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A REVIEW ON GEOPOLYMER CONCRETE BEHAVIOUR UNDER ELEVATED TEMPERATURE INFLUENCE

ARJAN FAKHRULDDIN ABDULLAH[1]*, MAZIN BURHAN AL-DEEN ABDUL-RAHMAN[1] AND ALYAA ABBAS AL-ATTAR[2]

[1]Department of Civil Engineering, Structure Engineering, Faculty of Engineering, Tikrit University, Tikrit, Saladin Governorate, Iraq. [2]Department of Civil Engineering, Building Construction Material, Northern Technical University, Nineveh Governorate, Iraq.

**Corresponding author: arjan.fakhruldeen@st.tu.edu.iq*
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Abstract: Geopolymers are considered promising, environmentally friendly, and sustainable substitutes for Ordinary Portland Cement (OPC). Geopolymers exhibit commendable mechanical characteristics, including resistance to high temperatures and noteworthy environmental advantages. This review article focuses on geopolymer concrete (GPC) and mortar behaviour under high temperatures, addressing problems, and improvement methods. The main problem considered is concrete spalling induced by fire which poses a significant threat to concrete structures, particularly those constructed with high-strength concrete. This review aims to elucidate the behaviour of geopolymer concrete under high temperatures and explore strategies to mitigate the impact of such conditions. Critical findings indicate that geopolymer concrete can maintain up to 80% of its compressive strength after exposure to temperatures as high as 800°C. Additionally, incorporating steel fibres into geopolymer concrete has been shown to enhance its residual compressive strength by up to 25% and significantly reduce spalling. These results underscore the potential of geopolymer concrete as a resilient material in fire-prone environments and highlight the benefits of using steel fibres to improve its performance under elevated temperatures.

Keywords: Geopolymer, fire exposure, problems, improvements.

Introduction

Concrete made with Ordinary Portland Cement (OPC) usually offers sufficient resistance against fire. Nevertheless, it is worth noting that the strength of OPC tends to diminish when subjected to significant temperatures due to both chemical and physical alterations (Crozier & Sanjayan, 1999; Tuama *et al*., 2020). Moreover, it should be noted that traditional concrete is susceptible to spalling when subjected to fire. This spalling phenomenon results in the gradual and sequential removal of concrete cover, which can ultimately expose the primary reinforcements embedded within the concrete to the fire hazard (Sanjayan & Stocks, 1993). Consequently, attempts were undertaken to ascertain an alternative adhesive exhibiting commendable resistance against fire, encompassing the ability to withstand strength deterioration under great temperatures, and spalling resistance.

The construction and transportation industries release carbon dioxide (CO_2) into the atmosphere. The construction industry is responsible for approximately 7% of global carbon dioxide (CO_2) emissions, which contribute to 65% of global warming.

The ecological consequences of cement production are substantial, posing risks to both human health and wildlife. Increasing carbon dioxide emissions means that production consumes natural resources and necessitates more significant energy expenditure. From an environmental standpoint, the use of OPC had certain constraints (Singh & Middendorf, 2020; Al-Husseinawi *et al*., 2022). On 25 January 2016, India decided to attain complete utilisation of Fly Ash (FA) by power industries within five years. During the initial half of the fiscal year 2019 to 2020, 194 thermal power plants were assessed with 76 plants, demonstrating a utilisation rate exceeding 100%. India's thermal plant produced 169.25 million tonnes of FA, with 107.10 million tonnes utilised across different sectors (Hanoon *et al*., 2021; Yadav *et al*., 2022). Therefore, it is possible to synthesise GP, a subclass of alkali-activated materials, utilising industrial by-products involving FA, ground-granulated blast furnace slag (GGBS), and other silica-rich wastes which are discarded worldwide. Geopolymerisation is an emerging technology utilised in manufacturing geopolymer concrete (GPC) (Shubbar *et al*., 2020a; Shubbar *et al*., 2020; Majdi *et al*., 2020b; Al-Faluji *et al*., 2021; Al-Mamoori *et al*., 2021; Marshdi *et al*., 2021; Shubbar *et al*., 2022).

The carbon dioxide equivalent emissions (CO^{2-e}) generated by the processes involved in acquiring raw materials, including for concrete production were determined by Turner and Collins (2013). The underlying presumptions were predicated upon the various tasks entailed in fabricating a single cubic metre of Grade 40 concrete (such as concrete possessing a compressive strength of 40 MPa) within the confines of the Melbourne Metropolitan region. These assumptions encompassed the implementation of construction methodologies, manufacturing techniques, and utilising materials readily accessible within the local vicinity.

The alkaline activator utilised in the production of geopolymers was sodium hydroxide, which had a concentration of 16 M. GPC exhibited a notable reduction of approximately 9% in CO_2 emissions compared to conventional concrete, consisting of a 100% OPC binder without any supplementary additives or replacement materials. The observed outcome deviated from preceding investigations. The incorporation of transportation, treatment, and extraction of raw materials in the manufacturing phase of alkali activators for geopolymers, the energy expenditure during the production process of alkali activators, and the necessity for elevated curing temperatures to achieve adequate strength in GPC were the key factors contributing to emissions exceeding initial estimates for GPC.

"Geopolymer" refers to inorganic polymers composed of aluminosilicates (Davidovits, 1993). The geopolymer composite exhibits exceptional fire and corrosion resistance properties (Akbari *et al*., 2013). Geopolymer has recently gained recognition as an innovative engineering binder material due to its environmentally sustainable features (Duxson *et al*., 2007). These polymers can be created by combining pozzolanic compounds or aluminosilicate source materials with strongly alkaline solutions (Davidovits & Davidovics, 1991). GPs are widely regarded as having favourable resistance against fire, primarily attributed to their ceramic-like features (Cheng & Chiu, 2003). Hence, geopolymer-based concrete may exhibit enhanced resistance against fire in comparison to conventionally produced concrete utilising OPC.

In the present investigation, GPs are synthesised through the combination of fly ash that possesses essential quantities of silicon and aluminium with an alkaline solution. The fly ash utilised for this application is classified as Class F. Fly ash is a by-product of coal-fired power stations (Bakharev, 2005). Consequently, utilising fly ash as a raw material for GPs offers the advantage of reduced energy usage. The energy consumption is estimated to be around 60% lower than OPC, as stated by Z. Li *et al*. (2004).

Geopolymerisation involves converting aluminosilicate raw material into an interconnected 3D network characterised by covalently bonded [-Si-O-Al-O-]n bonds. In essence, the geopolymerisation process pertains to geosynthesis of chemically integrated minerals. The process of polymerisation yields a highly viscous cementitious slurry, which upon undergoing the hardening process, transforms into a robust, long-lasting, and densely packed polymeric substance (Al-Khafaji *et al*., 2018;

Zeini *et al*., 2023). Regarding the pressing issue of climate change and the impact of greenhouse gas emissions, it is worth noting that geopolymers could potentially mitigate the release of CO_2 from cement plants significantly. Geopolymers offer several notable advantages in the realm of civil engineering.

- Waste utilisation: GPC can utilise various waste products, including fly ash, bottom ash, furnace slag, red mud, and more, as valuable constituents in its composition.
- Mitigation of CO_2 emissions: By implementing measures to curtail the demand for OPC, it is possible to effectively reduce the CO_2 emissions associated with OPC production (Shubbar *et al*., 2021).
- Optimisation of natural resource utilisation: Geopolymer technology offers a significant advantage by utilising waste materials while OPC relies on consuming natural resources.
- Minimised spatial requirements for the disposal of waste materials.
- Reduced water usage: Within the geopolymerisation process, water assumes a subordinate function, OPC production, and the use of water as a hydration is significant.

The thermal gradient exhibited by OPC is an essential factor contributing to its substandard performance under extremely high temperatures. Efforts are undertaken to explore alternative construction materials that exhibit outstanding resistance to heat stress, particularly their ability to withstand elevated temperatures without essential loss in strength and spalling resistance. Remarkably, the inorganic structure of GPs possesses inherent fire-resistant properties, displaying exceptional thermal stability as the gel structure only experiences a minor degradation when subjected to temperatures ranging from 700°C to 800°C (Amin *et al*., 2020; Tobbala *et al*., 2020). The primary advantage of GPs over composites based on OPC lies in their ability to resist deterioration caused by the dehydration of hydrate content. GPs have demonstrated essential chemical stability when subjected to significant temperatures (Li *et al*., 2013; Abdulkareem *et al*., 2014; Luhar *et al*., 2021; Marvila *et al*., 2021).

In a broad sense, the strength of concrete is derived from the process of cement particle hydration, which leads to the creation of calcium silicate hydrates (C-S-H) as a by-product. Similarly, the geopolymer solidification process occurs when the abundant aluminosilicate substance triggers the activation of an alkaline activator, referred to as polymerisation. The geopolymerisation process results in the formation of various primary forms, including poly (silicon-oxo aluminate) [-Si-O-Al-O], poly (silicon-oxo-aluminate-siloxo) [-SiO-Al-O-Si-O], and poly (silicon-oxo-aluminate-disiloxo) [-Si-O-Al-O-SiO-Si-O]. Based on the given information, the users text appears to be simply the number (Inti *et al*., 2017).

The interaction between alumina-silica oxide and an alkaline medium forms a three-dimensional polymer chain in the presence of water. The compound $M_2O•Al_2O_3$-$xSiO_2·yH_2O$ is frequently encountered in civil engineering applications, particularly in geopolymer materials. In this compound, the symbol M represents an alkaline element, indicating its presence in an alkaline medium. The alkali M-OH and $R_2O(n)\ SiO_2$- based silicate is widely recognised as the predominant alkaline activator in civil engineering applications. Various types of M-based alkali mediums can be found in civil engineering applications. These include sodium carbonate ($NaCO_3$), sodium hydroxide (NaOH), sodium sulfate (Na_2SO_4), and potassium hydroxide (KOH). These mediums exhibit an aluminosilicate impact and ultimately form calcium-alumino-silicate hydrates (CA-S-H) as the final product (Ryu *et al*., 2013).

The inception of geopolymer research can be traced back to Ukraine during the late 1950s when Glukhovsky made a ground-breaking discovery regarding the potential synthesis of binders through the utilisation of aluminosilicates (such as clays, rocks, and slags) in conjunction with alkali metal solutions.

He referred to the binder as "soil cement" and the corresponding concrete as "soil silicates". The material was employed in constructing structures in Mariupol, Ukraine during the 1960s. After over half a century, it is noteworthy to observe that the structures have persevered and remain upright today (Xu *et al*., 2008). Several additional structures were constructed utilising this advanced technology. In 1989, a pioneering residential structure was erected in Lieptsk, Russian Federation, showcasing the utilisation of alkali-activated concrete exclusively, devoid of any Portland cement. Moreover, prior research has demonstrated that GPC exhibits exceptional resistance against fire, Alkali-Silica Reaction (ASR), and acid. Moreover, in the event of fire exposure, it does not release any hazardous gases. Hence, using lightweight GPC as a sustainable construction material with essential potential for sustainable development and resistance against fire has been explored in previous studies (Nematollahi *et al*., 2017; Lahoti *et al*., 2019; Xu *et al*., 2021).

Discussion

GPC at Elevated Temperature

In a study by Khoury (1992), the researcher identified and categorised the four stages of heating in concrete specimens as "more-or-less distinct". Furthermore, it was argued that each heating stage has a diverse impact on the mechanisms that influence the properties of concrete. As per his analysis, these four distinct phases, as depicted in Figure 1, encompass the initial heating phase, maintaining a constant temperature, the subsequent cooling phase, and finally, the post-cooling stage. It has been contended that concrete undergoes alterations to its properties in the initial phase, specifically the primary heating; some are detrimental while others are beneficial. The identification of relaxation resulting from transient creep, heightened hydration, evaporation of water, and hydrothermal reactions have been recognised as advantageous phenomena.

Conversely, spalling, heightened porosity, and breakage in certain chemical bonds has been acknowledged as detrimental phenomena. It is recommended that any unfinished processes from the initial stage be finalised during the constant temperature phase.

Additionally, it should be noted that during the cooling phase, the impact of thermal-induced cracking becomes essential. The characteristics of concrete after cooling are determined by the influence of reabsorbed moisture. In the study conducted by Schneider (1988), it was determined that the examination of concrete under elevated temperatures involves the consideration of three primary variables. These variables, namely heating, load application, and strain rate are crucial in testing.

Concrete exhibits exceptional fire resistance characteristics compared to alternative construction materials such as steel and wood. Concrete is widely acknowledged in civil engineering for its exceptional fire-resistant qualities, owing to its incombustible nature and remarkable capacity to withstand structural failure when exposed to elevated temperatures. Exposing a concrete structure to significantly elevated temperatures can induce substantial alterations in the concrete's crucial mechanical and structural characteristics. An extensive structural failure from the progressive degradation caused by fire has been duly noted. The fire-resistant nature of concrete can be attributed to the inherent characteristics it acquires from its constituent materials, including aggregates, cement, fibres, and more. Combining these elements will form a substance known as "concrete", which exhibits chemical inertness. This material exhibits no reactivity when exposed to fire and produces no hazardous or noxious gases as a by-product.

Concrete possesses the potential to undergo combustion, yet it does not emit any hazardous fumes, as previously stated. In order to induce more significant structural degradation, a heightened susceptibility

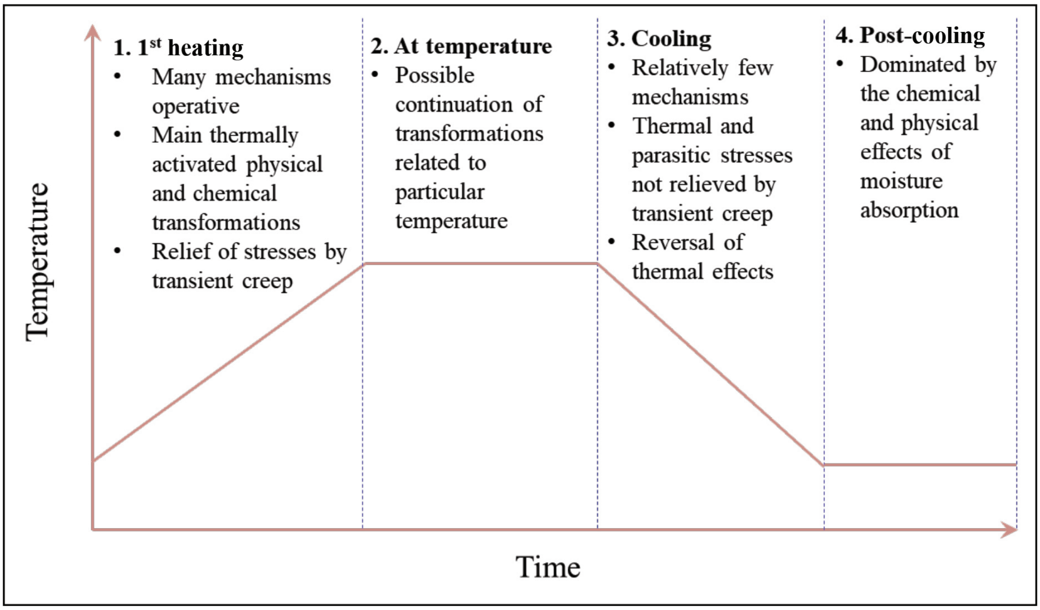

Figure 1: Stages of heating of concrete

to elevated temperatures is necessary. As previously stated, an elevated temperature will induce alterations in the characteristics of the concrete. Temperature and the constituent concrete particles primarily influence the behaviour of concrete structures under fire. Table 1 illustrates the observed changes in concrete as the temperature increases.

Fire Effect on Concrete

Physico-chemical Modifications

Before assessing concrete's durability and performance, it is imperative to examine the influences of fire on concrete, considering its various components at multiple scales and phases. Geopolymeric materials possess inherent resistance against fire. In contrast to organic polymers, inorganic polymers possess a non-carbon-based structure and lack combustibility. The materials in question possess non-toxic and smoke-free properties and exhibit a comparatively lower processing temperature when compared to traditional ceramic composites. Table 2 shows the various chemical and physical modifications detected in GP composites upon exposure to fire.

Table 1: Impact of temperature on concrete - fire resistant properties

Temperature (˚C)	Concrete Changes
100	Simple dilatation
100-150	Evaporable water lost
150-500	Cement paste contract: Since the evaporation of hydration water above 300˚C, a large change in density is detected
400-500	Calcium hydroxide is decomposed $Ca(OH)_2 \rightarrow CaO + H_2O$
500-1,300	Calcium silicate hydrate is decomposed with a 50% decrease in concrete strength at 500˚C

Table 2: Previous research on fire's impact on GP

Reference	Findings
Zhang *et al*. (2015)	The GP mortar exhibits superior resistance to temperature-induced degradation in terms of tensile and bending strength compared to OPC mortar. However, it demonstrates inferior degradation in terms of bond and compressive strength.
Hosan *et al*. (2016)	The Na_2SiO_3/NaOH proportion of three substantially enhances compressive strength, resulting in an elevated residual compressive resistance of up to 600°C.
Duan *et al*. (2017)	The GP's compressive resistance experienced a reduction in strength because of thermal cycles. The compressive strength and mass experienced an increase in losses as the temperature escalated.
Zhang *et al*. (2014)	The compressive and bending performance of the GP specimens, which were produced utilising metakaolin and fly ash, is similar to that of the OPC specimens. This similarity is detected at ambient temperatures and even after being subjected to great temperatures. Using metakaolin and fly ash, GPs offer a feasible alternative to traditional OPC in various practical construction scenarios.
Lahoti *et al*. (2018)	The GP containing Potassium experienced an essential amendment of approximately 30% to 40% while the GP containing sodium exhibited a decline of 10%. After being subjected to great temperatures, the GP strength of a mixture of potassium and sodium remained unaltered.
Kong and Sanjayan (2010)	The research identifies the two primary factors influencing GP performance under elevated temperatures (800 degrees centigrade), namely the dimensions of the sample and the aggregate. Utilising aggregates with dimensions exceeding 1 cm enhances structural integrity under varying temperatures. When subjected to great temperatures, the thermal instability detected between the aggregates and GP matrix can be attributed to an essential reduction in the GPC's structural integrity.
Samal (2019)	The GPs notably influenced the thermal shrinkage decline as the Si/Al proportions increased, resulting in a decrease in porosity throughout the sintering and dehydroxylation processes.
Sarker *et al*. (2014)	In light of the fire incidents, the GPC samples exhibited a lesser degree of damage in terms of cracking than the OPC concrete samples. The concrete cylinders exhibited essential spalling at temperatures ranging from 800°C to 1,000°C, whereas the GPC samples showed no signs of spalling. The GPC specimens exhibited superior strength compared to the OPC samples.
Pan *et al*. (2014)	The GP exhibited an essential increase in strength, reaching a remarkable 192% enhancement when subjected to a temperature of 550°C. In contrast, the strength of the OPC paste experienced only minor alterations. The residual strength and ages of OPC and GPC, after being subjected to a temperature of 550°C were found to be in proximity.
Lahoti *et al*. (2018)	After being subjected to a high temperature of 900°C, the compressive strength of all GP samples underwent an essential reduction. Although the GP mixes exhibit commendable chemical stability at a microscopic level, their stability at a mesoscale is notably inadequate, with an essential propensity for thermal shrinkage.
Mathew and Joseph (2018)	At the prevailing temperature situations, the deformation features of GPC beams exhibit parity with those of reinforced cement beams. Thus, the strain compatibility technique tends to underestimate the deformation features of reinforced GPC beams once they are subjected to elevated temperatures.

Kljajević *et al*. (2017)	The cross-linking phenomenon detected in the GP samples subjected to a temperature of 600°C decreases the Si-O-Na bonding. The thermal influences experienced at a temperature of 900°C resulted in a substantially reduced oxygen and sodium transformation in a highly articulated manner. These changes are accompanied by essential alterations in the overall morphology, explicitly creating a sophisticated pore structure.
Sivasakthi *et al*. (2018)	The linear dimensional stability of the GP mortar and paste remains unaltered up to a temperature of 800°C. Incorporating 10% micro silica in the GP composites results in a heightened filling impact, consequently enhancing the compressive strength through compromising the bulk sample's integrity.
Luhar *et al*. (2018)	Concerning the rubberised GPC, the reduction in strength when subjected to great temperatures is slightly higher than that associated with the control GPC, which can be attributed to the potential variations in the thermal expansion coefficients of the constituent materials.

Concrete Spalling

Exposure to fire leads to increased temperatures, potentially resulting in spalling of the concrete and adversely affecting its structural integrity, which can compromise the mechanical features of concrete, specifically its compressive strength. The detected occurrence of concrete spalling can contribute to the failure of critical structural components (Ma *et al*., 2015; Ding *et al*., 2016). Explosive spalling can be attributed to two primary factors: The build-up of vapour pressure within the pores and the non-uniform distribution of thermal stresses. Water vaporisation occurs due to elevated temperatures, as elucidated by (Vu *et al*., 2009).

The hydraulic gradient within the concrete matrix facilitates water migration from the internal domain toward the external domain. The designed stratum provides an additional barrier against the vapour diffusion originating from the interior of the concrete thereby, increasing the pore pressure. If the heating rate is increased and the density of the concrete; pore structure is enhanced, the timely dissipation of the vapour layer becomes inadequate, resulting in a substantial pore pressure build-up. This leads to spalling and subsequent disintegration of structural elements, mainly if the tensile strength of the concrete is insufficient.

According to the findings of Shoukry *et al*. (2011), Figure 2 illustrates pore pressure expansion in the underlying soil, resulting in concrete spalling due to thermal processes. The advancement of a thermal gradient within concrete under elevated temperatures is an additional consideration (Ichikawa & England, 2004). As the temperature of the concrete surface increases, compressive stresses are developed parallel to the heated surface at elevated temperatures. Simultaneously, specific tensile stresses occur in a perpendicular direction. If the differential stresses exceed the tensile strength of the concrete, it shall result in spalling, as illustrated in Figure 3.

Furthermore, it is imperative to consider that the occurrence of concrete matrix cracking can be attributed to the hastened temperature acceleration resulting from the chemical decomposition of hydrates, differential reduction in shrinkage of the concrete paste, thermal instability, and expansion of coarse aggregates. The potential for cracking in the Interfacial Transition Zone (ITZ) between phases can be attributed to aggregates' thermal and elastic incompatibility and the cementitious mixture at elevated temperatures. Consequently, this can lead to concrete deterioration and contribute to the aforementioned detrimental processes (Ma *et al*., 2015).

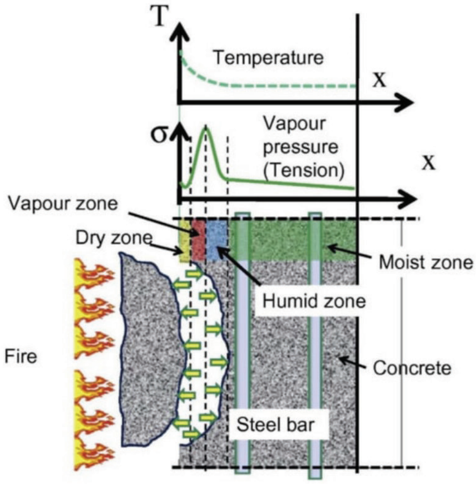

Figure 2: Concrete spalling mechanism since vapour pressure (Ozawa *et al.*, 2012)

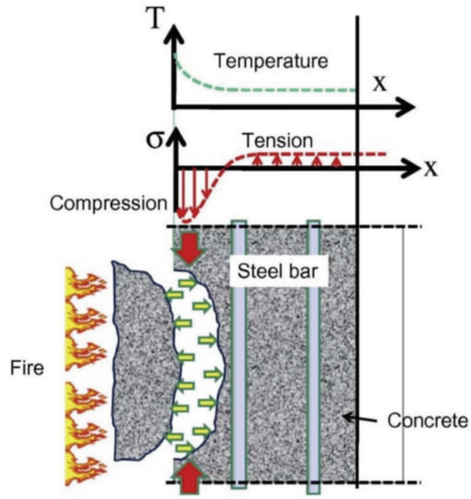

Figure 3: Concrete spalling mechanism since thermal dilation (Ozawa *et al.*, 2012)

Features of Post-fire Exposure Residual Compressive Strength

The investigation performed by Hosan *et al.* (2016) examines the influences of sodium and potassium activators on the mechanical compressive strength properties and visual changes of GP produced from Class F fly ash when exposed to elevated temperatures. The GP pastes fabricated utilising sodium activator exhibited commendable compressive strength at room temperature and superior compressive strength at high temperatures of 400 degrees centigrade compared to their potassium-based counterparts. When produced with a potassium activator at a temperature of 600 degrees centigrade, the GP's compressive strength exhibits a faintly greater magnitude than its sodium-containing counterpart. The GP paste generated utilising a potassium activator exhibited incredible compressive strengths at higher temperatures than the GP paste produced with a sodium activator.

The GP paste, synthesised by applying a potassium activator with a K_2SiO_3/KOH proportion of three, exhibited superior residual compressive strength at high temperatures compared to the ambient temperature, in contrast to the GP paste that utilised sodium activators.

The investigation by Duan *et al.* (2017) elucidated the effects of silica fumes on the performance of GP derived from fly ash when subjected to thermal cycles. The increase in silica fumes leads to a corresponding enhancement in the GP compressive strength. Incorporating silica fumes is deemed appropriate to facilitate expeditious strength development in GP. The GP compressive strength experiences an essential decrease when subjected to thermal cycles, particularly after 56 consecutive thermal cycles. As the temperature increases within the 200 to 800 degree centigrade range, there is a decrease in compressive strength. The GP's pore structure is degraded due to successive thermal cycles.

Nevertheless, the consistent decline in strength remains a commendable attribute, particularly considering the satisfactory thermal exposure performance detected. The research on metakaolin and fly ash combined GP binders as a specialised precursor for resistance against fire materials showed exceptional outcomes. Notably, GP binders composed of 50% metakaolin and 50% fly ash exhibited optimal compressive strength and excellent bending properties under normal atmospheric conditions and after exposure to elevated temperatures (Zhang *et al*., 2014). GP composites' compressive resistance and bending properties were detected to exhibit a certain degree of enhancement after exposure at a temperature of 100°C. However, subsequent exposure within the temperature range of 100°C to 800°C resulted in a decline in these properties. The discrepancy in shrinkage of GP binders and expansion of aggregates causes a decrease in strength and cracks in GPC after being subjected to significant temperatures. The compressive strength and bending properties of the GP composites, which were synthesised using a combination of fly ash and metakaolin, exhibited similar performance to that of mixes containing OPC under ambient temperature.

Furthermore, these GP composites maintained their strength and structural integrity after being subjected to elevated temperatures. The investigation by Lahoti *et al*. (2018) examined the influence of alkalis involving potassium, sodium, or a mixture of both on the strength features of GPs. These GPs were produced utilising fly ash as a precursor and intended for structural integrity applications, particularly at elevated temperatures. The results indicate that alkali cations influence the compressive strength of GPs derived from fly ash after being subjected to significant temperatures.

Nevertheless, the structural integrity of GPs containing potassium and sodium remained unaltered even under elevated thermal situations. Furthermore, the investigation by Kong and Sanjayan (2010) meticulously compiled the research results about the impact of elevated temperatures on GP composites formulated utilising fly ash. Various experimental factors were examined, including specimen size, aggregate size and kind, and the specific superplasticiser utilised. The research highlights the significance of sample size and aggregate properties as crucial variables governing the behaviour of GP under extreme temperatures involving 800°C. Aggregate sizes over 10 mm have demonstrated strength resilience under average and elevated temperatures. The reduction in strength detected in GPC at elevated temperatures can be attributed to the thermal mismatch between the aggregates and the GP mixture. Therefore, it is crucial to consider the aggregate size when assessing the performance of GPC under incredible temperatures. Aggregates with dimensions below 10 mm tend to promote extensive spalling and cracking within the GPC while aggregates exceeding 10 mm in size exhibit enhanced stability under elevated temperatures.

Utilising superplasticisers in GPC for performance at elevated temperatures is not advantageous. The potential cause for the decrease in strength in GPC subjected to elevated temperatures is likely attributed to the thermal incompatibility between the GP matrix and the aggregates. This finding was established by conducting a comparative analysis of GPCs produced utilising two distinct aggregate sizes exhibiting different thermal features. It was detected that the specimen incorporating a more significant aggregate size disparity experienced a greater strength reduction. According to the findings of Sarker *et al*. (2014), GPCs exhibit compressive strength ranging between 93% to 107% after being subjected to a temperature of 400°C.

In contrast, the investigation by Lahoti *et al*. (2018) revealed the influence of contextual disparities on the Si/Al molar proportion in terms of volume stability, specifically at the mesoscale and strength endurance levels. These findings pertain to the macro-scale features of metakaolin GPs. Based on the observations, the compressive strength of all the GP samples experienced a reduction after exposure at 300°C. The GP sample, characterised by a Si/Al proportion of 1.75, exhibited a remarkable compressive strength of six MPa after being subjected to a temperature of 900°C. Based on the detected data, it has been determined that an essential level of damage is caused by cracking and a decrease in residual compressive strength. Therefore, it is imperative to improve the overall stability of GPs at a macro-scale by incorporating metakaolin. This enhancement is crucial for utilising GPs as a fire-resistant material in structural applications. According to the investigation by Mathew and Joseph (2018), although the compressive strength of cube samples of GPC remains relatively stable between 600°C to 800°C due to the ongoing polymerisation process of primarily non-reacted materials, it is essential to note that the load-bearing capacity of GPC beams diminishes rapidly prior to reaching 600°C. The primary factor contributing to this phenomenon is the reduction in the strength capacity of the reinforcing steel, which decreases the load-bearing capacity of GPC beams when subjected to temperatures exceeding 600°C. Pan and Sanjayan (2010) identified two distinct behavioural patterns before achieving glass transition performance.

The GP's strength increases within the 200°C to 290°C temperature range, accompanied by essential contraction from additional geopolymerisation. An additional increase in strength was detected within the temperature range of 380°C to 520°C. However, it is noteworthy that the GP exhibited superiority throughout this phase. According to the findings of Vickers *et al.* (2014), reduced Si/Al proportions in GPs derived from fly ash improved strength after exposure to temperatures of 1,000°C. The incorporation of acicular Wollastonite resulted in enhanced retention of flexural and compressive strengths post-firing.

Alumina with a reduced surface area may be deemed more suitable for accommodating increased levels of aggregate or filler; thereby, facilitating the production of concrete and mortar (Sivasakthi *et al*., 2018). The investigation analysed the impact of incorporating microsilica in varying quantities of 0%, 5%, and 10% in the GP composites primarily composed of fly ash. The analysis focused on assessing the strength features of these composites under two distinct situations: Room temperature and elevated temperature of 800°C. The investigation results suggest that GPs' compressive strength can be enhanced by incorporating 5% microsilica. However, this improvement is reduced when 10% microsilica is added. The measured GP compressive strength composites, including paste, mortar, and concrete with 5% micro silica were determined to be 34, 35, and 29 MPa, respectively. These results were obtained while maintaining a consistent Si/Al proportion of 1.9. The utilisation of microsilica has played a substantial function in enhancing the densification and compaction of the microstructure; thereby, resulting in notable enhancements in compressive strength.

Specimens' Visual Observation of Post-heating

The investigation by Hosan *et al*. (2016) examined the influences of elevated temperatures on the physical performance of activators, specifically potassium and sodium, utilised to synthesise fly ash-based GPs. Upon careful monitoring, it has been detected that no discernible cracks were formed in either variant of GP, even when subjected to temperatures as great as 400°C. However, it has been detected that the GP exhibits cracks at 600°C when synthesised utilising sodium activators. This issue becomes more severe when the temperature increases to 800°C, resulting in numerous deep cracks on the surface. However, it is worth noting that the GP, which was produced utilising a potassium activator, demonstrated resilience against the development of surface cracking when subjected to a temperature of 600°C.

However, it is essential to mention that there were indications of fine cracks propagating at a higher temperature of 800°C. The volumetric and GP paste shrinkage mass synthesised with a potassium activator is less essential than its sodium counterpart. In the context of employing a potassium-based activator for synthesising GP pastes, it was detected that surface cracks were comparatively reduced compared to GP paste prepared with a sodium-based activator. The investigation by Lahoti *et al*. (2018) showcases the observable modifications in the appearance of all three samples under varying temperatures. The GP samples transition towards a reddish-brown colour, especially at 900°C. The detected change in colour can be attributed to the iron oxidation in the fly ash, as mentioned by Rickard *et al.* (2011) and Hosan *et al.* (2016).

The monitoring of cracking behaviour and damage to the GP mixture can also be detected due to the pores' contraction and the free water evaporation from said pores, leading to the propagation of cracks and subsequent shrinkage of the samples. However, it has been detected that the GP activated by potassium exhibits a lower degree of damage after being subjected to temperatures of 500°C and 900°C compared to the GP activated by both sodium and potassium and the GP activated solely by sodium. The monitoring system employed in this investigation utilises dilatometry techniques to analyse the stability to volume relationship (Figure 4) of potassium-based GP mixtures. The physical attributes of the fibre, matrix, and fibre-reinforced GP composites at ambient temperature have been elucidated by Samal (2019) and Haridharan *et al.* (2020). The DSC curve of the GP composite exhibits two distinct peaks when subjected to temperatures of 101°C and 248°C, respectively. The initial peak at 101°C corresponds to water vapour dehydration and evaporation.

On the other hand, the second peak at 248°C signifies the mass losses within the GP matrix (Zhang *et al*., 2012). According to the investigation by Sarker *et al*. (2014), it was found that in the context of thermal conductivity during fire exposure, it is detected that GPC samples exhibit a greater heat transfer rate than specimens made of OPC concrete. Essential transformations in the context of colour have been detected in GP samples subjected to temperatures exceeding 650°C, resulting in a transition from brown to red. Essential spalling phenomena are detected in the specimens of OPC subjected to elevated temperatures of 800 and 1,000°C. Contrarily, spalling did not occur in the GP samples subjected to the same temperatures. The OPC samples exhibited extensive surface cracking upon being subjected to temperatures of 400°C, 650°C, 800°C, and 1,000°C, revealing a comprehensive deterioration. However, it is worth noting that only minor surface cracking was detected in the GP specimens subjected to temperatures of 800°C and 1,000°C. This demonstrated an increased capacity to withstand cracking and spalling in GPC compared to OPC samples in fire situations.

The investigation by Lahoti *et al*. (2018) provided insights into the damage pattern, visual appearance, and colour changes detected in GP samples when subjected to elevated temperatures. Due to the thermal situations experienced by the GP samples at a temperature of 300°C, the process of water evaporation from the pores occurs, causing an improvement in cracks in the samples. A multitude of expansive and more refined fissures were documented.

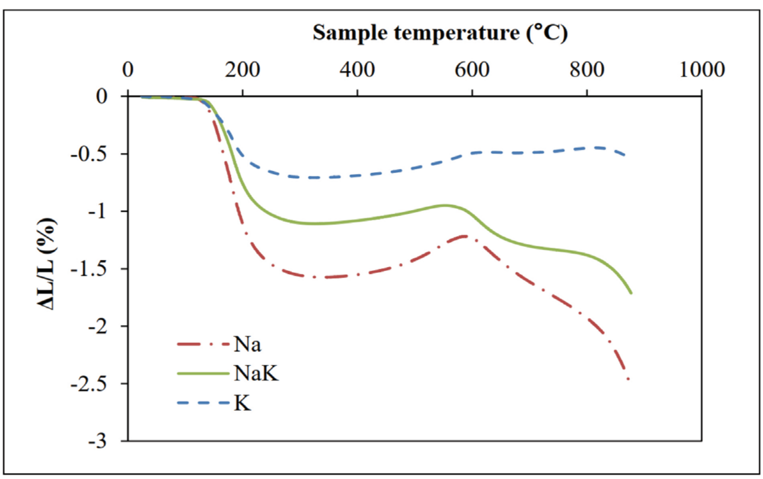

Figure 4: GPs' thermal distortion by dilatometry processing (Lahoti *et al.*, 2018)

Following exposure to a temperature of 900°C, the GP samples exhibited a higher degree of visible damage in the form of cracks than at a temperature of 300°C. According to research by Mathew and Joseph (2018), the load capacity of GP beams decreases as the temperature of exposure increases. This phenomenon is influenced by the depth of the concrete cover used for the reinforcement. Upon reaching a temperature of 800°C, the beam that had a concrete cover of 20 mm experienced cracking at a magnitude equivalent to 66% of the load at ambient atmospheric temperature.

Conversely, the beam with a concrete cover of 40 mm exhibited cracking at a lower threshold, specifically 75% of the load. According to the findings of Rickard and Van Riessen (2014), panels subjected to fire exhibited surface cracks on both the hot and cold sides. The monitoring of cracking during the cold phase of the samples was not performed until after the initial one-hour period of dehydration, indicating the potential absence of extensive damage caused by water evaporation. The primary factor contributing to the appearance of cracks in the cold phase of the samples is likely the differential shrinkage between the hot and cold phases. The sufficiently heated phase, which experienced temperatures ranging from 600°C to 900°C would have undergone a more significant contraction than the cooler regions. As a result, cracks have developed.

Ways of Reducing the Effect of High Temperatures on GPC

Several methodologies exist to effectively tackle this matter to enhance the structural integrity and performance of GP materials, as depicted in Figure 5. In order to enhance the tensile strength, certain researchers (Ranjbar & Zhang, 2020; Silva *et al*., 2020) have suggested using fibre elements with varying shapes, lengths, and chemical compositions to reinforce a delicate matrix. An alternative approach to enhance the robustness of structural GP frameworks involves implementing a reinforcing mesh utilising a polymer compound involving epoxy resin that is incorporated into the GP matrix. The structures are commonly denoted as hybrid materials (Ferone *et al*., 2013; Roviello *et al*., 2015; 2016; 2019). Roviello *et al*. (2015) presented a technique of fabricating hybrid composites utilising GP and epoxy-melamine resins, which exhibited a notable level of compatibility between the inorganic and organic elements. This was accomplished by implementing a technique rooted in the amalgamation of a polymer and GP network within a fluid state facilitated by the infiltration of the resin into the inorganic matrix at the nanoscale. By employing a hybrid framework, the GP composites exhibited enhanced mechanical properties compared to the unmodified composites (Rajabi *et al*., 2020). Simultaneously, the heat and fire resistance characteristics exhibited no alteration compared to unmodified GPs.

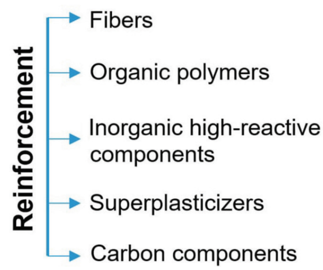

Figure 5: Reinforcement methods of cellular GPs

Fibres to Enhancement Performance of GPC

Artificial fibres and natural fibres are employed to enhance the structural capabilities of GPC (Prasad *et al*., 2022). Artificial fibre encompasses synthetic, inorganic, and steel fibres while natural fibre comprises plant, mineral, and animal fibres. To address the issue of brittleness and susceptibility to cracking in GPC, incorporating various type of fibres has emerged as a prevalent approach within engineering applications (Murali *et al*., 2020; Rithanyaa *et al*., 2021).

Steel fibre is primarily composed of plate, cold-drawn wire, or other variations of steel with its cross-sectional configuration predominantly being rectangular, square, or round (Ali *et al*., 2022; Wu *et al*., 2022). Incorporating steel fibre into GPC is a prevalent practice owing to its notable attributes involving superior density, remarkable tensile strength, and cost-effectiveness (Pająk & Ponikiewski, 2013). To mitigate the phenomenon of steel fibre extraction from the concrete matrix, a considerable quantity of steel fibres featuring diverse geometries and shapes are produced globally (Hussain & Al-Khafaji, 2021). The steel fibres utilised in GPC exhibit various geometries involving corrugated, twisted, straight, crimped, hooked-end fibres, and additional variations (Wang *et al*., 2021). Figure 6 illustrates the most common kinds of steel fibres.

The incorporation of steel fibre has been empirically demonstrated to effectively regulate the initiation and propagation of fissures; thereby, enhancing the crack resistance of GPC, a material inherently susceptible to brittleness. The advantageous utilisation of steel fibre to alter the characteristics of GPC is primarily evident in the subsequent domains (Aisheh *et al*., 2022; Prasad *et al*., 2022):

- Enhance the flexural strength, toughness, and ductility of cementitious materials.
- Facilitate energy absorption, bridge connections amidst cracks, and facilitate load transfer.
- Enhance the mitigation of permeability, creep, and shrinkage in concrete.
- Optimise the enhancement resistance of fatigue and impact in concrete.

Furthermore, it is imperative to consider the impact of the physical features of steel fibre on the comprehensive mechanical characteristics of GPCs with steel fibre reinforcement. Currently, Table 2 exhibits the predominant attributes of steel fibres extensively employed in GPC investigations. As shown in Table 3, the prevalent range for the steel fibres employed is between

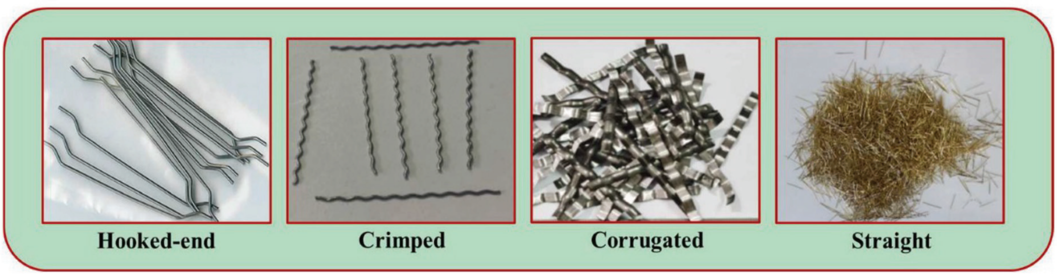

Figure 6: Regular steel fibre kinds

Table 3: Fundamental mechanical characteristics of steel fibres

References	Kinds	Length (mm)	Diameter (mm)	Tensile Strength (MPa)	Elastic Modulus (GPa)
da Silva *et al*. (2022)	Hooked-end	13	0.20	2,000	200
Kim *et al*. (2015)		30	0.56	1,100	200
Tran *et al*. (2019)		35	0.55	1,350	210
Prasad *et al*. (2022)	Crimped	25	0.50	900-1,250	200-210
Kumar *et al*. (2020)		25	0.50	2,670	-
Al-Majidi *et al*. (2017)	Straight	13	0.16	2,500	200
Liu *et al*. (2021)		15	0.12	1,200	200
Liu *et al*. (2021)		10	0.12	1,200	200

10 and 35 mm. Similarly, the diameter of said steel fibres falls within the range of 0.12 to 0.56 mm. Furthermore, the tensile strength of these steel fibres is confined within the span of 900 to 2670 MPa. The steel fibres' elastic modulus is primarily in the range of approximately 200 while the density of steel fibres commonly employed typically hovers around 7.85 grams per cubic centimetre (g/cm^3).

Mechanical Features of GPC Fibres Reinforcement

Through the amalgamation of experimental data about the mechanical characteristics of GPC fibres reinforcement as documented in the published articles, an assessment has been conducted to ascertain the steel fibre's impact on GPC's flexural, splitting tensile, and compressive strength. The findings are summarised in Table 4. The steel fibre variations shown in Table 4 are primarily of the straight, hooked-end, and crimped kinds. Table 5 illustrates the impact of varying fibre volume rates on GPC's flexural, splitting tensile, and compressive strength.

Conclusions

In conclusion, the scientometric analysis of GPCs' thermal and fire-resistant properties demonstrates their effectiveness in ensuring the safety and security of both lives and properties. These findings advocate for GPCs as construction materials offering enhanced durability and sustainability. The exceptional mechanical and durability properties of GPCs at high temperatures position them as strong competitors to OPC in the construction sector.

GPC has garnered significant global attention due to advantages like reduced energy consumption, early strength, exceptional durability, and fire resistance. Unlike OPC systems, these benefits stem from their ceramic-like features and inorganic structure, which do not decompose under high temperatures. Heat-

Table 4: The impact of steel fibre shape on GPC

References	Fibre Shapes	Rate of Fibre Volume (%)	Strength (MPa)		
			Compressive	Splitting Tensile	Flexural
Ganesan *et al*. (2015)	Hooked-end	0-1.00	37.00-43.80	3.56-4.90	4.10-5.10
Rabiaa *et al*. (2020)	Hooked-end	0-1.50	38.00-41.00	2.70-3.10	4.60-5.60
Farhan *et al*. (2018)	Straight	0-3.00	44.10-47.90	3.50-5.30	4.40-5.40
Bellum (2022)	Straight	0-2.50	54.30-61.50	5.62-8.52	7.70-12.15
Rabiaa *et al*. (2020)	Crimped	0-1.50	38.00-40.00	2.70-2.96	4.60-5.30
Farhan *et al*. (2018)	Crimped	0-2.00	44.10-45.90	3.50-5.50	4.40-6.10

Table 5: The impact of fibre volume on GPC

References	Rate of Fibre Volume (%)	Strength (MPa)		
		Compressive	Splitting Tensile	Flexural
Aisheh *et al*. (2022)	0-0.25	115.00-162.00	6.10-8.60	7.60-13.70
Bashar *et al*. (2016)	0-0.75	30.00-31.35	2.22-2.93	4.33-4.86
Kumar *et al*. (2022)	0-1.00	43.00-47.05	4.75-6.70	5.75-7.35
Pham *et al*. (2019)	0-1.50	32.05-57.02	3.70-4.98	5.89-9.65
Bellum (2022)	0-2.50	54.30-61.50	5.62-8.52	7.70-12.15

cured GPC, using precursors like metakaolin and low-calcium F-type fly ash is an exemplary material for precast structures.

Due to their exceptional thermal and fire-resistant properties, GPC materials are increasingly used in applications requiring heat resistance such as ships, airplanes, foundries, refractory panels, high-rise buildings, and tunnels. Studies confirm that GPCs exhibit chemical stability under high temperatures and do not experience structural degradation like OPC hydration products.

Research shows that regulating water quantity in GP mixtures is crucial, directly influencing thermal deformation, spalling resistance, and strength properties. Incorporating fibre-reinforced constituents enhances the compressive strength of GPC, although the extent varies based on aggregate type, curing environment, age, and water-to-binder ratio. The splitting tensile and flexural strengths of GPC are closely linked to fibre characteristics, including type, aspect ratio, volume rate, and shape. Hooked-end steel fibres exhibit superior performance.

Supplementary Fillers (SFs) are essential for improving GPC's mechanical characteristics. A positive correlation exists between the amount of steel fibre and the flexural, splitting tensile, and compressive strengths of GPC. Incorporating fibres significantly enhances the fracture toughness of GPC within a specific range of fibre volume rate. However, fracture toughness may decline beyond a certain threshold despite increased fibre volume.

Overall, this review underscores the scientific advancements and practical applicability of GPCs, highlighting their potential as sustainable, durable, and fire-resistant alternatives to OPC in the construction industry.

Recommendations and Future Works

This review exclusively examines the macro structural and mechanical characteristics of GPC fibres-reinforcement. To enhance its comprehensiveness, further exploration into the microstructure of GPC fibres-reinforcement can be undertaken. Additionally, an investigation can be carried out to establish the correlation between the macroscopic properties and microstructure of GPC fibres-reinforcement. Compare GPC from different base materials under high temperatures to identify the variation in chemical and thermal stability.

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Conflict of Interest Statement

The authors declare that they have no conflict of interest.

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