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Review

Fiber-reinforced geopolymer materials for intumescent fireproofing plasters

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ABSTRACT

This review rigorously analyzes the advancement of fiber-reinforced geopolymer plasters for fireproofing purposes in construction. Geopolymers possess superior thermal resistance and reduced environmental impact relative to ordinary Portland cement. The addition of fibers such as steel, glass, basalt, and synthetic materials markedly improves mechanical strength, thermal insulation, and fire resistance. Recent research is comprehensively summarized, focusing on the mechanical behavior, thermal conductivity, microstructural evolution, and degradation mechanisms of fiber-reinforced geopolymers subjected to elevated temperatures and fire exposure. Special emphasis is placed on intumescent properties and fire-protection mechanisms that support the prospective advancement of geopolymer-based surface protection plasters. This review delineates significant research deficiencies, such as long-term durability, fiber–matrix interactions under cyclic thermal loading, and standardized fire-testing protocols, while also addressing burgeoning prospects for artificial intelligence-assisted material design and performance forecasting. Fiber-reinforced geopolymers are identified as a viable low-carbon fireproofing material that meets the sustainability and safety requirements of contemporary construction.

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Introduction

Geopolymers, initially presented by Davidovits in the 1970s, are inorganic aluminosilicate polymers synthesized through the alkali activation of silicate- and aluminate-rich industrial by-products or calcined clays, including fly ash, blast-furnace slag, and metakaolin, utilizing alkaline solutions based on sodium hydroxide (NaOH) or potassium hydroxide (KOH), often augmented with sodium or potassium silicate to facilitate geopolymerization [1]. Geopolymers have emerged as a viable low-carbon substitute for Ordinary Portland Cement (OPC), garnering significant international research interest in sustainable construction materials. In contrast to OPC, which necessitates energy-intensive clinker production at temperatures above 1400 °C, geopolymers are produced at ambient or moderately elevated temperatures, leading to considerably reduced embodied energy and greenhouse gas emissions. Thus, geopolymer binders present significant potential for diminishing the carbon footprint of the construction industry [2]. Figure 1 illustrates the comparative carbon emissions linked to conventional construction materials and activities [3].

Analyses of carbon footprints indicate that significant construction materials and activities disproportionately contribute to overall building-related emissions. Concrete, structural steel, reinforcing bars, clay bricks, and plaster contribute approximately 24%, 14%, 13%, and 10% to the total embodied carbon, respectively. In light of these environmental issues, Davidovits advocated for geopolymers as an eco-friendly binder system due to their capacity to incorporate industrial by-products like fly ash as aluminosilicate precursors and their low-energy synthesis process, which significantly diminishes CO_2 emissions in comparison with OPC-based systems [4–6]. In addition to sustainability, geopolymers demonstrate remarkable durability and thermal stability, facilitating their use in various domains such as structural construction, heavy-metal immobilization, pavement rehabilitation, and nuclear waste encapsulation [2]. Geopolymer concrete (GPC) has been documented to surpass OPC concrete in various mechanical and physical properties, including superior compressive strength and reduced setting time [7]. However, under dynamic bending or impact loading, GPC frequently demonstrates brittle failure characterized by abrupt crack propagation, potentially jeopardizing structural integrity [8, 9]. Extensive research has concentrated on optimizing the chemical composition and microstructure of geopolymer matrices to improve their mechanical performance [10]. Among the diverse strategies, fiber incorporation has demonstrated notable efficacy in enhancing toughness, crack resistance, and energy absorption capacity. Despite the possible

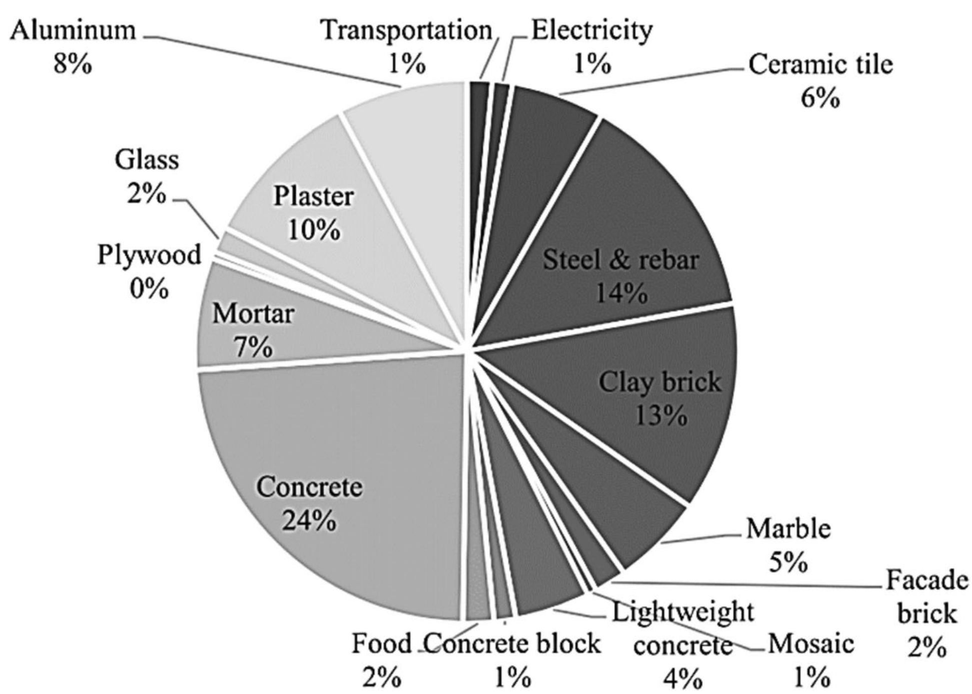
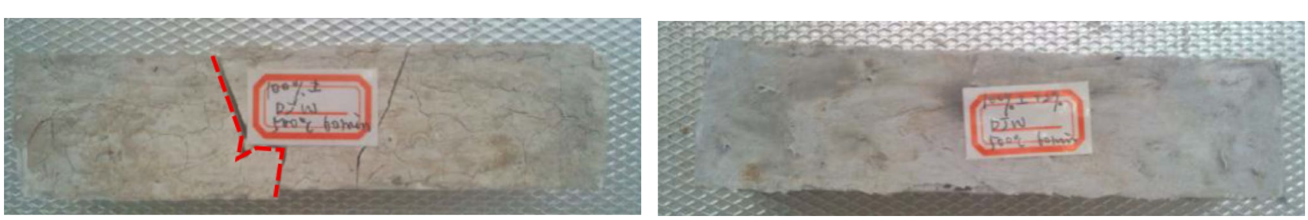


Figure 1 Contribution of construction material and operations of the building with common materials in carbon footprint [3].

significance demonstrated in past research, this review aims to highlight the development of optimized fiber-reinforced geopolymer material system as an intumescent fireproofing plaster. The variability types of fibers and weight percentage of fiber that required in standardization mix design of geopolymer plasters remain unstandardized. There is no standard of inclusion of fiber into geopolymer materials to mitigate the mechanical properties, thermal properties, and structural performance, especially during extended fire exposure or cyclic fire exposure. Although geopolymer systems have shown promise for fireproofing, the mechanisms of intumescence related to the chemical composition functioning as plasters application remain unclear. This review highlights the necessity of sustainable and thermally stable plaster materials for the development of fire-resistant building materials based on geopolymer formulations and critically discusses the underlying fire-protection mechanisms to identify key gaps in the current knowledge. Zhang et al. formulated fiber-reinforced metakaolin–fly ash geopolymers for fire-resistant applications [11]. Figure 2a illustrates that those specimens devoid of carbon fibers (CF) experienced significant cracking and early failure under comparatively low loads, while geopolymer composites with 2 wt.% CF exhibited no discernible cracking as shown in Fig. 2b, highlighting the considerable crack-bridging and reinforcement effects conferred by the inclusion of fibers.

To alleviate the intrinsic brittleness of geopolymer matrices, considerable study has concentrated on the integration of diverse reinforcing fibers, such as glass, steel, basalt, and polypropylene. Fiber reinforcement has repeatedly demonstrated improvements in fracture toughness, crack resistance, and load-bearing capacity of geopolymer composites [12]. Rashad et al. [12] indicated that the incorporation of steel fibers successfully mitigates fracture propagation and markedly enhances flexural and splitting tensile strength. Liu et al. [13] similarly showed that augmenting fiber volume fraction while diminishing fiber diameter results in significant improvements in compressive strength and flexural performance. Besides mechanical enhancements, fiber-reinforced geopolymers have demonstrated significant potential in fire prevention applications. Shahari et al. [14] examined the integration of glass fiber-reinforced geopolymer layers to enhance the fire resistance of epoxy-based composites. Moreover, geopolymer-based solutions have been effectively engineered as fire-resistant coatings for steel substrates [15], fire-retardant boards and flexible sheets [16], and insulating foams for passive fire-protection applications [17].

The intrinsic thermal stability and minimal thermal conductivity of geopolymers, along with their production from industrial by-products, highlight their promise as sustainable fireproofing materials [18]. The fire performance of geopolymer systems is typically evaluated based on crack formation, spalling behavior, and residual compressive strength after exposure to elevated temperatures [19]. Conversely, traditional fire-protection materials, such as gypsum plasters, OPC-based coatings, and commercial intumescent paints, frequently demonstrate inadequate interfacial adhesion, elevated thermal conductivity, and restricted endurance against extended fire exposure. Intumescence is an essential process in fire-retardant systems, in which heat exposure triggers the development of a thermally stable, foamed, multicellular char layer [20–22]. This char coating serves as an insulating barrier that markedly diminishes heat transport to the underlying substrate, thereby postponing material degradation and ignition [20–25]. Despite extensive research on fiber-reinforced geopolymer concrete and coatings for fireproofing applications, there is a paucity of studies focusing on their use as intumescent plaster layers in building construction. Figure 3 depicts the cross-sectional design of standard external and internal wall systems, wherein plaster or tile layers



(a) (b)

Figure 2 Cracking in geopolymer specimens **a** without CF and **b** with 2% CF after exposure to 500˚C [11].

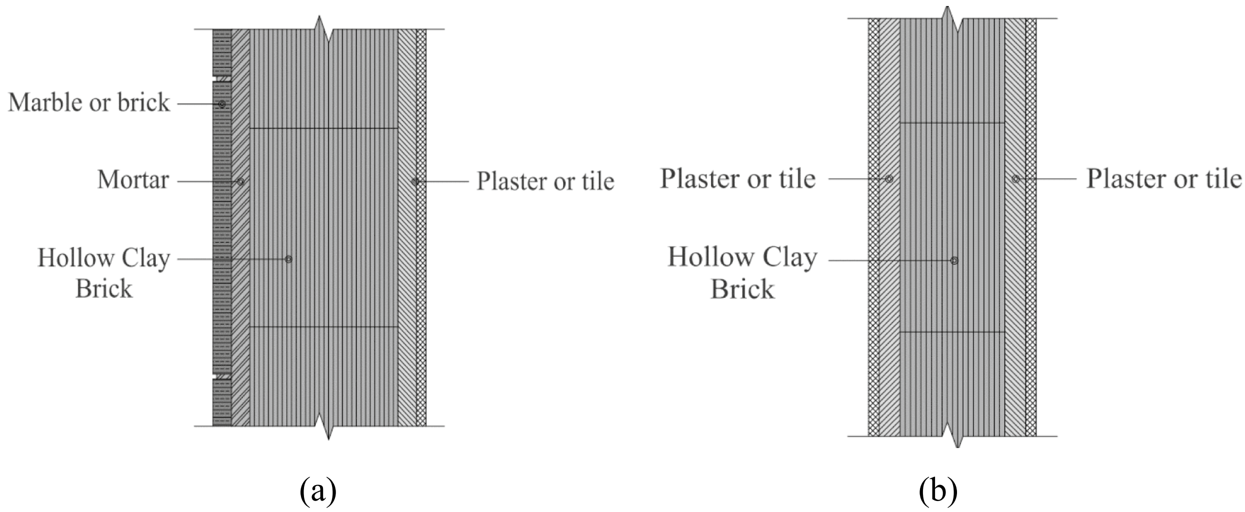


Figure 3 Cross-section details of the structural elements; **a** external and **b** internal walls for the building with common materials [3].

safeguard hollow clay brick substrates and function as bonding agents for tile installation.

Although studies on fiber-reinforced geopolymer coatings have increased in recent years, their potential application as fireproof plaster layers in construction systems remains insufficiently explored. Most existing research has primarily focused on geopolymer coatings and concrete systems, with limited attention given to fiber-reinforced geopolymer formulations specifically designed for plaster applications. In this review, the discussion is therefore emphasized within the context of fiber-reinforced geopolymers as intumescent fireproof plaster layers for building fire protection. The review critically evaluates the fire-resistance performance of fiber-reinforced geopolymer systems and assesses their suitability as geopolymer-based plastering materials for high-temperature applications. In addition, the role of plaster layers is considered beyond their conventional function as finishing materials, highlighting their potential as practical protective barriers for structural elements during fire exposure. Through this discussion, the review also identifies key research gaps and outlines directions for future investigations on the application of geopolymer coating technologies in practical building environments [26, 27].

Selection of literature

This study adopts a narrative review approach to critically analyze the existing literature on fiber-reinforced geopolymer concrete and coatings for fire-protection applications. Relevant literature was collected from major scientific databases including Scopus, Web of Science, ScienceDirect, and Google Scholar. The search focused on publications related to geopolymer binders, fiber-reinforced geopolymer coatings, and their fire-resistance performance under high-temperature exposure. Keywords such as "fiber-reinforced geopolymer," "geopolymer concrete," "geopolymer coating," "fire resistance," "intumescent geopolymer," and "fireproofing materials" were used to identify relevant studies. Only peer-reviewed journal articles and conference papers reporting experimental investigations on geopolymer-based fire-protection materials were considered, while studies unrelated to high-temperature performance or not involving geopolymer systems were excluded. The selected publications were then critically analyzed based on their reported mechanical properties, microstructural characterization, thermal behavior, and fire-protection performance.

Geopolymers

Geopolymers are inorganic binders characterized by a binding phase predominantly consisting of sodium aluminosilicate hydrate (N–A–S–H) gel, which is fundamentally different from the calcium silicate hydrate (C–S–H) phase prevalent in OPC systems. Geopolymer binders are produced via the alkali activation of aluminosilicate-rich precursors, including fly ash, blast-furnace slag, and metakaolin, which are generally industrial by-products characterized by elevated silica and alumina concentrations. The geopolymerization process commences when the solid precursor is mixed with an alkaline activator solution, resulting in a reactive slurry that experiences a series of physicochemical alterations before solidification. Figure 4 demonstrates that the process commences with dissolution, wherein the Si–O–Si and Al–O–Al covalent connections in the precursor are severed, resulting in the liberation of silicate and aluminate species into the alkaline medium. Following nucleation and polycondensation reactions, a continuous gel network is established. In the reorganization phase, the gel transforms into a three-dimensional aluminosilicate framework, thereafter undergoing hardening and curing that solidify and densify the matrix, finally producing a robust geopolymer binder [28, 29].

Geopolymers are acknowledged for having diminished carbon dioxide (CO_2) emissions due to the use of industrial by-products, therefore leading to a lessened environmental impact compared to OPC-based systems [30, 31]. Geopolymer binders demonstrate significant compressive strength, exceptional longevity, and outstanding fire resistance from both mechanical and physical viewpoints. Numerous investigations indicate that specific geopolymer formulations maintain up to 80% of the original compressive

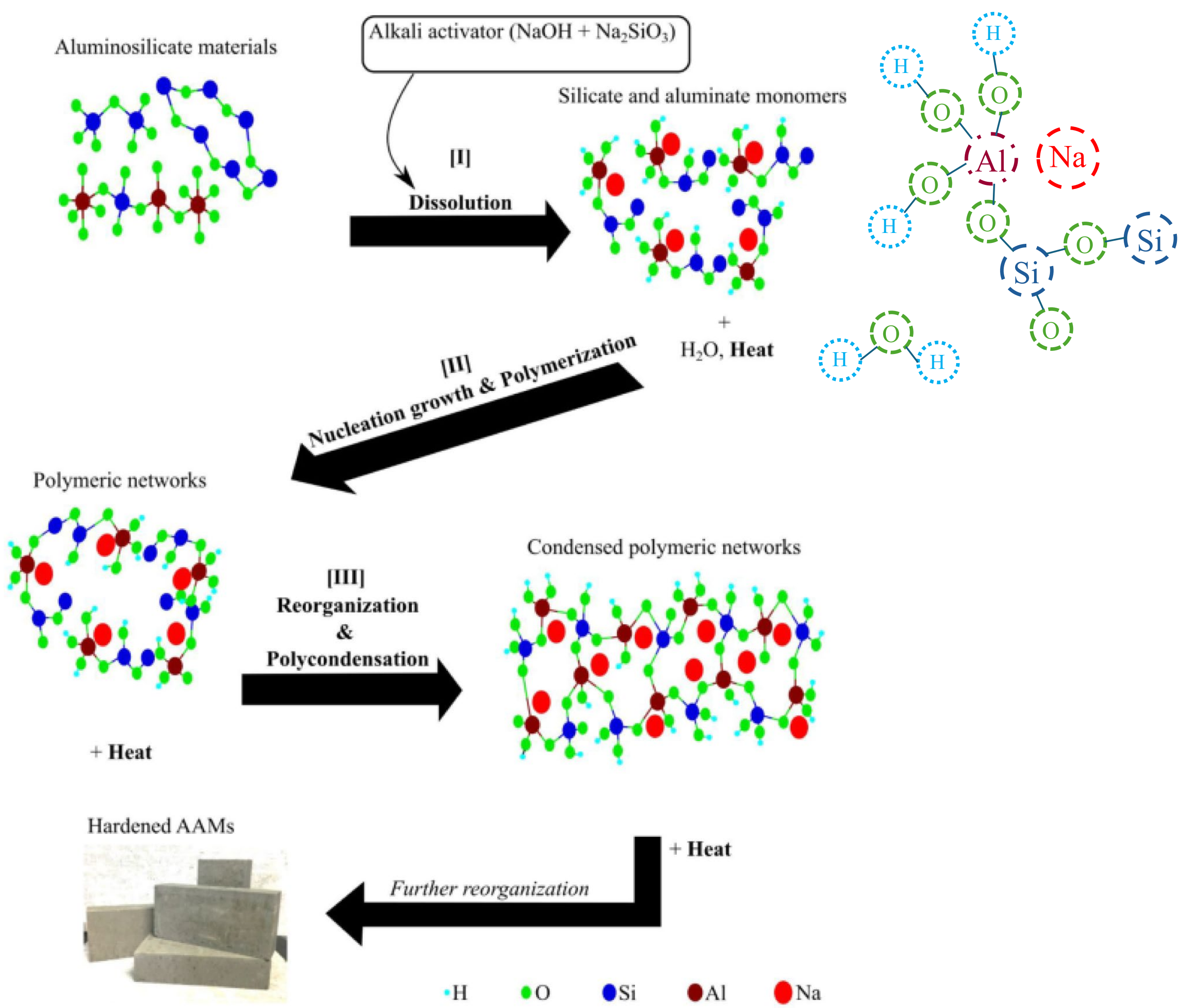


Figure 4 Formation of three-dimensional aluminosilicate network products in AAMs [28].

strength following exposure to temperatures nearing 800 °C [32]. The resistance to heat degradation, cracking, and spalling makes geopolymers especially appropriate for high-risk fire situations, such as petrochemical facilities, tunnels, and high-rise buildings [33]. The efficacy of geopolymer materials can be augmented by integrating reinforcing fibers, including steel, basalt, and glass, into the geopolymer matrix. Fiber reinforcement enhances mechanical properties, crack resistance, and thermal stability, all of which are essential for fireproofing applications. Materials that inhibit crack growth and diminish heat transmission to internal structural components prolong evacuation time for occupants and alleviate structural damage during fire incidents. Thus, fiber-reinforced geopolymers constitute a viable category of high-performance, sustainable construction materials for sophisticated fire-protection systems.

Fiber-reinforced geopolymer

The reinforcement of geopolymers can be accomplished using three primary categories of fibers. Synthetic fibers such as polypropylene, polyethylene, polyamide, and polyolefin are extensively utilized owing to their affordability, simplicity of integration, and ability to improve mechanical strength [34–36]. Metallic fibers, including brass- and alumina-coated steel, markedly enhance toughness and durability due to their robust interfacial interaction with the geopolymer matrix [34, 35]. Natural fibers, such as kenaf, provide an eco-friendly and economical alternative, while also enhancing structural performance significantly [37].

The notion of fiber-reinforced geopolymer coatings has been thoroughly examined in both historical and contemporary research, emphasizing advancements in mechanical properties, durability, and environmental applications. Recent research predominantly investigates the integration of diverse fiber types, including metallic fibers (e.g., brass- and alumina-coated steel), synthetic fibers (e.g., polyamide and polyethylene), and natural fibers such as kenaf [37]. The incorporation of these fibers seeks to alleviate the intrinsic brittleness of the geopolymer matrix while improving strength, toughness, and chemical resistance. For example, kenaf fibers enhance sustainability while maintaining mechanical performance, and research on altering fiber percentage (0.25–1.00%) has revealed ideal combinations for enhanced mechanical qualities [34]. Alumina-coated steel fibers demonstrate advantageous outcomes owing to enhanced interfacial adhesion with the geopolymer matrix [35]. Likewise, minor increments of polypropylene or polyolefin fibers (0.15–0.25%) have been documented to improve ductility and adhesion [36]. Additional assessments have assessed carbon, glass, and basalt fibers, specifically for applications necessitating fire resistance and eco-friendly solutions [38].

Zhang et al. [39] underscored the essential function of fire-resistant materials in improving building safety and efficacy in hazardous settings. Fibers have been integrated into geopolymer matrices to mitigate intrinsic limits including brittleness and vulnerability to cracking under thermal stress, hence enhancing mechanical and thermal properties [40]. Frequently examined fibers comprise steel [12], basalt [41], glass [42, 43], polypropylene [42], and polyethylene [44]. The resultant fiber-reinforced geopolymers (FRGs) demonstrate improved crack resistance, less spalling, and heightened toughness at increasing temperatures [45–49]. Fibers serve as conduits across microcracks, enabling stress redistribution and energy absorption, thus preserving structural integrity under mechanical or thermal stress. The bridging mechanism depicted in Fig. 5 is essential for enhancing tensile and flexural strength by obstructing crack progression [50, 51]. Various fiber kinds provide distinct advantages; for instance, polypropylene fibers reduce explosive spalling after fire exposure, while steel fibers improve ductility and overall strength [52].

Numerous researches have examined the integration of various fibers into geopolymer coatings, such as basalt, charcoal, glass, steel, polyvinyl alcohol (PVA), and polypropylene. These fibers have demonstrated the ability to improve essential qualities, including flexural strength, toughness, and adhesion [48]. Table 1 presents a detailed description of research investigating the impact of various fiber types on the mechanical properties and microstructural attributes of fiber-reinforced geopolymer composites.

The previous research summarized in Table 1 indicates that various fiber types significantly affect geopolymer performance. Steel fibers are recognized for improving compressive, tensile, and flexural strength [54–56], offering substantial mechanical support; nevertheless, their efficacy diminishes at high temperatures due to oxidation and softness [68–70]. Glass fibers, thoroughly researched for fire-resistant

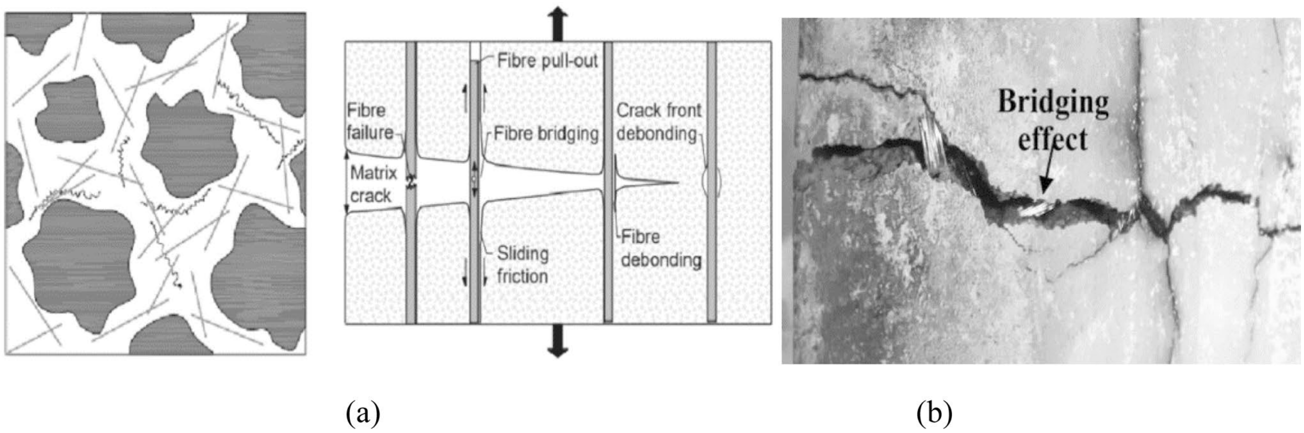


Figure 5 **a** Schematic illustration of the fiber bridging mechanism [51], **b** Visual depiction of the fiber bridging effect [53].

applications, demonstrate exceptional thermal stability up to 1200 °C, proficient fracture management, and mechanical reinforcement [59–61, 71], while also exhibiting significant compatibility with geopolymer matrices, especially metakaolin-based systems [61]. Basalt fibers enhance high-temperature resistance and matrix adhesion, while their characteristics may degrade above 1000 °C, contingent upon composition [41, 66]. Synthetic fibers such as polypropylene (PP), polyethylene (PE), and polyvinyl alcohol (PVA) successfully diminish shrinkage and alleviate cracking during initial curing [29, 62, 63]. However, these fibers are prone to melting or degradation at temperatures over 300 °C, hence restricting long-term fire resistance [62, 65]. Natural fibers, including flax and hemp, offer environmentally friendly reinforcing. Flax fibers demonstrate excellent matrix adherence owing to their rough surface shape; nevertheless, their thermal stability is confined to around 260 °C, hence limiting high-temperature applications [66, 67]. Notwithstanding these thermal constraints, fiber reinforcement reliably improves toughness, microstructural integrity, and crack resistance in geopolymer matrices. Although steel fibers demonstrate superior mechanical strength, their fire resistance is inferior to that of glass fibers. In contrast, glass fibers exhibit stability at high temperatures and efficiently mitigate shrinkage-related cracking, making them exceptionally appropriate for fireproofing applications [72–74]. Fiber-reinforced geopolymers are a diverse and resilient category of materials for fire-resistant coatings and plasters. Optimal fiber selection necessitates a balance between mechanical performance and thermal resilience; among the available options, glass fibers provide the most advantageous combination of mechanical reinforcement and fire resistance, whereas steel and polymeric fibers are selected according to specific design criteria [68–70, 75–77].

Prior research suggests that maximum performance is attained when fibers are used at roughly 0.25–1.00% by volume, with flexural toughness often peaking around 0.75% [34]. Regarding mechanical properties, both compressive and flexural strength may enhance by 50–100% relative to fiber-free mixtures [35, 78]. Moreover, numerous fiber-reinforced geopolymer coatings preserve their structural integrity at temperatures over 100 °C, which is essential for fire-resistant applications [36, 38].

Potential application as fireproofing materials

Fiber-reinforced geopolymer composites exhibit significant potential for fireproofing applications. These materials can serve as protective layers in architectural elements, such as wall panels, structural beams, and fire barrier systems. Their elevated thermal stability, robust adherence to various surfaces, limited thermal conductivity, and capacity to maintain mechanical strength post-heat exposure render them exceptionally useful in reducing fire damage. Prior research indicates that fiber-reinforced geopolymers may endure tremendous temperatures, reaching as high as 1200 °C, without substantial degradation of mechanical integrity or cohesion. This makes them appropriate for structural fire protection in buildings as well as in industrial settings like power plants

Table 1 Summary of studies on fiber-reinforced geopolymer composites

Study	Aluminum silicate/ precursor	Fiber types	Compressive strength	Microstructure	Phase composition	Fiber–matrix interface
Chen et al. [54]	Ground blast furnace slag (GBFS) and low-calcium FA	Steel	104.5 MPa	NR	NR	NR
Alrefaei et al. [55]	Low-calcium Class-F fly ash, ground granulated blast-furnace slag (GGBS),	Steel, Poly-ethylene	56 MPa	Sand addition improves both flexural cracking and ultimate strengths	NR	NR
Baziak et al. [56]	Fly ash and microspheres	Steel, Carbon	18.3 MPa 2 wt.% steel 14.8 Mpa 0% 15.4 MPa 0.5 wt.% Carbon and 1.5 wt.% steel	Fibers are regularly dispersed and coherent with the matrix; CF create agglomeration due to internal structure	NR	Fibers have a smooth surface and are coherent with the matrix
Shah et al. [57]	Fly ash slag-based mortar	Micro-steel, PVA, Basalt	Compressive strength 45 MPa for 1.0% steel fiber, 2.0%PVA	Tiny cracks in case of micro-steel fibers reinforced AAM	NR	NR
Alves et al. [43]	GBFS	Glass	Compressive strength 0.50%: 68.5 MPa at 28 days 0.75%: 74.3 MPa at 28 days 1.00%: 31.1 MPa at 28 days	Multifilament fibers, non-uniformity, and agglomeration of the matrix at high fiber content (1.00%)	NR	NR
Korniejenko et al. [58]	Fly ash	Short glass fibers	Compressive strength 30.00 MPa	Glass fibers can improve the mechanical properties of geopolymer composites	NR	NR
Mat Yaakob et al. [59]	Fly ash	Glass	NR	Porous surface, partially reacted fly ash; glass fibers act as fillers for pores, making the composite denser	NR	Glass fibers act as fillers for pores, improving mechanical properties; specific interface details not provided
Archez et al. [60]	Metakaolin	Glass	NR	Different polycondensation reactions due to reinforcement elements	NR	Glass fibers act as anchoring sites during geopolymerization

Table 1 continued

Study	Aluminum silicate/ precursor	Fiber types	Compressive strength	Microstructure	Phase composition	Fiber–matrix interface
Korniejenko et al. [61]	Metakaolin and fly ash	Glass, Carbon, Aramid	NR	CF did not degrade in the matrix. Glass fibers degraded in fly ash-based matrices but not in metakaolin matrices. Aramid fibers retained ductility but lost cohesion after multiple tests	NR	Glass fibers showed better adhesion in metakaolin matrices compared to CF
Zahid et al. [46]	High-calcium fly ash	PVA (thick and thin), Steel (straight, hooked, recycled tire wires)	Compressive strength was enhanced by up to 18%, Incorporation of PVA fibers reduced it by up to 14% Flexural toughness achieved 21.13 N m	Ns is crucial for enhancing post-crack behavior, while YM significantly improves compressive and flexural strength in FRGCs	NR	NR
Hasan et al. [62]	Low-calcium fly ash	PVA	1.0 and 2.0 wt% NS 24–25%	Denser microstructures in composites with 1.0 and 2.0 wt% nanosilica; less dense with more cracks at 3.0 wt%	NR	Strong bond with PVA fibers at 1.0 and 2.0 wt% nanosilica; poor bonding at 3.0 wt%
Ranjbar et al. [63]	Class F fly ash	Polypropylene	Tensile strength about 310 to 414 MPa	Texture of PPF, microstructure of fly ash based geopolymer, micro cracks, interfacial transition zone	Main crystalline phases are quartz and mullite; no new phases introduced by PPF	Weak contact due to hydrophobic and smooth surface of PPF
Luo et al. [64]	Metakaolin/slag	Polyacrylonitrile (PAN)	Compressive strength values: 99.84 MPa	Non-brittle fractural mode through fiber bridging and pull-out effects	No effect on the phase composition	Fiber bridging and pull-out effects changed fractural behavior from brittle to non-brittle

Table 1 continued

Study	Aluminum silicate/precursor	Fiber types	Compressive strength	Microstructure	Phase composition	Fiber–matrix interface
Meng et al. [65]	Metakaolin	PVA, Carbon Nanotubes (CNTs)	Compressive strength values: 44.7 Mpa—46.4 MPa	Key microstructural observations: Even distribution of CNTs and PVA fibers; CNTs wrapped by geopolymer gel	Phase composition changes: Primarily amorphous material; changes in XRD peak positions	Good bonding interface observed for CNTs
Frydrych et al. [66]	Metakaolin	Flax, Basalt	Compressive strength values: Highest—0.62 MPa (without fibres), Lowest—0.33 MPa (with flax fibres)	Flax fibers are better anchored in the geopolymer matrix due to their rough surface; basalt fibers peel off due to their smooth surface	Cellulose degradation observed in flax-reinforced geopolymers at 260.74 °C	Flax fibers are well-anchored; basalt fibers peel off due to smooth surface
Brugaletta et al. [67]	Fly ash and river sand	CF (CF), Flax fibers (FF)	Compressive strength: 42 MPa	Microcracks in pure geopolymers, random distribution of fibers, fractured CF in hybrid geopolymers	Similar peak patterns for geopolymers and fly ash	Better coherency with flax fibers; instances of fiber fracture and pull-out

and refineries, where fire resistance is essential. The integration of fibers, such as basalt, carbon, glass, and polypropylene, augments fireproofing efficacy by enhancing crack management, diminishing heat penetration, and elevating overall toughness. Notwithstanding these encouraging experimental outcomes, practical applications like spray-on plasters and thick coatings are still little investigated. These applications are crucial for comprehensive building protection, highlighting the necessity for more study to confirm long-term efficacy under actual fire circumstances.

Table 2 summarizes various research that have examined the thermal and mechanical performance of fiber-reinforced geopolymer coatings. Previous research has shown that fiber-reinforced geopolymer systems work well, especially in geopolymer concrete and coating applications. Many studies have proven that adding fibers to geopolymer concrete improves its mechanical properties, such as its ability to resist cracking and its compressive and flexural strength at both normal as well as elevated temperatures. Meanwhile, fiber-reinforced geopolymer coatings are mostly made to enhance adhesion, thermal durability, and resistance to fire when they are used as thin protective layers on underlying structural materials. These outcomes provide significant knowledge about how fibers and substrates interact, how cracks can be bridged, and how materials behave when they are exposed to elevated temperature. This is directly related to the fabrication of geopolymer materials for plastering application, where thin-layer performance and durability are very crucial. However, there aren't many direct studies on fiber-reinforced geopolymer systems that are made specifically for plastering applications, especially when it comes to designing the formulation and testing its performance. This review gathers the fundamental findings based on geopolymer concrete and coating applications and focuses on the potential of new fiber-reinforced geopolymer plastering materials applications. It also emphasizes on closing the gap between the basic performance of the materials and the needs of practical applications. This includes investigating how easy it is to work with, how well it adheres to surfaces, and how stable it is when used in thin layers. The possibility of creating one-part geopolymer plaster systems, also known as just-add-water formulations, is also talked about as a promising way to make them more fire-resistant and easier to use on a larger scale in industry.

The previous research summarized in Table 2 consistently demonstrates that the inclusion of fibers, specifically carbon, basalt, glass, and synthetic polymers like polypropylene, improves the fire resistance of geopolymer composites. Shaikh et al. [79] and Haque [80] indicated that incorporating carbon and basalt fibers markedly diminished cracking and enhanced fire resistance at temperatures reaching 1100 °C. Ye et al. [81] established that geopolymer composites reinforced with glass fiber textiles preserved 25–30% of their flexural strength following fire exposure and sustained structural integrity up to 700 °C. Le et al. [82] noted significant enhancements in strength, with a 123% increase in compressive strength and a 111% increase in flexural strength, as well as over two hours of fire resistance in basalt-reinforced geopolymer foams. Alongside strength retention, studies including Basri et al. [90] and Tatlisu et al. [96] emphasized the significance of robust adhesion, little mass loss, and preserved microstructures, highlighting the essential influence of material composition and fiber–matrix bonding on successful fire resistance. Nonetheless, the majority of current research has concentrated on surface coatings instead of geopolymer-based plastering systems, which are more effective for extensive fire protection in structures. This underscores a notable study deficiency, especially regarding the fire behavior of plaster-like coatings, encompassing their thickness, adherence, and performance under cyclic thermal exposure.

Moreover, Irshidat et al. [86] indicated that polypropylene fibers, although proficient in diminishing heat conductivity, may liquefy at high temperatures, hence jeopardizing matrix integrity. Le et al. [85] established that specific geopolymer systems can maintain stability at temperatures up to 1200 °C; still, these results necessitate verification in full-scale or actual fire conditions. While SEM and XRD investigations have validated excellent fiber–matrix adhesion and reduced microcracks, numerous researches have not evaluated long-term durability, repeated fire exposure, and weathering impacts. Welter [98] reported a compressive strength retention of up to 145 MPa, Lyon et al. [103] noted a 67% retention of flexural strength at 1000 °C, and Petrova et al. [88] recorded fireproof periods over 180 min.

Although plaster-type fireproofing solutions exhibit significant potential for construction applications, their long-term performance remains largely unexamined. Subsequent research must rectify this

Table 2 Mechanical properties, thermal conductivity, and microstructural behavior of fiber-reinforced geopolymer coatings

Study	Alunimosilicate	Substrate	Fiber Type	Test Conditions	Primary Outcomes	Temp. Range	Strength Retention	Thermal Conductivity	Coating Integrity	Protection duration	Failure Mode	Microstructural Changes SEM / XRD
Shaikh et al. [79]	Fly ash, sodium/potassium-based geopolymer	Timber	CF (1.5%), basalt fiber	1100 °C, 10 min fire	Char depth reduction, fewer cracks, improved fireproof properties	1100 °C, 10 min	NR	Lower for potassium-based	Fewer cracks, char depth reduced 35–79%	10 min at 1100 °C	Cracking, char	NR
Haque [80]	Fly ash, nanosilica, fine sand	Timber	CF (1–1.5%), basalt fiber (1%)	200–800 °C, 1100 °C fire	Higher residual strength, lower mass loss, fewer cracks	200–800 °C, 1100 °C	Higher residual compressive (potassium-based, nano silica, CF)	Lower for potassium-based	Fewer cracks, less shrinkage	12–20 min at 1100 °C	Fewer cracks (potassium-based)	Higher amorphous content, CF: compact, low pores
Ye et al. [81]	Sodium/potassium metakaolin geopolymer	n/a	Glass fiber fabrics	ISO 834 fire curve, up to 1000 °C	53–69 min fire resistance, 25–30% flexural strength retention	Up to 1000 °C	25–30% flexural retention	NR	Stable to 700 °C, cracks at dehydration	53–69 min	Cracking at dehydration	Stable to 700 °C, crystallization at 1000 °C
Le et al. [82]	Foam	Aluminum plate	Basalt ground fiber (30%)	Cured at room temperature 105 °C, fire test up to 600 °C	111% flexural, 123% compressive strength increase	Up to 600 °C	111% flexural,123% compressive gain at 85 °C	NR	Stiffened, hardened, no major change at 600 °C	120 min (20 mm)	None at 600 °C	Micropores, fibers intact
Thanh [83]	NR	3 mm panels	CF fabric	Up to 1000 °C	More than 30 min fire rating, shrinkage cracking resistance	Up to 1000 °C	NR	NR	Shrinkage cracking resistance	More than 30 min	Shrinkage cracking	Large pores at 600 °C, oxidized/homogeneous at high temperature
Akarken et al. [84]	Metakaolin geopolymer	n/a	Basalt, glass fiber	200, 400, 800 °C, 1 h at 200 °C	51–76 MPa compressive at 200 °C, stable structure	200, 400, 800 °C	51–76 MPa at 200 °C	NR	Stable structure, no major damage	1 h at 200 °C	None	Stable, fibers prevent cracks
Le et al. [85]	Potassium-metakaolin, foam	Wood/ steel plates	Ground basalt fiber, aluminum powder (foaming)	400–1200 °C	108% compressive, 116% flexural strength increase at 1200 °C, 99–134 min fireproof	400–1200 °C	108% compressive, 116% flexural gain at 1200 °C	0.13–0.14 W/mK	No macroscopic damage	99–134 min	None	Amorphous to crystalline, dense at high temperature
Irshidat et al. [86]	Class F fly ash	n/a	Poly-propylene microfiber (0.05–0.2%)	200, 400, 600 °C	14–15% higher compressive at 200–400 °C, 7% mass loss, reduced thermal conductivity	200, 400, 600 °C	14–15% higher compressive at 200–400 °C,84%/70%/34% retention	Reduced with polypropylene	Microcracks, fibers bridge cracks	NR	Microcracks	Fibers bridge cracks, melt at high temperature
Kanagaraj et al. [87]	High alumina cement	Geo-polymer concrete columns	NR	ISO 834 fire	Residual axial strength, composite coating effective	ISO 834	NR	NR	Residual axial strength improved	NR	NR	NR

Table 2 continued

Study	Alunimosilicate	Substrate	Fiber Type	Test Conditions	Primary Outcomes	Temp. Range	Strength Retention	Thermal Conductivity	Coating Integrity	Protection duration	Failure Mode	Microstructural Changes SEM / XRD
Petrova et al. [88]	Geopolymer fire-insulating mixture	Reinforced concrete substrate	NR	180 min fire	Surface less than 380 °C, armature less than 500 °C, improved integrity	180 min fire	NR	NR	Surface/armature temperature less than 380/500 °C	180 min	None	Fine-pore, glass-like state
Foden et al. [89]	Potassium alumino-silicate	n/a	CF	200–1000 °C, 50 kW/m^2 irradiance	327 MPa tensile, 245 MPa flexural, 63% flexural retention at 800 °C	200–1000 °C	63% flexural at 800 °C	NR	No ignition/ smoke, high retention	Extended	None	NR
Basri et al. [90]	Rice husk ash-based geopolymer	Steel plate	NR	900 °C, 20 min,	29–32% mass loss, strong adhesion, glassy microstructure	900 °C, 20 min	NR	NR	Strong adhesion, glassy gel	20 min at 900 °C	Partial disintegration	Glassy, dense gel, amorphous to crystalline
Kielė et al. [91]	Slag/ phospho-gypsum coating	OPC concrete	Glass fiber-reinforced polymer bars, slag	Up to 1100 °C, 3 h fire	33–47 MPa residual strength, 58–84% retention, improved bond	Up to 1100 °C, 3 h	58.8–83.7% (coated), 57.3% (uncoated)	NR	Improved bond, higher residual strength	3 h	None	Zeolitic, calcium-silicate-hydrate, calcium-alumino-silicate-hydrate, new phases at 1000 °C
Rajendran [92]	Fly ash geopolymer	Ferrocement panels	Steel wire mesh	Up to 900 °C,	46–99% retained strength, 12.9% flexural improvement at 900 °C	Up to 900 °C	46–99% retained strength	NR	12.9% flexural gain at 900 °C	NR	NR	NR
Amir et al. [93]	Intumescent coating	Steel	Hybrid: rock-wool + glass wool	800–1000 °C, 1 h,	197 °C steel temperature, 19–36% residual char, dense char structure	800–1000 °C, 1 h	NR	NR	19–36% residual char, dense char	1 h at 800–1000 °C	None	Dense char, fibers intact, oxygen increased, carbon decreased
Rahman et al. [94]	Fly ash, fumed silica potassium hydroxide activation	n/a	Glass fiber	800–1200 °C,	No deformation/ blistering, solidation up to 250 °C	800–1200 °C	NR	NR	No deformation up to 250 °C	NR	Delamination at 1200 °C	Dynamic mechanical analysis: consolidation up to 250 °C
Temuujin et al. [95]	Class F fly ash, sodium-geopolymer	Steel substrate	None	NR	More than 3.5 MPa adhesive strength, fire resistant	NR	More than 3.5 MPa adhesive	NR	Fire resistant	NR	NR	NR
Tatlisu et al. [96]	Fly ash, metakaolin	Spray on metal	Hollow glass microspheres	300 °C	Adhesion 5.0 MPa	300 °C	NR	0.055 W/mK	High adhesion, stable	NR	NR	NR

Table 2 continued

Study	Alunimosilicate	Substrate	Fiber Type	Test Conditions	Primary Outcomes	Temp. Range	Strength Retention	Thermal Conductivity	Coating Integrity	Protection duration	Failure Mode	Microstructural Changes SEM / XRD
Raza et al. [97]	Geopolymer mortar	n/a	Polyethylene fiber (0–1.5%)	25–800 °C	16–36% compressive gain at 25 °C, pores/ cracks at high temperature	25–800 °C	16–36% compressive gain at 25 °C	NR	Pores/ cracks at high temperature	NR	Pores/cracks at high temperature	Thickening, more pores/ cracks, fiber melt
Welter [98]	Alumina geopolymer	n/a	Basalt, carbon, alumina fiber	Up to 1000 °C	79–145 MPa compressive, 200–470 Pa flexural, basalt stable to 600 °C	Up to 1000 °C	79–145 MPa compressive, 200–470 Mpa flexural	NR	Basalt stable to 600 °C	NR	Basalt: embrittle above 600 °C, CF: degrade at 600 °C	Phase change, bonding, stability
Pei et al. [99]	Vermiculite/ perlite fillers geopolymer composite	Sandwich panel	Basalt fiber mat	800 °C, 3 h	66.5% compressive retention, 0.19 W/mK, low mass loss	800 °C, 3 h	66.5% compressive strength	0.19 W/mK	Low mass loss, good integrity	3 h at 800 °C	NR	NR
Zakaria [100]	Intumescent coating	Steel	Basalt fiber	Bunsen burner, UL 1709	25% temperature reduction, 18.8% char reduction, improved char	Bunsen, UL 1709	NR	NR	25% temperature, 18.8% char reduction	NR	NR	Scanning electron microscopy: fiber condition/ dispersion
Watolla et al. [101]	Intumescent alumino-silicate	Steel	NR	NR	More than 30 min delay to 500 °C (6 mm), ceramic foam	ISO 834	NR	NR	More than 30 min delay to 500 °C	More than 30 min (6 mm)	None	Ceramic/ glass–ceramic foam
Prasad et al. [102]	Geopolymer concrete	n/a	Steel/ polypropylene/ basalt/ hybrid	ISO 834	Geopolymer concrete-basalt fiber: less weight loss, higher residual strength	ISO 834	NR	NR	Geopolymer concrete-basalt fiber: less weight loss, higher strength	NR	NR	Fiber contribution, damage
Lyon et al. [103]	Potassium alumino-silicate	n/a	CF	50 kW/m^2 irradiance	67% flexural retention, no ignition/ smoke	50 kW/m^2	67% flexural retention	NR	No ignition/ smoke	Extended	None	NR

XRD = X-ray diffraction; SEM = Scanning electron microscopy; energy-dispersive analysis of X-rays, n/a = not available, NR = Not Reported deficiency by creating and validating fiber-reinforced geopolymer plasters that exhibit consistent performance under authentic fire circumstances, taking into account application scalability, coating thickness, and fiber stability over prolonged heat exposure. Table 2 summarizes those multiple studies have explored geopolymer coatings on substrates including timber, steel, concrete, and aluminum; however, the use of geopolymer-based plasters for high-temperature fireproofing has not been investigated. Currently, there are no standardized ways to assess the efficacy of geopolymer plasters in safeguarding inside building structures from harm.

Fireproofing properties

Fireproofing qualities denote the capacity of materials to safeguard structures at high temperatures. Efficient fire-resistant materials are engineered to impede or obstruct heat transfer, therefore protecting structures and infrastructure during fire events. These materials must be non-combustible, maintain structural integrity at elevated temperatures, and produce minimum smoke or poisonous gases to guarantee human safety. Furthermore, fireproof coatings and plasters must sustain adhesion to surfaces during fire exposure to ensure ongoing protection. Resistance to cracking, spalling, and shrinkage due to thermal stress is essential to avert premature failure. Geopolymers are frequently utilized as surface-protective materials, including coatings and plasters, providing benefits such as superior mechanical strength, thermal stability, and improved resistance to fire damage.

Microstructure properties

The microstructure of geopolymer coatings is a crucial factor influencing their fire resistance, mechanical strength, and long-term durability. At the microscopic scale, geopolymers consist predominantly of a three-dimensional aluminosilicate framework, referred to as N–A–S–H gel (sodium aluminosilicate hydrate), which is generated when aluminosilicate precursors, such as fly ash or metakaolin, interact with alkaline activators like sodium or potassium hydroxide. The magnitude and quality of this response profoundly affect the ultimate characteristics of the solidified matrix. An essential determinant of performance is the internal arrangement of pores, fibers, and the bonding network. Research indicates that a denser and more homogeneous microstructure is significantly associated with increased strength, diminished heat conductivity, and superior fire resistance [80, 85]. Porosity exhibits a dual effect: Micropores can diminish heat transmission, hence enhancing intumescent fire-protection coatings, yet excessive or uneven porosity may undermine structural integrity, resulting in cracking or water infiltration. Raza et al. [97] indicated that including polyethylene fibers enhanced porosity and microcracking, thus diminishing strength and thermal stability. Regulating pore size and distribution is thus crucial. SEM investigations conducted by Haque [80] and Welter [98] demonstrate that samples characterized by dense gel structures and reduced voids display enhanced thermal performance. When subjected to heat, these well-bonded matrices withstand internal stress and inhibit spalling, a principal failure mechanism in fires. Fiber–matrix adhesion is another critical issue. Robust fiber adhesion connects microcracks, improving toughness and resistance to thermal shock. SEM analyses conducted by Irshidat et al. [86] validated those polypropylene microfibers significantly inhibited crack progression. Welter [98] similarly observed that basalt and alumina fibers maintained their integrity at temperatures up to 600 °C, thereby strengthening the matrix and postponing structural breakdown. At elevated temperatures, fibers like carbon may deteriorate or compromise their mechanical integrity, leading to embrittlement, whereas polymer fibers such as polypropylene may melt, resulting in micro voids that serve as stress concentrators. Thermal exposure also causes chemical and structural changes inside the matrix. Certain geopolymers experience phase transitions from an amorphous to a crystalline form. Ye et al. [81] noted that such changes commenced at 1000 °C, leading to matrix dehydration and possible fracturing. In contrast, Le et al. [85] indicated that heightened densification and crystallization at 1200 °C can improve mechanical integrity, yet may also elevate thermal conductivity, which is unfavorable for insulating materials.

Exposure to fire frequently results in shrinkage and the development of microcracks, especially during swift moisture evaporation. Haque [80] and Thanh [83] established that geopolymer coatings characterized by high amorphous content and uniformly dispersed fibers exhibited enhanced microstructural stability under thermal stress, while systems with inadequate internal cohesion displayed surface cracking and partial degradation [90]. The microstructure of geopolymer coatings is dynamic, developing under thermal stress, with critical parameters, such as porosity, fiber dispersion, bonding strength, and crystallinity, collectively influencing material performance. Notwithstanding these findings, considerable gaps persist in comprehending long-term microstructural activity during fire exposure. This encompasses the resilience of fiber–matrix adhesion during successive thermal cycles, quantitative relationships between microstructural attributes and fire insulation efficacy, the impact of additives and foaming agents on pore structure, and the scalability and reproducibility of laboratory results in practical applications. Future research should employ integrated analytical methodologies, incorporating SEM, XRD, TGA, FTIR, and NMR, to observe structural changes over time and within various thermal conditions. The type of fiber is crucial for performance. Steel and basalt fibers demonstrate robust interfacial adhesion with the matrix, hence improving mechanical strength, durability, and fire resistance, whereas natural fibers like coir offer diminished bonding strength but enhanced environmental sustainability. The incorporation of fiber influences porosity: Optimal fiber loading can occupy micro voids, yielding a denser and more resilient matrix, whereas excessive fiber content, especially with glass or polypropylene, can cause agglomeration, heightened porosity, and diminished composite efficacy. Significantly, the inclusion of fiber generally does not modify the chemical composition of the geopolymer matrix. Certain fibers, like basalt and carbon, may facilitate the evolution of crystalline phases over time; however, no new compounds are generated, hence maintaining the fundamental fire-resistant characteristics of the material.

Thermal conductivity properties

Thermal conductivity is a crucial factor in assessing the efficacy of geopolymer coatings in mitigating heat transfer, crucial for fire-protection applications. Research repeatedly shows that geopolymer coatings possess reduced thermal conductivity compared to traditional cementitious materials, attributable to their amorphous gel matrix and intrinsic porosity, which impede heat transfer. Significantly low thermal conductivity values have been documented, specifically 0.13–0.14 W/m·K for potassium–metakaolin foam coatings [85] and 0.19 W/m·K for basalt-reinforced panels [99], underscoring their exceptional insulating properties.

Discrepancies in testing methodologies, curing environments, fiber selection, and sample dimensions persistently hinder comparability among investigations. Fiber reinforcement can either improve or reduce thermal insulation based on the type of material. Metallic fibers can enhance heat transfer, but non-metallic fibers like polypropylene and basalt typically preserve or enhance insulation when evenly distributed [86, 90]. The effects of temperature are significant: Some coatings undergo matrix densification at elevated temperatures exceeding 1200 °C, potentially enhancing thermal conductivity; nevertheless, extensive post-fire evaluation data are still limited [85]. To enhance thermal performance, researchers have explored foamed and intumescent geopolymer systems that expand when exposed to heat, creating a porous protective layer. Zakaria [100] and Watolla et al. [101] proved their efficacy in decreasing surface temperatures during flame exposure; nonetheless, the long-term durability of char necessitates additional investigation. Microstructural characteristics, especially pore distribution and fiber–matrix adhesion, significantly affect heat transport. SEM investigations conducted by Haque [80] and Welter [98] demonstrate that fine, uniformly distributed porosity diminishes heat conductivity, but flaws resulting from melted fibers might undermine insulation, as noted by Raza et al. [97].

Modifications in mix design, particularly the integration of thermal fillers, facilitate thermal conductivity values between 0.1 and 0.3 W/m·K, as evidenced by Carvalho et al. [104]. The incorporation of lightweight materials like vermiculite and perlite significantly improves insulation, as evidenced by Pei et al. [99], who documented considerable decreases in heat transfer. Fibers, such as polypropylene and basalt, help sustain consistent thermal resistance at high temperatures [12, 47]. Nevertheless, an excessive amount of fiber may lead to increased porosity or agglomeration, adversely impacting performance. A restricted number of research measure thermal conductivity under standardized conditions. Tatlisu et al. [96] documented an extraordinarily low thermal conductivity of 0.055 W/m·K utilizing hollow glass microspheres, although further studies corroborate those additions like microspheres, polystyrene, and foaming agents can markedly diminish conductivity [105, 106]. Le et al. [85]

indicated that formulations containing ground basalt fibers and aluminum powder attained a thermal conductivity of 0.13 W/m·K, while basalt-composite sandwich constructions exhibited a thermal conductivity of 0.19 W/m·K, as reported by Pei et al. [99]. Identified high-temperature failure mechanisms encompass cracking, shrinkage due to dehydration, and fiber degradation; nevertheless, specific basalt-reinforced coatings maintained structural integrity at temperatures above 1000 °C. Existing study deficiencies encompass the absence of defined high-temperature testing methodologies, inadequate comprehension of the effects of fiber type and distribution on insulation, and a scarcity of long-term fire-aging investigations. Subsequent efforts should concentrate on establishing standardized testing protocols, utilizing sophisticated characterization techniques like Laser Flash Analysis and SEM–XRD mapping, and refining mix designs via the regulated application of foaming agents, lightweight aggregates, and fiber systems. Optimizing thermal conductivity is essential for enhancing the fire-resistant properties of fiber-reinforced geopolymer coatings, allowing them to comply with stringent contemporary safety regulations.

Intumescence and fireproofing mechanism

Intumescent coatings are a category of passive fire-protection materials that experience substantial expansion when subjected to high temperatures, generally above 200 °C [107, 108]. Upon thermal exposure, these coatings undergo a chemical reaction that generates a dense, foam-like char layer, serving as both a thermal and physical barrier. This char efficiently insulates and safeguards underlying substrates, such as steel, wood, or plaster, from heat and flames. The principal benefit of intumescent coatings is their self-activation during fire incidents: They expand and create a protective barrier without external assistance, thereby retarding heat transfer and maintaining the structural integrity of essential components like steel beams and concrete elements [109]. The delayed heat penetration is essential for preserving structural integrity, prolonging evacuation duration, and enhancing firefighting efficacy [110]. Without such protection, structural materials, especially steel, can quickly diminish in load-bearing capability during a fire, resulting in premature failure and increased danger to inhabitants and emergency responders [111].

Intumescent plasters are essential in reducing fire damage by limiting direct thermal exposure to structural materials. The creation of a char layer diminishes thermal conductivity and acts as a sacrificial surface, mitigating thermal stress and averting ignition or breakdown of the underlying substrate [109]. These features make intumescent coatings necessary in contemporary construction, where compliance with fire safety regulations and building codes is crucial. The intumescence mechanism encompasses a series of physical and chemical transformations, initiating with softening and melting, succeeded by swelling and charring. This method generates a substantial, carbon-rich char, frequently fortified with gas-entrapping cells, hence improving thermal insulation and structural integrity. Zhang et al. [112] observed that this intumescent char is especially proficient in preserving mechanical performance under fire exposure. Hysek et al. [109] further proved that the use of both traditional and innovative elements, including fiber additions, can enhance the efficacy of intumescent coatings. The incorporation of fibers in fiber-reinforced geopolymer plasters improves fireproofing efficacy by offering mechanical reinforcement to the char layer. Fibers restrict shrinkage, crack propagation, and delamination in response to thermal stress. The integration of these fibers with the intrinsically fire-resistant geopolymer matrix has a synergistic effect, enhancing the protective barrier and augmenting heat retention during fire incidents. The incorporation of fiber reinforcement and intumescent properties markedly enhances the longevity and effectiveness of fire-protective plaster systems.

An essential aspect affecting the efficacy of intumescent coatings is the adherence between the coating and its substrate. Inadequate bonding may lead to early failure or delamination of the protective layer when subjected to fire exposure. SEM investigations [113] demonstrate that augmented surface roughness improves mechanical interlocking and adhesion. SEM enables the evaluation of coating thickness and interface quality, offering critical insights into structural integrity under heat stress [114]. Nonetheless, whereas SEM proficiently elucidates surface morphology and cross-sectional characteristics, it is constrained in its ability to investigate internal microstructural development. In this context, neutron diffraction functions as a potent, non-destructive method for examining the behavior of bulk materials. The ENGIN-X time-of-flight neutron diffractometer at the ISIS spallation neutron source is explicitly developed for materials science applications, encompassing residual stress measurement and phase transition analysis in coatings and engineered materials [115]. This method facilitates real-time observation of fiber-reinforced geopolymer coatings subjected to thermal or fire exposure. In contrast to SEM, neutron diffraction provides unique benefits by elucidating internal stress distributions, phase transitions, and long-term structural alterations inside the matrix. Faisal et al. [115] illustrated its ability to assess internal stresses and phase evolution, whereas Mo et al. [116] emphasized its efficacy in monitoring structural transformations over time and under varying environmental conditions. Advanced characterization techniques are essential for assessing the durability, fire-resistance performance, and long-term reliability of construction materials.

The integration of fibers into geopolymer matrices markedly affects stress distribution inside the material, especially at the interface between the geopolymer matrix and the intumescent layer. This reinforcement reduces cracking and delamination under heat stress, hence improving structural integrity during fire exposure [115, 117]. Advanced characterization techniques offer profound insights into these systems. Figure 6, derived from Nagler et al. [118], illustrates a neutron diffraction apparatus where protons from an accelerator interact with a spallation target to generate neutrons. Neutrons are directed toward the material, where diffraction takes place, and time-of-flight measurements ascertain neutron wavelengths for Bragg scattering. This methodology facilitates accurate structural analysis of fiber-reinforced geopolymer-intumescent systems, documenting internal stress relaxation, phase transitions, and microcrack development under thermal stress.

Neutron diffraction data can be examined using the Rietveld method with dual detector banks to determine elemental and phase compositions in geopolymer systems. The instrumental configuration depicted in Fig. 7 enables the rotation and vertical arrangement of specimens, hence permitting multi-angular and layered investigation. In-situ evaluations accurately replicate fire exposure or thermal cycling, offering comprehensive insights into the development of geopolymer–fiber composites during fire incidents. Although SEM is important in evaluating surface geometry and morphological characteristics [113], neutron diffraction enhances this analysis by revealing interior dynamics such as stress relaxation, phase disintegration, and crack progression over time [119].

In protection and restoration work, it's important to know the difference between plaster and coating. Plasters are used as a base material that provides a structural and protective layer for surfaces. Meanwhile, coatings are put on top to enhance the surface protection layer. Most previous research investigations have indicated intumescent behavior in geopolymer coating

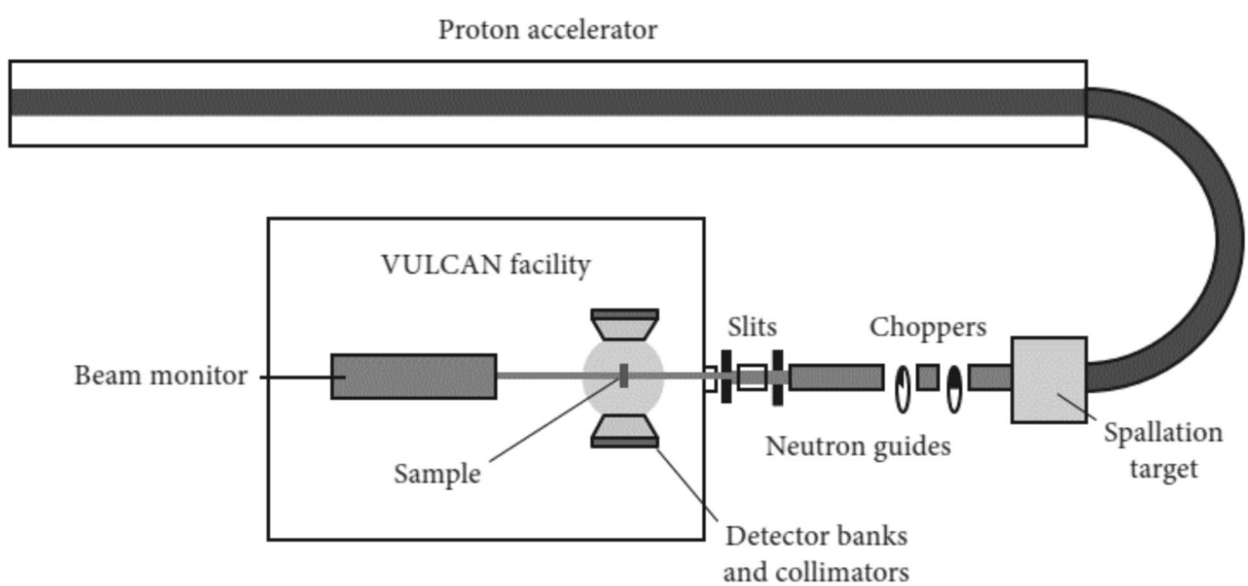


Figure 6 Spallation Neutron Source and VULCAN instrument facility at Oak Ridge National Laboratory (ORNL) [118].

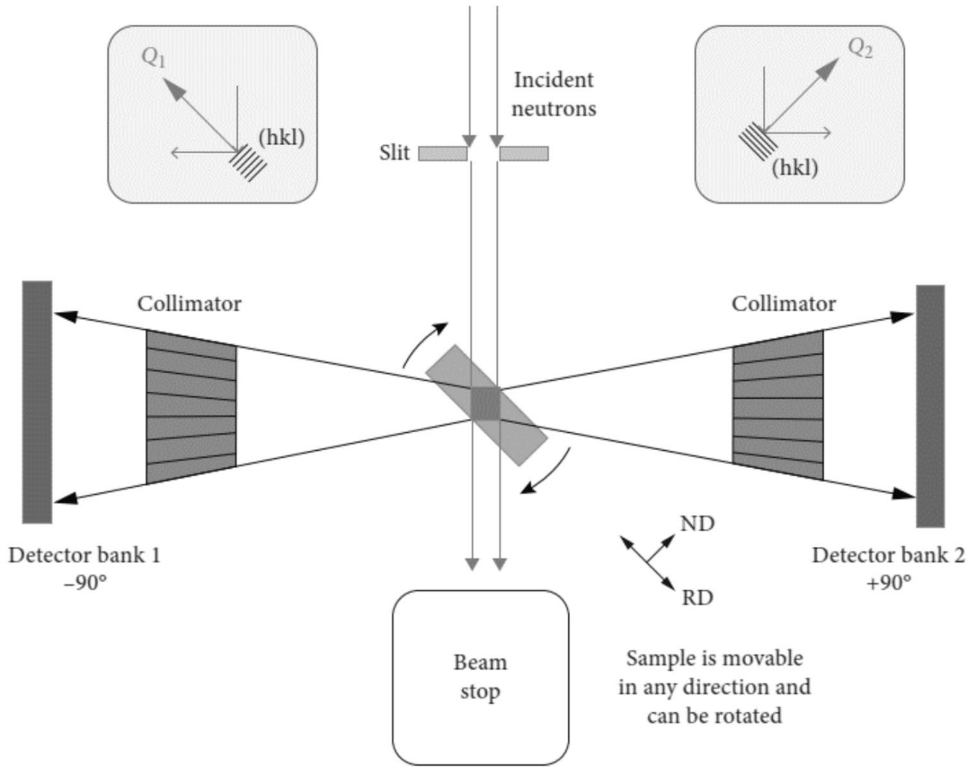


Figure 7 Neutron time-of-flight diffraction technique schematics for pulsed neutron sources [118].

systems, which are generally utilized as thin insulating layers on steel or concrete substrates. These coatings are usually less than 5 mm thick and protect surfaces by forming an insulating char layer when exposed to fire. On the other hand, geopolymer plaster systems employ significantly thicker layers, generally between 10 and 20 mm that aimed to protect both the surface and the internal structure from fire. Because of these differences, plaster systems need to be considered as addition requirement in terms of workability, adhesion, compatibility with the substrate, and stability when exposed to elevated temperature for extended time period. Unlike coatings, plaster not only protects surfaces but also reduces heat transmission to the interior structure. Nonetheless, current literature predominantly emphasizes coating-based systems, and investigations into intumescent behavior within substantial geopolymer plaster materials, especially under real fire exposure conditions are still insufficient. This shows that there is a clear gap in research on how geopolymer plaster systems behave and stay strong when exposed to fire, depending on their thickness.

In conclusion, intumescence serves as an essential fireproofing mechanism that significantly improves the thermal resistance of geopolymer-based plasters. When integrated with fiber reinforcement, these systems demonstrate enhanced mechanical integrity, structural resilience, and fire resistance. Employing advanced analytical techniques, including SEM and neutron diffraction, is crucial for thorough characterization and optimization, facilitating the development of sustainable, high-performance fire-protection plaster materials for modern construction.

Surface protection of fiber-reinforced geopolymer

Fiber-reinforced geopolymers (FRGPs) are gaining recognition for their potential in surface protection applications, especially as fireproof coatings. Multiple investigations, as outlined in preceding sections, have shown that geopolymer coatings offer efficient thermal protection by creating a strong barrier against high temperatures. These coatings provide superior adherence to diverse substrates, such as steel, wood, and concrete, allowing them to maintain integrity under intense temperature stress. Notwithstanding comprehensive investigations into geopolymer coatings, the application of geopolymer-based plasters for surface protection is still inadequately examined. The majority of research has concentrated on thin coatings, resulting in a deficiency in understanding the efficacy of geopolymer plasters. Therefore, additional research is necessary to assess their adhesion strength, structural integrity, and fire resistance effectiveness in practical scenarios.

FRGPs are a highly promising alternative for construction applications owing to their exceptional fire-resistance capabilities. The escalating requirements of severe fire safety laws have rendered the demand for high-performance fireproofing materials essential. FRGPs integrate the inherent thermal and mechanical benefits of geopolymers with the reinforcing characteristics of fibers, offering a holistic passive fire prevention solution. Zhou et al. [120] emphasized the intumescent properties of FRGPs, which efficiently inhibit heat transfer, rendering them ideal for protective coatings on structural elements. The integration of fibers like basalt or glass significantly improves mechanical performance and fire resistance. These fibers serve as thermal stabilizers and crack-bridging agents, reducing thermal deterioration and spalling during exposure to fire. Zhang et al. [39] showed that hybrid fiber reinforcement in geopolymer matrix significantly mitigates explosive spalling, a prevalent failure mode in OPC-based systems.

FRGPs are utilized not only for surface treatments but also for structural elements like wall panels and fire-resistant cladding. These applications amalgamate fire safety with structural advantages, such as less weight, hence enhancing load management efficiency in edifices. Furthermore, numerous FRGPs originate from industrial by-products, offering sustainable choices that bolster green construction activities. Hysek et al. [109] established that geopolymer sandwich composites exhibit superior mechanical stability under elevated temperature stress compared to traditional materials. Likewise, Yang et al. [121] indicated that hybrid fiber-reinforced geopolymer concretes demonstrate improved spalling resistance while maintaining structural integrity under thermal stress. The integration of natural fibers in these systems aligns with environmentally sustainable design principles. Zhang et al. [112] noted that hybrid composites including steel and polyvinyl alcohol (PVA) fibers enhanced fire resistance and mechanical stability, underscoring their significance for high-rise structures and infrastructure subjected to high heat requirements. Le et al. [122] examined geopolymer foams applied to polystyrene boards, demonstrating that these systems can endure elevated temperatures for extended durations while offering efficient thermal insulation. These composite systems provide substantial benefits for both commercial and residential fireproofing applications. Moreover, Ali et al. [123] established that geopolymer concrete facades surpass OPC-based concrete in fire resistance, highlighting the growing significance of geopolymer materials in providing safe, sustainable, and high-performance solutions for contemporary building.

FRGCs are set to significantly impact sustainable construction and innovative materials engineering. The integration of ecological consciousness, performance demands, and material innovation is creating new prospects for these composites across various sectors. Current developments indicate that hybrid geopolymer systems utilizing nano-additives, synthetic fibers, or phase-change materials can significantly improve the thermal, mechanical, and fire-resistant properties of FRGCs. Advancements in multifunctional materials seek to offer adjustable flexibility, enhanced durability, and exceptional fire resistance to satisfy contemporary construction requirements [19, 84]. The incorporation of lightweight aggregates and fillers facilitates the creation of structurally sound, thermally efficient, and visually adaptable elements for walls, ceilings, and façade systems. Additive manufacturing, especially 3D printing, offers a significant opportunity for geopolymer applications. Layered manufacturing enables intricate designs with less material waste and enhanced precision [52]. Optimized fiber-reinforced geopolymer formulations for 3D printing have the potential to transform architectural design by facilitating the creation of bespoke structural components, precast panels, and fire-resistant enclosures. The increasing focus on passive fire protection persists in propelling the advancement of sophisticated fire-retardant plasters and claddings. The elevated temperature resistance of FRGCs, along with their ability to generate insulating char layers while preserving mechanical integrity, renders them ideal for essential infrastructure in fire-prone settings [27, 124]. Moreover, as smart building technologies gain prominence, geopolymer composites may be incorporated with sensor systems to develop intelligent, self-monitoring buildings that may identify temperature anomalies or structural alterations in real time. The amalgamation of superior material science and digital innovation has the capacity to improve safety and resilience in modern construction.

In summary, fiber-reinforced geopolymer plasters exhibit significant potential for fireproofing applications and sustainable construction. Nonetheless, ongoing study is essential to fully actualize their potential. Addressing existing knowledge deficiencies—especially for long-term performance, fiber–matrix compatibility, sustainable formulations, and predictive modeling—will be crucial for the advancement of the discipline. The simultaneous incorporation of developing technologies, such as 3D printing, AI-driven material design, and hybrid composite research, is anticipated to propel future innovation. These innovations will improve the safety and durability of the built environment while furthering global goals for sustainable and resilient infrastructure.

Research gaps, challenges and future works

Fiber-reinforced geopolymer materials have garnered increasing attention as intumescent fireproof plasters due to their sustainability, mechanical strength, thermal stability, and fire resistance. Despite the growing body of research, several critical gaps and challenges must be addressed to enable broader industrial application.

i. Long-term durability and performance: Limited data exist regarding the behavior of fiber-reinforced geopolymer plasters over extended periods and under real environmental conditions, such as temperature fluctuations, moisture, or freeze–thaw cycles. While initial fire resistance is promising, prolonged exposure can weaken fiber–matrix bonding, reducing overall fireproof performance [27, 125]. Future studies should include long-term and environmental testing to assess material degradation and identify strategies to enhance durability for practical use.
ii. Fiber–matrix–substrate interaction: The bonding between fibers, the geopolymer matrix, and the substrate remains insufficiently understood and sometimes inadequate. Variations in fiber type, surface treatment, and geometry can significantly affect adhesion, with weak bonding leading to microcracks, debonding, or fiber pull-out, which compromise both mechanical strength and thermal stability during fire [38, 126]. Systematic studies on different fibers, including carbon, basalt, glass, and natural fibers, and surface treatments such as plasma or sizing agents are needed to optimize compatibility and performance.
iii. Thermomechanical behavior under fire conditions: The response of fiber-reinforced geopolymer plasters to simultaneous high temperatures and mechanical loading, as occurs in real fires, is still not well understood. Differential expansion of fibers and matrix, fiber softening, or degradation can reduce the effectiveness of the fireproof layer [125, 127]. Detailed studies incorporating computational simulations and full-scale fire testing are essential to elucidate these effects and enhance thermomechanical performance.
iv. Standardized testing and benchmarking: Currently, no standardized protocols exist to evaluate the fireproof performance of fiber-reinforced geopolymer plasters. Many fire resistance standards do not consider critical factors such as expansion behavior, thermal insulation, or char layer stability, making inter-study comparisons and industrial readiness assessments difficult [25, 128]. Comprehensive testing methods that replicate realistic fire conditions are needed to provide reliable performance metrics.
v. Interaction with intumescent additives: The compatibility and performance of geopolymer matrices with intumescent additives, such as expandable graphite or ammonium polyphosphate, remain poorly defined. Additives can influence workability, curing, and mechanical strength while affecting char formation and thermal protection [15, 129]. Further research is required to optimize additive integration and maximize fireproofing efficiency.
vi. Environmental impact and life cycle assessment: Although fiber-reinforced geopolymers are promoted as environmentally friendly, few studies quantify their full life cycle impact, including synthesis, curing, usage, and end-of-life disposal. Potential emissions during production and additive leaching remain underexplored [130]. Life cycle assessments and improved mix designs are necessary to reduce environmental footprints.
vii. Toughness and crack resistance: Geopolymers are inherently brittle, and while fibers improve ductility, achieving sufficient toughness under sudden or uneven thermal and mechanical stress remains challenging. Microcracks and

delamination under high stress can compromise both structural integrity and fire resistance [78]. Combining different fiber types and developing advanced geopolymer chemistries may enhance crack resistance and overall toughness.

viii. Adhesion to diverse substrates: The bonding of geopolymer fireproofing plasters to materials such as steel, concrete, or wood is not fully understood. Poor adhesion can lead to plaster detachment or cracking, exposing the underlying substrate to heat and reducing fire protection [15, 130]. Future work should explore primers or specialized formulations to improve adhesion across different surfaces.

In summary, fiber-reinforced geopolymer materials offer considerable potential as eco-friendly, high-performance, intumescent fireproofing solutions. However, key challenges remain, including long-term durability, fiber–matrix interactions, standardized testing, thermomechanical behavior, additive compatibility, environmental impact, toughness, and substrate adhesion. Addressing these gaps through coordinated research, engineering innovation, and industrial collaboration will be essential to transition these materials from laboratory studies to practical, large-scale applications in resilient and sustainable infrastructure.

Conclusion

Fiber-reinforced geopolymer composites signify a notable progression in the creation of sustainable intumescent fireproofing plaster application. These composites exhibit significant enhancements in mechanical performance, thermal insulation, and structural integrity at elevated temperatures, surpassing traditional cementitious methods. The synergistic benefits of fire resistance and environmental sustainability highlight the promise of geopolymer technology as an advanced option for robust infrastructure. Notwithstanding these encouraging characteristics, numerous problems remain. Commercial scalability, the lack of defined testing methodologies, and restricted industrial adoption impede extensive implementation. Furthermore, the long-term performance under realistic fire scenarios and climatic circumstances is still little investigated. It is clearly observed that most existing studies are still focused on geopolymer concrete and coating applications. However, research on geopolymer as plaster material is still very limited, especially in terms of mix design standardization, workability, adhesion, and large-scale application. One important future direction is the development of one-part geopolymer plaster system, that is, just adding water is more practical for construction industry. This type of material can simplify application process and increase industrial acceptance. Several challenges still need to be addressed, including long-term durability, performance under real fire condition, and lack of standard testing methods for plaster system. Therefore, ongoing research is crucial to refine mix compositions, improve durability, and verify fireproofing methods using modern analytical and non-destructive evaluation techniques. Future research should emphasize thorough examinations of the interplay among fiber types, thermal properties, and structural performance, especially during extended or cyclic fire exposure. Bridging these knowledge gaps will enable the transformation of geopolymer-based fireproofing systems from intriguing laboratory concepts to effective, practical solutions for safer and more sustainable built environments.

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Author contributions

Mohd Sabri Mustapa was involved in writing—original draft, writing—review and editing, conceptualization, formal analysis, and literature research investigation. Mohd Mustafa Al Bakri Abdullah contributed to supervision, conceptualization, and writing—review and editing; Rafiza Abd Razak was involved in supervision and writing—review and editing. Zarina Yahya contributed to supervision and validation; Ana

Armada Bras, Thanongsak Imjai, and Petrica Vizureanu were involved in validation and writing—editing. Shayfull Zamree Abd Rahim and Rosnita Mohamed contributed to writing—review.

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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 is not any known competing 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] Wang K, Lin B, Wu B, Yao Y (2024) Repair of ordinary concrete using basalt fiber reinforced geopolymer: high temperature resistance and micro structure evolution of adhesive interface. J Build Eng 97:110712. https://doi.org/10.1016/j.jobe.2024.110712

[2] Qin L et al (2023) Mechanical properties and durability of fiber reinforced geopolymer composites: a review on recent progress. Eng Reports 5(12):1–22. https://doi.org/10.1002/eng2.12708

[3] Chamasemani NF, Kelishadi M, Mostafaei H (2024) Environmental impacts of reinforced concrete buildings: comparing common and sustainable materials : a case study, pp. 1–15

[4] Mohamed R et al (2025) Review: geopolymers for fire protection applications. J Mater Sci 60(40):18678–18709. https://doi.org/10.1007/s10853-025-11496-z

[5] Freire AL et al (2020) Geopolymers produced with fly ash and rice husk ash applied to CO_2 capture. J Clean Prod. https://doi.org/10.1016/j.jclepro.2020.122917

[6] 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

[7] Karakoç MB, Türkmen İ, Maraş MM, Kantarci F, Demirboğa R, Uğur Toprak M (2014) Mechanical properties and setting time of ferrochrome slag based geopolymer paste and mortar. Constr Build Mater 72:283–292. https://doi.org/10.1016/j.conbuildmat.2014.09.021

[8] Unterweger C et al (2020) Impact of fiber length and fiber content on the mechanical properties and electrical conductivity of short carbon fiber reinforced polypropylene composites. Compos Sci Technol 188:107998. https://doi.org/10.1016/j.compscitech.2020.107998

[9] Zhang D, Tu H, Li Y, Weng Y (2022) Effect of fiber content and fiber length on the dynamic compressive properties of strain-hardening ultra-high performance concrete 328. https://doi.org/10.1016/j.conbuildmat.2022.127024.

[10] Xing Z, Li Z, Wang P, Li C, Song Z (2025) Research on the mechanical properties and microstructure of fiber geopolymer mortar. Coatings 15(1239):1–17. https://doi.org/10.3390/coatings15111239

[11] Zhang HY, Kodur V, Cao L, Qi SL (2014) Fiber reinforced geopolymers for fire resistance applications. Procedia Eng 71:153–158. https://doi.org/10.1016/j.proeng.2014.04.022

[12] Rashad AM (2020) Effect of steel fibers on geopolymer properties – the best synopsis for civil engineer. Constr Build Mater 246:118534. https://doi.org/10.1016/j.conbuildmat.2020.118534

[13] Liu Y, Zhang Z, Shi C, Zhu D, Li N, Deng Y (2020) Development of ultra-high performance geopolymer concrete (UHPGC): influence of steel fiber on mechanical properties. Cem Concr Compos. https://doi.org/10.1016/j.cemconcomp.2020.103670

[14] Shahari S, Fathullah M, Abdullah MMAB, Shayfull Z, Mia M, Budi Darmawan VE (2021) Recent developments in fire retardant glass fibre reinforced epoxy composite and geopolymer as a potential fire-retardant material: a review. Constr Build Mater. https://doi.org/10.1016/j.conbuildmat.2021.122246

[15] Wang K, Le H (2023) The development of cement-based, intumescent and geopolymer fire-retardation coatings for metal structures: a review. Coatings 13(3):495. https://doi.org/10.3390/coatings13030495

[16] Gravit M, Dmitriev I, Shcheglov N, Radaev A (2024) Oil and gas structures: forecasting the fire resistance of steel structures with fire protection under hydrocarbon fire conditions. Fire 7(6):173. https://doi.org/10.3390/fire7060173

[17] Łach M, Mierzwiński D, Korniejenko K, Mikuła J (2018) Geopolymer foam as a passive fire protection. MATEC Web Conf 247:00031. https://doi.org/10.1051/matecconf/201824700031

[18] Yong HC, Ming LY, Al Bakri Abdullah MM, Hussin K (2015) Fire resistant properties of geopolymers: a review. Key Eng Mater 660:39–43

[19] Amran M, Huang SS, Debbarma S, Rashid RSM (2021) Fire resistance of geopolymer concrete: a critical review. Constr Build Mater 324(October):2022. https://doi.org/10.1016/j.conbuildmat.2022.126722

[20] Camino G (1998) Flame retardants: intumescent systems, pp. 297–306, https://doi.org/10.1007/978-94-011-5862-6_33.

[21] Calabrese L, Bozzoli F, Bochicchio G, Tessadri B, Rainieri S, Pagliarini G (2014) Thermal characterization of intumescent fire retardant paints. J Phys Conf Ser. https://doi.org/10.1088/1742-6596/547/1/012005

[22] Aziz H, Ahmad F, Yusoff PSMM, Zia-ul-Mustafa M (2015) Fire performance, microstructure and thermal degradation of an epoxy based nano intumescent fire retardant coating for structural applications. AIP Conf Proc. https://doi.org/10.1063/1.4919143

[23] Ji J, Nie J, Zhu H, Han Y, Liu H, Wang X (2024) Experimental analysis of intumescence fireproofing coating on base material of substation frames. Case Stud Therm Eng 64:105478. https://doi.org/10.1016/j.csite.2024.105478

[24] Ge X, Hu X, Shi C (2022) The effect of different types of class F fly ashes on the mechanical properties of geopolymers cured at ambient environment. Cem Concr Compos. https://doi.org/10.1016/j.cemconcomp.2022.104528

[25] A. Fu, B. Ulusoy, H. Ahmadi, H. Wu, and K. Dam-Johansen, "Intumescent Coatings: Comprehensive Advances with a Focus on Inorganic-dominant Systems," *Prog. Org. Coatings*, vol. 199, no. November 2024, p. 108939, Feb. 2025, https://doi.org/10.1016/j.porgcoat.2024.108939.

[26] Fateh T, Benkorichi S, Robinet L, Consalvi JL (2018) Numerical study of the decomposition mechanism of intumescent coating. J Phys Conf Ser 1107(3):4–10. https://doi.org/10.1088/1742-6596/1107/3/032010

[27] R. Alzeebaree, A. O. Mawlod, D. K. Amen, K. H. Younis, and A. Mohammedameen, "Fire Resistance Performance of Fiber Reinforced Geopolymer Concrete: Review," *E3S Web Conf.*, vol. 318, p. 03003, Nov. 2021, https://doi.org/10.1051/e3sconf/202131803003.

[28] R. Mohamed et al., "Heat Evolution of Alkali-Activated Materials: A Review on Influence Factors," *Constr. Build. Mater.*, vol. 314, 2022, https://doi.org/10.1016/j.conbuildmat.2021.125651.

[29] R. Abd Razak et al., "Performance of Sintered Pozzolanic Artificial Aggregates as Coarse Aggregate Replacement in Concrete," *Lect. Notes Civ. Eng.*, vol. 129, no. August, pp. 191–210, 2021, https://doi.org/10.1007/978-981-33-4918-6_10.

[30] J. A. Tchio et al., "Improving Thermal Insulation and Thermal Resistance Properties of Laterite-based Geopolymer Foams by Direct Foaming," *Int. J. Appl. Ceram. Technol.*, vol. 22, no. 2, 2025, https://doi.org/10.1111/ijac.14959.

[31] W. P. Zakka, N. H. Abdul Shukor Lim, and M. Chau Khun, "A Scientometric Review of Geopolymer Concrete," Jan. 20, 2021, Elsevier Ltd. https://doi.org/10.1016/j.jclepro.2020.124353.

[32] Abdullah AF, Abdul-Rahman MBA-D, Al-Attar AA (2024) A review on geopolymer concrete behaviour under elevated temperature influence. J Sustain Sci Manag 19(12):239–259. https://doi.org/10.46754/jssm.2024.12.014

[33] Hassan A, Arif M, Shariq M, Alomayri T, Pereira S (2023) Fire resistance characteristics of geopolymer concrete for environmental sustainability: a review of thermal, mechanical and microstructure properties. Environ Dev Sustain 25(9):8975–9010. https://doi.org/10.1007/s10668-022-02495-0

[34] K. Nazir, O. Canpolat, M. Uysal, A. Niş, and Ö. F. Kuranlı, "Engineering Properties of Different Fiber-Reinforced Metakaolin-red Mud Based Geopolymer Mortars," *Constr. Build. Mater.*, vol. 385, no. January, 2023, https://doi.org/10.1016/j.conbuildmat.2023.131496.

[35] S. Riahi, A. Nemati, A. R. Khodabandeh, and S. Baghshahi, "Investigation of Interfacial and Mechanical Properties of Alumina-coated Steel Fiber Reinforced Geopolymer Composites," *Constr. Build. Mater.*, vol. 288, 2021, https://doi.org/10.1016/j.conbuildmat.2021.123118.

[36] A. B. Moradikhou, A. Esparham, and M. Jamshidi Avanaki, "Physical and Mechanical Properties of Fiber Reinforced Metakaolin-based Geopolymer Concrete," *Constr. Build. Mater.*, vol. 251, 2020, https://doi.org/10.1016/j.conbuildmat.2020.118965.

[37] A. G. Noor Abbas, F. Nora Aznieta Abdul Aziz, K. Abdan, N. Azline Mohd Nasir, and G. Fahim Huseien, "Experimental Evaluation and Statistical Modeling of Kenaf Fiber-Reinforced Geopolymer Concrete," *Constr. Build. Mater.*, vol. 367, no. September 2022, 2023, https://doi.org/10.1016/j.conbuildmat.2022.130228.

[38] Ranjbar N, Zhang M (2019) Fiber-Reinforced Geopolymer Composites: A Review. Cem Concr Compos 107(November):2020. https://doi.org/10.1016/j.cemconcomp.2019.103498

[39] X. Zhang et al., "Thermal Behavior and Mechanism Study of Geopolymers Prepared from Ferronickel Slag with High Fire Resistance," *Constr. Build. Mater.*, vol. 438, 2024, https://doi.org/10.1016/j.conbuildmat.2024.137282.

[40] Yang G, Park M, Park SJ (2019) Recent progresses of fabrication and characterization of fibers-reinforced composites: a review. Compos Commun 14(May):34–42. https://doi.org/10.1016/j.coco.2019.05.004

[41] K. Korniejenko, G. Mucsi, N. Papné Halyag, R. Szabó, D. Mierzwiński, and P. Louda, "Mechanical Properties of Basalt Fiber Reinforced Fly Ash-Based Geopolymer Composites," *KnE Eng.*, vol. 2020, pp. 86–100, Apr. 2020, https://doi.org/10.18502/keg.v5i4.6800.

[42] Asrani NP et al (2019) A feasibility of enhancing the impact resistance of hybrid fibrous geopolymer composites: experiments and modelling. Constr Build Mater 203:56–68. https://doi.org/10.1016/j.conbuildmat.2019.01.072

[43] Alves L, Leklou N, de Souza F, De Barros S (2021) Assessment of the effect of fiber percentage in glass fiber reinforced slag-based geopolymer. J Asian Ceram Soc 9(3):1265–1274. https://doi.org/10.1080/21870764.2021.1966977

[44] Zhang N, Yan C, Li L, Khan M (2021) Assessment of fiber factor for the fracture toughness of polyethylene fiber reinforced geopolymer. Constr Build Mater 319(December):2022. https://doi.org/10.1016/j.conbuildmat.2021.126130

[45] Le VS, Setlak K (2024) Revolutionizing Construction safety with geopolymer composites: unveiling advanced techniques in manufacturing sandwich steel structures using formwork-free

spray technology. Coatings 14(1):146. https://doi.org/10.3390/coatings14010146

[46] Zahid M, Khan MI, Shafiq N, Abbas YM, Khatib JM (2024) Achieving superior mechanical performance in one-part geopolymer composites through innovative hybrid fiber systems of recycled steel and PVA fibers. J Mater Res Technol 32(August):1772–1787. https://doi.org/10.1016/j.jmrt.2024.08.002

[47] Ding C, Xue K, Yi G (2023) Research on fire resistance and economy of basalt fiber insulation mortar. Sci Rep 13(1):1–22. https://doi.org/10.1038/s41598-023-44591-9

[48] Chen K et al (2023) Performance characteristics of micro fiber-reinforced ambient cured one-part geopolymer mortar for repairing. Constr Build Mater 415(December):2024. https://doi.org/10.1016/j.conbuildmat.2024.135086

[49] Arredondo SP et al (2022) Strength, elastic properties and fiber-matrix interaction mechanism in geopolymer composites". Polymers. https://doi.org/10.3390/polym14061248

[50] Pham TM (2025) Fibre-reinforced concrete: state-of-the-art-review on bridging mechanism, mechanical properties, durability, and eco-economic analysis. Case Stud Constr Mater. https://doi.org/10.1016/j.cscm.2025.e04574

[51] Camille C, Hewage DK, Mirza O, Mashiri F, Kirkland B, Clarke T (2020) Post-cracking strength classification of macro-synthetic fibre reinforced concrete for sleeper application, vol. 30, Springer International Publishing, 2021. https://doi.org/10.1007/978-3-030-58482-5_64.

[52] Huang Z, Zhou Y, Salahuddin H (2024) Development and performance evaluation of sustainable lightweight geopolymer based fireproofing coatings for steel construction. Sustain Struct. https://doi.org/10.54113/j.sust.2024.000044

[53] Ahmed T, Bediwy A, Islam MJ (2025) Durable and sustainable nano-modified basalt fiber-reinforced composites for elevated temperature applications. J Build Eng. https://doi.org/10.1016/j.jobe.2025.112865

[54] Chen W et al (2023) Improving mechanical properties of 3d printable 'one-part' geopolymer concrete with steel fiber reinforcement. J Build Eng 75:107077. https://doi.org/10.1016/j.jobe.2023.107077

[55] Alrefaei Y, Dai J-G (2019) Deflection hardening behavior and elastic modulus of one-part hybrid fiber-reinforced geopolymer composites. J Asian Concr Fed 5(2):37–51. https://doi.org/10.18702/acf.2019.12.5.2.37

[56] Baziak A, Pławecka K, Hager I, Castel A, Korniejenko K (2021) Development and characterization of lightweight geopolymer composite reinforced with hybrid carbon and steel fibers. Materials 14(19):5741. https://doi.org/10.3390/ma14195741

[57] Shah SFA, Chen B, Oderji SY, Aminul Haque M, Ahmad MR (2020) Comparative study on the effect of fiber type and content on the performance of one-part alkali-activated mortar. Constr Build Mater 243:118221. https://doi.org/10.1016/j.conbuildmat.2020.118221

[58] Korniejenko K, Mikula JB, Łach M (2015) Characterization of mechanical properties of short glass fiber-reinforced geopolymer composites. [Online]. Available: https://api.semanticscholar.org/CorpusID:136051404

[59] Mat Yaakob S, Sufian S, Rabat NE, Mohd Azizli KA (2019) The microstructural and mechanical properties of glass fiber reinforced geopolymer composites. Malaysian J Microsc 15(1):164–176

[60] Archez J, Texier-Mandoki N, Bourbon X, Caron JF, Rossignol S (2020) Influence of the wollastonite and Glass fibers on geopolymer composites workability and mechanical properties. Constr Build Mater 257:119511. https://doi.org/10.1016/j.conbuildmat.2020.119511

[61] Korniejenko K et al (2021) Mechanical and fracture properties of long fiber reinforced geopolymer composites. Materials (Basel) 14(18):5183. https://doi.org/10.3390/ma14185183

[62] Assaedi H et al (2019) Effect of nanosilica on mechanical properties and microstructure of PVA fiber-reinforced geopolymer composite (PVA-FRGC). Materials 12(21):3624. https://doi.org/10.3390/ma12213624

[63] Ranjbar N et al (2016) A comprehensive study of the polypropylene fiber reinforced fly ash based geopolymer. PLoS ONE. https://doi.org/10.1371/journal.pone.0147546

[64] Luo XC, Wang CA (2016) Effects of short PAN fiber contents on mechanical properties of metakaolin-blast furnace slag based geopolymers. Key Eng Mater 697:608–611. https://doi.org/10.4028/www.scientific.net/KEM.697.608

[65] Meng T, Yang X, Yu Y, Yu H, Huang M (2021) Hybrid effect of PVA fibre and carbon nanotube on the mechanical properties and microstructure of geopolymers. Front Mater 8(November):1–14. https://doi.org/10.3389/fmats.2021.773103

[66] Frydrych M et al (2019) Impact of flax and basalt fibre reinforcement on selected properties of geopolymer composites. Sustainability 12(1):118. https://doi.org/10.3390/su12010118

[67] Brugaletta F et al (2024) The different properties of geopolymer composites reinforced with flax fibers and carbon fibers. Materials (Basel) 17(11):2633. https://doi.org/10.3390/ma17112633

[68] Rengasamy Kannasthan K, Krasnikovs A, Macanovskis A (2023) Ingredients degradation in steel fiber reinforced concrete after thermal loading. Environ Technol Resour Proc Int Sci Pract Conf 3:124–128. https://doi.org/10.17770/etr2023vol3.7228

[69] Maikano HA (2024) Steel fiber reinforced lightweight lytag concrete: an investigation of splitting tensile strength and compressive properties. Brill Eng 5(2):1–6. https://doi.org/10.36937/ben.2024.4933

[70] Zhang T et al (2017) Steel fiber volume fraction and splitting tensile strength of steel fiber reinforced concrete. Ammee 114:5–8. https://doi.org/10.2991/ammee-17.2017.2

[71] Korniejenko K, Łach M, Mikuła J (2021) The influence of short coir, glass and carbon fibers on the properties of composites with geopolymer matrix. Materials (Basel). https://doi.org/10.3390/ma14164599

[72] Feih S, Manatpon K, Mathys Z, Gibson AG, Mouritz AP (2009) Strength degradation of glass fibers at high temperatures. J Mater Sci 44(2):392–400. https://doi.org/10.1007/s10853-008-3140-x

[73] Atkinson FW (1939) Fiber glass - an inorganic insulation. Electr Eng 58(June):277–286. https://doi.org/10.1109/T-AIEE.1939.5057959

[74] Mirza FA, Soroushian P (2002) Effects of alkali-resistant glass fiber reinforcement on crack and temperature resistance of lightweight concrete. Cem Concr Compos 24(2):223–227. https://doi.org/10.1016/S0958-9465(01)00038-5

[75] Zhang M, Jing J, Zhang S (2025) Effect of steel fiber content on fatigue performance of high-strength concrete beams. Sci Rep 15(1):1–14. https://doi.org/10.1038/s41598-025-96217-x

[76] M. Maksum, H. Alrasyid, M. Irmawan, and B. Piscesa, "Effect of Steel Fiber Volume Fraction to the Tensile Splitting Strength of Concrete Cylinder," IOP Conf. Ser. Mater. Sci. Eng., vol. 930, no. 1, 2020, https://doi.org/10.1088/1757-899X/930/1/012058.

[77] Lolla S, Oinam RM, Furtado A, Varum H (2025) Tensile strength and flexural behavior of steel fiber-reinforced

concrete beams. Struct Concr 26(1):501–530. https://doi.org/10.1002/suco.202400074

[78] Samal S (2022) Interface Failure and delamination resistance of fiber-reinforced geopolymer composite by simulation and experimental method. Cem Concr Compos. https://doi.org/10.1016/j.cemconcomp.2022.104420

[79] Uddin Ahmed Shaikh F, Haque S, Sanjayan J (2018) Behavior of fly ash geopolymer as fire resistant coating for timber. J Sustain Cem Mater 8(5):259–274. https://doi.org/10.1080/21650373.2018.1537015

[80] Haque S (2017) Behaviour of fly ash geopolymer containing fillers and fibres at elevated temperatures and its application as fire resistant coating for timber. https://api.semanticscholar.org/CorpusID:139726519

[81] Ye K, Dasari A, Hooper TJN (2023) Structural characterization and fire performance of geopolymer-glass fiber composite panels. Constr Build Mater 400:132633. https://doi.org/10.1016/j.conbuildmat.2023.132633

[82] Le VS, Louda P (2021) Research of curing time and temperature-dependent strengths and fire resistance of geopolymer foam coated on an aluminum plate. Coatings 11(1):87. https://doi.org/10.3390/coatings11010087

[83] Nhan PT (2017) Investigation of mechanical properties and microstructure of various fabric-reinforced geo-composite at elevated temperature. https://dpi-proceedings.com/index.php/dmac/article/view/5235

[84] Akarken G, Cengiz U (2023) Fabrication and characterization of metakaolin-based fiber reinforced fire resistant geopolymer. Appl Clay Sci 232:106786. https://doi.org/10.1016/j.clay.2022.106786

[85] Le VS et al (2020) Study on temperature-dependent properties and fire resistance of metakaolin-based geopolymer foams. Polymers 12(12):2994. https://doi.org/10.3390/polym12122994

[86] Irshidat MR, Al-Nuaimi N, Rabie M (2022) Thermal behavior and post-heating fracture characteristics of polypropylene microfiber-reinforced geopolymer binders. Constr Build Mater 332:127310. https://doi.org/10.1016/j.conbuildmat.2022.127310

[87] Kanagaraj B, Anand N, Raj SR, Jerry R, Lukose J, Lubloy E (2024) Influence of coatings on residual strength of geopolymer concrete columns subjected to fire exposure: an experimental investigation. Case Stud Constr Mater 20:e02990. https://doi.org/10.1016/j.cscm.2024.e02990

[88] Petrova O, Manushkina T, Shevchuk N, Kachanova T (2023) Modern materials for fire protection of reinforced concrete agro-industrial structures. Key Eng Mater 952:105–110. https://doi.org/10.4028/p-Bnrf9F

[89] Foden AJ, Balaguru P, Lyon RE (1996) Mechanical Properties and fire response of geopolymer structural composites. In: International SAMPE symposium and exhibition (proceedings), SAMPE, 1996, pp. 748–758. https://www.osti.gov/biblio/412070.

[90] Mohd Basri MS, Mustapha F, Mazlan N, Ishak MR (2021) Rice-husk-ash-based geopolymer coating: fire-retardant, optimize composition, microstructural, thermal and element characteristics analysis. Polymers 13(21):3747. https://doi.org/10.3390/polym13213747

[91] Kielė A et al (2023) Alkali-activated slag coatings for fire protection of OPC concrete. Materials 16(23):7477. https://doi.org/10.3390/ma16237477

[92] Rajendran M (2023) Parametric investigation on the post-fire flexural behaviour of novel ferrocement panels with geopolymer mortar. Eur J Environ Civ Eng 27(9):2985–3000. https://doi.org/10.1080/19648189.2022.2121765

[93] Amir N, Abd Majid AA, Ahmad F (2016) Effects of Hybrid fibre reinforcement on fire resistance performance and char morphology of intumescent coating. MATEC Web Conf 38(03):03001. https://doi.org/10.1051/matecconf/20163803001

[94] Rahman AS, Shah C, Gupta N Structural evaluation of fly ash based geopolymer composites for high temperature applications. In: American society for composites 2020, Lancaster, PA: DEStech Publications, Inc., Sep. 2020, pp. 1370–1381. https://doi.org/10.12783/asc35/34938.

[95] Temuujin J, Minjigmaa A, Rickard W, Lee M, Williams I, van Riessen A (2010) Fly ash based geopolymer thin coatings on metal substrates and its thermal evaluation. J Hazard Mater 180(1–3):748–752. https://doi.org/10.1016/j.jhazmat.2010.04.121

[96] Tatlisu GC, Aciksari C, Celebi S, Turan S (2022) Developing a Hollow glass microsphere/geopolymer thermal insulation composite for hot metal surface coating. Ceram Int 48(9):11924–11939. https://doi.org/10.1016/j.ceramint.2022.01.042

[97] Raza A, Ahmed B, El Ouni MH, Ghazouani N, Chen W (2024) Microstructural and thermal characterization of polyethylene fiber-reinforced geopolymer composites. J Build Eng 94:109904. https://doi.org/10.1016/j.jobe.2024.109904

[98] Welter M (2013) Unidirectional fibre reinforced geopolymer matrix composites. https://doi.org/10.26686/wgtn.17006011

[99] Pei R, Hua L, Zhao H, Wang X, Li S, Wu Z (2025) Experimental study on mechanical and thermal insulation properties of a geopolymer-based fireproof sandwich panel. Int J Appl Ceram Technol. https://doi.org/10.1111/ijac.14966

[100] Zakaria MZ, Enhancement of strength and fire resistance properties of intumescent coatings by basalt fibre, Mater Sci Eng, 2016, [Online]. Available: https://api.semanticscholar.org/CorpusID:182366574

[101] 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

[102] Vijaya Prasad B et al (2023) Investigation on residual bond strength and microstructure characteristics of fiber-reinforced geopolymer concrete at elevated temperature. Case Stud Constr Mater 19:e02526. https://doi.org/10.1016/j.cscm.2023.e02526

[103] Lyon RE, Balaguru PN, Foden A, Sorathia U, Davidovits J, Davidovics M (1997) Fire-resistant aluminosilicate composites. Fire Mater 21(2):67–73. https://doi.org/10.1002/(SICI)1099-1018(199703)21:2%3c67::AID-FAM596%3e3.0.CO;2-N

[104] de Carvalho AR, Pita RP, de Oliveira TM, Silva GJB, Mendes JC (2025) Exploratory literature review and scientometric analysis of artificial intelligence applied to geopolymeric materials. Eng Appl Artif Intell 145:110210. https://doi.org/10.1016/j.engappai.2025.110210

[105] Duan P, Song L, Yan C, Ren D, Li Z (2017) Novel Thermal insulating and lightweight composites from metakaolin ggeopolymer and polystyrene particles. Ceram Int 43(6):5115–5120. https://doi.org/10.1016/j.ceramint.2017.01.025

[106] Shao N, Zhang Y, Liu Z, Wang D, Zhang Z (2018) Fabrication of hollow microspheres filled fly ash based foam geopolymers with ultra-low thermal conductivity and relative high strength. Constr Build Mater 185:567–573. https://doi.org/10.1016/j.conbuildmat.2018.07.077

[107] Fu A, Ulusoy B, Ahmadi H, Wu H, Dam-Johansen K (2024) Mechanistic study of a silicon-based intumescent coating system. Prog Org Coatings. https://doi.org/10.1016/j.porgcoat.2024.108354

[108] Kang J, Takahashi F, T'ien JS (2018) In situ thermal-conductivity measurements and morphological characterization of intumescent coatings for fire protection. J Fire Sci 36(5):419–437. https://doi.org/10.1177/0734904118794955

[109] Hýsek Š et al (2019) Fire-resistant sandwich-structured composite material based on alternative materials and its physical and mechanical properties. Materials 12(9):1432. https://doi.org/10.3390/ma12091432

[110] Zhang HY, Lv HR, Kodur V, Qi SL (2018) Performance comparison of fiber sheet strengthened rc beams bonded with geopolymer and epoxy resin under ambient and fire conditions. J Struct Fire Eng 9(3):174–188. https://doi.org/10.1108/JSFE-01-2017-0023

[111] Giannopoulou I et al (2023) Novel blast and fire resistant composite materials: design and preliminary results. Lect Not Civil Eng 349(LNCE):888–897. https://doi.org/10.1007/978-3-031-32519-9_88

[112] Zhang P, Feng Z, Guo J, Zheng Y, Yuan P (2024) Mechanical behavior and microscopic damage mechanism of hybrid fiber-reinforced geopolymer cconcrete at elevated temperature. Ceram Int 50(24):53851–53866. https://doi.org/10.1016/j.ceramint.2024.10.238

[113] Yu J, Zhang F, Li X, Li S, Lu Y, Cheng Y (2024) Study on interface adhesion between EP/IFR/HBPSi epoxy intumescent coating and steel substrate. Int J Adhes Adhes. https://doi.org/10.1016/j.ijadhadh.2024.103679

[114] Jesbains K, Faiz A, Y. M. P. S. M, U. Sami, (2011) The Study of Bonding Mechanism of Expandable Graphite based Intumescent. Res J Chem Environ 15(2):401–504

[115] Faisal NH, Ahmed R, Prathuru AK, Paradowska A, Lee TL (2022) Measuring residual strain and stress in thermal spray coatings using neutron diffractometers. Exp Mech 62(3):369–392. https://doi.org/10.1007/s11340-021-00803-9

[116] Mo F et al (2018) Recent progress of residual stress distribution and structural evolution in materials and components by neutron diffraction measurement at RSND. Quantum Beam Sci 2(3):15. https://doi.org/10.3390/qubs2030015

[117] Liu T et al (2020) Neutron diffraction analysis of residual strain in high-pressure die cast A383 engine blocks. J Mater Eng Perform 29(8):5428–5434. https://doi.org/10.1007/s11665-020-05019-x

[118] Nagler SE et al (2019) Time-of-flight neutron diffraction (TOF-ND) analyses of the composition and minting of ancient Judaean 'Biblical' coins. J Anal Methods Chem 2019:1–18. https://doi.org/10.1155/2019/6164058

[119] Wang LL, Wang YC, Li GQ (2013) Experimental study of hydrothermal aging effects on insulative properties of intumescent coating for steel elements. Fire Saf J 55:168–181. https://doi.org/10.1016/j.firesaf.2012.10.004

[120] 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

[121] Yang S, Zhao R, Zeng X, Jia W, Jin H, Li F (2021) Reinforced geopolymer materials with natural fibers: a review. Cailiao Daobao Mater Rep 35(7):7107–7113. https://doi.org/10.11896/cldb.19100048

[122] Le VS et al (2022) Fire resistance of geopolymer foams layered on polystyrene boards. Polymers 14(10):1945. https://doi.org/10.3390/polym14101945

[123] 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. https://doi.org/10.3390/buildings13102444

[124] Subramanian S, Davis R, Thomas BS (2024) Microstructure and residual strength properties of engineered geopolymer composites (EGC) subjected to high temperatures. J Build Eng 96:110637. https://doi.org/10.1016/j.jobe.2024.110637

[125] Zhao J, Trindade ACC, Liebscher M, de Silva FA, Mechtcherine V (2023) A Review of the Role of Elevated Temperatures on the Mechanical Properties of Fiber-Reinforced Geopolymer (FRG) Composites". Cem Concr Compos 137(2022):104885. https://doi.org/10.1016/j.cemconcomp.2022.104885

[126] Mishra J, Panigrahi R (2020) Mini-review on structural performance of fiber reinforced geopolymer concrete. Int J Innov Technol Interdiscip Sci 3(2):435–442. https://doi.org/10.15157/IJITIS.2020.3.2.435-442

[127] Fahim TA, Emon RA, Al Kafi A, Nath PD, Debnath AK, Hasib MA (2025) Recent advances in fiber-reinforced geopolymer composites : a systematic review of optimization strategies. Next Res 2(4):100955. https://doi.org/10.1016/j.nexres.2025.100955

[128] Puri RG, Khanna AS (2017) Intumescent coatings: a review on recent progress. J Coatings Technol Res 14(1):1–20. https://doi.org/10.1007/s11998-016-9815-3

[129] Zhan W et al (2024) Research progress of Carbon-based materials in intumescent fire-retardant coatings: a review. Eur Polym J. https://doi.org/10.1016/j.eurpolymj.2024.113486

[130] Samal S, Blanco I (2021) An application review of fiber-reinforced. Fibers 9(4):1–21. https://doi.org/10.3390/fib9040023