*J Mater Sci* (2025) 60:18678–18709

**Review**

# Review: geopolymers for fire protection applications

Rosnita Mohamed[1,2], Mohd Mustafa Al Bakri Abdullah[1,2,*], Rafiza Abd Razak[2,3], Tung Lik Lee[4], Thanongsak Imjai[5], Md Azree Othuman Mydin[6], Zarina Yahya[2], Pilomeena Arokiasamy[1,3], and Dickson Ling Chuan Hao[2,3]

[1] *Faculty of Chemical Engineering & Technology, Universiti Malaysia Perlis (UniMAP), Perlis, Malaysia*
[2] *Geopolymer & Green Technology, Centre of Excellence (CEGeoGTech), Universiti Malaysia Perlis (UniMAP), Perlis, Malaysia*
[3] *Faculty of Civil Engineering & Technology, Universiti Malaysia Perlis (UniMAP), Perlis, Malaysia*
[4] *ISIS Neutron and Muon Source, STFC Rutherford Appleton Laboratory, Harwell Campus, Didcot, UK*
[5] *School of Engineering and Technology, Walailak University, 222 Thaiburi, Thasala, Nakhon Si Thammarat 80160, Thailand*
[6] *School of Housing, Building and Planning, Universiti Sains Malaysia, 11800 Penang, Malaysia*

**Received:** 4 July 2025
**Accepted:** 3 September 2025

## ABSTRACT

Geopolymers are known to exhibit excellent thermal stability under elevated temperature exposure, highlighting their potential as surface-protective coatings for fire resistance applications. This thermal stability is primarily attributed to matrix densification, pore refinement, and phase crystallization, as demonstrated by previous studies on thermal behavior, microstructural evolution, phase transformation, tomography, and residual mechanical strength. This review provides a critical discussion of the thermal performance, microstructural characteristics, and coating behavior of geopolymers, with particular emphasis on potential for intumescence. Despite the promising fire protection capabilities observed, the underlying mechanisms of intumescence in geopolymer systems remain insufficiently understood specifically regarding the contribution of chemical composition. Therefore, this review also identifies key research gaps and proposes future directions to advance the development and application of geopolymer-based intumescent coatings.

## Introduction

Geopolymers have emerged as a sustainable class of inorganic binders synthesized through the alkali activation of aluminosilicate precursors offering an environmentally viable alternative to traditional cementitious materials. The synthesis of geopolymer or known as geopolymerization process involves dissolution, polymerization, and polycondensation mechanisms for the formation of a three-dimensional aluminosilicate network, which can be varied in terms of mix designation through variations in precursor type, alkali concentration, and solid-to-liquid ratios [1, 2]. Given the low-carbon footprint and ability to incorporate industrial by-products such as fly ash, metakaolin, and slag, geopolymers have attracted increasing interest

Handling Editor: Stephen Eichhorn.

Address correspondence to E-mail: mustafa_albakri@unimap.edu.my

Springer

https://doi.org/10.1007/s10853-025-11496-z

across variation of applications such as infrastructures in construction buildings [3, 4], protection against chemical attack [5, 6], wastewater treatment [7, 8] as well as fire protection potential [9–11]. Among those potential applications, geopolymers have gained attention in terms of fire protection potential which can be either applied directly as bulks or acted as surface-protective coatings.

Numerous past researches have widely explored on the favorable thermal behavior of geopolymer materials when subjected to elevated temperatures [12–15]. It is believed that upon heating, geopolymers may undergo transformations such as densification, partial crystallization, and vitrification, which lead to the formation of stable and coherent matrices capable of resisting heat-induced deterioration [16, 17]. These thermal transformations are known to be highly influenced by the material's chemical composition, particularly the Si/Al ratio [18], type of alkali activator [19, 20], and nature of the precursor [21, 22]. Higher silica content and appropriate aluminosilicate balance contribute to the formation of crosslinked networks, which are critical in maintaining structural integrity and minimizing shrinkage during thermal exposure. The performance of geopolymers in fire environments has also been evaluated in terms of their residual mechanical properties [14, 15]. This residual strength is closely influenced by microstructural evolution, including pore refinement, gel transformation, and the formation of crystalline phases formation.

Additionally, in further exploration of alternatives to organic coating, geopolymers have also been proposed as coating materials for passive fire protection due to the ability to form dense and thermally insulating surface layers [23–25]. While organic intumescent coatings typically rely on foaming agents and carbonization mechanisms, recent findings suggest that geopolymer coatings may exhibit expansion or swelling behavior triggered by matrix softening, structural water release, and viscous phase formation under heat [19]. However, the intumescence mechanism for geopolymer specifically on the chemical composition contribution for the intumescence behavior is still not fully understood and remains an active area of research. Despite the considerable potential demonstrated in past research, challenges remain in the optimization and standardization of geopolymer coatings for fire protection. The variability in chemical formulation as well as further elucidation on the mechanism presents key gaps in the current knowledge. A systematic evaluation of these parameters is necessary to advance the development of geopolymer coatings with predictable and reliable fire performance. This review critically examines the performance of geopolymers at elevated temperatures, with a focus on their application as surface-protective coating specifically on the intumescent potential. This review briefly discussed on the thermal behavior, residual strength, microstructural stability, and coating effectiveness, while emphasizing the role of chemical composition in determining fire resistance. The gaps identified throughout this review are believed to be significant for further exploration in terms of utilizing geopolymer toward sustainability environment.

## Basis of geopolymers and potential on high-temperature exposure

Geopolymers were first proposed in 1972 by Davidovits and have attracted major research interest worldwide over the past decade as a 'green' material, due to their proven potential for reducing carbon dioxide ($CO_2$) emissions and the easy availability of required precursors [11, 26]. Geopolymers are inorganic polymers typically synthesized via alkali activation (using alkali activator) of aluminosilicate precursors (binding materials), thus forming amorphous to semi-crystalline three-dimensional silica (Si) and alumina (Al) polymeric networks (–Si–O–Si–, Al–O–Si–) in IV-fold coordination [1, 2, 27]. The chemical formula of geopolymers can be written as follows:

$Mn\,[-(SiO_2)\,z-AlO_2]\,n.wH_2O$ (1).

($M$ = the alkaline element or cation such as $Na^+$,$K^+$, or $Ca^+$, $n$ = the degree of polymerization and $z$ = number of silicate units.)

The geopolymerization process typically involves a reaction between aluminosilicate materials with alkaline activators such as sodium hydroxide (NaOH) or sodium silicate ($Na_2SiO_3$) solutions as precursors. This process leads to the formation of three-dimensional framework structure with amorphous to semi-crystalline network [28]. This structure is formed by sharing oxygen atoms with silicon oxygen tetrahedra and aluminum-oxygen tetrahedra, creating a short-range ordered network achieved through alternating chemical bonding [10]. In terms of geopolymer precursor, the flexibility in selecting aluminosilicate sources makes geopolymers recognized as one of the more sustainable construction materials. This is due to the fact that most of the aluminosilicate precursors utilized for geopolymer are derived from waste including biomass and industries. Numerous aluminosilicate materials have been widely researched for their potential as geopolymer precursors including kaolin, metakaolin, fly ash, slag, red mud, rice husk ash, and volcanic ash [29, 30]. Meanwhile, for liquid precursor, solution with high alkalinity is much required for the synthesis of the geopolymers. The most common alkali solution, also known as an alkali activator, is a hydroxide solution such as sodium hydroxide or potassium hydroxide. The alkali solution can also be a combination of sodium hydroxide or potassium hydroxide with sodium silicate or potassium hydroxide with potassium silicate [31, 32].

Generally, the use of geopolymers in the construction industry has gained significant attention due to their eco-friendly nature and has been widely explored in construction field applications such as precast panels, road pavements, and bricks production. Unlike conventional Portland cement, which emits a significant amount of $CO_2$ during production, geopolymer is believed to reduce this emission while maintaining the environmental approach due to its utilization of waste as precursors. In addition, geopolymers are believed to exhibit superior performance under thermal stress while maintaining structural integrity and mechanical strength at elevated temperatures [33–35]. This is attributed by the inorganic framework that does not burn like organic polymers, thus making it reliable as potential fire protection and resistance materials. Fire damage can be critical, affecting both people and infrastructures of the buildings and thus becoming one of the main concerns in construction field [36]. In order to evaluate the potential of geopolymer upon fire exposure, the elevated temperature performance of any material is crucial, particularly when it is intended for use as a fireproof material in structures, as a thermal insulator, or for refractory applications.

Some of the previous researches conducted on the exposure of geopolymers to elevated temperatures are summarized in Table 1. Table 1 summarizes the exploration of geopolymers derived from variation of aluminosilicate precursors for their potential as fire-resistant materials, including fly ash [15, 37, 38], metakaolin [39, 40], and slag [14, 41]. Geopolymers have been exposed a wide range of temperatures from ambient temperature conditions (20–25 °C) up to 1200 °C, in effort to monitor the thermal behavior of the geopolymer upon thermal exposure. In addition, the geopolymers' performance was also evaluated with a focus on key mix design factors, such as $SiO_2/Al_2O_3$ [39, 40] and the addition of other aluminosilicate materials when dealing with blended geopolymers such as percentage addition of fly ash [14, 42], glass powder [41], and fillers such as silica sands [43].

For instance, Lahoti et al. [36] highlighted that the properties of geopolymers can be investigated at different scales through elevated temperature exposure in order to guarantee their reliability prior to

**Table 1** Summary of past studies evaluating geopolymer performance at elevated temperatures

| References | Aluminosilicate precursor | Significant variable | Temperature exposure |
|---|---|---|---|
| Xiang et al. [42] | MK-FA geopolymer | Percentage FA addition | 500, 800 °C |
| Barzoki and Gowayed [39] | MK geopolymer | $SiO_2/Al_2O_3$ molar ratio | 200–1000 °C |
| Saludung et al. [13] | FA/slag geopolymer | Curing condition | 500, 750, 950 °C |
| X. Jiang et al. [37] | FA geopolymer | Different type of FA as precursor | 100–1200 C |
| Moutaoukil et al. [38] | FA geopolymer | Different alkali activator ratio | 200–1000 °C |
| Abd Razak et al. [15] | FA geopolymer | Effects of burning temperature | 500 °C and 1200 °C |
| Luo et al. [44] | FA geopolymer | Addition of slag | 20–1000 °C |
| J.C. Kuri et al. [14] | Slag geopolymer | Percentage FA addition | 200–1000 °C |
| A.N. Derinpinar et al. [41] | Slag geopolymer | Addition of glass powder | 150–750 °C |
| Zhang et al. [45] | FNS geopolymer | Effect of temperature exposure | 200–1100 °C |
| Kim et al. [40] | MK geopolymer | Various Si/Al ratios and sodium activators | 25–1000 °C |
| Javed et al. [46] | LS geopolymer | Addition of silica fume and FA | 300, 500, 700, 950 °C, |
| Perna et al., [43] | Calcined clay geopolymer | Addition of filler (silica sands and cordierites) | 100–1000 °C |
| Peng et al. [17] | FAC-MK geopolymer | Percentage FAC addition | 20–1100 °C |

[*] *MK* Metakaolin, *FA* Fly ash, *FNS* Ferronickel slag, *LS* Lithium slag, *FAC* Fly ash cenosphere

application. This encompasses micro-, meso-, and macroscales. According to Lahoti et al. [36], micro-scale study entails investigating phase transitions and nano-structural alterations in geopolymers subjected to elevated temperatures, which markedly affect their chemical stability. Ensuring stability at the micro-scale level is essential for maintaining material integrity at higher hierarchical levels including the meso- and macro-scales which are evaluated through volumetric changes, including crack resistance due to thermal stress, and its capacity to retain mechanical strength and resist spalling at elevated temperatures [36]. Consequently, a comprehensive analysis encompassing thermogravimetric analysis to observe thermal behavior, visual, and phase transformations upon exposure including morphology, porosity, and cracking should be further explored prior to application to ensure its durability particularly in terms of residual strength after thermal exposure.

## Thermal behavior of geopolymer at elevated temperature

Thermogravimetric analysis (TGA) is a widely utilized technique in materials science for investigating the thermal behavior of geopolymer including thermal stability and decomposition patterns of materials by continuously monitoring mass changes as a function of temperature under controlled atmosphere. TGA provides crucial insights on the degradation processes, typically including the evaporation of physically bound water (< 200 °C), dehydroxylation of chemically bound hydroxyl groups (300–600 °C), and structural reorganization or densification at higher temperatures (> 800 °C) [45, 47]. The comparison of thermal behavior of geopolymers before and after exposure to high temperature had been reported and is summarized in Table 2. From Table 2, variations of aluminosilicate precursors, including fly ash, metakaolin, and slag, are reported in terms of their mass loss under exposure to elevated temperatures, which lead to variations in mass loss. In most studies, the highest temperature used to evaluate mass loss was either 1000 °C or 1200 °C. This temperature range is particularly significant, as it provides insight into the thermal stability and structural integrity of the geopolymers.

According to past research in Table 2, the percentage of mass loss varies significantly depending on the aluminosilicate precursors utilized. Slag possesses higher mass loss (5–20%) in comparison with other aluminosilicate materials. For instance, the mass loss was observed to be 16% with temperature exposure at 550 °C [48]. This observation can be attributed to the high-calcium composition contained in slag. Slag contains a high proportion of calcium oxide (CaO), which facilitates the formation of calcium-rich hydration products such as portlandite ($Ca(OH)_2$) and calcium carbonate ($CaCO_3$). Both phases decompose thermally between roughly 400 °C and 800 °C, releasing water and carbon dioxide and thereby accounting for much of the recorded mass loss [49]. Despite this drawback, slag is often selected for its superior strength

**Table 2** Thermogravimetric analysis (TGA) in past studies

| References | Geopolymer | Heating rate, °C/min | Atmosphere | Maximum temperature, °C | Mass loss, % |
|---|---|---|---|---|---|
| Rivera et al. [48] | Fly ash/metakaolin/slag-based geopolymer | 10 °C/min | Nitrogen | 550 °C | 2 (fly ash), 4.5 (metakaolin), 16 (slag) |
| Javed et al. [46] | Lithium slag-based geopolymer | 10 °C/min | Nitrogen | 1000 °C | 5.02–6.71 |
| Sivasakthi et al. [50] | Fly ash-based geopolymer | 10 °C/min | Nitrogen | 1200 °C | ~ 10.00–11.50 |
| Moutaoukil et al. [38] | Fly ash-based geopolymer | 10 °C/min | Helium | 1000 °C | ~ 4.00–16.000 |
| Barzoki and Gowayed [39] | Metakaolin-based geopolymer | 20 °C/min | Nitrogen | 1000 °C | ~ 6.00–9.80 |
| Caballero et al. [47] | Metakaolin-based geopolymer | 10 °C/min | Nitrogen | 1000 °C | ~ 2.90–4.60 |
| Xiang et al. [42] | Metakaolin-based geopolymer | 5 °C/min | Nitrogen | 800 °C | ~ 11.00–14.00 |
| Kashani et al. [51] | Fly ash and slag blends-based geopolymer | 6.60 °C/min | Nitrogen | 1000 °C | ~ 17.00–19.50 |
| Perna et al. [43] | Calcined clay-based geopolymer | 20 °C/min | Nitrogen | 1100 °C | ~ 2.50–6.00 |

development and its ability to cure at ambient temperature without additional energy input. Adjusting the chemical composition to improve thermal stability is therefore a worthwhile research direction. Javed et al. [46] demonstrated that addition of fly ash and silica fume minimizes mass loss obtained as listed in Table 2.

In addition, it is believed that significant mass loss is usually observed after 100 °C as it represents the mass loss directly related to geopolymeric networks. Javed et al. [46] utilized TGA to compare the thermal stability of lithium slag-based geopolymer modified with the addition of fly ash and silica fume. Both geopolymers with addition of fly ash ($LSG_{FA}$) and silica fume ($LSG_{SF}$) were heated from room temperature to 1000 °C at a rate of 10 °C per minute. The TGA is depicted in Fig. 1. According to Fig. 1, in temperature zone I, the mass loss corresponds to the evaporation of pore water. This is followed by zone II (100–300 °C), where dehydroxylation occurs, involving the release of bound water from hydroxyl groups within the geopolymer network, leading to reduced density and pore formation through self-desiccation. The $LSG_{FA}$ mix showed higher weight loss than $LSG_{SF}$ in zones I and II is linked to a higher degree of aluminosilicate dissolution in the fly ash-based system, followed by polycondensation processes that release water [46]. During dissolution, water is consumed in forming monomeric species such as $SiO(OH)_2$, $Si(OH)_4$, and $Al(OH)_4$ and liberated again as these species undergo polycondensation, leading to gel formation [46]. Meanwhile, in zone III, continued dehydroxylation of the aluminosilicate gel causes microstructural shrinkage and transformation into new mineral phases. Finally, in zone IV, viscous sintering progressively reduces porosity, induces thermal shrinkage, and densifies the matrix, marking the completion of phase transformation. This was further supported by Manzoor et al. [49] who reported that between 300 °C and approximately 800 °C, a continuous decrease in mass occurs due to the removal of structural water. Beyond 800 °C, no significant weight loss was observed, owing to the absence of further thermal decomposition reactions. It is believed that the sintering process during this temperature leads to the formation of a ceramic body [49]. Apart from proving that geopolymer has a better thermal stability based on the minimal weight loss (5.02 and 6.71%, respectively, for both addition of fly ash and silica fume) throughout the evolution of temperature, Javed et al. [46] also emphasized that $LSG_{FA}$ has higher thermal stability and resistance to dehydroxylation than $LSG_{SF}$ for up to 300 °C. However, it was also found that the silica fume-incorporated LSG exhibits less shrinkage and cracking and higher residual strength at 900 °C due to the viscous sintering of silica-fume particles, which enhances the material's suitability for fire protection and thermal stability at elevated temperatures. This study proves that the composition of silicon (Si) which acts as the backbone of geopolymeric gels is significant to be optimized in order to avoid poor thermal stability due thermal deterioration.

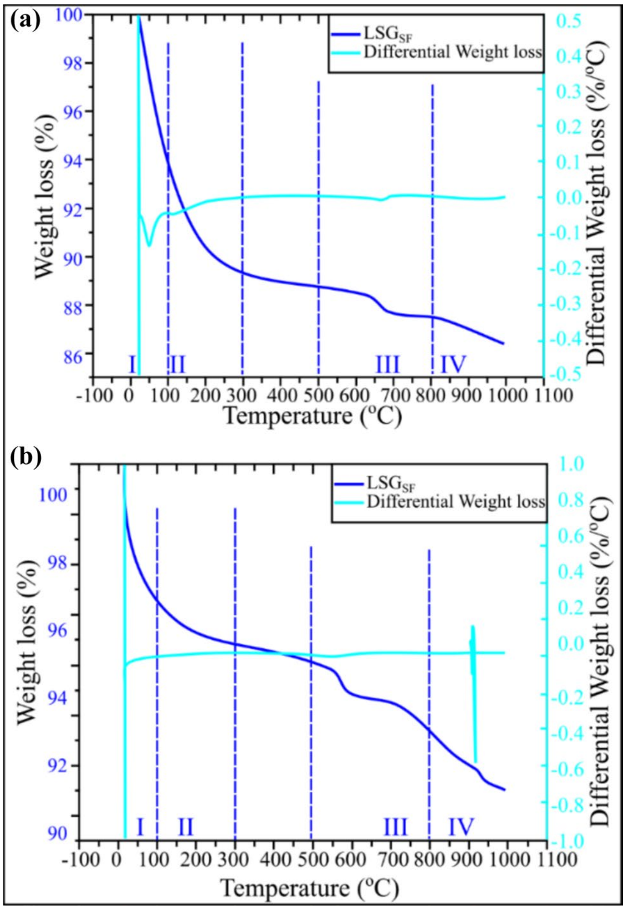


**Figure 1** Thermogravimetric analysis of lithium slag-based geopolymer: **a** addition of fly ash and **b** addition of silica fume [46].

Meanwhile, another study carried out by Barzoki and Gowayed [39] showed contradictory findings on the influence of $SiO_2$ by varying $SiO_2/Al_2O_3$ molar ratios on the thermal properties of metakaolin-based geopolymer. According to this study, geopolymers and their raw materials (silica fume, alumina powder, and metakaolin) were subjected to heat treatments at 200, 400, 600, 800, and 1000 °C in a laboratory furnace with each target temperature maintained for 1 h. The samples were immediately removed and cooled to room temperature under ambient conditions after completion of heating and dwelling [39]. The TGA obtained can be depicted as in Fig. 2 in which the "no-conditioning" curves correspond to samples tested without prior thermal exposure, whereas the other curves correspond to samples that were preheated to the specified temperatures before undergoing TGA. A reduction in total mass loss was observed when the alumina content in the geopolymers was increased, as evidenced by the mass loss result in Fig. 2. This was particularly evident in the metakaolin-based geopolymer with the lowest $SiO_2/Al_2O_3$ molar ratio (0.7), which suggests that alumina-rich specimens have enhanced thermal stability. However, as being evidenced by this study, a balance of silica ($SiO_2$) and alumina ($Al_2O_3$) has been shown to be crucial, with alumina improving thermal stability by minimizing dehydration and encouraging secondary geopolymerization, and silica contributing to the enhanced mechanical strength [39]. Therefore, further exploration on the optimization of both $SiO_2$ and $Al_2O_3$ is essential to develop geopolymers with optimal thermal and mechanical properties for high-temperature applications focusing on various aluminosilicate materials as precursor. This is because each aluminosilicate precursor possesses a different composition of $SiO_2$ and $Al_2O_3$ which are significant for geopolymeric matrix formation.

The importance of controlling optimal composition of $SiO_2$ and $Al_2O_3$ can be further proven by the lowest range of mass loss obtained by metakaolin-based geopolymers at elevated temperature exposure depicted in Table 2 [39, 47]. Metakaolin-based geopolymers are believed to exhibit superior thermal stability with minimal mass loss during high-temperature exposure, as evidenced by the mass loss from the thermogravimetric analysis (TGA). This behavior is primarily due

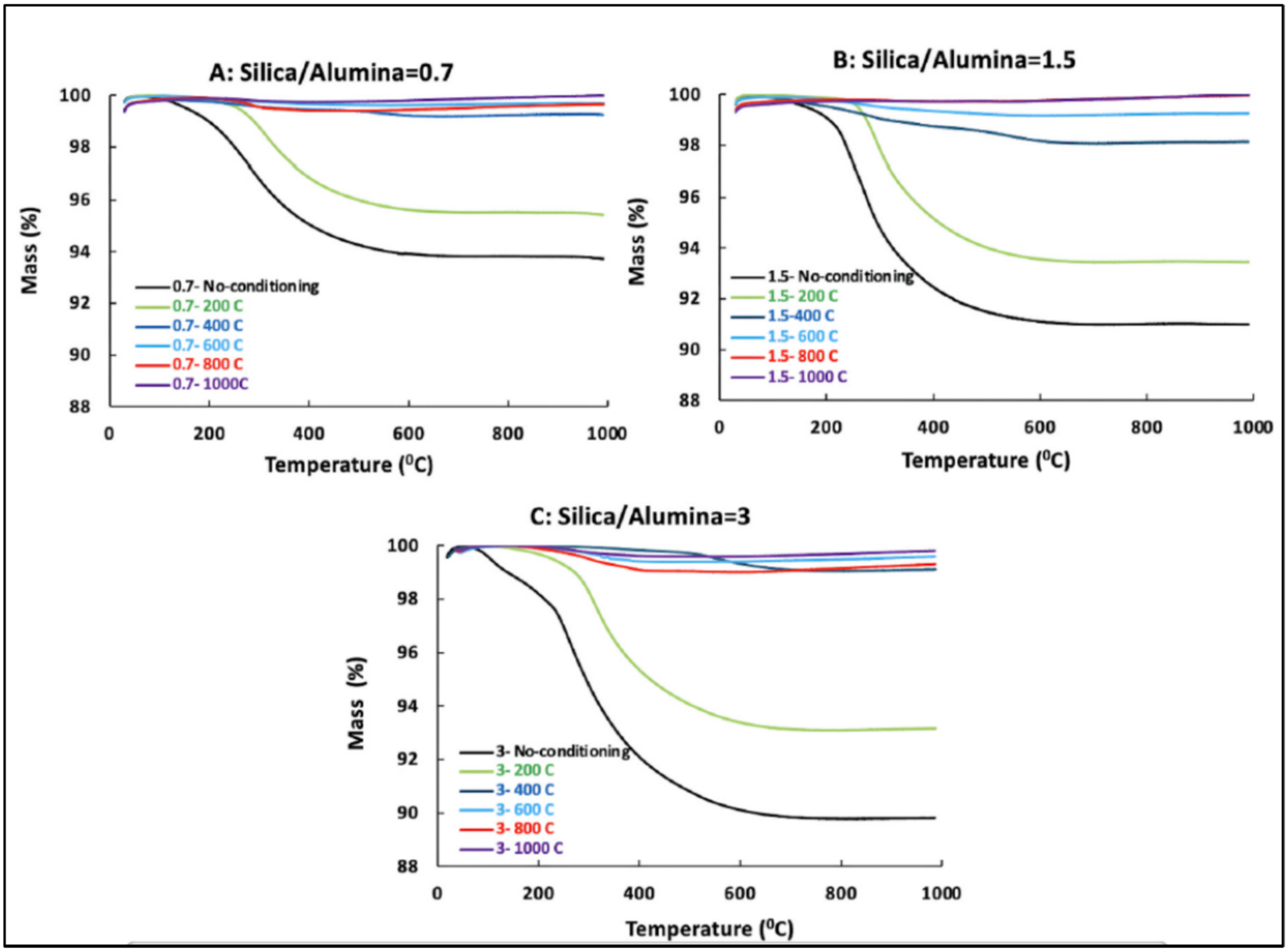


**Figure 2** The effect of different $SiO_2/Al_2O_3$ molar ratios on geopolymer performance under high-temperature exposure.

to the dehydroxylation of kaolinite during calcination at 600–800 °C, which substantially reduces the chemically bound water in the precursor material [52]. As a result, the amount of physically and chemically bound water released during heating was minimized, leading to reduced mass loss compared to geopolymers derived from other precursors [52]. Moreover, the gel phase in metakaolin-based systems is dominated by sodium aluminosilicate hydrate (N–A–S–H), which forms a stable amorphous polymeric network of silica and alumina that resists thermal decomposition, maintaining its structural integrity even at temperatures exceeding 600 °C.

In terms of comparison with ordinary Portland cement (OPC), the superior thermal stability of geopolymers for fire protection was further emphasized by Kashani et al. [51] in which both geopolymers and OPC mortars were utilized. From the study reported, it was found that below 100 °C, both OPC and geopolymer showed similar pattern of mass loss associated with evaporation of water. However, OPC mortar was found to exhibit a noticeably higher mass loss above 100 °C compared to geopolymers with total mass loss exceeding 25%. This is attributed to the sequential removal of free water and the breakdown of hydration products. The reactions also include the dehydration of ettringite and C–S–H phases between 200 and 400 °C, followed by the decomposition of Portlandite near 450 °C [48]. In contrast, the mass loss for geopolymer above 100 °C is attributed to the dehydration of gels such as C–(N)–A–S–H and N–A–S–(H), along with the removal of terminal hydroxyl groups from the geopolymer matrix, leading to densification of the matrix. This is consistent across various geopolymers with different formulations in this study which were observed from the mass loss data tabulated in Table 2. Additionally, at 1000 °C, Portland cement (PC) samples continued to exhibit greater mass loss, indicating a higher content of chemically bound water within their hydration structure compared to geopolymers. This proves that the thermal degradation of these hydration products in OPC is a key factor contributing to its reduced thermal stability relative to geopolymers [51].

This finding is in line with a study by Perna et al. [43] which compares the physicomechanical properties of geopolymers and OPC mortars after high-temperature exposure. TGA was determined prior further evaluation on temperature exposure; thus, all the samples presented in Fig. 3 are denoted as “ref” which is referred as reference samples. The TGA coupled with differential thermal analysis (DTA) was utilized, and the sample exposure was in the range between 25 and 1100 °C and the result is illustrated in Fig. 3. In addition, from the TG-DTA plot, it is assumed that the endothermic effects are oriented downward and exothermic effects upward, as per the instrument configuration. Meanwhile, in order for ensuring comparability between compositions, the TG data, originally recorded as absolute mass change (*mg*), were normalized to the initial sample mass and expressed as relative mass loss (%). As this study emphasizes on utilization of fillers, therefore variation of geopolymer samples was prepared where GP_C1_ref denotes a metakaolin-based geopolymer containing cordierite filler in two particle size fractions (C65_0.1 and C65_0.5), GP_C2_ref contains cordierite filler in a single fine fraction (C65_0.1), GP_S1_ref contains silica sand filler in two particle size fractions (ST6 and STJ25), and GP_S2_ref contains silica sand filler in a single fine fraction (ST6). Meanwhile, OPC_ref represents a fine-grained mortar prepared from CEM I 42.5 R with silica-mined aggregate in a 1:3 cement-to-aggregate weight ratio. Similar to Kashani et al.[51], significant mass loss was found to be more pronounced after 100 °C for both geopolymers and OPC mortars as it can be seen by the humps observed in Fig. 3. However, the mass loss of OPC mortar was found to be higher than mass loss of geopolymer mortar, as evidenced by increasing percentage of porosity determined. Additionally,

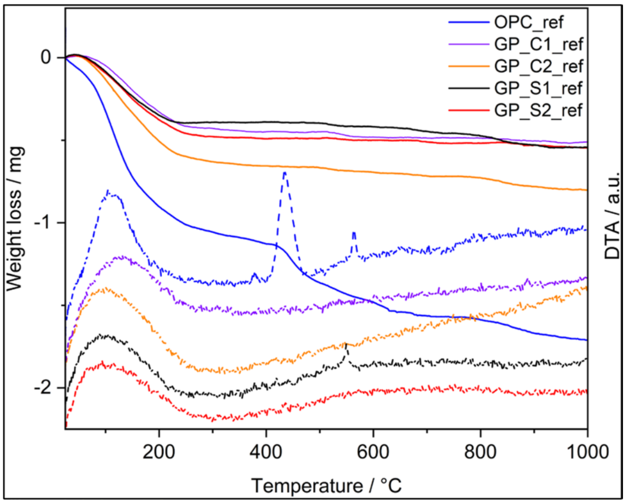


**Figure 3** Thermogravimetric analysis comparison for OPC and geopolymers [43].

this study also claimed that the significant mass loss in the temperature range ~ 400–800 °C corresponds to the decomposition of portlandite into free lime (CaO) and the decomposition of calcium carbonates into CaO and $CO_2$. This aligns with the findings of Kashani et al.[51] and Rivera et al. [48]. Even though the specific percentage of mass loss is not mentioned, it was determined that the overall mass loss aligns with typical OPC thermal behavior observed in previous studies. TGA results demonstrate that geopolymers specifically with proper optimization of fillers addition are capable to exhibit better thermal performance and lower mass loss compared to OPC.

## Microstructural analysis upon high-temperature exposure

The thermal behavior of geopolymer materials correlates with the microstructure and phase composition upon exposure to elevated temperatures. While thermogravimetric analysis (TGA) provides significant data on mass loss associated with dehydration, dehydroxylation, and gel reorganization, the microstructural and phase analyses are significant in offering deeper insight into the structural properties of the geopolymers that lead to its thermal degradation or stability. Geopolymers are known to undergo physicochemical changes, including pore coarsening, microcrack development, densification, and vitrification, which often correlate with the thermal events detected by TGA [45]. Therefore, elucidation on the microstructural evolution is therefore critical to provide further understanding on how geopolymers function as thermal barrier under high-temperature exposure. This can be achieved by conducting detailed observations including visual appearance, morphology, tomography, and phase transformation analysis. These microstructural analyses can also be further correlated with the residual compressive strength measured after thermal exposure to further justify the material's performance.

### *Visual appearance observation*

One of the most common observations upon exposure to high temperature is the visual appearance of geopolymers. The visual appearance of geopolymers during and after exposure to elevated temperatures offers important qualitative insights into their thermal responses, structural transitions, and surface protection capability. Notable observations include color shifts, surface texturing, expansion, and char production, which closely correlate with underlying physicochemical processes. This can be seen in a study reported by Abd Razak et al. [15] on visual appearance of fly ash-based geopolymers and ordinary Portland cement (OPC) concretes as depicted in Fig. 4. In this study, three samples for each OPC concretes were prepared by following the specific grade of concrete (standard strength grades of 20, 40, and 60 MPa for the OPC-based concrete). Meanwhile, the mix proportions for geopolymer samples (G20, G40, and G60) were also prepared following the specific grade by utilizing response surface methodology (RSM). Comparison on

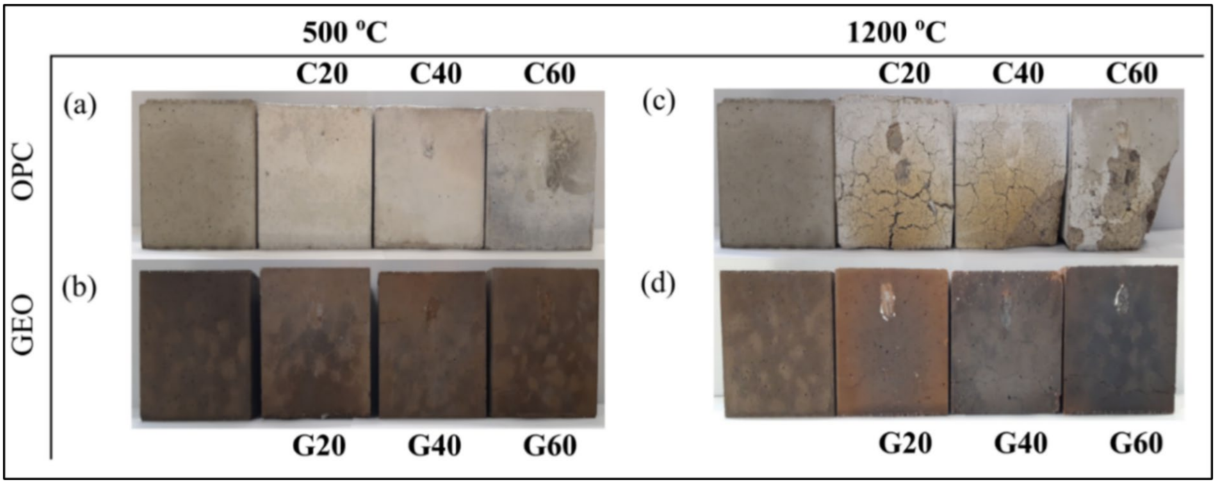


**Figure 4** Visual comparison of concrete in cm/cube: **a** OPC at 500 °C; **b** GEO at 500 °C; **c** OPC at 1200 °C; **d** GEO at 1200 °C [15].

physical appearance of samples was made on before (the most left for each Fig. 4a–d) and after thermal exposure. As depicted in Fig. 4, the study discovered that the cracks were more pronounced in the OPC compared to geopolymers. This can be attributed to the total loss of moisture within the concrete. Additionally, spalling was also detected which resulted from thermal strains induced by the quick temperature increase and the variable internal pore pressure inside the concrete during fire exposure. Elevated pore pressure could not dissipate from the concrete, hence inducing tensile tension that led to spalling. In contrast, the geopolymer concrete examples exhibited no spalling as observed. Meanwhile, cracks on the surface of the specimens were apparent following exposure to fire at 1200 °C, although they were less pronounced than those on the OPC-based concrete specimens, hence demonstrating superior fire resistance of the tested material relative to OPC-based concrete.

Similar observation was also found in a study reported by Luo et al. [44], specifically in terms of color, texture, and cracks as depicted in Fig. 5. By utilizing fly ash and ground-granulated blast furnace slag as precursors of geopolymers in this study (AAFS), this geopolymer is known to be treated as hybrid binder. According to Fig. 5, the surface color gradually turned reddish-brown from room temperature to 800 °C, owing to the oxidation of iron present in fly ash, which has always been the case in the fly ash-based system when exposed to high temperature. In addition, crack development was observed between 100 and 600 °C, likely due to the migration and evaporation of moisture within the hybrid binder. Meanwhile, a smooth texture with fewer cracks was observed after exposure to 800 °C, which might be attributed to the healing effect caused by viscous sintering reaction [44].

## Morphology and tomography analysis

Apart from visual appearance, several past studies have briefly focused on examining the morphology of geopolymers after high-temperature exposure, as presented in Fig. 6. It should be noted that the comparison was made for temperatures ranging between 800 and 1200 °C only since it is commonly selected as the maximum temperature of evaluation by past studies. The observations on the morphology include internal microcracks and possibility of degradation and shrinkage occurring when being exposed to high temperature. Variations of geopolymers including metakaolin-based geopolymers, fly ash-based geopolymers, ferronickel slag-based geopolymers, and blended geopolymers of metakaolin and rice husk ash, palm oil fuel ash, and ground-granulated blast furnace slag are compared as illustrated in Fig. 6.

As depicted in Fig. 6, metakaolin-based geopolymer is one of the most commonly studied materials in terms of morphology after high-temperature exposure,

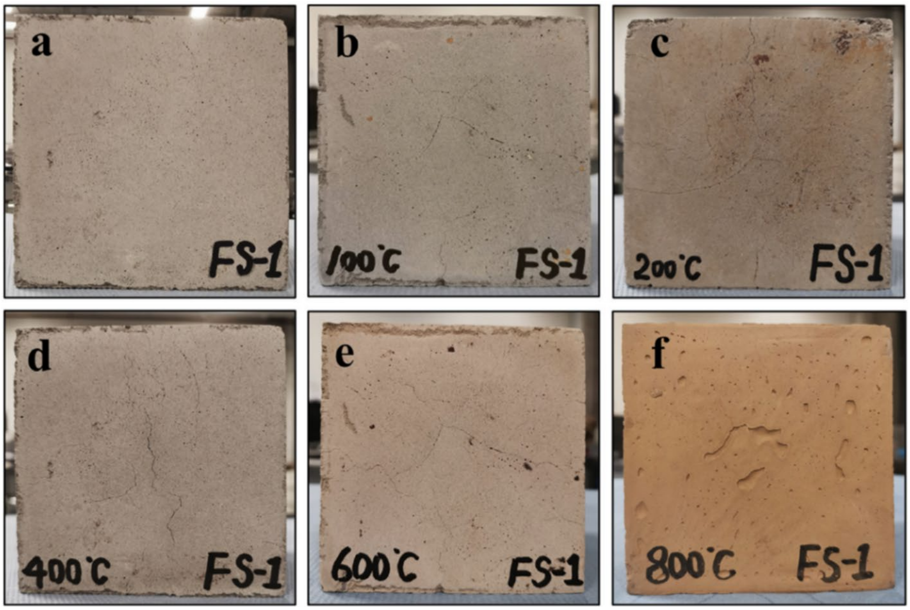
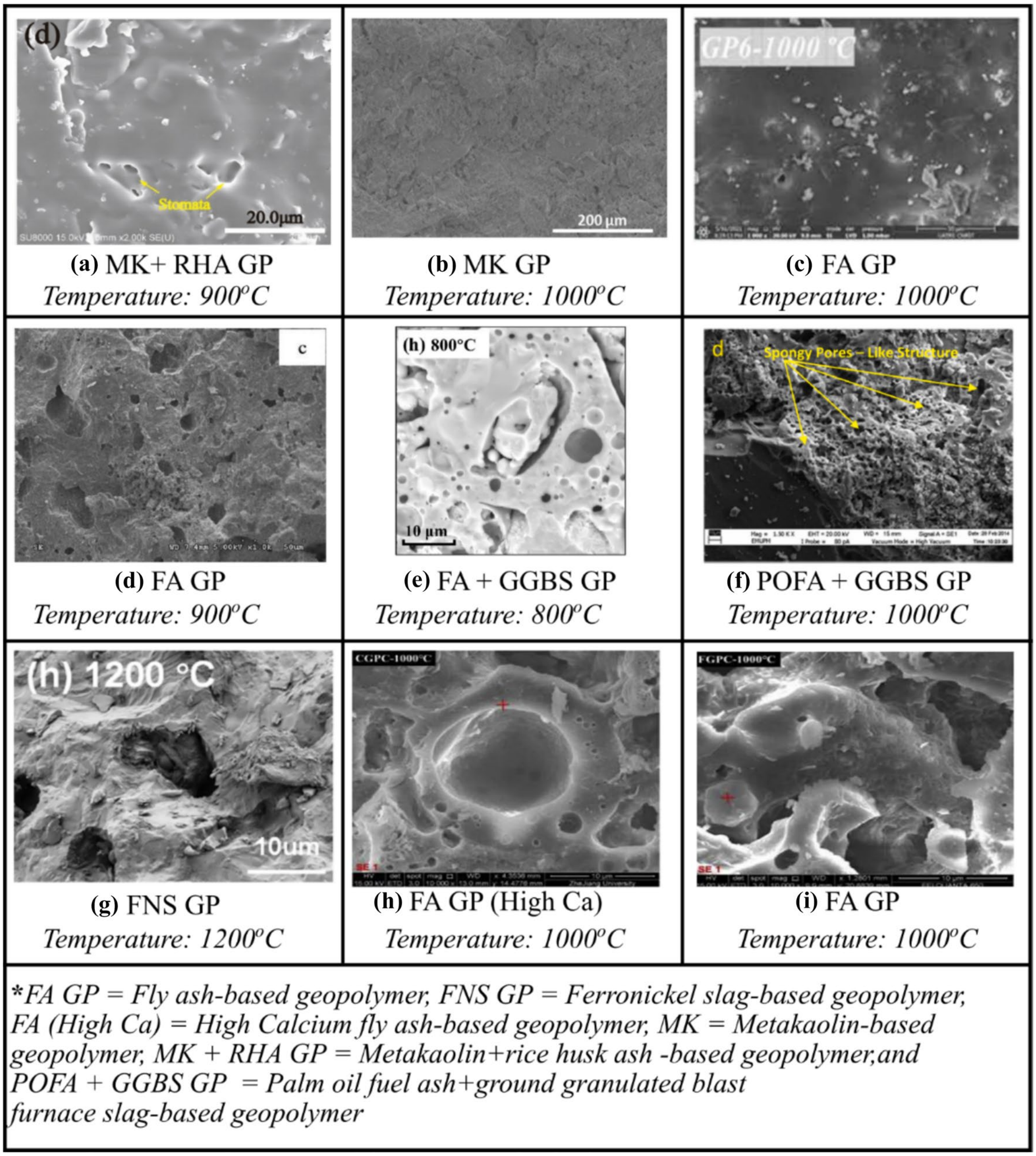


**Figure 5** Visual appearance development under elevated temperature exposure [44].



**(a)** MK+ RHA GP *Temperature: 900°C*

**(b)** MK GP *Temperature: 1000°C*

**(c)** FA GP *Temperature: 1000°C*

**(d)** FA GP *Temperature: 900°C*

**(e)** FA + GGBS GP *Temperature: 800°C*

**(f)** POFA + GGBS GP *Temperature: 1000°C*

**(g)** FNS GP *Temperature: 1200°C*

**(h)** FA GP (High Ca) *Temperature: 1000°C*

**(i)** FA GP *Temperature: 1000°C*

**FA GP = Fly ash-based geopolymer, FNS GP = Ferronickel slag-based geopolymer, FA (High Ca) = High Calcium fly ash-based geopolymer, MK = Metakaolin-based geopolymer, MK + RHA GP = Metakaolin+rice husk ash -based geopolymer,and POFA + GGBS GP = Palm oil fuel ash+ground granulated blast furnace slag-based geopolymer*

**Figure 6** Comparison of various morphologies of geopolymers after high-temperature exposure reported by **a** Liu et al. [18], **b** Lila et al. [53], **c** Moutaoukil et al. [38], **d** Wongsa et al. [56], **e** Luo et al. [44], **f** Salih et al. [58], **g** Zhang et al. [45], **h** and **i** Jiang et al. [37].

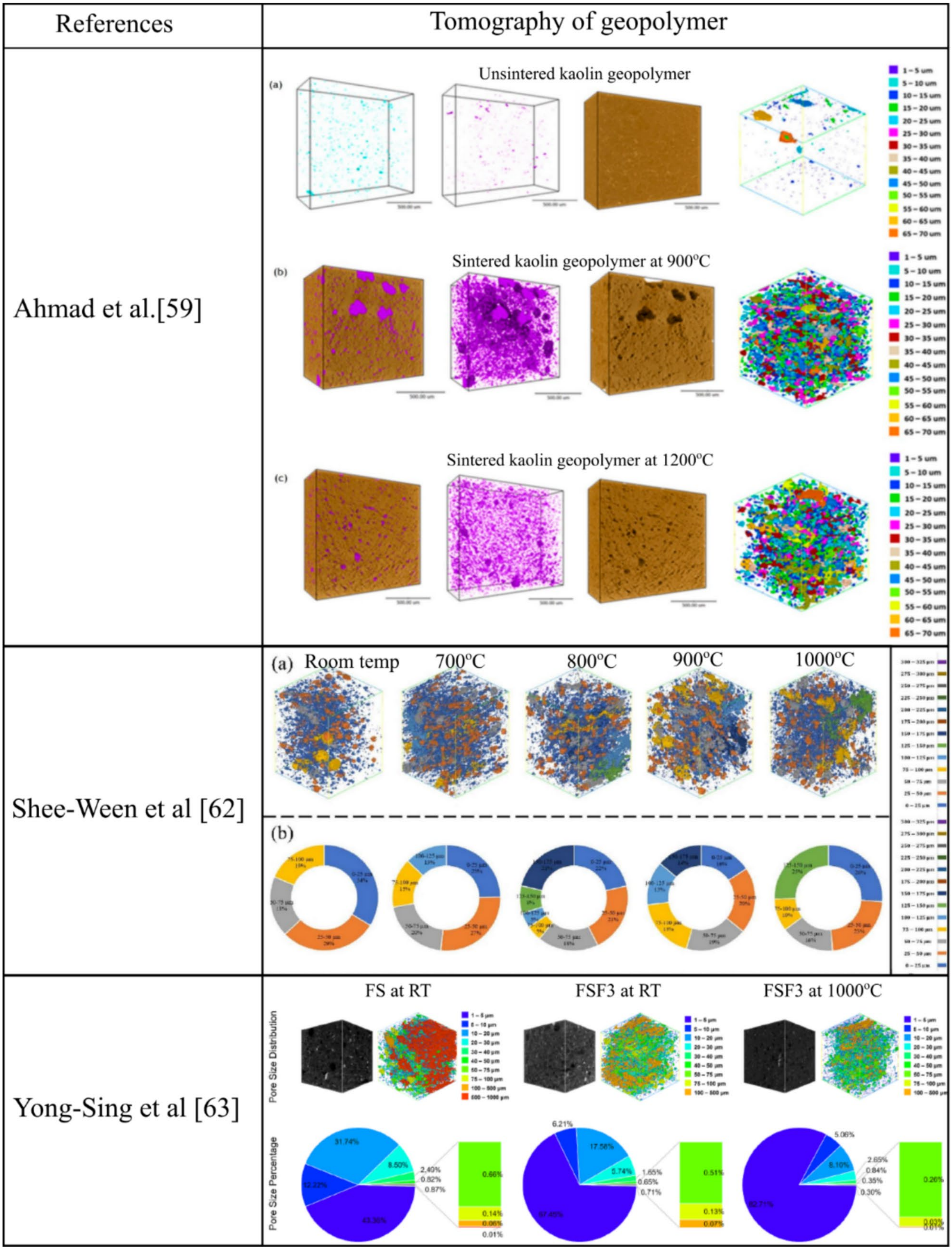
due to its reported superior thermal stability. As reported by Lila et al. [53], pure MK geopolymer displayed in Fig. 6b demonstrates vitrification and surface smoothening after exposure to 1000 °C, indicating effective sintering without crack propagation which is an ideal characteristic for ceramic fire barrier layers [54]. In terms of blended geopolymers, MK blended with rice husk ash shown in Fig. 6a and reported by Liu et al. [18] exhibited even greater performance at 900 °C. The preserved matrix and observed pore formation were attributed to reduced thermal stress. These structures are believed to be capable of resisting explosive spalling by allowing steam diffusion while maintaining overall integrity [55].

Meanwhile, fly ash (FA)-based geopolymers, particularly those derived from low-calcium (Class F) FA, show a promising potential under high-temperature exposure due to its densification. As reported by Wongsa et al. [56] and depicted in Fig. 6d, low-Ca FA geopolymer retains a relatively compact and coherent matrix even after heating to 900 °C, with minimal pore coarsening or cracking. This highlights its suitability for passive fire protection due to its low Ca content and stable aluminosilicate gel network [49]. This is in line with findings depicted in Fig. 6h, i, respectively, which represent the comparison of morphologies observed for both fly ash with high and low calcium after exposure at 1000 °C. In contrast, according to the morphology observed by Moutaoukil et al. [38] as in Fig. 6c, geopolymers with high-Ca FA exposed to a temperature of 1000 °C exhibit visible matrix degradation and void formation. These can be attributed to the decomposition of Ca-bearing phases such as calcium silicate hydrates and carbonates, which promote internal pressure and cracking [57]. This occurrence was found to affect the structural reliability under thermal stress, making low-Ca FA systems a more favorable choice for fire-resistant applications.

Additionally, calcium-rich blended systems such as FA + GGBS as observed by Luo et al. [44] in Fig. 6e also showed thermal instability at elevated temperatures (≥ 800 °C), with enlarged pores and emerging cracks, weakening their post-fire strength, thus confirming the drawback of excessive calcium. However, the addition of another aluminosilicate precursor such as palm oil fuel ash (POFA) as observed in Fig. 6f and utilization of ferronickel slag (FNS) as shown in Fig. 6g demonstrates controlled foaming or vitrification while maintaining a coherent matrix up to 1200 °C. FNS-based geopolymer exhibited minimal cracking and surface degradation under extreme temperatures, indicating their potential as refractory-grade geopolymer materials [45]. Thus, the integration of low-calcium aluminosilicate matrices with thermally stable additives such as silica-rich biomass ash or ferronickel slag contributes to improved fire resistance performance. This is achieved by promoting viscous sintering, reducing the formation and propagation of thermally induced microcracks, and stabilizing the overall microstructure at elevated temperatures. The resulting morphology, which is characterized by a continuous and densified matrix with minimal pore enlargement, indicates the material's ability to preserve its structural integrity and resist spalling under extreme thermal conditions. These features collectively demonstrate the superior high-temperature durability of geopolymer systems compared to conventional cementitious binders.

Apart from morphology, tomography can be indicated as one of useful observation for providing insight analysis on the behavior of geopolymer upon thermal exposure due to its utilization on observation for the pore distribution [8, 59–61]. It is believed that thermal stability of geopolymer is highly influenced by the porosity and densification, some of the past researches had utilized tomography for observing the pore distribution of the geopolymer after thermal exposure which can be depicted as in Fig. 7. According to Ahmad et al. [59] the different temperature applied led to different size of pore percentage. It was observed that unsintered kaolin-based geopolymers had small and uniformly distributed pores. Upon sintering at 900 °C as in (b), wider and more visible pores appeared, particularly in the form of air spaces (purple color). Regardless of the fact that both sintered samples consist of pores ranging from 10 to 15 μm, the sample at 900 °C is believed to have larger pores than the 1200 °C sample. These larger pores at 900 °C have contributed to the lower flexural strength obtained in this study. Meanwhile, the reduction in pore size at higher temperatures is attributed to densification, where atomic diffusion forms bridges at particle contact points, reducing porosity and enhancing mechanical integrity.

Similar observation was found with Shee-Wen et al. [62] and Yong-Sing et al. [63]. Both of the studies employed X-ray tomography sourced from the Synchrotron Light Research Institute of Thailand. The findings indicate that elevating the temperature to 900 °C resulted in enhanced pore formation in fly ash-based geopolymer, as demonstrated by Shee-Wen et al. [62] in the figure, which can be ascribed to the evaporation of water from the silicate network during thermal exposure. A reduction in overall porosity was seen at a temperature of 1000 °C, indicating structural densification as mentioned by Ahmad et al. [59]. The finding is also in line with the tomography observed by Yong-Sing et al. [63] as in Fig. 7. The study concluded that exposure to 1000 °C resulted in decreased porosity (6.8%) compared to room temperature (10.4%), indicating that high-temperature exposure facilitated the phase transformation in the geopolymer matrix, leading to the formation of more crystalline phases and enhanced structural compactness. Additionally, this study also proved the enhancement on the densification of geopolymer matrix at high temperature with the addition of silica fume. The incorporation of silica fume was found to affect the porosity of



| References | Tomography of geopolymer |
|---|---|
| Ahmad et al.[59] | (a) Unsintered kaolin geopolymer<br>(b) Sintered kaolin geopolymer at 900°C<br>(c) Sintered kaolin geopolymer at 1200°C |
| Shee-Ween et al [62] | (a) Room temp, 700°C, 800°C, 900°C, 1000°C<br>(b) |
| Yong-Sing et al [63] | FS at RT, FSF3 at RT, FSF3 at 1000°C |

**Figure 7** Tomography of geopolymer from past researches upon exposure to high temperature.

the fly ash-based geopolymer, facilitating the densification of the geopolymer matrix, as evidenced by the decrease of pore sizes in the fly ash-silica fume-based geopolymer (FSF3) relative to the fly ash-based geopolymer (FS).

## Phase transformation analysis

In addition, the potential of geopolymers for fire resistance application can also be attributed to the mineral phase's transformation during exposure to elevated temperature. Some of significant phases observed after high-temperature exposure are summarized in Table 3, which utilized common aluminosilicate materials including fly ash, metakaolin, and variation of slag as geopolymer precursor. It should be noted that the observation of phases could be varied accordingly, based on the chemical composition of the geopolymer precursor utilized. According to Table 3, it can be concluded that different chemical compositions contribute significantly to the phase transformation of the geopolymers upon high-temperature exposure. For instance, geopolymers synthesized using fly ash as geopolymer precursor form some of the thermally stable crystalline phases including sodium and calcium aluminosilicates such as nepheline ($NaAlSiO_4$), anorthite ($CaAl_2Si_2O_8$), and sometimes cancrinite ($Na_2Al_6Si_7O_{26}5H_2O$) due to the transformation of mullite and quartz at elevated temperatures, leading to the formation of anhydrous crystals with a stable network structure [64].

Similar observation was also found in the blend system of fly ash-based geopolymers. Additional observable phases were found due to the utilization of high-calcium aluminosilicate materials, and this includes modernite, akermanite, and gehlenite [46, 66]. According to Zhao et al. [66], these crystalline phases exhibit better thermal stability than OPC. This can be attributed to the calcium-based phases of akermanite and gehlenite which contribute to densification as commonly observed in the morphology and promote thermal stability through matrix hardening. Moreover, anorthite and mullite provide refractory stability under high-temperature conditions. Furthermore, in terms of utilizing metakaolin as geopolymer precursor, the formation of sodium (Na)–based phases, silica ($SiO_2$)–based, and alumina ($Al_2O_3$)–based phases is likely to be observed.

As being observed by Kim et al. [40], the presence of nepheline which is formed in the process of liquification and coagulation of metakaolin-based geopolymers during exposure to high temperatures was evident when the geopolymer pastes were heated up to 1000 °C, and the corresponding crystalline phases were observed in the SEM images. However, proper optimization is required, specifically when dealing with Si/Al ratio as excessive formation of new crystalline phases at high-temperature exposure has been proven to negatively impact mechanical strength of the metakaolin-based geopolymer [40]. Meanwhile, iron-rich systems, such as those incorporating ferronickel slag, display the development of fayalite ($Fe_2SiO_4$), hematite ($Fe_2O_3$), and magnetite ($Fe_3O_4$) after heating [65]. These phases are believed to be capable of enhancing sintering behavior and contributing to oxidation resistance, reinforcing the geopolymer's ceramic network. Similarly, in hybrid formulations that include lithium slag and silica fume, the crystallization of mordenite, a zeolitic phase, strengthens the matrix while preserving lightweight properties and reducing volumetric shrinkage [46].

From the microstructural analysis collected by past researches, it can be surmised that geopolymers exhibit a sequence of progressive changes in response

**Table 3** Phases analysis of geopolymers after high-temperature exposure

| Precursor | Exposure temperature | Phases identified (XRD after heating) | Reference |
|---|---|---|---|
| Fly ash (class F) | 800 °C | Nepheline, anorthite, cancrinite | Kozhukhova et al. [64] |
| Metakaolin | 1000 °C | Nepheline, cristobalite, illite | Kim et al. [40] |
| Ferronickel slag | 900 °C | Fayalite, magnetite, hematite | Arce et al. [65] |
| Lithium slag + FA/SF | 900 °C | Mordenite, alkali aluminosilicates | Javed et al. [46] |
| FA + GGBFS | 800 °C | Akermanite, gehlenite, anorthite, mullite | Zhao et al. [66] |
| Fayalite slag + MK | 1150 °C | Leucite, sanidine, hematite | Nikolov et al. [67] |
| Fly ash + MK + SF | 800–1000 °C | Leucite, kaliophilite, microcline, akermanite | Cao et al. [68] |
| Fly ash + ladle slag | 800 °C | Anorthite, gehlenite, akermanite | Luo et al. [69] |

to elevated temperatures, as reflected across visual, microstructural, and phase transformation. In terms of visual appearance and morphology, discoloration and surface densification are frequently reported, often attributed to dehydration and initial matrix compaction due to polymerization. Morphological assessments also reveal the development of microcracking, pore coarsening, and in some cases, partial vitrification, indicating thermal stress redistribution within the matrix. Meanwhile, tomographic studies complement these findings by highlighting internal densification and pore formation upon high-temperature exposure. In regard to phase transformation, geopolymers continuously exhibit the conversion of the amorphous aluminosilicate framework into crystalline phases, such as nepheline and leucite, at elevated temperatures, generally exceeding 600 °C. These modifications are strongly connected with enhanced dimensional stability, which could be further investigated for a better understanding of how certain phases transform upon exposure. The application of neutron diffraction could be proposed for further exploration such as using the ENGIN-X beamline at Rutherford Appleton Laboratory (STFC, UK) to investigate the phase transformation and stress–strain behavior of geopolymer matrices under thermal exposure. Neutron diffraction is capable to provide superior penetration depth and enhanced sensitivity to light elements due to their higher neutron absorption cross sections, thus providing high-resolution, non-destructive measurements through the material thickness, enabling precise analysis of crystallographic changes [70]. By monitoring variations in interplanar lattice spacing associated with the formation of crystalline phases such as nepheline and leucite, this technique allows for the evaluation of internal strain and its influence on microstructural stability while offering a unique opportunity to observe stress evolution in real time. These insights are expected to advance the fundamental understanding of geopolymer behavior at elevated temperatures specifically on the microstructure analysis and contribute to the development of more thermally stable construction materials.

## Residual compressive strength analysis upon high-temperature exposure

The strength performance upon high-temperature exposure is known to be one of indicators as initial evaluation of the geopolymer durability. The residual strength performance also can be attributed to the geopolymer's insight properties including thermal behavior and microstructure. In evaluating the performance of construction materials under fire conditions, residual compressive strength serves as a critical metric for assessing post-fire structural reliability. Figure 8 illustrates the residual compressive strength of various geopolymer systems in comparison with ordinary Portland cement (OPC) pastes and mortar after exposure to elevated temperatures. At the 700–800 °C range, OPC paste reported by Yang et al. [71] shows a marked decline in strength in comparison with the geopolymers derived from variation of aluminosilicate precursor. This severe degradation is attributed to the decomposition of hydrated phases such as C–S–H and portlandite, which leads to pore generation, matrix disintegration, and subsequent loss in load-bearing capacity [71, 72].

In contrast, FA-based geopolymers demonstrate much superior strength retention, either used alone or in a blended system. For instance, fly ash-based geopolymers (FA GP) reported in previous studies by Jiang et al. [37], Pacios et al. [12] Luo et al. [44], and Sivasakthi et al. [50], as well as FA combined with silica fume and ground-granulated blast furnace slag (GGBS + FA + SF GP and GGBS + FA GP) [13, 51, 73], and high magnesium nickel slag (FA + HMNS GP) [71], demonstrate compressive strengths exceeding 15 MPa and reaching up to 50 MPa within a temperature range of 700–800 °C, surpassing the values reported for OPC [71]. These results suggest that the alkali-activated aluminosilicate network offers superior thermal resistance due to its gel densification and partial crystallization into nepheline and anorthite which were observed from the XRD.

The distinction becomes more prominent in the 850–1000 °C range. FA GP systems were proven to have higher compressive strength, with some exceeding 50 MPa as reported by Lahoti et al. [20] in comparison with OPC paste and mortar reported by Pacios et al. [12] and Kashani et al. [51]. Meanwhile, combination of fly ash and metakaolin as geopolymer precursor (FA + MK GP) reported by Li et al. [74] demonstrated the highest residual strength in this range, reaching above 60 MPa, likely due to synergistic phase development of leucite and microstructural vitrification facilitated by metakaolin composition [42]. This increase is associated with thermally activated sintering and ceramic transformation which reinforces the matrix and minimizes thermal shrinkage. Another

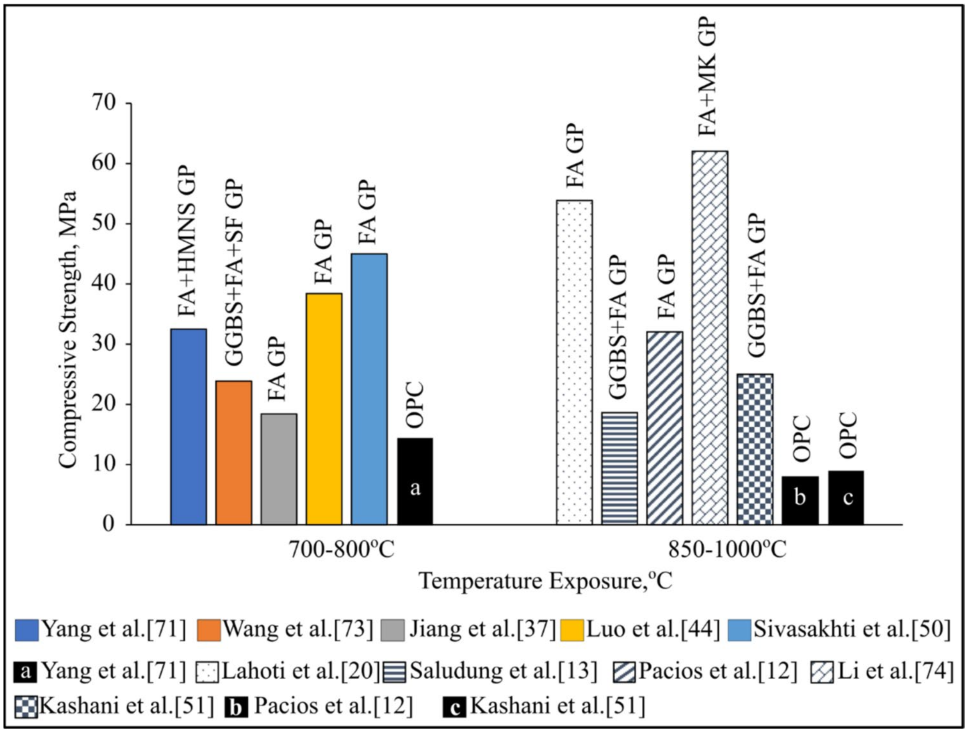


**Figure 8** Variation of compressive strength from past researches upon high-temperature exposure.

notable comparison was found beyond 800 °C for blended system containing ground-granulated blast furnace slag (GGBS). The residual compressive strength for GGBFS + FA GP reported by Saludung et al. [13] and Kashani et al. [51] was found to be almost similar (approximately less than 30 MPa) after exposure to temperatures below 800 °C. This can be attributed to the calcium composition of GGBS which contributes to thermal degradation, possibly due to the destabilization of Ca-rich phases and lack of aluminosilicate gel reinforcement. Thus, no significant strength improvement was observed with increasing temperature [44].

This performance trend underlines the importance of precursor selection; geopolymers with high-Si and Al content (such as FA and MK) demonstrate superior strength due to the formation of stable ceramic products and matrix densification. From this comparison data, it can be concluded that geopolymers, particularly those derived from low-Ca sources such as FA and MK, offer substantial fire resistance with high residual strength beyond 1000 °C. Their ability to densify as being observed from the morphology and tomography, thermally stable crystalline phases such as leucite, anorthite, and mullite explains their mechanical endurance under extreme heat. These findings reinforce the suitability of FA- and MK-based geopolymers for structural fire protection applications, far exceeding the high-temperature performance of OPC-based systems regardless in paste or mortar formed.

## Surface protection of geopolymer coating upon fire exposure

Beyond structural applications, geopolymers have demonstrated potential as protective coatings. The.

maintenance and repair of infrastructures in the civil and construction engineering industry have become critical issues, making the preservation of structures and elements a primary concern. Protective coatings are crucial and advantageous due to their resistance to harmful chemicals (e.g., acids, alkalis, and salts) and harsh conditions (e.g., thermal shock, high temperatures, and drying–wetting cycles) in the operational environments of civil constructions [75]. Owing to their ceramic-like microstructure and absence of combustible organic components, geopolymer coatings offer enhanced resistance against aggressive environments, including corrosion, chloride penetration, and elevated temperatures. Protective coatings are classified into two categories: organic and inorganic coatings. Organic coatings such as epoxy, expanded polystyrene foam, phenolic foam, polyurethane foam, and polyisocyanurate foam are frequently utilized; nonetheless, they are deemed undesirable due to the possible emission of hazardous gasses, including carbon monoxide (CO), nitrogen oxides (Nox), and hydrogen cyanide (HCN), when subjected to fire [76]. In the meantime, the development of inorganic coatings has garnered a growing amount of attention, with the introduction of geopolymer as a coating material. This is because geopolymers have the potential to provide a reliable safeguard for infrastructure against corrosion, fire, and environmental degradation, as a result of their strong adhesion properties, chemical resistance, and thermal stability.

One of the most promising applications identified, as summarized in Table 4, is the use of geopolymer coatings for fire resistance application [10, 19, 77]. As mentioned in Sect. "Basis of geopolymers and potential on high-temperature exposure" earlier, geopolymers exhibit inherently higher thermal stability compared to conventional cementitious materials, making geopolymers highly suitable as durable and inorganic solutions for passive fire protection and fire resistance application. The fire resistance of geopolymers arises from a unique physicochemical mechanism involving gradual dehydration and subsequent sintering into thermally stable ceramic phases. This transformation results in the formation of a dense aluminosilicate matrix that can provide both thermal insulation and physical shielding against fire exposure, while simultaneously preserving the structural integrity and aesthetic quality of the coated substrate. Recent advancements have further expanded the use of geopolymer coatings for fire protection through two main approaches: direct application as a thin layer and modification into foam structures prior to coating.

It has been previously mentioned that geopolymers can be used as a coating material in an effort

**Table 4** Past studies on the utilization of geopolymer as surface-protective coatings

| References | Geopolymer | Substrate | Manipulative variable (s) | Fire test | Technique of coating |
|---|---|---|---|---|---|
| Yang et al. [19] | Metakaolin-based geopolymer | Steel | Different cations of alkali solution: Na+, K+ | "Burn-through" test | Not specified |
| Sun et al. [78] | Slag-based geopolymer | Steel | Different alkali activator | Small-scale combustion test | No specified |
| Shaikh et al. [79] | Fly ash-based geopolymer | Pine timber | Addition of fiber: carbon and basalt | Direct fire test using fire torch | Troweling technique |
| Wang et al. [77] | Slag-fly ash-based geopolymer | Plywood | Percentage of slag addition: 5–25% | Cone calorimeter test | Brushing technique |
| Kiele et al. [80] | Slag-based geopolymer | Concrete | Addition of phosphogypsum | Fire test: prEN 1364-1 rev | Not specified |
| Zhou et al. [10] | Manganese slag-based geopolymer | Pine wood | Addition of PVA fibers: 0.5–2% | Not conducted | Brushing technique |
| Qu et al. [81] | Copper tailings-based geopolymer | Plywood | Percentage addition of filler: KH-560 nanosilica, MPP, ADP | Not conducted | Brushing technique |
| Sarazin et al. [82] | Metakaolin-based geopolymer | Steel | Addition of $H_2O_2$ and CTABr | "Burn-through" test: ISO2685:1998 | Not specified |
| Kaczmarski et al. [83] | Fly ash-based geopolymer | Wall | Spraying technique | Not conducted | Spraying technique |
| Le et al. [84] | Metakaolin-based geopolymer | Polystyrene | Addition of silica fume as filler | Fire test: CSN EN 13381-3 | Not specified |
| Anyou Zhu et al. [85] | Fly ash-based geopolymer | Wood | Mix designation of foam | Not specified | Not specified |

[*] *PVA* Polyvinyl alcohol, *$Na^+$* Sodium cation, *$K^+$* Potassium cation, *$H_2O_2$* Hydrogen peroxide, *CTABr* Cetyltrimethyl ammonium bromide, $CH_3(CH_2)15N+(Br)(CH_3)3$, *MPP* Melamine polyphosphate, *ADP* Aluminum diethyl phosphate

to improve fire resistance. This can be achieved by directly applying the material as a thin layer [79, 80], which depends on the thickness, and by modifying the appearance of the geopolymer coating as a foamed structure [82, 83] prior to exposure to fire. In order to ensure that geopolymers perform better as fire-protective coatings, modifications to the mix design are often made through the inclusion of fillers, stabilizers, and surfactants. In some cases, the geopolymer is made as foam coatings as it is believed that foamed appearance provides an additional mechanism of fire resistance by incorporating controlled porosity. This approach relies on the use of chemical foaming agents such as aluminum powder or peroxides [83, 86], or the inclusion of inert, low-density fillers like perlite [78] or expanded glass. A wide range of additives has been explored to tune the fire performance of geopolymer coatings. Fibers (e.g., polypropylene, basalt, ceramic, or PVA fibers) are commonly used to reinforce the coating matrix and improve crack resistance in the char layer. The resulting cellular structure also enhances insulation by impeding conductive and convective heat transfer within the material.

## Geopolymer foam coating

Past studies have gained interests in producing geopolymer foam for fire protection applications in the construction industry. This is largely because foamed materials have superior fire resistance compared to conventional materials due to their low unit weights and high air contents and porous structures [85]. Prior to their application in fire protection, preliminary investigation on the potential of geopolymer foam has been reported by Kaczmarski et al. [84]. They utilized different additives for foam generation using aluminum powder and hydrogen peroxide ($H_2O_2$). Both additives show promising formation of foam, but further exploration should be made in terms of its suitability when using spraying technique for applying the coatings on surface due to the contradicting effect when spraying. Meanwhile, a study reported by Peng et al. [86] investigated the potential of coal fly ash-metakaolin based geopolymer foams (CFA-MK-based GP) as protective coating on fireproofing performance, utilizing sodium peroxide ($Na_2O_2$) as the foaming agent. The evaluation focused on the coating itself, which included fire resistance analysis and thermal conductivity analysis. It was found that increasing the proportion of CFA reduced the viscous sintering temperature and affected the phase composition of sintering products, which led to the deterioration of the porous structure GFs during fire-resistance testing. This porous structure deterioration was found to affect the thermal insulation performance of geopolymers. However, with the presence of metakaolin in the geopolymer system, the conversion of MK-based geopolymer gel to ceramics has helped to maintain the main skeleton structure stability of the geopolymer, thus proving the excellency in fire resistance due to the result showing that the back-side temperature always remained within 250 °C, three hours after the fire-resistance testing. This finding underscores the potential of geopolymer foam coating as a protective layer, where the aluminosilicate materials incorporated into the geopolymer system play a crucial role in stabilizing the structural networks of the geopolymers, thereby enhancing its function as a protective barrier.

Continuous studies have emphasized the potential of geopolymer foam coating specifically for fire protection application. Sarazin et al. [82] evaluated the performance of metakaolin and silica fume (SF)–based geopolymer foam coatings for steel fire protection. Hydrogen peroxide ($H_2O_2$) was utilized as foaming agent due to its capability to induce closed-cell porosity. Three formulations of geopolymer foam coatings were developed: a reference geopolymer without additives (Reference GP), geopolymer foam 1 containing $H_2O_2$ (GP 1), and geopolymer foam containing both $H_2O_2$ and cetyltrimethyl ammonium bromide, $CH_3(CH_2)15N + (Br)(CH_3)3$, or also known as CTABr, which is referred to as GP 2. A "burn-through" fire test was conducted to evaluate the performance of geopolymer foam coatings under exposure to fire, and the visual appearance is depicted in Fig. 9. According to Sarazin et al. [82], a burn-through test is a standardized method designed to replicate aeronautical jet fuel fire conditions, as specified in ISO 2685:1998, for assessing material fire resistance of the geopolymer samples and their capacity to prevent steel from reaching its critical failure temperature (≈ 550–600 °C). The test setup includes a propane burner (Bullfinch) supplied with high-purity propane (99.95%), a flowrate meter, a water-cooled calorimeter, a cooling thermostat, an infrared camera (0–1000 °C range), and calcium silicate fireproof panels.

According to Fig. 9, GP 1 was found to have more open bubbles compared to the reference GP. This is attributed to the reaction of hydrogen peroxide in the

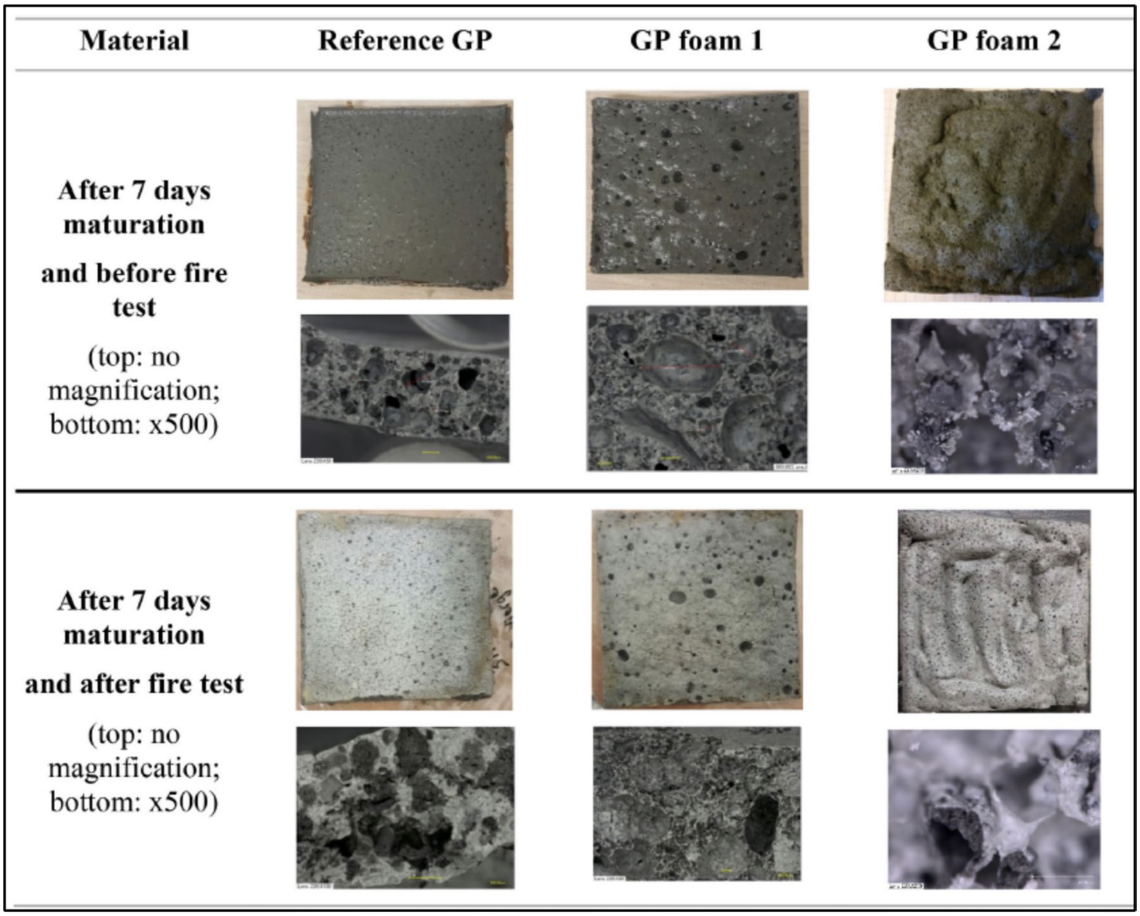


**Figure 9** Visual appearance of geopolymer foam for before and after fire test by Sarazin et al. [82].

formulation, which generates oxygen gas. The oxygen gas is believed to reach the coated surface but does not reside inside the GP particles. Meanwhile, GP 2 showed contradictory findings to GP 1, which is likely due to CTABr's stabilizing effect. GP 2 was found to be less fluid than other GP coatings due to the high concentration of CTABr in the formulation, making it quite challenging to be applied on steel plates, as evidenced by its overall appearance in Fig. 10. The positive finding of GP 2 with CTABr was also proven by the fire testing. The decrements in the temperature of the back steel were the highest compared to other GPs. This finding proved that optimal and selection of additive are significant in improving the performance of geopolymer foam as coating material for fire protection. Similar finding was also observed by Zhu et al. [85] who compared non-foamed and foamed fly ash-based geopolymers, high-performance cement mortar (HPCM), and magnesium phosphate cement mortar (MPCM) as coating materials. The results are in line with past research, which foamed coating materials have a lower heat transfer rate than their non-foamed counterparts. This indicates that incorporating foam in materials improves their fire resistance quality and reduces the heat transfer rate.

In another research reported by Le et al. [84], apart from adding fillers including silica fume and aluminum powder to enhance the fire protection performance, an attempt was also made on enhancing the mechanical properties of the geopolymer foam by utilizing chopped basalt fibers (CBFs). Different thickness layers (10, 15, and 20 mm) were applied on the substrate (polystyrene), and the temperature variations for fire resistance testing were monitored. Similar to other positive findings on geopolymer foam coatings, it has been demonstrated that the foaming process induced by aluminum powder reduces thermal conductivity, thereby supporting the use of these low-density geopolymer composites as effective fire-resistant coating materials. The addition of chopped

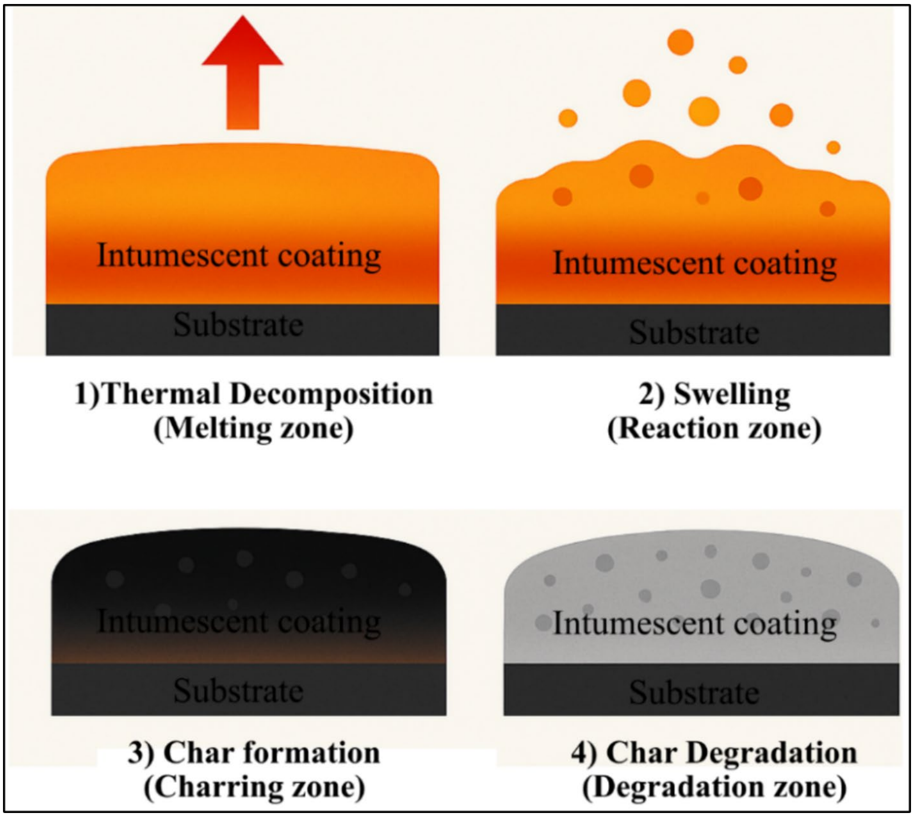


**Figure 10** Reaction stages occurred during intumescence process.

basalt fibers helps stabilize the porous suspension during the foaming process by increasing the viscosity of the mixture, which in turn reduces the likelihood of pore collapse.

## Direct application as coating material

Meanwhile, some of the past studies prefer to utilize direct application of geopolymer coating onto the substrate. For this purpose, geopolymer is typically applied in layers of a few millimeters (depending on desired thickness). The protective layer becomes more densified, exhibiting a compact microstructure with low porosity, which contributes to its high thermal stability and strong adhesion to substrates. Upon exposure to elevated temperatures, these coatings undergo progressive densification due to dehydration, micro-void collapse, and sintering of the aluminosilicate matrix. This densification enhances surface hardness and structural integrity but may also lead to shrinkage or cracking if not properly controlled.

An investigation on the potential of slag-based geopolymer as a fire-resistive coating for steel structures was conducted by Sun et al. [78] focusing on the influence of various alkali activators. The study incorporated calcium oxide (CaO), sodium carbonate ($Na_2CO_3$), and sodium sulfate ($Na_2SO_4$) into the alkali activator system composed of sodium hydroxide (NaOH) and sodium silicate ($Na_2SiO_3$), and the fire resistance performance was monitored based on the temperature of the back steel which has been applied with coated geopolymers. The prepared coating was uniformly applied to Q235 steel plates sized 150 mm × 70 mm × 10 mm, with a coating thickness of 20 ± 1 mm. The experimental results demonstrated that the superior fire resistance of the slag-based geopolymer coating can be attributed to a combination of lower bulk density, increased total porosity, reduced ink-bottle porosity, and the formation of hydrotalcite phases. These microstructural and mineralogical characteristics were notably observed when sodium silicate was employed in combination with sodium carbonate ($Na_2CO_3$) and calcium oxide (CaO) as the alkali activation system. The effectiveness of the slag-based geopolymer coating was further validated by its thermal performance, wherein the recorded maximum surface temperature remained significantly below the critical limit of 538.0 °C prescribed by the Chinese fire protection standard GB 14907–2018, indicating excellent thermal shielding capability under fire exposure conditions.

Furthermore, direct application of geopolymer as protective layer has also been investigated on timber as substrate due to its drawback of being a highly combustible material, which limits its widespread application in the building industry. Shaikh et al. [79] used trowelling method in applying Na–based and the K–based fly ash geopolymer coating on surface of timber before undergoing fire resistance test. In order to enhance the fire retardancy, fibers (carbon and basalt) were added. It was found that sodium-based and potassium–based fly ash geopolymer coatings exhibited comparable adhesion to pine timber substrates, with bond strengths of approximately 0.90 and 0.85 MPa, respectively. The potassium-based geopolymer demonstrated improved fire resistance, as indicated by reduced surface cracking and lower char depth after exposure to temperatures up to 1100 °C. An increase in coating thickness resulted in a further reduction in char depth by approximately 35–45%. The incorporation of carbon fibers, particularly at a volume fraction of 1.5 percent, significantly enhanced fire protection performance by reducing char formation by up to 67 percent and mitigating thermal cracking. This finding is valuable in demonstrating that materials with lower thermal conductivity and reduced shrinkage are crucial for effective fire protection coatings. The results reflect enhanced thermal insulation capacity and improved dimensional stability under fire exposure.

The incorporation of fillers and fibers into geopolymer coating formulations has been reported in various studies as an effective approach to enhance fire-retardant performance. The addition of polyvinyl alcohol (PVA) fibers, for instance, serves multiple functions by improving the mechanical strength of the coating, reducing the risk of cracking, and enhancing overall structural durability under thermal stress [10]. Similarly, the integration of supplementary fillers such as ground-granulated blast furnace slag in fly ash-based systems [77] and addition of phosphogypsum in slag-based geopolymer [80] contribute to the modification of the microstructure and thermal response of the coating. These additions have been shown to promote higher compressive and interfacial bonding strength following fire exposure [10, 80]. Moreover, the geopolymer matrix undergoes transformation into a siliceous barrier layer, which effectively inhibits heat and mass transfer. This transformation is associated with measurable improvements in fire-related performance indices, including reductions in heat release rate (HRR) and fire growth index (FGI), and an increase in the fire performance index (FPI) [77].

Meanwhile, another investigation reported on utilizing direct application of geopolymer as coating involved the intumescence behavior as one of its significant findings. A study reported by Yang et al. [19] investigated the potential of metakaolin-based geopolymer as a fire protection coating material of steel structures. Two types of geopolymer coatings were produced which were sodium-based metakaolin geopolymer (Na–GP) and potassium-based metakaolin geopolymer (K–GP) due to the different cation of alkali activator utilized. "Burn-through" test was carried out for evaluating the fire performance of geopolymer coatings. The evaluation also considered the influence of aluminum and variations in alkali activator cations by incorporating removal of metakaolin in the geopolymer system alongside with employing either sodium hydroxide or potassium hydroxide prior to the formation of the geopolymer coatings. According to the study, both potassium-based and sodium-based geopolymers without aluminum demonstrate notable intumescent behavior, effectively reducing the temperature at which substrate failure occurs by 360 and 336 °C, respectively, in comparison with uncoated steel plate. According to the study, this expansion results from the transformation of silicate structures Si($Q^2$) to higher-order species such as Si($Q^3$) and Si($Q^4$), combined with internal stresses caused by moisture evaporation which is observed from the NMR analysis. Incorporating the aluminum into the geopolymer matrix improved the fire protection performance of potassium-based systems, as shown by their lower thermal expansion compared to sodium-based geopolymers, which developed rapid cracking when heated. Potassium-based systems were also observed to retain Si($Q^2$) units, suggesting that the presence of $Q^2$ plays an important role in promoting intumescence. These observations suggest that while both alkali cations are effective in aluminum-free formulations, potassium is more favorable in aluminum-rich geopolymers since the polycondensation of Si($Q^2$) could trigger intumescence which could act as a thermal barrier. This finding highlights the significant potential of geopolymers to function as intumescent coatings, warranting further investigation, particularly into the chemical compositions that contribute to intumescence behavior.

## Intumescent behavior mechanism upon fire exposure

When dealing with fire resistance application, one of the most known protective behavior of coatings is its intumescent properties capability. Intumescent organic coatings are specialized fire protection materials that play a crucial role in safeguarding structural elements, such as steel, from fire damage. These coatings expand when exposed to high temperatures, forming an insulating char layer that shields the underlying substrate from the destructive effects of fire. This expansion results from a series of chemical reactions within the coating that generate a carbonaceous foam. This foam acts as an insulating barrier, reducing heat transfer to the underlying material and delaying its temperature rise.

## Mechanism of intumescence behavior

Previously, intumescent coatings were derived by utilizing organic materials for its formulation. Their formulations generally consist of an acid source that serves as catalyst such as ammonium polyphosphate, a carbonaceous compound such as pentaerythritol (PER), starch, mannitol, and a blowing agent or known as foaming agent such as melamine, urea, dicyandiamide [87, 88]. The roles of these components have been extensively documented in the literature, and over the past decades, the formulations have been progressively refined to promote the formation of a stable and effective protective char upon exposure to heat [89, 90]. According to Lucherini et al. [90], the intumescent process involves several stages of reactions. The reaction stages can be illustrated as in Fig. 10. The first stage is known as the thermal decomposition (melting zone). This stage initiates as the acid source decomposes, converting the surface into a viscous fluid. This is followed by the swelling stage (reaction zone), where the blowing agent activates and decomposes endothermically, releasing gases that become trapped within the molten matrix [90]. This expansion forms a low-density, thermally insulating porous layer, often increasing the coating thickness by up to 100 times. As temperatures rise, the char formation (charring zone) which is denoted as the next stage occurs, where the porous structure solidifies, releasing residual volatiles and forming a carbon-rich char, typically dark in color [90]. Finally, in the char degradation zone, the char oxidizes, releasing $CO_2$ and gradually converting into a brittle, white, porous residue, signaling the decline of thermal protection.

Recent advances in intumescent coatings continue to garner significant attention in the field of passive fire protection, driven by the critical need to mitigate structural damage and enhance safety during fire incidents. Numerous studies have focused on optimizing the formulation of organic-based intumescent systems to improve their flame retardancy and overall durability such as the incorporation of amino-polysiloxanes into epoxy-based intumescent coatings due to the flexibility, heat resistance, flame retardancy, hydrophobicity, and UV resistance of polysiloxanes [91]. Meanwhile, Nazrun et al. [92] also have examined the application of intumescent coatings on non-traditional substrates such as solid aluminum skins in composite panels, demonstrating their potential in safeguarding lightweight structural materials under fire conditions [92]. In addition, dual function of intumescent coating focusing on fire retardancy with strong water resistance has also been emphasized by a recent study of Wang et al. [93]. In terms of construction buildings, Cirpici et al. [94] also determined the effect of intumescent coating thickness utilized, steel wall thickness, and varied fire exposures on the fire performance of concrete-filled steel columns in terms of steel and concrete core temperature prediction. Despite these developments, organic intumescent coatings present inherent limitations under high-temperature conditions, including thermal degradation, the release of toxic gases, and the incorporation of hazardous species. These challenges have prompted a transition toward the exploration of inorganic intumescent systems. In particular, alkali silicate-based and aluminosilicate-based coatings have shown promising intumescent behavior through mechanisms involving matrix softening and the liberation of chemically bound water, which together contribute to volumetric expansion and formation of insulating char layers [87].

## Geopolymer-based intumescent coating

The conceptual framework for utilizing geopolymers as intumescent coatings is grounded in the potential of inorganic silicate-based systems to address the limitations associated with organic intumescent formulations. Alkali silicates possess inherent intumescent behavior, initiating expansion at temperatures as low as 100 °C due to the release of water bound within the matrix in physical, ionic, or chemical forms, particularly as hydroxyl groups. This expansion leads to the formation of a thermally stable, multicellular ceramic structure, highlighting their suitability for high-performance fire protection applications [95]. Some of the recent research attempt on utilizing inorganic silicate materials as intumescent coating including geopolymers and alkali-activated materials which can be summarized as in Table 5.

As listed in Table 5, several studies have been conducted to evaluate the potential of intumescent behavior for fire protection. Accordingly, most of these studies involved fire testing as part of their evaluation. For instance, Watolla et al. [96] highlight that the coatings exhibited partial foaming during curing and further expansion upon thermal exposure, confirming their intumescent behavior. This expansion was linked to a viscous phase transition occurring during significant water release, as indicated by rheological analysis (loss factor > 1), distinguishing them from conventional geopolymer systems. Additionally, coating thickness played a crucial role in expansion behavior and delayed the temperature rise of the underlying steel to 500 °C. The potential of geopolymer as intumescent coating was also emphasized by alkali-activated borosilicate inorganic polymers [99]. Additionally, Nicoara et al. [99] demonstrated that alkali-activated borosilicate inorganic polymer (AABSIP) coatings synthesized from waste glass, borax, and alkali hydroxides exhibit effective intumescent behavior and thermal insulation properties. When applied to steel and plasterboard substrates, these coatings significantly delayed heat transfer and maintained substrate temperatures below the critical limit of 500 °C. The inclusion of coal ash and optimization of water-to-solid ratios enhanced coating performance, while SEM-EDX analysis confirmed strong adhesion and chemical compatibility with the substrates. These findings highlight AABSIP as a promising sustainable fire protection material for structural applications which have emerged as a particularly attractive class of materials for intumescent coating applications [99].

Another exploration on the potential of geopolymer as intumescent coating had been reported by Al-Saadi et al. [24] which utilize glass waste as aluminosilicate precursor for the formation of geopolymer coating. The intumescent properties were observed with the addition of different amount of graphite. The study demonstrated that geopolymer materials synthesized from glass waste and activated with NaOH exhibited notable intumescent behavior upon thermal exposure. The inclusion of intercalated graphite (IG) at 0.1–0.3 wt% effectively enhanced this behavior, promoting

**Table 5** Research on intumescent of alkali-activated material and geopolymers

| Reference | Material system | Testing analysis | Duration exposure | Temperature exposure | Expansion behavior |
|---|---|---|---|---|---|
| Watolla et al. [96] | Metakaolin + microsilica | Furnace application ISO 834—1:1999 | 30 min | ~ 840 °C | Yes |
| Al-Saadi et al. [24] | Glass waste geopolymer + graphite | Thermal treatment | 60 min | 400–800 °C | Not specified |
| Chen et al. [23] | Na-silicate + metakaolin + APP & fillers | Burn-through fire test | 60 min | ~ 1000 °C | Yes |
| Ulusoy et al. [25] | Kaolin/metakaolin/Fly Ash + $CaCO_3$ | Furnace hydrocarbon fire tests (UL1709) | 40 min | 500 °C | Not specified |
| Dhasindrakrishna et al. [97] | RHA-based geopolymer | Furnace application | 300 min | 300 °C | Yes |
| Yang et al. [19] | Na-GP and K-GP et al./Si = 0 and 0.54 | Burn-through fire test | 30 min | 1000 °C | Yes |
| Yang et al. [76] | Na-GP with varying Al/Si (burn-through) | Burn-through fire test | 30 min | 1100 °C | Not specified |
| Wang et al. [98] | Gangue-based geopolymer in intumescent paint | Burn-through fire test | 80 min | 800–1100 °C | Yes |

[*] *AAM* Alkali-activated material, *APP* Ammonium polyphosphate, *Al/Si* Alumina/silica ratio, *MASNMR* Magic angle spinning nuclear magnetic resonance, *Na-GP* Sodium-based geopolymer, *K-GP* Potassium-based geopolymer, *RHA* Rice husk ash

earlier onset of expansion at 500 °C compared to 600 °C for compositions without IG. The most significant volume increase for all compositions was observed at 700 °C, indicating that IG not only facilitates early activation of the intumescent process but also amplifies its extent by increasing porosity and swelling. This study demonstrates that the addition of graphite leads to an improvement in the intumescent behavior of geopolymer systems. However, further exploration is necessary to achieve optimal performance by varying the type of aluminosilicate precursors used in the formulation.

In addition to the exploration on the addition of graphite, Chen et al. [23] investigated the enhancement of intumescent behavior in inorganic coatings through the incorporation of various fillers and additives, including sodium silicate, metakaolin, ammonium polyphosphate, pentaerythritol, aluminum hydroxide, and expandable graphite. Each component contributed to the fire protection mechanism, where metakaolin, fly ash, and wollastonite serve as cementitious agents forming geopolymer-like matrices. Ammonium polyphosphate and pentaerythritol facilitate carbon-char formation, while aluminum hydroxide and expandable graphite enhance overall flame retardancy [23]. This study also elaborates on the reaction mechanisms involved, including the formation of –Si–O–Si– networks through hydrolysis and self-condensation reactions, which are similar to the geopolymerization process. In addition, it discusses the role of polyphosphates in contributing to the intumescent behavior, highlighting their potential for flame retardancy. Continuous exploration on the role of these materials is highly encouraged to provide proper optimization on chemical components that contribute to optimal fire protection performance of geopolymer.

In addition, further investigation on the potential of utilizing metakaolin, kaolin and fly ash as precursor of intumescent geopolymer coating had been explored by Ulusoy et al. [25]. It was revealed that among these three materials, kaolin-based geopolymer coatings can provide superior intumescent protection which was proven in terms of its adhesion and compressive strengths. Although further optimization is required for geopolymer coatings to achieve the performance consistency of commercial organic intumescent systems, the observed expansion behavior demonstrated comparable potential, with the kaolin-based formulation exhibiting slightly higher final expansion. Meanwhile, Dhasindrakrishna et al. [97] explored the potential of rice husk ash (RHA) as a precursor for its intumescent geopolymer coating. The observation under high-temperature exposure is depicted in Fig. 11. The intumescent behavior of alkali-activated RHA coatings was evaluated across three formulations (Mix 1–3) with increasing sodium content (5.2–11.4 M), as illustrated in Fig. 11A. All mixes exhibited expansion with rising temperatures, but Mix 1 consistently formed a more homogeneous and finer pore structure across the studied range (150–300 °C), while Mixes 2 and 3 displayed coarser, radially inhomogeneous pores, especially at lower temperatures. The uniform microstructure of Mix 1, which is advantageous for reducing thermal conductivity, led to its selection for fire barrier fabrication. As shown in Fig. 11B, the Mix 1 panel (a, c) demonstrated significant expansion and surface integrity under simulated fire exposure, outperforming the aerated geopolymer panel (b, d) in insulation capacity despite its reduced thickness. These results underscore the potential of RHA-based geopolymers as promising inorganic intumescent coatings, highlighting the need for further investigation into other influencing factors beyond alkali concentration to optimize their fire protection performance.

In addition to exploring further influencing factors on intumescence of geopolymer coating, Yang et al. [19, 76, 100] had investigated the variation of Al/Si molar ratio and effect of cation on the performance of geopolymer coatings derived from metakaolin as geopolymer precursor. In terms of variation of Al/Si molar ratio [76], it was found that proper optimization on aluminum composition is necessary for intumescent behavior to occur as thermal barrier protection on steel as softening phenomenon is predominantly observed in formulations with low Al/Si ratios ($< 1.5$). In contrast, the Na–1.5Al system exhibits negligible softening or expansion, maintaining a constant Compression Storage Modulus Value (CSMV) in the order of $10^7$ Pa throughout thermal exposure. The elevated aluminum content contributes to a more rigid and thermally stable matrix, which not only suppresses intumescence but may also induce shrinkage and cracking under elevated temperatures.

This is also in line with its continuous exploration upon utilizing different cation of sodium (Na) and potassium (K) for its alkali solution. The expansion behavior can be depicted as in Fig. 12. According to Yang et al. [19] one significant feature observed in this study was the temperature plateau at $Ts = 105 \pm 2$ °C

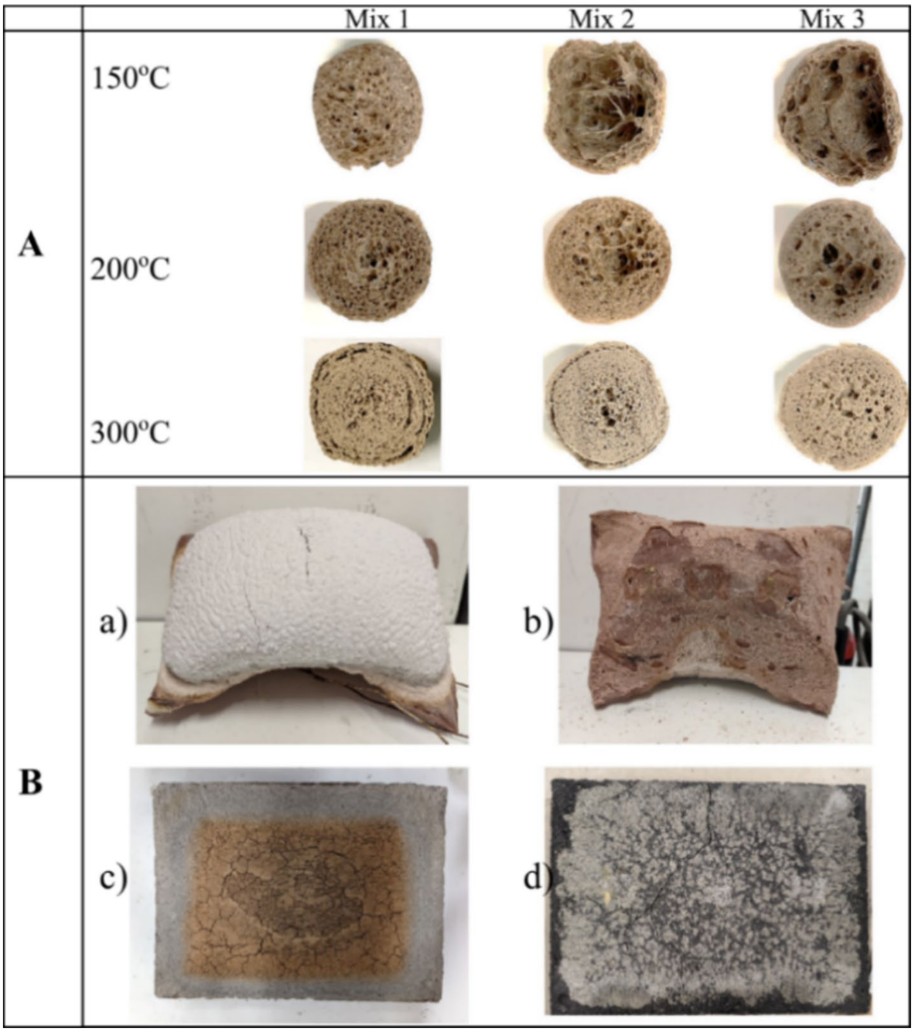


**Figure 11** Pore structures of RHA-based geopolymer coating with different alkali content and its application as coating on panels.

for all formulations (except for Na–based GP with $n(\mathrm{Al}) = 1.5$, which cracked during the fire test), which was assigned to water evaporation (boiling) The starting time and ending time for this temperature plateau were defined as $t_{1,\mathrm{K}}$, $t_{2,\mathrm{K}}$, $t_{1,\mathrm{Na}}$, and $t_{2,\mathrm{Na}}$ for K–0Al and Na–0Al, respectively. Moreover, two temperatures at $t = 0$ and 30 min, corresponding to the start and to the end of the experiment, were defined as $t_0$ and $t_3$ [19]. As illustrated in Fig. 12a, both K–0Al and Na–0Al formulations exhibited considerable expansion during fire exposure, effectively lowering the steel substrate temperature by 360 and 336 °C, respectively. This expansion is attributed to thermally induced softening, involving the transformation of silicate species from Si($Q^2$) to Si($Q^3$ and $Q^4$) which was evidenced by utilizing solid-state$^{29}$Si magic angle spinning nuclear magnetic resonance (MAS NMR), alongside internal vapor pressure generated by moisture evaporation. In contrast, Fig. 12b shows that the inclusion of aluminum significantly altered the response; while K–1.5Al maintained moderate expansion and structural cohesion, Na–1.5Al exhibited negligible swelling and suffered extensive surface cracking. Solid-state$^{29}$Si magic angle spinning nuclear magnetic resonance (MAS NMR) analysis confirmed that Si($Q^2$) species, which are essential for initiating softening and expansion, were retained exclusively in potassium-based systems.

Both studies demonstrate the effectiveness of geopolymers as thermal barrier coatings through their intumescent response, while also offering critical insights into the underlying chemical transformations that enable such behavior. The observed expansion and swelling are strongly associated with structural changes in the silicate framework during thermal exposure, particularly the progression from less to

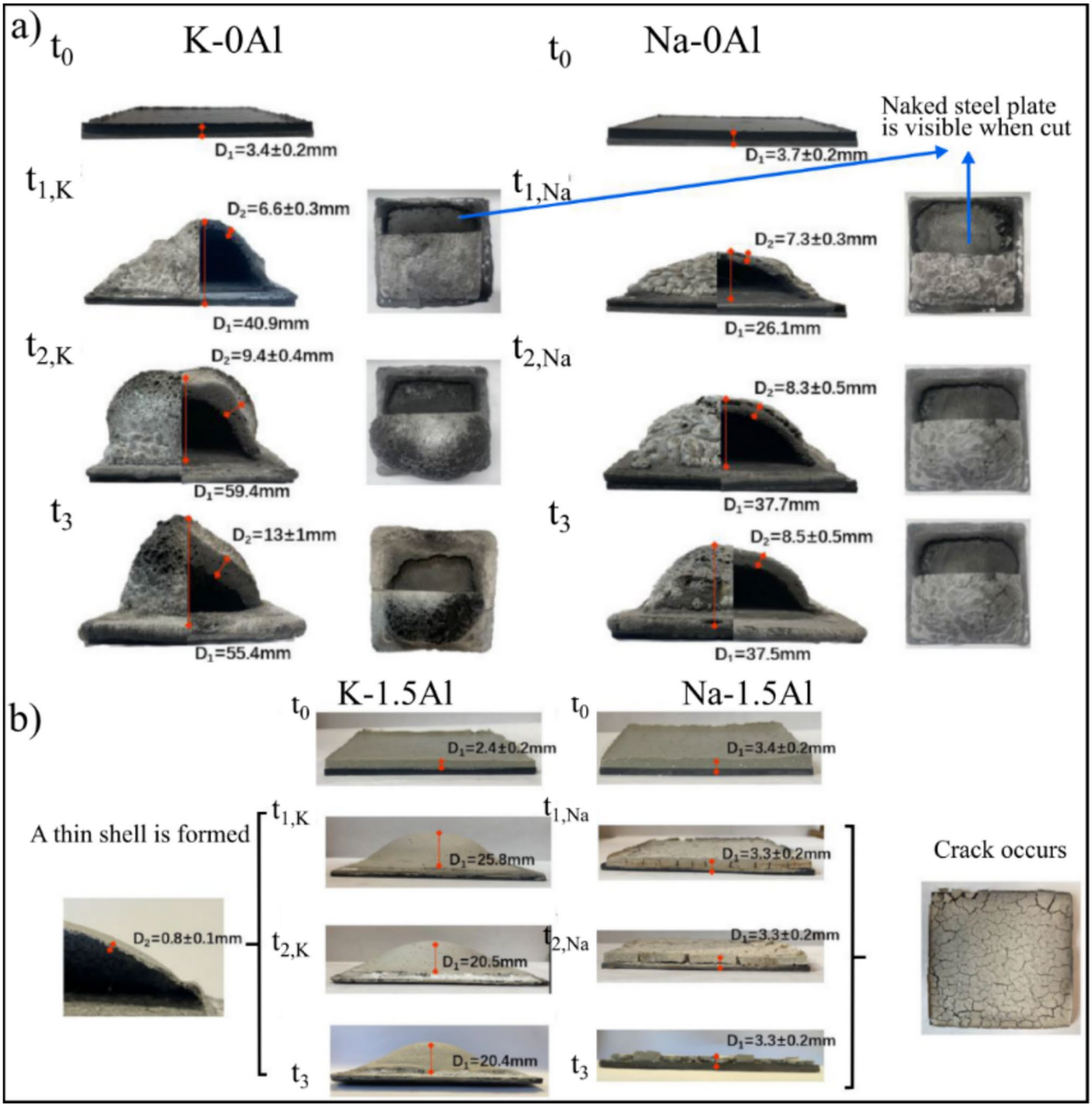


**Figure 12** Pore structures of RHA-based geopolymer coating with different alkali content and its application as coating on panels by Yang et al. [76].

more polymerized silicate species. These findings highlight the importance of chemical composition, where the type of alkali cation and the silicon-to-aluminum molar ratio significantly influence the ability of the material to undergo thermal softening and develop a stable porous structure. The application of solid-state $^{29}$Si magic angle spinning nuclear magnetic resonance has proven especially valuable, providing detailed information on the evolution of silicate species and enabling the identification of reactive configurations such as Si($Q^2$), which are essential for facilitating intumescence. The significance of solid-state Magic Angle Spinning Nuclear Magnetic Resonance (MAS NMR) was also emphasized for its ability to elucidate the intumescence mechanism, as outlined in the recent publication by Yang et al. [100].

From the findings observed on the intumescent behavior of geopolymer including alkali-activated materials and alkali silicate particles as inorganic intumescent coating, it can be concluded that geopolymers indeed have different mechanisms in comparison with organic intumescent coating. The intumescence mechanisms of geopolymer and organic coatings differ fundamentally in their chemical nature and thermal response. Geopolymer intumescent coatings rely on inorganic transformations, where expansion is primarily driven by the release of physically and chemically bound water and the structural softening of the aluminosilicate network upon heating. This softening is associated with the depolymerization and subsequent re-polymerization of silicate species, particularly the transition from Si($Q^2$) to Si($Q^3$) and Si($Q^4$) configurations, which facilitates viscous flow and the development of a stable, porous ceramic structure.

Unlike organic systems, the geopolymer mechanism does not rely solely on char formation when exposed to elevated temperatures. Instead, geopolymer coatings are capable to form a rigid, thermally resistant expansion layer that provides a similar insulating function to char, without requiring an acid source, carbon source, or blowing agent. In contrast, organic intumescent coatings operate through a multi-component reaction involving an acid source, typically ammonium polyphosphate, a carbon source such as pentaerythritol, and a blowing agent like melamine. Upon thermal activation, the acid catalyzes dehydration of the carbon source, promoting char formation, while the blowing agent releases inert gases to expand the softened matrix into a protective foam. However, this mechanism is inherently reliant on the decomposition of organic binders, which are susceptible to thermal degradation and may release combustible or toxic volatiles. Unlike conventional organic binders, geopolymer matrices do not undergo significant decomposition at elevated temperatures and are capable of forming ceramic-like protective layers upon exposure to fire [15, 37, 42, 45]. These characteristics not only enable the geopolymer to act as a thermal barrier but also potentially allow it to expand under fire conditions, fulfilling the criteria for an inorganic intumescent system. Furthermore, the ability to tailor geopolymer composition through the addition of functional additives or fillers broadens their applicability in protective coatings, making them a compelling candidate for next-generation intumescent technologies by focusing on optimizing the mix designation.

## Conclusions and summary of future works

In conclusion, geopolymers have demonstrated strong potential as fire protection materials which can be attributed to its minimal mass loss, densified, and non-combustible inorganic matrix. From the thermal analysis such as thermogravimetric analysis (TGA), as well as visual appearance, morphological and tomography, and phase evolution observations, past studies have shown that upon exposure to high temperatures, geopolymers typically undergo densification, vitrification, and partial crystallization, resulting in thermally stable matrices. The stability of the polymeric structure upon fire exposure is highly influenced by the chemical composition of the geopolymer system which can be varied in terms of precursors utilized, addition of additives and fillers, as well as controlling the mix designation of the geopolymers. The chemical composition of the geopolymer system plays a crucial role in governing its fire performance. Specifically, the type of aluminosilicate precursor, the concentration and composition of alkali activators, and the Si/Al molar ratio collectively influence the extent of crosslinking within the geopolymer network. A well-optimized Si/Al ratio supports the development of a more interconnected aluminosilicate matrix. In contrast, excess alkali content without sufficient reactive silica may result in instability or strength loss when exposed to elevated temperatures. The incorporation of mineral additives such as metakaolin, fly ash, or slag has also been reported to improve thermal behavior by promoting phase crystallization and contributing to residual strength.

Furthermore, due to the promising properties evidenced on the geopolymer after high-temperature exposure, geopolymers are believed to offer promising potential as coating for fire protection. The fire testing results reviewed in this section confirm that geopolymer coatings can significantly delay heat transfer to the substrate, with backface temperatures remaining below critical failure thresholds for extended duration. Coatings incorporating fillers such as wollastonite, graphite, or ceramic additives further enhanced thermal shielding by contributing to densification and improved heat insulation. The effectiveness of surface protection was found to correlate strongly with coating thickness, where increased thickness generally improved fire resistance by prolonging the time to reach failure temperatures. Overall, the evidence supports that geopolymer coatings, when properly formulated in terms of foam structure or direct application as thin layer, can serve as reliable thermal barriers in fire scenarios, with fire resistance performance depending on both composition and physical characteristics.

Finally, geopolymer coatings have demonstrated promising intumescent characteristics under fire exposure, with several studies reporting visible expansion, foaming, or swelling during thermal testing. The degree of intumescence is strongly influenced by the chemical composition, particularly the type of activator, presence of silicates, and alkali content. Coatings exhibiting intumescence formed porous or foamed ceramic-like structures effectively reduced backface temperatures and extended protection times. Fire resistance was shown to improve with increased expansion, although the extent and stability of intumescence varied across systems. These findings highlight the potential of geopolymers to function not only as passive thermal barriers but also as inorganic intumescent coatings, offering expanded thermal protection through composition-dependent expansion mechanisms.

Based on this review, it is worthwhile to continue exploring the potential of geopolymers with an emphasis on fire protection applications. The promising intumescent characteristic is useful for functioning as a thermal barrier to protect substrates. Based on the gaps that were discovered in this research, the following potential future efforts on the development of geopolymer coating specialized for fire protection applications can be proposed:

- Future investigations should be further emphasized on optimizing the chemical composition of geopolymer specifically on the silicon-to-aluminum molar ratio, the type of alkali activator, and the presence of calcium as all of these influence factors significantly contribute to both the thermal behavior and the residual mechanical performance. Further exploration could also be focused on the contribution of which chemical composition that contributes for fire protection for the ease of controlling and optimizing the influence factors.
- The microstructural and phase changes that occur in geopolymers when exposed to high temperatures are still not fully understood. Although the formation of crystalline phases such as nepheline and leucite has been reported and is sometimes linked to improved residual strength, their exact contribution to thermal stability, insulation properties, and post-fire structural performance remains unclear. Future work should therefore focus on using advanced characterization methods that can monitor these changes in real time. Techniques such as in situ synchrotron analysis, as well as neutron and muon-based investigations, are especially promising for capturing the structural evolution and phase transitions that take place during heating. These high-resolution tools can provide valuable insights at the atomic and microstructural levels, helping to clarify the mechanisms behind geopolymer performance under thermal stress. Incorporating these advanced methods will be essential for developing a more complete understanding of how geopolymers behave in fire-resistant applications.
- The intumescent behavior of geopolymer-based coatings shows considerable potential for passive fire protection, although its effectiveness is highly dependent on formulation. Variability in expansion behavior has been associated with differences in alkali cation type, silicate content, and the presence of additives such as graphite or polyphosphate. A comprehensive investigation into the influence of these factors is essential for achieving consistent and controlled swelling. This should encompass a deeper exploration of the development of expansion layers and the associated chemical processes that govern both char formation and inorganic expansion. This future exploration will be significant toward elucidating the mechanisms underlying intumescence, with a particular focus on how the chemical composition of the geopolymer system contributes to its swelling behavior and fire protection performance.
- Last but not least, the employed method of evaluating the fire protection performance of geopolymer coatings is inconsistent across the literature, which requires consistency enhancement for the ease of comparison of the findings. There is a critical need to adopt standardized testing protocols that include consistent heating conditions, duration of fire exposure for the ease of application specifically when dealing with fire testing evaluation. This will ensure the reliability and

practical applicability of geopolymer coatings for fire-resistant applications in real construction environments.

## Acknowledgements

The authors gratefully acknowledge the Centre of Excellence Geopolymer and Green Technology (CeGeoGTech), School of Material Engineering, Universiti Malaysia Perlis, for their expertise and support. Special thanks are also dedicated to ISIS Neutron and Muon Source (ISIS), UK, for mentoring for this funding. Lastly, the authors would like to acknowledge the reviewer(s) for the helpful advice and comments provided.

## Author contributions

Rosnita Mohamed helped in writing—original draft, writing—review and editing, conceptualization, formal analysis, and literature research investigation. Mohd Mustafa Al Bakri Abdullah contributed to supervision, conceptualization, writing—review and editing, validation. Rafiza Abd Razak helped in supervision, writing—review and editing. Tung Lik Lee, Thanongsak Imjai, Md Azree Othuman Mydin, Pilomeena Arokiasamy, and Dickson Ling Chuan Hao helped in validation. Zarina Yahya contributed to visualization, validation.

## Funding

Open access funding provided by The Ministry of Higher Education Malaysia and Universiti Malaysia Perlis. ISIS Neutron and Muon Source Project supported this research under reference No: JPT.S (BPKI)2000/016/018/019 Jld. (10) under Program ISPF: Use of the ISIS Neutron and Muon Source (ISIS), UK 2024 from the Ministry of Education Malaysia and Science and Technology Facilities Council (STFC) United Kingdom.

## Data availability

Not applicable since this review is based on published literature. No new data were created or analyzed.

## Declarations

**Conflict of interest** The authors declare that there are not any known conflict of financial interests or personal relationships that could have appeared to influence the work reported in this paper.

**Ethical approval** Our study did not require an ethical board approval because it did not contain human or animal trails.

## References

[1] Yun-ming L, Cheng-yong H, Mustafa M, Bakri A, Hussin K (2016) Progress in Materials Science Structure and properties of clay-based geopolymer cements : A review. Prog Mater Sci 83:595–629. https://doi.org/10.1016/j.pmatsci.2016.08.002

[2] Journal AI, Rao F, Liu Q (2015) Geopolymerization and Its potential application in mine tailings consolidation: a review. Miner Process Extr Metall Rev. https://doi.org/10.1080/08827508.2015.1055625

[3] Tan J, Cai J, Li X, Pan J, Li J (2020) Development of eco-friendly geopolymers with ground mixed recycled aggregates

and slag. J Clean Prod 256:120369. https://doi.org/10.1016/j.jclepro.2020.120369

[4] Yuan Z, Pang Z, Lu C, Yao Y (2024) Feasibility study of engineered geopolymer composites based high-calcium fly ash and micromechanics analysis. Case Stud Constr Mater 20:e02701. https://doi.org/10.1016/j.cscm.2023.e02701

[5] Fernando S, Gunasekara C, Law DW, Nasvi MCM, Setunge S, Dissanayake R (2023) Assessment of long term durability properties of blended fly ash-rice husk ash alkali activated concrete. Constr Build Mater 369:130449. https://doi.org/10.1016/j.conbuildmat.2023.130449

[6] Tejas S, Pasla D (2023) Assessment of mechanical and durability properties of composite cement-based recycled aggregate concrete. Constr Build Mater 387:131620. https://doi.org/10.1016/j.conbuildmat.2023.131620

[7] Popovich J, Chen S, Iannuzo N, Ganser C, Seo DK, Haydel SE (2020) Synthesized geopolymers adsorb bacterial proteins, toxins, and cells. Front Bioeng Biotechnol 8:1–12. https://doi.org/10.3389/fbioe.2020.00527

[8] Arokiasamy P, Abdullah MMAB, Arifi E, Jamil NH, Mydin MAO, Rahim SZA, Sandu AV, Ishak S (2025) Sustainable geopolymer adsorbents utilizing silica fume as a partial replacement for metakaolin in the removal of copper ion from synthesized copper solution. Case Stud Constr Mater 22:e04142. https://doi.org/10.1016/j.cscm.2024.e04142

[9] Rihan MAM, Onchiri RO, Gathimba N, Sabuni B (2024) Effect of elevated temperature on the mechanical properties of geopolymer concrete: a critical review. Discov Civ Eng 1:24. https://doi.org/10.1007/s44290-024-00028-4

[10] Zhou Z, Zeng C, Wei H, Ding Y (2025) Preparation and property study of geopolymer composite fireproof coating with PVA fiber and manganese slag. Clean Mater 15:100289. https://doi.org/10.1016/j.clema.2024.100289

[11] Freire AL, Moura-Nickel CD, Scaratti G, De Rossi A, Araújo MH, De Noni Júnior A, Rodrigues AE, Castellón ER, Moreira RFPM (2020) Geopolymers produced with fly ash and rice husk ash applied to $CO_2$ capture. J Prod Clean. https://doi.org/10.1016/j.jclepro.2020.122917

[12] Pacios A, Tejado E, Martín A, Fernández A, Pastor JY (2024) High-temperature performance of clay-enhanced alkali-activated binders: a sustainable alternative to Portland cement. Constr Build Mater 453:138860. https://doi.org/10.1016/j.conbuildmat.2024.138860

[13] Saludung A, Azeyanagi T, Ogawa Y, Kawai K (2023) Mechanical and microstructural evolutions of fly ash/slag-based geopolymer at high temperatures: effect of curing conditions. Ceram Int 49:2091–2101. https://doi.org/10.1016/j.ceramint.2022.09.175

[14] Kuri JC, Majhi S, Sarker PK, Mukherjee A (2021) Microstructural and non-destructive investigation of the effect of high temperature exposure on ground ferronickel slag blended fly ash geopolymer mortars. J Build Eng 43:103099. https://doi.org/10.1016/j.jobe.2021.103099

[15] Abd Razak SN, Shafiq N, Nikbakht EH, Mohammed BS, Guillaumat L, Farhan SA (2022) Fire performance of fly-ash-based geopolymer concrete: effect of burning temperature on mechanical and microstructural properties. Mater Today Proc 66:2665–2669. https://doi.org/10.1016/j.matpr.2022.06.491

[16] Cantarel V, Motooka T, Yamagishi I (2017) Geopolymers and their potential applications in the nuclear waste management field. JAEA Rev 14:11484. https://doi.org/10.11484/jaea-review-2017-014

[17] Peng X, Li H, Hu Y (2023) Preparation of metakaolin-fly ash cenosphere based geopolymer matrices for passive fire protection. J Mater Res Technol 23:604–610. https://doi.org/10.1016/j.jmrt.2022.12.163

[18] Liu H, Jing W, Qin L, Duan P, Zhang Z, Guo R, Li W (2022) Thermal stability of geopolymer modified by different silicon source materials prepared from solid wastes. Constr Build Mater 315:125709. https://doi.org/10.1016/j.conbuildmat.2021.125709

[19] Yang Q, Davy CA, Sarazin J, Bourbigot S, Fontaine G (2024) Effect of cation in sodium/potassium-based geopolymer coatings for the fire protection of steel structures. Ceram Int 51:4532–4548. https://doi.org/10.1016/j.ceramint.2024.11.428

[20] Lahoti M, Wong KK, Tan KH, Yang EH (2018) Effect of alkali cation type on strength endurance of fly ash geopolymers subject to high temperature exposure. Mater Des 154:8–19. https://doi.org/10.1016/j.matdes.2018.05.023

[21] Ma H, Zhu H, Yi C, Fan J, Chen H, Xu X, Wang T (2019) Preparation and reaction mechanism characterization of alkali-activated coal gangue-slag materials. Materials 12:2250. https://doi.org/10.3390/ma12142250

[22] Hadi MNS, Zhang H, Parkinson S (2019) Optimum mix design of geopolymer pastes and concretes cured in ambient condition based on compressive strength, setting time and workability. J Build Eng 23:301–313. https://doi.org/10.1016/j.jobe.2019.02.006

[23] Chen SN, Li PK, Hsieh TH, Ho KS, Hong YM (2021) Enhancements on flame resistance by inorganic silicate-based intumescent coating materials. Materials 14(6628):1–16. https://doi.org/10.3390/ma14216628

[24] Abood Al-Saadi TH, Hameed Mohammad S, Daway EG, Mejbel MK (2021) Synthesis of intumescent materials by alkali activation of glass waste using intercalated graphite additions. Mater Today Proc 42:1889–1900. https://doi.org/10.1016/j.matpr.2020.12.228

[25] Ulusoy B, Fu A, Ahmadi H, Dam-Johansen K, Wu H (2023) Intumescent alkali silicate and geopolymer coatings against hydrocarbon fires. J Coat Technol Res 20:233–248. https://doi.org/10.1007/s11998-022-00659-1

[26] Prakasan S, Palaniappan S, Gettu R (2020) Study of energy use and $CO_2$ emissions in the manufacturing of clinker and cement. J Inst Eng Ser A 101(1):221–232. https://doi.org/10.1007/s40030-019-00409-4

[27] Gao B, Jang S, Son H, Lee HJ, Lee HJ, Yang JJ, Bae C-J (2020) Study on mechanical properties of kaolin-based geopolymer with various Si/Al ratio and aging time. J Korean Ceram Soc 57(6):709–715. https://doi.org/10.1007/s43207-020-00075-4

[28] Klima KM, Schollbach K, Brouwers HJH, Yu Q (2022) Thermal and fire resistance of class F fly ash based geopolymers: a review. Constr Build Mater 323:126529. https://doi.org/10.1016/j.conbuildmat.2022.126529

[29] Nawaz M, Heitor A, Sivakumar M (2020) Geopolymers in construction: recent developments. Constr Build Mater 260:120472. https://doi.org/10.1016/j.conbuildmat.2020.120472

[30] Tchadjie LN, Ekolu SO (2018) Enhancing the reactivity of aluminosilicate materials toward geopolymer synthesis. J Mater Sci 53:4709–4733. https://doi.org/10.1007/s10853-017-1907-7

[31] Wang YS, Alrefaei Y, Dai JG (2019) Silico-aluminophosphate and alkali-aluminosilicate geopolymers: a comparative review. Front Mater 6:1–17. https://doi.org/10.3389/fmats.2019.00106

[32] Prochon P, Zhao Z, Courard L, Piotrowski T, Michel F, Garbacz A (2020) Influence of activators on mechanical properties

of modified fly ash based geopolymer mortars. Materials 13(1033):1–24. https://doi.org/10.3390/ma13051033

[33] Abdullah AF, Abdul-Rahman MBAD, Al-Attar AA (2024) A review on geopolymer concrete behaviour under elevated temperature influence. J Sustain Sci Manag 19:239–259. https://doi.org/10.46754/jssm.2024.12.014

[34] Verma M, Meena RK, Singh I, Gupta N, Saxena KK, Reddy MM, Salem KH, Salmaa U (2023) Investigation on the impact of elevated temperature on sustainable geopolymer composite. Adv Mech Eng 15(9):1–16. https://doi.org/10.1177/16878132231196402

[35] Ali HK, Abid SR, Tayşi N (2023) Thermal behaviour and microstructure of self-cured high-strength plain and fibrous geopolymer concrete exposed to various fire scenarios. Buildings 13:2444. https://doi.org/10.3390/buildings13102444

[36] Lahoti M, Tan KH, Yang EH (2019) A critical review of geopolymer properties for structural fire-resistance applications. Constr Build Mater 221:514–526. https://doi.org/10.1016/j.conbuildmat.2019.06.076

[37] Jiang X, Zhang Y, Xiao R, Polaczyk P, Zhang M, Hu W, Bai Y, Huang B (2020) A comparative study on geopolymers synthesized by different classes of fly ash after exposure to elevated temperatures. J Clean Prod 270:122500. https://doi.org/10.1016/j.jclepro.2020.122500

[38] Moutaoukil G, Alehyen S, Sobrados I, Safhi AeM (2023) Effects of elevated temperature and activation solution content on microstructural and mechanical properties of fly ash-based geopolymer. KSCE J Civ Eng 27:2372–2384. https://doi.org/10.1007/s12205-023-1102-0

[39] Barzoki PK, Gowayed Y (2025) Tailoring metakaolin-based geopolymers for high-temperature stability: chemical, thermal and mechanical insights. Ceram Int 51:11346–11353. https://doi.org/10.1016/j.ceramint.2024.12.553

[40] Kim G, Cho S, Im S, Yoon J, Suh H, Kanematsu M, Machida A, Shobu T, Bae S (2024) Evaluation of the thermal stability of metakaolin-based geopolymers according to Si/Al ratio and sodium activator. Cem Concr Compos 150:105562. https://doi.org/10.1016/j.cemconcomp.2024.105562

[41] Derinpinar AN, Karakoç MB, Özcan A (2022) Performance of glass powder substituted slag based geopolymer concretes under high temperature. Constr Build Mater 331:127318. https://doi.org/10.1016/j.conbuildmat.2022.127318

[42] Xiang S, Guo M, Zhou Y, Huang Z (2025) Tailoring thermal performance of geopolymer via metakaolin/fly ash ratio and activator variation. J Build Eng 103:111856. https://doi.org/10.1016/j.jobe.2025.111856

[43] Perná I, Zárybnická L, Mácová P, Šupová M, Ševčík R (2024) Physico-mechanical properties of geopolymers after thermal exposure: influence of filler, temperature and dwell time. Constr Build Mater 451:138893. https://doi.org/10.1016/j.conbuildmat.2024.138893

[44] Luo Y, Li SH, Klima KM, Brouwers HJH, Yu Q (2022) Degradation mechanism of hybrid fly ash/slag based geopolymers exposed to elevated temperatures. Cem Concr Res 151:106649. https://doi.org/10.1016/j.cemconres.2021.106649

[45] Zhang X, Zhang Z-Y, Zhou J, Du R, Yin X, Kang S, Zheng Y, Liu Y (2024) Thermal behavior and mechanism study of geopolymers prepared from ferronickel slag with high fire resistance. Constr Build Mater 438:137282. https://doi.org/10.1016/j.conbuildmat.2024.137282

[46] Javed U, Shaikh FUA, Sarker PK (2024) Thermal stability and strength degradation of lithium slag geopolymer containing fly ash and silica fume. Constr Build Mater 425:135976. https://doi.org/10.1016/j.conbuildmat.2024.135976

[47] Caballero LR, Paiva MDDM, Fairbairn EDMR, Filho RDT (2019) Thermal, mechanical and microstructural analysis of metakaolin based geopolymers. Mater Res 22:1–8. https://doi.org/10.1590/1980-5373-MR-2018-0716

[48] Rivera OG et al (2016) Effect of elevated temperature on alkali-activated geopolymeric binders compared to portland cement-based binders. Cem Concr Res 90:43–51. https://doi.org/10.1016/j.cemconres.2016.09.013

[49] Manzoor T, Bhat JA, Shah AH (2024) Performance of geopolymer concrete at elevated temperature: a critical review. Constr Build Mater 420:135578. https://doi.org/10.1016/j.conbuildmat.2024.135578

[50] Sivasakthi M, Jeyalakshmi R, Rajamane NP, Jose R (2018) Thermal and structural micro analysis of micro silica blended fly ash based geopolymer composites. J Non Cryst Solids 499:117–130. https://doi.org/10.1016/j.jnoncrysol.2018.07.027

[51] Kashani A, Ngo TD, Walkley B, Mendis P (2017) Thermal performance of calcium-rich alkali-activated materials: a microstructural and mechanical study. Constr Build Mater 153:225–237. https://doi.org/10.1016/j.conbuildmat.2017.07.119

[52] Chairunnisa N, Haryanti NH, Nurwidayati R, Pratiwi AY, Arnandha Y, Manik TN, SaputraSuryajaya Y, Hazizah N (2024) Characteristics of metakaolin-based geopolymers using bemban fiber additives AIMS. Mater Sci 11:815–832. https://doi.org/10.3934/matersci.2024040

[53] Lila O, Ameni G, Benoit N-A, Jenny J, Guillaume B, Patrice D, Chinaya C, Eric G, Rossignol S (2023) Thermally resistant geopolymer to 1300 °C: scale-up and structural evolution. Open Ceram 16:100462. https://doi.org/10.1016/j.oceram.2023.100462

[54] Zhang Z, Yu J, Qin F, Sun F (2023) Thermal effect on mechanical properties of metakaolin-based engineered geopolymer composites (EGC). Case Stud Constr Mater 18:e02150. https://doi.org/10.1016/j.cscm.2023.e02150

[55] Gencel O, Benli A, Bayraktar OY, Kaplan G, Sutcu M, Elabade WAT (2021) Effect of waste marble powder and rice husk ash on the microstructural, physico-mechanical and transport properties of foam concretes exposed to high temperatures and freeze–thaw cycles. Constr Build Mater 291:123374. https://doi.org/10.1016/j.conbuildmat.2021.123374

[56] Wongsa A, Wongkvanklom A, Tanangteerapong D, Chindaprasirt P (2020) Comparative study of fire-resistant behaviors of high-calcium fly ash geopolymer mortar containing zeolite and mullite. J Sustain Cem Mater 9(5):307–321. https://doi.org/10.1080/21650373.2020.1748741

[57] Luo X, Huang L, Li Y, Chen Z (2024) Preparation of geopolymers from thermally activated lithium slag as sole precursor: mechanical properties and microstructure. Case Stud Constr Mater 20:e03248. https://doi.org/10.1016/j.cscm.2024.e03248

[58] Amer Salih M, Farzadnia N, Demirboga R, Ali AAA (2022) Effect of elevated temperatures on mechanical and microstructural properties of alkali-activated mortar made up of POFA and GGBS. Constr Build Mater 28:127041. https://doi.org/10.1016/j.conbuildmat.2022.127041

[59] Ahmad R, Ibrahim WMW, Abdullah MMAB, Pakawanit P, Vizureanu P, Abdullah AS, Sandu AV, Zaidi FHA (2022) Geopolymer-based nepheline ceramics: effect of sintering profile on morphological characteristics and flexural strength. Crystals 12:1–9. https://doi.org/10.3390/cryst12091313

[60] Aziz IHA, Abdullah MMAB, Razak RA, Yahya Z, Salleh MAAM, Chaiprapa J, Rojviriya C, Vizureanu P, Sandu AV, Tahir MFM (2023) Evolution of fly ash geopolymer after ten years of curing age. Materials 16:1096. https://doi.org/10.3390/ma16031096

[61] Khrongchaiyaphum F, Wantana N, Kansirin S, Pakawanit P, Vittayakorn N, Kothan S, Chanthima N, Kim HJ, Kaewkhao J (2023) $Eu^{3+}$ doped $Na_2O$–$Gd_2O_3$–BaO–$B_2O_3$–$P_2O_5$ glasses for x-ray scintillator application. Optik 292:171355. https://doi.org/10.1016/j.ijleo.2023.171355

[62] Ong SW, Heah CY, Liew YM, Ho LN, Lee WH, Abdullah MMAB, Pakawanit P, Part WK, Hang YJ, Lim JN, Gao DW, Liu MJ (2024) Physico-mechanical and microstructural evolution of sintered pressed geopolymer: dual effects of aging period and sintering temperature. Constr Build Mater 438:137242. https://doi.org/10.1016/j.conbuildmat.2024.137242

[63] Ng YS, Liew YM, Heah CY, Abdullah MMAB, Rojviriya C, Khalid MS, Ong SW, Ooi WE, Hang YJ (2023) nteraction of silica fume on flexural properties of 10 mm-thickness geopolymers based on fly ash and ladle furnace slag under the thermal conditions. J Build Eng 69:106331. https://doi.org/10.1016/j.jobe.2023.106331

[64] Kozhukhova N, Kozhukhova M, Zhernovskaya I, Promakhov V (2020) The correlation of temperature-mineral phase transformation as a controlling factor of thermal and mechanical performance of fly ash-based alkali-activated binders. Materials 13:5181. https://doi.org/10.3390/ma13225181

[65] Arce A, Komkova A, Van De Sande J, Papanicolaou CG, Triantafillou TC (2022) Optimal design of ferronickel slag alkali-activated material for high thermal load applications developed by design of experiment. Materials 15:4379. https://doi.org/10.3390/ma15134379

[66] Zhao J, Wang K, Wang S, Wang Z, Yang Z, Shumuye ED, Gong X (2021) Effect of elevated temperature on mechanical properties of high-volume fly ash-based geopolymer concrete, mortar and paste cured at room temperature. Polymers 13:1473. https://doi.org/10.3390/polym13091473

[67] Nikolov A, Karamanov A (2022) Thermal properties of geopolymer based on fayalite waste from copper production and metakaolin. Materials 15:2666. https://doi.org/10.3390/ma15072666

[68] Cao B, Li Y, Li P (2024) Synergistic effect of blended precursors and silica fume on strength and high temperature resistance of geopolymer. Materials 17:2975. https://doi.org/10.3390/ma17122975

[69] Luo Y, Klima KM, Brouwers HJH, Yu Q (2022) Effects of ladle slag on class F fly ash geopolymer: reaction mechanism and high temperature behavior. Cem Concr Compos 129:104468. https://doi.org/10.1016/j.cemconcomp.2022.104468

[70] Wang B et al (2020) In-situ neutron diffraction study of micromechanical shear failure in an aerospace composite. AIAA Scitech Forum. https://doi.org/10.2514/6.2020-0969

[71] Yang T, Wu Q, Zhu H, Zhang Z (2017) Geopolymer with improved thermal stability by incorporating high-magnesium nickel slag. Constr Build Mater 155:475–484. https://doi.org/10.1016/j.conbuildmat.2017.08.081

[72] Wang Y, Liu H, Nie Z, Xue R, Zhu W, Sun X (2025) Experimental investigation into the influence of calcium aluminate cement on the micro- and macro-mechanical properties of the interfacial transition zone in geopolymer concrete. Dev Built Environ 21:100618. https://doi.org/10.1016/j.dibe.2025.100618

[73] Wang T, Yu M, Lin H, LiyuanLi DL (2024) Experimental investigation of mechanical properties of GGBS-FA-SF blended geopolymer concrete at elevated temperatures. Fire Saf J 146:104156. https://doi.org/10.1016/j.firesaf.2024.104156

[74] Li P, Li Y, Ou W, Ran X (2024) Conceptual design and properties of ultra-high residual strength geopolymer after 1000 ℃ thermal exposure. Mater Lett 373:137153. https://doi.org/10.1016/j.matlet.2024.137153

[75] Jiang C, Wang A, Bao X, Ni T, Ling J (2020) A review on geopolymer in potential coating application: materials, preparation and basic properties. J Build Eng 32:101734. https://doi.org/10.1016/j.jobe.2020.101734

[76] Yang Q, Davy CA, Sarazin J, Bourbigot S, Fontaine G (2024) Effect of the Al/Si ratio on intumescent Na–based geopolymer. Fire Saf J 148:104220. https://doi.org/10.1016/j.firesaf.2024.104220

[77] Wang YC, Zhao JP (2019) Facile preparation of slag or fly ash geopolymer composite coatings with flame resistance. Constr Build Mater 203:655–661. https://doi.org/10.1016/j.conbuildmat.2019.01.097

[78] Sun H, Zhang Z, Liang Y, Ji T (2025) Preparation and fireproof performance of alkali activated cement based fire resistive coatings with different alkali activators for steel structures. Case Stud Constr Mater 22:e04428. https://doi.org/10.1016/j.cscm.2025.e04428

[79] Ahmed Shaikh FU, Haque S, Sanjayan J (2019) Behavior of fly ash geopolymer as fire resistant coating for timber. J Sustain Cem-Based Mater 8:259–274. https://doi.org/10.1080/21650373.2018.1537015

[80] Kielė A, Vaičiukynienė D, Bertašius Š, Krivenko P, Bistrickaitė R, Jocius V, Ramukevičius D (2023) Alkali-activated slag coatings for fire protection of OPC concrete. Materials 16:7477. https://doi.org/10.3390/ma16237477

[81] Qu CL, Wang YC (2024) Flame-retardant coatings with ultraviolet resistance by doping KH-560 modified nano-silica into Na2SiO3/NaOH-activated copper tailings geopolymer. Constr Build Mater 446:138004. https://doi.org/10.1016/j.conbuildmat.2024.138004

[82] Sarazin J, Davy CA, Bourbigot S, Tricot G, Hosdez J, Lambertin D, Fontaine G (2021) Flame resistance of geopolymer foam coatings for the fire protection of steel. Compos Part B Eng 222:109045. https://doi.org/10.1016/j.compositesb.2021.109045

[83] Kaczmarski K, Pławecka K, Kozub B, Bazan P, Łach M (2022) Preliminary investigation of geopolymer foams as coating materials. Appl Sci 12:11205. https://doi.org/10.3390/app122111205

[84] Le VS, Nguyen VV, Sharko A, Ercoli R, Nguyen TX, Tran DH, Łoś P, Buczkowska KE, Mitura S, Špirek T, Louda P (2022) Fire resistance of geopolymer foams layered on polystyrene boards. Polymers. https://doi.org/10.3390/polym14101945

[85] Zhu A, Wu H, Wang YD, Liu J (2023) Evaluation of feasibility and performance of foamed fire-resistant coating materials. Constr Build Mater 400:132692. https://doi.org/10.1016/j.conbuildmat.2023.132692

[86] Peng X, Shuai Q, Li H, Ding Q, Gu Y, Cheng C, Xu Z (2020) Fabrication and fireproofing performance of the coal fly ash-metakaolin-based geopolymer foams. Materials 13:1750. https://doi.org/10.3390/ma13071750

[87] Fu A, Ulusoy B, Ahmadi H, Wu H, Dam-Johansen K (2025) Intumescent coatings: comprehensive advances with a focus on inorganic-dominant systems. Prog Org Coat 199:108939. https://doi.org/10.1016/j.porgcoat.2024.108939

[88] Anees SM, Dasari A (2018) A review on the environmental durability of intumescent coatings for steels. J Mater Sci 53(1):124–145. https://doi.org/10.1007/s10853-017-1500-0

[89] Wang K, Le H (2023) The development of cement-based, intumescent and geopolymer fire-retardation coatings for metal structures: a review. Coatings 13:495. https://doi.org/10.3390/coatings13030495

[90] Lucherini A, Maluk C (2019) Intumescent coatings used for the fire-safe design of steel structures: a review. J Constr Steel Res 162:105712. https://doi.org/10.1016/j.jcsr.2019.105712

[91] Tan W, Guo Y, Xiang Y, Meng X, Wang C, Ren Q (2025) Optimization of the performance of epoxy intumescent fire-retardant coatings utilizing amino-polysiloxanes with varying compositions. React Funct Polym 210:106191. https://doi.org/10.1016/j.jcsr.2019.105712

[92] Nazrun T, Hassan MK, Hasnat MR, Hossain MD, Saha S (2025) Improving fire performance of solid aluminium of composite cladding panels incorporating intumescent coatings. Prog Org Coat 201:109142. https://doi.org/10.1016/j.porgcoat.2025.109142

[93] Du W, Wang Y, Wang L, Cao X, Zhu G (2025) Preparation and performance analysis of an intumescent fire-retardant coating with strong water resistance. Appl Surf Sci 706:163596. https://doi.org/10.1016/j.apsusc.2025.163596

[94] Cirpici BK, Aydin I (2023) Investigation of intumescent coating on the fire endurance of concrete-filled steel columns with varied characteristics. J Mater Res Technol 25:1959–1980. https://doi.org/10.1016/j.jmrt.2023.06.043

[95] Ahmadi H, Ulusoy B, Fu A, Dalmau G, Wu H, Dam-Johansen K (2024) Inorganic intumescing alkali silicate particles. Ceram Int 50:10906–10917. https://doi.org/10.1016/j.ceramint.2023.12.407

[96] Watolla MB, Gluth GJG, Sturm P, Rickard WDA, Krüger S, Schartel B (2017) Intumescent geopolymer-bound coatings for fire protection of steel. J Ceram Sci Technol 8(3):351–364. https://doi.org/10.4416/JCST2017-00035

[97] Dhasindrakrishna K, Ramakrishnan S, Pasupathy K, Sanjayan J (2022) Synthesis and performance of intumescent alkali-activated rice husk ash for fire-resistant applications. J Build Eng 51:104281. https://doi.org/10.1016/j.jobe.2022.104281

[98] Wang P, Tan X, Hao H, Wang P, Li H, Li B, Ma J, Guo C (2025) Gangue geopolymer to strength fire resistance of intumescent waterborne coating. J Coat Technol Res 22:985–998. https://doi.org/10.1007/s11998-024-01026-y

[99] Nicoară AI, Bădănoiu AI, Voicu G, Dinu C, Ionescu A (2020) Intumescent coatings based on alkali-activated borosilicate inorganic polymers. J Coat Technol Res 17:681–692. https://doi.org/10.1007/s11998-019-00274-7

[100] Yang Q, Davy CA, Sarazin J, Bourbigot S, Fontaine G (2024) Investigation of the intumescence mechanism of geopolymers by solid-state magic angle spinning NMR. Constr Build Mater 448:138216. https://doi.org/10.1016/j.conbuildmat.2024.138216