.1. Effect of temperature

The damages caused by exposure to high temperatures can be generally identified by examining at the surface of the concrete. Therefore, evaluation of fire damaged concrete typically begins with visual inspection for changes in colour, cracks, and spalling of the concrete surface in conventional as well as geopolymer concrete.

At temperatures of 200ºC and above, major changes in the colour are observed. Here are some common signs of damage caused by high temperatures in concrete is given in Table 9. The physical and chemical reactions in response to fire, as outlined in Table 10.

The impact of temperature on concrete is a crucial factor to consider, as it can greatly affect the structural integrity and durability of the material. In this context, the comparison between conventional concrete and geopolymer concrete highlights the advantages of the latter in terms of temperature resistance.

Overall, the findings underscore the potential of geopolymer concrete as a more durable and resilient alternative in high-temperature environments. Its ability to resist spalling and maintain structural integrity at

Table 9: 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 10: 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.

elevated temperatures, as observed up to 600ºC, makes it an attractive option for applications such as industrial settings, fire-resistant structures, and infrastructure exposed to extreme heat conditions.

It is worth noting that the performance of concrete at high temperatures can depend on various factors, including the specific composition, curing methods, and other environmental conditions. Therefore, further research and testing are necessary to fully understand the behaviour of geopolymer concrete under different temperature scenarios and optimize its design for specific applications.

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 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. These findings demonstrate the detrimental effects of prolonged exposure to high temperatures on both the load carrying capacity and compressive strength of conventional concrete and geopolymer concrete. It underscores the importance of considering the duration of exposure when designing concrete structures for fire or high-temperature environments, and highlights the potential advantages of geopolymer concrete in terms of improved load carrying capacity and strength retention under such conditions.

In conclusion, the duration of exposure plays a significant role in determining the behaviour and performance of concrete. The comparison between conventional concrete and geopolymer concrete sheds light on their respective responses to prolonged periods of exposure.

In the case of conventional concrete, minor cracks become apparent after being subjected to high temperatures for an extended duration. This indicates that the longer the duration of exposure, the more susceptible conventional concrete becomes to thermal stress and potential structural damage. On the other hand, the specific response of geopolymer concrete to prolonged exposure is not mentioned, but considering its superior performance in high-temperature environments, it is reasonable to infer that it would exhibit better durability and resistance to cracking compared to conventional concrete.

The behaviour of concrete over time is crucial in applications where sustained exposure to high temperatures is anticipated. It is essential to consider the potential deterioration and loss of structural integrity that conventional concrete may experience over extended durations, particularly when subjected to elevated temperatures. Geopolymer concrete, with its superior thermal properties, holds promise as a more reliable option for such applications, as it has shown resilience and stability even at high temperatures in shorter-duration tests.

4.3. Impact strength

Punching failure occurred for all slabs. Less bending cracks and lower punching resistance were observed. Comparing to geopolymer slabs, conventional concrete slabs performs better. In impact load testing, when the weight drops from a certain height, the spalling of concrete takes place immediately after the weight falls. The cracks develop from the center to the periphery of the slab. At 200 for 1 hour the impact strength in conventional concrete increased by 6.25 whereas geopolymer concrete 8.33% The process of impact testing is used to study the various characteristics of materials. These include toughness, hardness, ductility and strength. It involves the sudden application of a load to a specimen in order to determine its impact value.

The impact value of a material can change based on temperature, size and the amount of plastic deformation it can absorb. This is why it is important to ascertain whether the material is tough or brittle.Temperature can bring change to the impact value in a positive correlation. This means that, generally, lower the temperature, the lesser the impact energy of the material. As the temperature rises, the impact energy of the material is increased. The statement that "conventional concrete slabs demonstrate better performance than geopolymer concrete in impact tests" could be influenced by several factors related to the material properties of conventional concrete and geopolymer concrete. Possible reasons for conventional concrete outperforming geopolymer concrete in impact tests:

1. Brittle Behavior of Geopolymer Concrete: Geopolymer concrete tends to exhibit more brittle behavior compared to conventional concrete. Brittleness can result in faster crack propagation and a higher likelihood of sudden failure under impact loading.

2. Flexural Strength Differences: Conventional concrete might have better flexural strength characteristics, making it more resistant to bending or deformation under sudden impact loads. Geopolymer concrete, depending on the mix design, may have different flexural properties.
3. Microstructure and Porosity: Differences in the microstructure and porosity of conventional and geopolymer concrete can impact their response to impact loading. Geopolymer concrete formulations may have variations in these properties that affect their ability to absorb energy during impact.
4. Curing Conditions and Maturity: The curing conditions and maturity of the concrete can influence its overall strength and durability. Differences in curing practices between conventional and geopolymer concrete could contribute to variations in their impact resistance.
5. Material Testing Standards: Testing standards used for impact tests may be more tailored to conventional concrete performance, and the specific characteristics of geopolymer concrete may not align perfectly with these standards.

It's important to note that the performance of concrete in impact tests can be influenced by the specific mix design, curing conditions, testing methods, and the nature of the impact load. Research studies and comparative testing under standardized conditions can provide more specific insights into the impact resistance of different concrete types.

4.4. Practical difficulties in implementing

Geopolymer concrete is an innovative alternative to traditional Portland cement-based concrete, utilizing industrial byproducts and alkali activators to form a binder. While it offers several advantages such as reduced carbon emissions and improved durability, there are also practical difficulties and challenges associated with implementing geopolymer concrete in construction. Some of these difficulties include:

Material Sourcing and Consistency: Geopolymers often require specific raw materials such as fly ash or slag, which may not always be readily available or consistent in quality. The variability in material properties can affect the final mix and performance of geopolymer concrete.

High Alkalinity: The alkaline nature of geopolymer concrete can be detrimental to certain types of reinforcement materials, potentially leading to corrosion and reduced structural integrity over time. Special precautions and suitable coatings are necessary to mitigate this issue.

Shortage of Technical Expertise: Due to its novelty, there is a shortage of skilled professionals with expertise in geopolymer concrete technology. This can limit the ability to properly design, produce, and implement geopolymer concrete in construction projects.

Long-Term Durability Studies: While geopolymer concrete shows promising durability properties in the short term, its long-term performance under various environmental conditions is still being studied.

Setting Time: Geopolymer concrete may exhibit a faster setting time compared to conventional concrete.

Curing Requirements: Geopolymer concrete requires careful curing to develop its desired properties. The curing process can be more critical and sensitive compared to conventional concrete, demanding strict control over temperature, humidity, and duration.

As geopolymer technology continues to mature, these practical difficulties may become less significant, making geopolymer concrete a more viable and sustainable option for construction projects.

5. CONCLUSION

The following conclusions can be inferred from the above results and discussions obtained in this study.

- Comparing the fire-damaged cement concrete and geopolymer concrete slabs, visual inspections revealed minor crack development at 200ºC for cement concrete and at 400ºC for geopolymer concrete. No spalling was observed in either case.
- There was no spalling observed for geopolymer concrete slabs subjected to different temperatures like 200ºC, 400ºC and 600ºC for varying time periods.
- In terms of 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.
- Similarly, geopolymer concrete slabs showed a similar trend with crack development at 400ºC, no spalling, and a decline in ultimate load capacity with higher temperatures and prolonged exposure.

- The initial rise in the ultimate load-carrying capacity of geopolymer concrete slabs was observed after being subjected to 200ºC for one and two hours. However, this capacity declined with higher temperatures and prolonged exposure durations.
- In impact tests, conventional concrete slabs demonstrate better performance than geopolymer concrete.

6. ACKNOWLEDGMENTS

The authors would like to thank the Government College of Engineering, Tirunelveli for conducting the Experimental works.

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