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A REVIEW ON GEOPOLYMER CONCRETE BEHAVIOUR UNDER ELEVATED TEMPERATURE INFLUENCE

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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 paper 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 GPC (GPC) (A. A. Shubbar Jafer, *et al*., 2020; A. A. Shubbar Sadique, *et al*., 2020; Majdi *et al*., 2020; Al-Faluji *et al*., 2021; Al-Mamoori *et al*., 2021; Marshdi *et al*., 2021; A. A. 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 meter 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 Ordinary Portland Cement (OPC), it is possible to effectively reduce the carbon dioxide (CO^2) emissions associated with OPC production (A. Shubbar *et al*., 2021).
- Optimisation of natural resource utilisation: Geopolymer technology offers a significant advantage by utilising waste materials, while Ordinary Portland Cement (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, Ordinary Portland Cement (OPC) production, 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 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 (X. 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 $M_2O{\bullet}Al_2O_3\text{-}xSiO_2{\cdot}yH_2O$ 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 (H. 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; L.-Y. Xu *et al*., 2021).

Discussions

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 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.

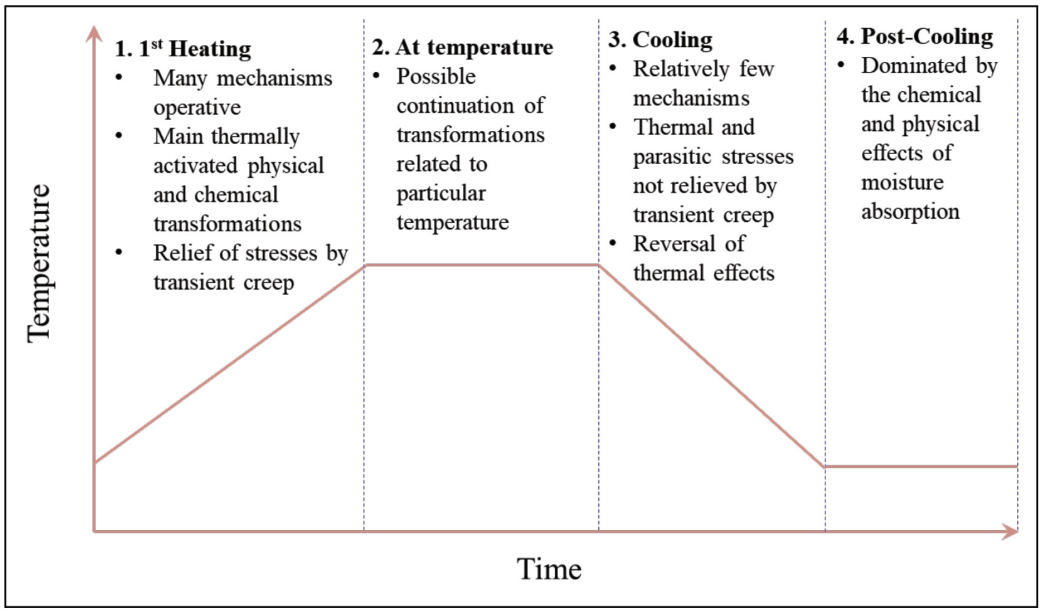

Figure 1: Stages of heating of concrete

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

Temperature	Concrete Changes
100°C	Simple Dilatation
100-150°C	Evaporable Water lost
150-500°C	Cement Paste Contract: since the evaporation of hydration water Above 300°C, a large change in density is detected
400-500°C	Calcium Hydroxide is Decomposed $Ca(OH)_2 \rightarrow CaO + H_2O$
500-1300°C	Calcium Silicate Hydrate is Decomposed with a 50% decrease in concrete strength at 500°C

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 2: Previous research on fire's impact on GP

Ref.	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 3 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.
(H. Y. 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, Wong, Yang, *et al*., 2018)	The GP containing Potassium experienced an essential amendment of approximately 30-40%, 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 & 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 to 1000°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 & ages of OPC and GPC, after being subjected to a temperature of 550°C, were found to be in proximity.
(Lahoti, Wong, Tan, *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 & 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).

Features of Post-fire Exposure Residual Compressive Strength

The investigation performed by Hosan *et al*. (2016) examines the influences of sodium

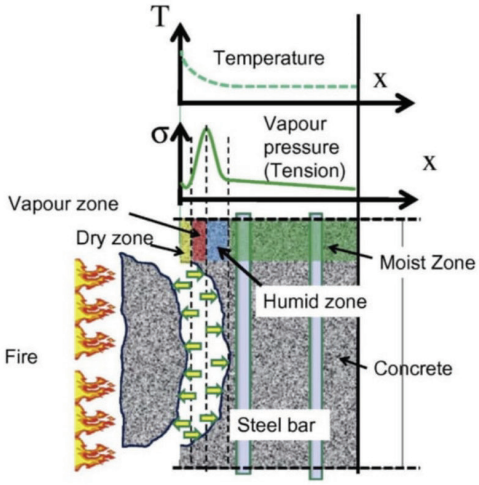

Figure 2: Concrete spalling mechanism since vapour pressure (Ozawa *et al.*, 2012)

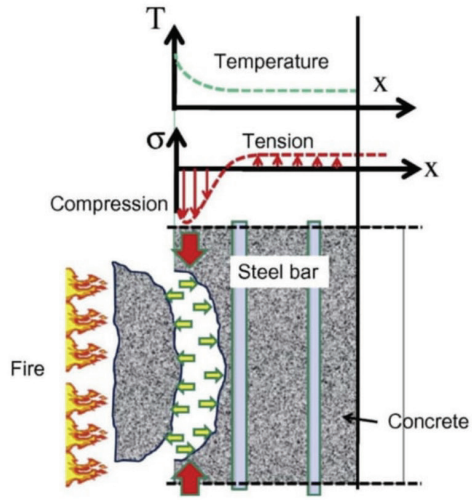

Figure 3: Concrete spalling mechanism since thermal dilation (Ozawa *et al.*, 2012)

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 (H. Y. 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 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 6 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 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 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 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 Hosan *et al*. (2016) and Rickard *et al*. (2011).

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 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 Haridharan *et al*. (2020) and Samal (2019). The DSC curve of the GP composite exhibits two distinct peaks when subjected to temperatures of 101 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 (Y. J. 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, 650, 800, and 1000°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 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. 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

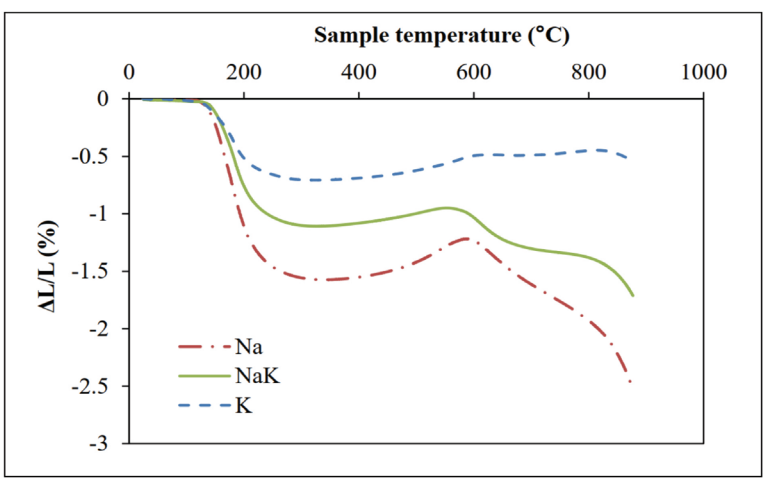

Figure 4: GPs' thermal distortion by dilatometry processing (Lahoti, Wong, Yang, *et al.*, 2018)

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 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; G. 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.

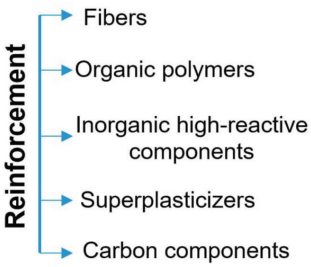

Figure 5: Reinforcement methods of cellular GPs

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 types 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 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).

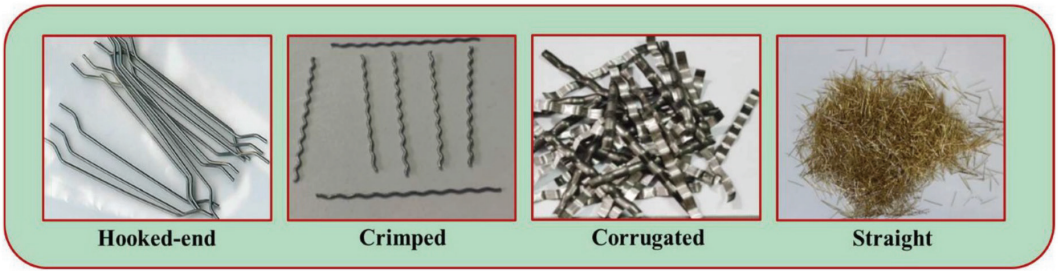

Figure 6: Regular steel fibre kinds

Table 3: Fundamental mechanical characteristics of steel fibres

References	Kinds	Length (mm)	Diameter (mm)	Tensile Strength (MPa)	Elastic Modulus (GPa)
(A. C. R. da Silva *et al*., 2022)	Hooked end	13	0.20-	2000	200
(Kim *et al*., 2015)		30	0.56	1100	200
(Tran *et al*., 2019)		35	0.55	1350	210
(Prasad *et al*., 2022)	Crimped	25	0.50	900–1250	200–210
(R. Kumar *et al*., 2020)		25	0.50	2670	--
(Al-Majidi *et al*., 2017)	Straight	13	0.16	2500	200
(Liu *et al*., 2021)		15	0.12	1200	200
(Liu *et al*., 2021)		10	0.12	1200	200

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, 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-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

Table 4: The shape of steel fibre impact 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 rate of fibre volume impact 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
(Y. N. 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

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.

References

Abdulkareem, O. A., Al Bakri, A. M. M., Kamarudin, H., Nizar, I. K., & Ala'eddin, A. S. (2014). Effects of elevated temperatures on the thermal behaviour and mechanical performance of fly ash geopolymer paste, mortar and lightweight concrete. *Construction and Building Materials*, *50*, 377-387.

Aisheh, Y. I. A., Atrushi, D. S., Akeed, M. H., Qaidi, S., & Tayeh, B. A. (2022). Influence of steel fibres and microsilica on the mechanical properties of ultra-high-performance geopolymer concrete (UHP-GPC). *Case Studies in Construction Materials*, *17*, Article e01245.

Akbari, H., Yang, X., & Kolay, P. K. (2013). Geopolymer-based concrete to reduce carbon footprint of the construction industry (Technical Paper). *Mining Engineer*, *65*(12), 57-62. https://www.researchgate.net/publication/281940167_Geopolymer-based_concrete_to_reduce_carbon_footprint_of_the_construction_industry

Al-Faluji, D., Al-Rubaye, M. M., Nasr, M. S., Shubbar, A. A., Al-Khafaji, Z. S., Alkhayyat, A., & Abdulraheem, M. S. (2021). Impact of substitute portland cement with CKD on the mechanical and durability characteristics of cement mortar. *IOP Conference Series: Materials Science and Engineering*, *1090*(1), 12035.

Al-Husseinawi, F. N., Atherton, W., Al-Khafaji, Z., Sadique, M., & Yaseen, Z. M. (2022). The impact of molar proportion of sodium

hydroxide and water amount on the compressive strength of Slag/Metakaolin (Waste Materials) geopolymer mortar. *Advances in Civil Engineering*, *2022*, 1-14. https://doi.org/10.1155/2022/5910701

Al-Khafaji, Z. S., Al-Naely, H. K., & Al-Najar, A. E. (2018). A review applying industrial waste materials in stabilisation of soft soil. *Electronic Journal of Structural Engineering*, *18*(2), 16-23. https://doi.org/10.56748/ejse.182602

Al-Majidi, M. H., Lampropoulos, A., & Cundy, A. B. (2017). Steel Fibre Reinforced Geopolymer Concrete (SFRGC) with improved microstructure and enhanced fibre-matrix interfacial properties. *Construction and Building Materials*, *139*, 286-307.

Al-Mamoori, S. F., Shubbar, A. A., Al-Khafaji, Z. S., Nasr, M. S., Alkhayyat, A., Al-Rifaie, A., Al-Mufti, R. L., Sadique, M., & Hashim, K. (2021). Production of ternary blend binder as an alternative to portland cement. *IOP Conference Series: Materials Science and Engineering*, *1090*(1), Article 12069.

Ali, A. M., Falah, M. W., Hafedh, A. A., & Al-Khafaji, Z. S. (2022). Evaluation the influence of steel- fibre on the concrete characteristics. *Periodicals of Engineering and Natural Sciences*, *10*, 368. http://dx.doi.org/10.21533/pen.v10i3.3111

Amin, M., Tayeh, B. A., & Agwa, I. S. (2020). Effect of using mineral admixtures and ceramic wastes as coarse aggregates on properties of ultrahigh-performance concrete. *Periodicals of Engineering and Natural Sciences (PEN), 10*(3), 368. https://doi.org/10.21533/pen.v10i3.3111

Amran, M., Huang, S.-S., Onaizi, A. M., Murali, G., & Abdelgader, H. S. (2022). Fire spalling behaviour of high-strength concrete: A critical review. *Construction and Building Materials*, *341*, 127902.

Bakharev, T. (2005). Geopolymeric materials prepared using Class F fly ash and elevated temperature curing. *Cement and Concrete Research*, *35*(6), 1224-1232.

Bashar, I. I., Alengaram, U. J., Jumaat, M. Z., Islam, A., Santhi, H., & Sharmin, A. (2016). Engineering properties and fracture behaviour of high volume palm oil fuel ash based fibre reinforced geopolymer concrete. *Construction and Building Materials*, *111*, 286-297.

Bellum, R. R. (2022). Influence of steel and PP fibres on mechanical and microstructural properties of fly ash-GGBFS based geopolymer composites. *Ceramics International*, *48*(5), 6808-6818.

Cheng, T.-W., & Chiu, J. P. (2003). Fire-resistant geopolymer produced by granulated blast furnace slag. *Minerals Engineering*, *16*(3), 205-210.

Crozier, D. A., & Sanjayan, J. G. (1999). Chemical and physical degradation of concrete at elevated temperatures. *Concrete in Australia*, 18-20.

da Silva, A. C. R., Almeida, B. M., Lucas, M. M., Candido, V. S., da Cruz, K. S. P., Oliveira, M. S., de Azevedo, A. R. G., & Monteiro, S. N. (2022). Fatigue behaviour of steel fibre reinforced geopolymer concrete. *Case Studies in Construction Materials*, *16*, Article e00829.

Davidovits, J. (1993). Geopolymer cements to minimise carbon dioxide greenhouse warming. *Ceramic Transactions*, *37*(1), 165-182.

Davidovits, J., & Davidovics, M. (1991). Geopolymer: Ultra-high temperature tooling material for the manufacture of advanced composites. *SAMPE*, *36*(2), 1939-1949. https://www.researchgate.net/publication/285674987_Geopolymer_Ultra-High_Temperature_Tooling_Material_for_the_Manufacture_of_Advanced_Composites

Ding, Y., Zhang, C., Cao, M., Zhang, Y., & Azevedo, C. (2016). Influence of different fibres on the change of pore pressure of self-consolidating concrete exposed to fire. *Construction and Building Materials*, *113*, 456-469.

Duan, P., Yan, C., & Zhou, W. (2017). Compressive strength and microstructure of fly ash based geopolymer blended with silica fume under thermal cycle. *Cement and Concrete Composites*, *78*, 108-119.

Duxson, P., Fernández-Jiménez, A., Provis, J. L., Lukey, G. C., Palomo, A., & van Deventer, J. S. J. (2007). Geopolymer technology: The current state of the art. *Journal of Materials Science*, *42*(9), 2917-2933.

Farhan, N. A., Sheikh, M. N., & Hadi, M. N. S. (2018). Engineering properties of ambient cured alkali-activated fly ash–slag concrete reinforced with different types of steel fibre. *Journal of Materials in Civil Engineering*, *30*(7), Article 4018142.

Ferone, C., Roviello, G., Colangelo, F., Cioffi, R., & Tarallo, O. (2013). Novel hybrid organic-geopolymer materials. *Applied Clay Science*, *73*, 42-50.

Ganesan, N., Abraham, R., & Raj, S. D. (2015). Durability characteristics of steel fibre reinforced geopolymer concrete. *Construction and Building Materials*, *93*, 471-476.

Hanoon, D. S., Sallal, A. K., Shubbar, A. A., Al-Khafaji, Z. S., Nasr, M. S., Al-Mamoori, S. F., Al-Fehaida, A., Abdulraheem, M. S., Abdulzahra, F. R., Alkhayyat, A., Al-Rifaie, A., & Hashim, K. (2021). Early age assessment of cement mortar incorporated high volume fly ash. *IOP Conference Series: Materials Science and Engineering*, *1090*(1), Article 012019. https://doi.org/10.1088/1757-899x/1090/1/012019

Haridharan, M. K., Matheswaran, S., Murali, G., Abid, S. R., Fediuk, R., Amran, Y. H. M., & Abdelgader, H. S. (2020). Impact response of two-layered grouted aggregate fibrous concrete composite under falling mass impact. *Construction and Building Materials*, *263*, Article 120628.

Hosan, A., Haque, S., & Shaikh, F. (2016). Compressive behaviour of sodium and potassium activators synthetised fly ash geopolymer at elevated temperatures: A comparative study. *Journal of Building Engineering*, *8*, 123-130.

Hussain, A. J., & Al-Khafaji, Z. S. (2021). Experimental investigation on applying waste iron filings in the engineering fields for protection the environment from contamination. *Materials Today: Proceedings*, *61*, 794-798. https://doi.org/10.1016/j.matpr.2021.09.039

Ichikawa, Y., & England, G. L. (2004). Prediction of moisture migration and pore pressure build-up in concrete at high temperatures. *Nuclear Engineering and Design*, *228*(1-3), 245-259.

Inti, S., Sharma, M., & Tandon, V. (2017). Influence of curing on the properties of geopolymer mortar made with low molarity sodium hydroxide. *Transportation in Developing Economies*, *3*, 1-8.

Khoury, G. A. (1992). Compressive strength of concrete at high temperatures: A reassessment. *Magazine of Concrete Research*, *44*(161), 291-309.

Kim, B., Boyd, A., Kim, H., & Lee, S. (2015). Steel and synthetic types of fibre reinforced concrete exposed to chemical erosion. *Construction and Building Materials*, *93*, 720-728. https://doi.org/10.1016/j.conbuildmat.2015.06.023

Kljajević, L. M., Nenadović, S. S., Nenadović, M. T., Bundaleski, N. K., Todorović, B. Ž., Pavlović, V. B., & Rakočević, Z. L. (2017). Structural and chemical properties of thermally treated geopolymer samples. *Ceramics International*, *43*(9), 6700-6708.

Kong, D. L. Y., & Sanjayan, J. G. (2010). Effect of elevated temperatures on geopolymer paste, mortar and concrete. *Cement and Concrete Research*, *40*(2), 334-339.

Kumar, R., Suman, S. K., & Sharma, M. (2020). Laboratory investigation on the synthesis and mechanical characterisation of fibre-reinforced geopolymer concrete. *Materials Today: Proceedings*, *32*, 268-273.

Kumar, Y. N., Kumar, B. D., & Swami, B. L. P. (2022). Mechanical properties of geopolymer concrete reinforced with steel and glass fibres with various mineral admixtures. *Materials Today: Proceedings*, *52*, 632-641. https://doi.org/10.1016/j.matpr.2021.10.050

Lahoti, M., Tan, K. H., & Yang, E.-H. (2019). A critical review of geopolymer properties for structural fire-resistance applications. *Construction and Building Materials*, *221*, 514-526. https://doi.org/10.1016/j.conbuildmat.2019.06.076

Lahoti, M., Wong, K. K., Tan, K. H., & Yang, E.-H. (2018). Effect of alkali cation type on strength endurance of fly ash geopolymers subject to high temperature exposure. *Materials & Design*, *154*, 8-19. https://doi.org/10.1016/j.matdes.2018.05.023

Lahoti, M., Wong, K. K., Yang, E.-H., & Tan, K. H. (2018). Effects of Si/Al molar ratio on strength endurance and volume stability of metakaolin geopolymers subject to elevated temperature. *Ceramics International*, *44*(5), 5726-5734. https://doi.org/10.1016/j.ceramint.2017.12.226

Li, X., Ma, X., Zhang, S., & Zheng, E. (2013). Mechanical properties and microstructure of class C fly ash-based geopolymer paste and mortar. *Materials*, *6*(4), 1485-1495. https://doi.org/10.3390/ma6041485

Li, Z., Ding, Z., & Zhang, Y. (2004). Development of sustainable cementitious materials. *Proceedings of International Workshop on Sustainable Development and Concrete Technology, Beijing, China*, pp. 55-76. https://citeseerx.ist.psu.edu/document?repid=rep1&type=pdf&doi=6c3416b82b70244bacaf7841f8e7786a3d0d75fe

Liu, J., Wu, C., Li, J., Liu, Z., Xu, S., Liu, K., Su, Y., Fang, J., & Chen, G. (2021). Projectile impact resistance of fibre-reinforced geopolymer-based ultra-high performance concrete (G-UHPC). *Construction and Building Materials*, *290*, Article 123189.

Luhar, S., Chaudhary, S., & Luhar, I. (2018). Thermal resistance of fly ash based rubberised geopolymer concrete. *Journal of Building Engineering*, *19*, 420-428.

Luhar, S., Nicolaides, D., & Luhar, I. (2021). Fire resistance behaviour of geopolymer concrete: An overview. *Buildings*, *11*(3), Article 82.

Ma, Q., Guo, R., Zhao, Z., Lin, Z., & He, K. (2015). Mechanical properties of concrete at high temperature—A review. *Construction and Building Materials*, *93*, 371-383.

Majdi, H. S., Shubbar, A. A., Nasr, M. S., Al-Khafaji, Z. S., Jafer, H., Abdulredha, M., Masoodi, Z. Al, Sadique, M., & Hashim, K. (2020). Experimental data on compressive strength and ultrasonic pulse velocity properties of sustainable mortar made with high content of GGBFS and CKD combinations. *Data in Brief*, *31*, Article 105961.

Marshdi, Q. S. R., Hussien, S. A., Mareai, B. M., Al-Khafaji, Z. S., & Shubbar, A. A. (2021). Applying of no-fines concretes as a porous concrete in different construction application. *Periodicals of Engineering and Natural Sciences*, *9*(4), 999-1012.

Marvila, M. T., Azevedo, A. R. G., Delaqua, G. C. G., Mendes, B. C., Pedroti, L. G., & Vieira, C. M. F. (2021). Performance of geopolymer tiles in high temperature and saturation conditions. *Construction and Building Materials*, *286*, Article 122994.

Mathew, G., & Joseph, B. (2018). Flexural behaviour of geopolymer concrete beams exposed to elevated temperatures. *Journal of Building Engineering*, *15*, 311-317.

Murali, G., Abid, S. R., Abdelgader, H. S., Amran, Y. H. M., Shekarchi, M., & Wilde, K. (2021). Repeated projectile impact tests on multi-layered fibrous cementitious composites. *International Journal of Civil Engineering*, *19*, 635-651.

Murali, G., Abid, S. R., Amran, Y. H. M., Abdelgader, H. S., Fediuk, R., Susrutha,

A., & Poonguzhali, K. (2020). Impact performance of novel multi-layered prepacked aggregate fibrous composites under compression and bending. *Structures*, *28*, 1502-1515.

Nematollahi, B., Ranade, R., Sanjayan, J., & Ramakrishnan, S. (2017). Thermal and mechanical properties of sustainable lightweight strain hardening geopolymer composites. *Archives of Civil and Mechanical Engineering*, *17*(1), 55-64.

Ozawa, M., Uchida, S., Kamada, T., & Morimoto, H. (2012). Study of mechanisms of explosive spalling in high-strength concrete at high temperatures using acoustic emission. *Construction and Building Materials*, *37*, 621-628.

Pająk, M., & Ponikiewski, T. (2013). Flexural behaviour of self-compacting concrete reinforced with different types of steel fibres. *Construction and Building Materials*, *47*, 397-408.

Pan, Z., & Sanjayan, J. G. (2010). Stress-strain behaviour and abrupt loss of stiffness of geopolymer at elevated temperatures. *Cement and Concrete Composites*, *32*(9), 657-664.

Pan, Z., Sanjayan, J. G., & Collins, F. (2014). Effect of transient creep on compressive strength of geopolymer concrete for elevated temperature exposure. *Cement and Concrete Research*, *56*, 182-189.

Pham, K. V. A., Nguyen, T. K., Le, T. A., Han, S. W., Lee, G., & Lee, K. (2019). Assessment of performance of fibre-reinforced geopolymer composites by experiment and simulation analysis. *Applied Sciences*, *9*(16), Article 3424.

Prasad, B. V., Anand, N., Kiran, T., Jayakumar, G., Sohliya, A., & Ebenezer, S. (2022). Influence of fibres on fresh properties and compressive strength of geo-polymer concrete. *Materials Today: Proceedings*, *57*, 2355-2363.

Rabiaa, E., Mohamed, R. A. S., Sofi, W. H., & Tawfik, T. A. (2020). Developing geopolymer concrete properties by using nanomaterials and steel fibres. *Advances in Materials Science and Engineering*, *2020*, 1-12.

Rajabi, A. M., Omidi Moaf, F., & Abdelgader, H. S. (2020). Evaluation of mechanical properties of two-stage concrete and conventional concrete using nondestructive tests. *Journal of Materials in Civil Engineering*, *32*(7), Article 4020185.

Ranjbar, N., & Zhang, M. (2020). Fibre-reinforced geopolymer composites: A review. *Cement and Concrete Composites*, *107*, Article 103498.

Rickard, W. D. A., & Van Riessen, A. (2014). Performance of solid and cellular structured fly ash geopolymers exposed to a simulated fire. *Cement and Concrete Composites*, *48*, 75-82.

Rickard, W. D. A., Williams, R., Temuujin, J., & Van Riessen, A. (2011). Assessing the suitability of three Australian fly ashes as an aluminosilicate source for geopolymers in high-temperature applications. *Materials Science and Engineering: A*, *528*(9), 3390-3397.

Rithanyaa, R., Murali, G., Salaimanimagudam, M. P., Fediuk, R., Abdelgader, H. S., & Siva, A. (2021). Impact response of novel layered two stage fibrous composite slabs with different support type. *Structures*, *29*, 1-13.

Roviello, G., Ricciotti, L., Ferone, C., Colangelo, F., & Tarallo, O. (2015). Fire resistant melamine based organic-geopolymer hybrid composites. *Cement and Concrete Composites*, *59*, 89-99.

Roviello, G., Ricciotti, L., Molino, A. J., Menna, C., Ferone, C., Cioffi, R., & Tarallo, O. (2019). Hybrid Geopolymers from Fly Ash and Polysiloxanes. *Molecules*, *24*(19), Article 3510.

Roviello, G., Ricciotti, L., Tarallo, O., Ferone, C., Colangelo, F., Roviello, V., & Cioffi, R. (2016). Innovative fly ash geopolymerepoxy composites: Preparation, microstructure and mechanical properties. *Materials*, *9*(6), Article 461.

Ryu, G. S., Lee, Y. B., Koh, K. T., & Chung, Y. S. (2013). The mechanical properties of fly ash-based geopolymer concrete with alkaline activators. *Construction and Building Materials*, *47*, 409-418.

Samal, S. (2019). Effect of high temperature on the microstructural evolution of fibre reinforced geopolymer composite. *Heliyon*, *5*(5), Article e01779. https://doi.org/10.1016/j.heliyon.2019.e01779.

Sanjayan, G., & Stocks, L. J. (1993). Spalling of high-strength silica fume concrete in fire. *Materials Journal*, *90*(2), 170-173.

Sarker, P. K., Kelly, S., & Yao, Z. (2014). Effect of fire exposure on cracking, spalling and residual strength of fly ash geopolymer concrete. *Materials & Design*, *63*, 584-592.

Schneider, U. (1988). Concrete at high temperatures—A general review. *Fire Safety Journal*, *13*(1), 55-68.

Shoukry, S. N., William, G. W., Downie, B., & Riad, M. Y. (2011). Effect of moisture and temperature on the mechanical properties of concrete. *Construction and Building Materials*, *25*(2), 688-696.

Shubbar, A. A., Jafer, H., Abdulredha, M., Al-Khafaji, Z. S., Nasr, M. S., Al Masoodi, Z., & Sadique, M. (2020). Properties of cement mortar incorporated high volume fraction of GGBFS and CKD from 1 day to 550 days. *Journal of Building Engineering*, *30*,101327. https://doi.org/10.1016/j.jobe.2020.101327.

Shubbar, A. A., Nasr, M. S., Islam, G. M., Al-Khafaji, Z. S., Sadique, M., Hashim, K., & Assi, L. N. (2022). Early age and long-term mechanical performance of mortars incorporating high-volume GGBS. In *Advances in Civil Engineering*, *Vol. 184*, (pp. 267-274). Springer. https://doi.org/10.1007/978-981-16-5547-0_26

Shubbar, A. A., Sadique, M., Nasr, M. S., Al-Khafaji, Z. S., & Hashim, K. S. (2020). The impact of grinding time on properties of cement mortar incorporated high volume waste paper sludge ash. *Karbala International Journal of Modern Science*, *6*(4), Article 7. https://doi.org/10.33640/2405-609x.2149

Shubbar, A., Nasr, M., Falah, M., & Al-Khafaji, Z. (2021). Towards net zero carbon economy: Improving the sustainability of existing industrial infrastructures in the UK. *Energies*, *14*(18), Article 5896. https://doi.org/10.3390/en14185896

Silva, G., Kim, S., Bertolotti, B., Nakamatsu, J., & Aguilar, R. (2020). Optimisation of a reinforced geopolymer composite using natural fibres and construction wastes. *Construction and Building Materials*, *258*, Article 119697.

Singh, N. B., & Middendorf, B. (2020). Geopolymers as an alternative to Portland cement: An overview. *Construction and Building Materials*, *237*, Article 117455.

Sivasakthi, M., Jeyalakshmi, R., Rajamane, N. P., & Jose, R. (2018). Thermal and structural microanalysis of micro silica blended fly ash based geopolymer composites. *Journal of Non-Crystalline Solids*, *499*, 117-130.

Tobbala, D. E., Abdelsalam, B. A., & Agwa, I. S. (2020). Bond performance of a hybrid coating zinc-rich epoxy incorporating nano-ferrite for steel rebars subjected to high temperatures in concrete. *Journal of Building Engineering*, *32*, Article 101698.

Tran, T. T., Pham, T. M., & Hao, H. (2019). Experimental and analytical investigation on flexural behaviour of ambient cured geopolymer concrete beams reinforced with steel fibres. *Engineering Structures*, *200*, Article 109707.

Tuama, W. K., Kadhum, M. M., Alwash, N. A., Al-Khafaji, Z. S., & Abdulraheem, M. S.

(2020). RPC effect of crude oil products on the mechanical characteristics of reactive-powder and normal-strength concrete. *Periodica Polytechnica Civil Engineering*, *64*(2), 422-429. https://doi.org/10.3311/ppci.15580

Turner, L. K., & Collins, F. G. (2013). Carbon dioxide equivalent (CO2-e) emissions: A comparison between geopolymer and OPC cement concrete. *Construction and Building Materials*, *43*, 125-130.

Vickers, L., Rickard, W. D. A., & Van Riessen, A. (2014). Strategies to control the high temperature shrinkage of fly ash based geopolymers. *Thermochimica Acta*, *580*, 20-27.

Vu, X. H., Malecot, Y., Daudeville, L., & Buzaud, E. (2009). Effect of the water/cement ratio on concrete behaviour under extreme loading. *International Journal for Numerical and Analytical Methods in Geomechanics*, *33*(17), 1867-1888.

Wang, X., Fan, F., Lai, J., & Xie, Y. (2021). Steel fibre reinforced concrete: A review of its material properties and usage in tunnel lining. *Structures*, *34*, 1080-1098.

Wu, F., Yu, Q., & Chen, X. (2022). Effects of steel fibre type and dosage on abrasion resistance of concrete against debris flow. *Cement and Concrete Composites*, *134*, Article 104776.

Xu, H., Provis, J. L., van Deventer, J. S. J., & Krivenko, P. V. (2008). Characterisation of aged slag concretes. *ACI Materials Journal*, *105*(2), Article 131.

Xu, L.-Y., Qian, L.-P., Huang, B.-T., & Dai, J.-G. (2021). Development of artificial one-part geopolymer lightweight aggregates by crushing technique. *Journal of Cleaner Production*, *315*, Article 128200.

Yadav, V. K., Gacem, A., Choudhary, N., Rai, A., Kumar, P., Yadav, K. K., Abbas, M., Khedher, N. Ben, Awwad, N. S., & Barik, D. (2022). Status of coal-based thermal power plants, coal fly ash production, utilisation in India and their emerging applications. *Minerals*, *12*(12), Article 1503.

Zeini, H. A., Al-jeznawi, D., Imran, H., Filipe, L., Bernardo, A., Al-khafaji, Z., & Ostrowski, K. A. (2023). Random forest algorithm for the strength prediction of geopolymer stabilised clayey soil. *Sustainability*, *15*(2), Article 1408. https://doi.org/10.3390/su15021408

Zhang, H. Y., Kodur, V., & Cao, L. (2015). Mechanical properties of geopolymer mortar after exposure to elevated temperatures. *Response of Structures Under Extreme Loading (PROTECT 2015)*. https://mail.dpi-proceedings.com/index.php/protect2015/article/view/21431

Zhang, H. Y., Kodur, V., Qi, S. L., Cao, L., & Wu, B. (2014). Development of metakaolin–fly ash based geopolymers for fire resistance applications. *Construction and Building Materials*, *55*, 38-45.

Zhang, Y. J., Li, S., & Wang, Y. C. (2012). Microstructural and strength evolutions of geopolymer composite reinforced by resin exposed to elevated temperature. *Journal of Non-Crystalline Solids*, *358*(3), 620-624.