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Geopolymer And Rubberized Cementitious Materials For Fire Protection Of FRP Strengthening Systems: A Review

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Abstract: Fiber-reinforced polymer (FRP) strengthening systems are highly vulnerable to elevated temperatures and fire exposure, which can lead to rapid degradation of their mechanical and bonding performance. Consequently, effective fire-protective solutions are essential to ensure the safety of FRP-strengthened reinforced concrete structures. This review critically examines geopolymer-based and rubberized cementitious materials as protective systems for FRP applications under elevated temperatures. The paper synthesizes recent studies addressing thermal behaviour, damage mechanisms, residual mechanical performance, and mitigation strategies. Geopolymer materials demonstrate superior fire resistance, reduced spalling tendency, and higher post-fire strength retention compared to conventional OPC-based systems, attributed to their stable aluminosilicate network. Rubberized mortars and concrete, in contrast, provide enhanced thermal insulation, deformation capacity, and resistance to explosive spalling due to controlled rubber degradation; however, with reduced mechanical strength at high temperatures. Hybrid systems incorporating fibers or surface-modified rubber show promising potential by balancing thermal protection and mechanical integrity. The review highlights the complementary roles of geopolymer and rubberized cementitious materials as effective fire-protective layers for FRP-strengthened concrete members.

Keywords: Geopolymer, Crumb Rubber, Fire Protection, Elevated Temperature, FRP Strengthening.

1. INTRODUCTION

The production of ordinary Portland cement (OPC), the primary binder used in conventional concrete, is a major contributor to global environmental concerns, accounting for approximately 5–8% of global anthropogenic CO_2 emissions due to limestone calcination and fossil fuel consumption during clinker production [1–8]. These environmental drawbacks, coupled with resource depletion and ecosystem disruption caused by raw material extraction, have motivated extensive research into alternative and more sustainable cementitious materials [1,3–6,8–12].

In this context, geopolymer materials have emerged as a promising alternative to OPC-based binders. Synthesized from aluminosilicate-rich industrial by-products such as fly ash, ground granulated blast furnace slag, and metakaolin, geopolymers reduce the demand for virgin raw materials while diverting industrial waste from landfills [13–15]. Beyond their environmental benefits, geopolymer binders often exhibit refined microstructures and favorable mechanical and durability properties, including high compressive strength, low permeability [3–5,11,16]. Also, several studies asserted their superior resistance to fire and elevated temperatures, making them attractive for applications requiring enhanced thermal stability [8,16].

Parallel to the development of alternative binders, the construction industry has increasingly explored the utilization of waste-derived aggregates, particularly recycled tire rubber, as partial replacements for natural sand. The use of recycled rubber provides substantial environmental benefits by reducing landfill accumulation while conserving natural aggregate resources [17,18,27–34,19–26]. From a performance perspective, rubberized cementitious composites exhibit enhanced ductility, energy absorption capacity, reduced density, and significantly lower thermal conductivity compared to conventional materials [17–22,26,28,35]. However, the incorporation of rubber particles is generally associated with a reduction in mechanical strength due to their low elastic modulus and weak interfacial bonding with the cementitious matrix.

Given the increasing use of fiber-reinforced polymer (FRP) systems for strengthening reinforced concrete structures and their vulnerability to elevated temperatures, the development of effective fire-protective layers has become critical. In this regard, geopolymer and rubberized cementitious materials offer complementary characteristics as protective systems, combining thermal resistance, insulation capacity, and controlled damage behaviour. Therefore, this review paper aims to critically assess the performance of geopolymer-based and rubberized cementitious materials under elevated temperatures, with a focus on their suitability as fire-protective systems for FRP-strengthened reinforced concrete members.

2. BEHAVIOUR OF GEOPOLYMER SYSTEMS WHEN SUBJECTED TO ELEVATED TEMPERATURE

2.1 General

Geopolymer binders often exhibit a dense and refined microstructure along with favorable mechanical and durability properties, including high compressive strength, low permeability, and superior resistance to chemical attack [3–5,11,16]. These characteristics make geopolymer concrete and mortars suitable for a wide range of structural and repair applications. In recent years, particular attention has been directed toward their behaviour under elevated temperatures due to their potential use in fire-resistant and protective systems.

2.2 Resistance of Geopolymer Concrete (GPC) Against Elevated Temperature

Numerous studies have consistently demonstrated that geopolymer concrete (GPC) exhibits superior resistance to elevated temperatures when compared to ordinary Portland cement concrete (OPCC) [5,6,8,16,17,36–40]. Owing to its three-dimensional aluminosilicate network, GPC is capable of retaining a significant portion of its mechanical strength after exposure to high temperatures [8,17]. In addition, GPC is generally less susceptible to explosive spalling and does not emit toxic fumes during fire exposure, making it a safer material under fire conditions [8,16,17,36,40]. The enhanced thermal stability of GPC has been attributed to its lower content of physically and chemically bound water, as well as its interconnected pore structure, which facilitates vapor transport and alleviates internal pore pressure at elevated temperatures [36,41].

The influence of precursor composition on the high-temperature performance of geopolymer systems has been widely investigated. Studies on slag-based binders have shown that increasing slag replacement levels (ranging from 5 % to 100 %) enhances both elevated-temperature resistance and cracking resistance, owing to the formation of a denser and more thermally stable matrix [37]. Similarly, investigations on geopolymer mortars incorporating fly ash (FA), ground granulated blast furnace slag (GBFS), and calcined clay (CC), with the addition of silica fume, revealed that silica fume improves compressive strength by accelerating geopolymerization and reducing porosity [40]. GBFS-based mortars exhibited the highest residual strength at temperatures up to 600 °C, whereas FA-based systems supplemented with silica fume demonstrated superior strength retention at 800–1000 °C due to their more porous, ceramic-like microstructure that allows effective vapor release. Although surface cracking intensified at higher temperatures, no explosive spalling was observed [40]. In contrast, other studies reported that slag-based GPC and OPCC may exhibit comparable mechanical degradation when exposed to temperatures between 400 °C and 800 °C, highlighting the binder chemistry in governing thermal performance [42].

Activator chemistry has also been shown to significantly influence the fire resistance of geopolymer materials. Potassium-based alkaline activators were reported to impart higher thermal stability and fire resistance compared to sodium-based systems, primarily due to the formation of more thermally stable gel phases [5,8]. At moderate temperatures (≤ 400 °C), fly ash-based geopolymers often exhibit an increase in compressive strength, which has been attributed to thermally induced dissolution of unreacted fly ash particles and subsequent secondary geopolymerization, leading to matrix densification and pore refinement [8].

Furthermore, geopolymers generally possess relatively low thermal conductivity compared to conventional building materials, enhancing their potential use as insulating and fire-protective layers. In this regard, fly ash-based GPC has been reported to exhibit superior thermal insulation performance compared to metakaolin-based systems [16].

2.3 Damage Mechanisms and Failure Modes of Geopolymer Concrete at Elevated Temperatures

The thermal response of geopolymer materials is governed by a series of microstructural and phase transformations that directly influence their damage mechanisms and failure modes. Exposure to moderate temperatures (up to approximately 400 °C) promotes the release of reactive species from partially unreacted fly ash particles, leading to secondary geopolymerization. This thermally activated process results in matrix densification and, in some cases, an increase in mechanical strength [8]. At temperatures exceeding 400 °C, progressive decomposition of the geopolymeric gel is observed, accompanied by an increase in porosity due to moisture loss and structural rearrangement. Further heating beyond 600 °C induces the formation of crystalline phases such as quartz, nepheline, and plagioclase within the geopolymer matrix. While the development of certain crystalline phases, particularly nepheline, may contribute to improved thermal stability, excessive crystallization and viscous sintering can lead to volumetric shrinkage, microcracking, and degradation of mechanical properties [8]. These mechanisms ultimately govern the transition from strength retention to strength loss at elevated temperatures.

In contrast to ordinary Portland cement concrete, fly ash-based geopolymer systems exhibit excellent resistance to explosive spalling when subjected to high temperatures. This behaviour is primarily attributed to their interconnected pore structure, which facilitates vapor transport and pressure release during heating, thereby preventing sudden internal stress buildup. Additionally, the relatively low thermal conductivity of geopolymer materials enhances their insulating capability, reducing heat penetration and delaying thermal damage under fire exposure [8]. A schematic representation illustrating the evolution of geopolymer performance across different temperature ranges is presented in Fig. 1.

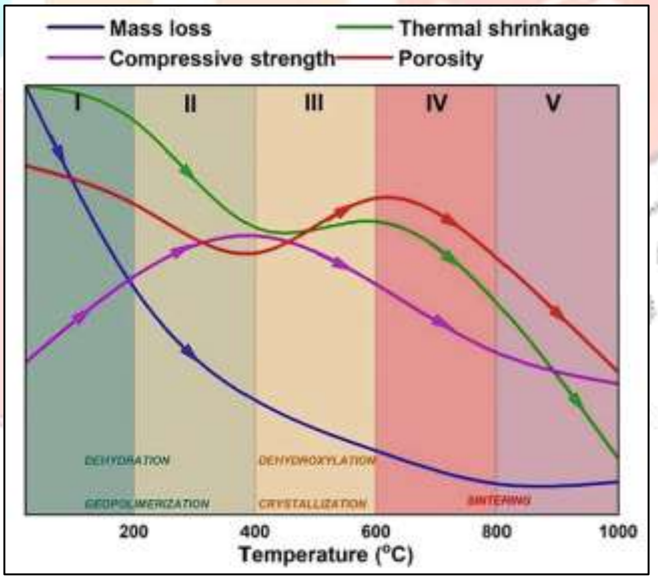

Figure 1: Schematic Diagram Illustrating the Performance of Fly ash-Based Geopolymer at High Temperatures [8]

2.4 Residual Mechanical Strength of Geopolymer Concrete after Elevated Temperature Exposure

Numerous studies have confirmed that geopolymer concrete (GPC) retains significantly higher residual compressive strength than ordinary Portland cement concrete (OPCC) after exposure to elevated temperatures [5,6,16,38,43,44]. This enhanced post-fire performance is primarily attributed to the stable aluminosilicate network and the absence of decomposition reactions typically associated with calcium hydroxide in OPC-based systems. In addition to compressive strength retention, the residual bond strength between steel reinforcement and fly ash- or metakaolin-based GPC has been reported to be comparable to, or even higher than, that of OPCC with similar initial compressive strength [36]. This finding highlights the favourable post-fire interaction between GPC and embedded reinforcement.

However, the residual strength performance of GPC is strongly influenced by its precursor composition. For instance, investigations on slag-based GPC revealed no significant difference in residual compressive strength compared to OPCC after high-temperature exposure, as both materials exhibited similar microstructural characteristics and degradation mechanisms [36]. In these systems, a pronounced reduction in strength was observed once temperatures exceeded 400 °C. A key distinction, however, was the absence of explosive spalling in GPC specimens, whereas high-strength OPCC (70 MPa) exhibited severe spalling when exposed to temperatures up to 800 °C. Furthermore, it has been reported that the residual strength of both GPC and OPCC decreases with increasing exposure temperature and higher original concrete grade, indicating greater thermal vulnerability of high-strength matrices [45].

At the structural level, studies on fire-exposed reinforced panels demonstrated that steel-reinforced GPC elements retained superior load-carrying capacity compared to OPCC counterparts. In particular, GPC panels exhibited approximately 10–20 % higher residual load-bearing capacity than OPCC panels after exposure to temperatures as high as 960 °C [46] as shown in Fig. 2. This improved performance was attributed to the denser and more homogeneous microstructure of GPC, which promotes more uniform heat transfer and reduces temperature gradients between the surface and the core. Consequently, lower thermal stress concentrations develop, leading to reduced cracking, delayed stiffness degradation, and the absence of spalling.

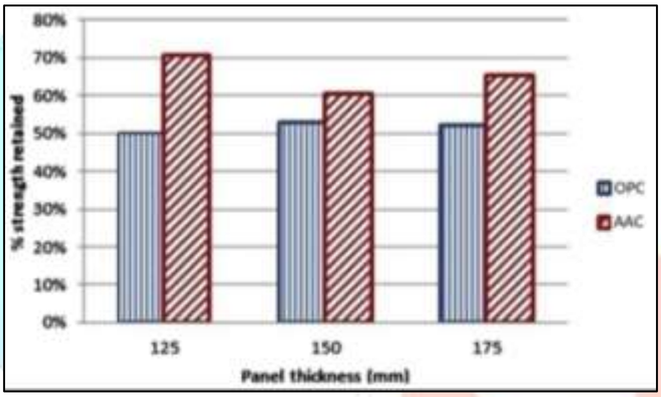

Figure 2: Residual Strength for Both GPC and OPCC Panels [46]

2.5 Mitigation Approaches for Enhancing the High-Temperature Performance of Geopolymer Systems

Various mitigation strategies have been proposed to enhance the thermal stability and fire resistance of geopolymer concrete (GPC), primarily focusing on microstructural control, crack mitigation, and heat-transfer reduction. Among these approaches, the incorporation of fibers has been widely recognized as an effective means to improve high-temperature performance. Previous studies have demonstrated that fiber reinforcement limits crack propagation and, upon melting, creates interconnected channels that facilitate the release of internal vapor pressure, thereby reducing the risk of spalling [16]. In addition, the inclusion of nano- or micro-scale silica has been reported to further enhance thermal resistance by refining pore structure and promoting geopolymerization [16].

The effectiveness of fiber-reinforced geopolymer composites has been confirmed across a range of fiber types and dosages. Experimental investigations on fire-resistant fiber-reinforced geopolymer composites incorporating basalt and glass fibers (0.5, 1, and 2 %) showed that increasing fiber content significantly mitigated surface cracking after exposure to temperatures up to 800 °C, while maintaining compressive strength at moderate temperatures (≤ 200 °C) [47]. Similar trends were observed in fly ash-based geopolymer mortars reinforced with glass and basalt fibers, where the fiber bridging effect improved residual compressive and flexural strength after exposure to temperatures up to 800 °C, despite a reduction in fresh-state workability [39].

More recently, rubber-based mitigation approaches have gained increasing attention due to their combined mechanical damping and thermal insulation capabilities. Studies on rubberized geopolymer mortars reported that partial replacement of fine aggregates with rubber particles enhanced crack resistance and high-temperature deformation behaviour, particularly when fine rubber particles are used [17]. At temperatures below 400 °C, the presence of rubber particles contributed positively to residual strength, whereas exposure to temperatures exceeding 600 °C resulted in significant strength degradation due to rubber decomposition. These findings highlight the importance of rubber particle size and exposure temperature in governing post-fire performance [17].

Investigations on geopolymer mortars incorporating high volumes of crumb rubber further demonstrated that, although mechanical strength is substantially reduced, rubber inclusion significantly improved ductility, failure behaviour, and thermal insulation properties [48]. In particular, complete replacement of river sand with crumb rubber resulted in notable reductions in density and thermal conductivity, by approximately 42 % and 79 %, respectively, indicating strong potential for fire-protective and insulating applications [48]. Complementary studies combining crumb rubber with polypropylene fibers confirmed that rubber content plays a dominant role in reducing thermal conductivity and diffusivity, while fibers mainly influence crack control and failure mode [18]. Similarly, the incorporation of alternative low-conductivity fillers such as auto glass waste has been shown to provide exceptional high-temperature strength retention and low thermal conductivity, classifying geopolymer mortars with high replacement levels as effective fire-resistant and insulating materials [49].

3. USE OF RUBBERIZED MORTARS AS PROTECTIVE SYSTEMS FOR FRP STRENGTHENED STRUCTURES

3.1 General

The incorporation of rubber particles into cementitious composites significantly alters their mechanical and physical behaviour. Acting as micro-cushioning inclusions, rubber particles enhance deformation capacity, improve fracture toughness, and increase resistance to cyclic loading. However, these benefits are typically accompanied by reductions in compressive strength and elastic modulus, particularly at higher replacement ratios. Consequently, rubberized mortars and concrete are primarily considered for non-structural or protective applications where energy dissipation, crack control, and thermal insulation are of primary importance.

3.2 Influence of Crumb Rubber on Fresh-State Properties of Cementitious Composites

The incorporation of crumb rubber (CR) as a partial replacement for fine aggregates has been widely reported to influence the fresh properties of cement mortars and concrete, with the observed effects strongly dependent on rubber content, particle characteristics, and surface condition. Several studies have shown that the inclusion of untreated crumb rubber generally increases water demand to achieve a target consistency, owing to the hydrophobic nature and low density of rubber particles [22]. This behaviour is commonly accompanied by a reduction in fresh bulk density, improved water retention, and an increase in entrapped air content within the matrix [22,24].

Conflicting trends have been reported regarding workability. While some studies observed a reduction in slump and an increase in Vebe time with increasing rubber content -attributed to particle floating, segregation tendency, and poor wettability of rubber particles [24]- others reported improved workability and mixture cohesiveness at low replacement levels (≤ 5 % by volume). This improvement has been associated with enhanced particle packing and lubrication effects within the fresh mix [23]. These contrasting observations highlight the sensitivity of fresh-state behaviour to rubber dosage, aggregate gradation, and mix design parameters.

Surface modification of crumb rubber as shown in Fig. 3 & Fig. 4, has been identified as an effective strategy to mitigate the adverse effects of rubber incorporation on fresh properties. Untreated rubber particles typically exhibit a high water contact angle (≈ 134°), leading to poor dispersion and non-uniform distribution within the fresh matrix [26]. In contrast, surface treatments such as polydopamine (PDA) coating significantly enhance rubber hydrophilicity, reducing the contact angle to approximately 73° and improving rubber–cement paste compatibility during mixing [26]. Similar improvements in workability and fresh-state homogeneity were reported for concretes incorporating surface-modified crumb rubber, where reduced porosity and fewer internal defects were observed compared to mixes containing untreated rubber particles [50].

Overall, the available literature indicates that while the inclusion of crumb rubber can negatively affect certain fresh properties -particularly at high replacement levels- the adverse effects can be effectively alleviated through optimized rubber content, appropriate particle size selection, and surface modification techniques.

Figure 3: Process of Crumb Rubber Surface Modification [26]

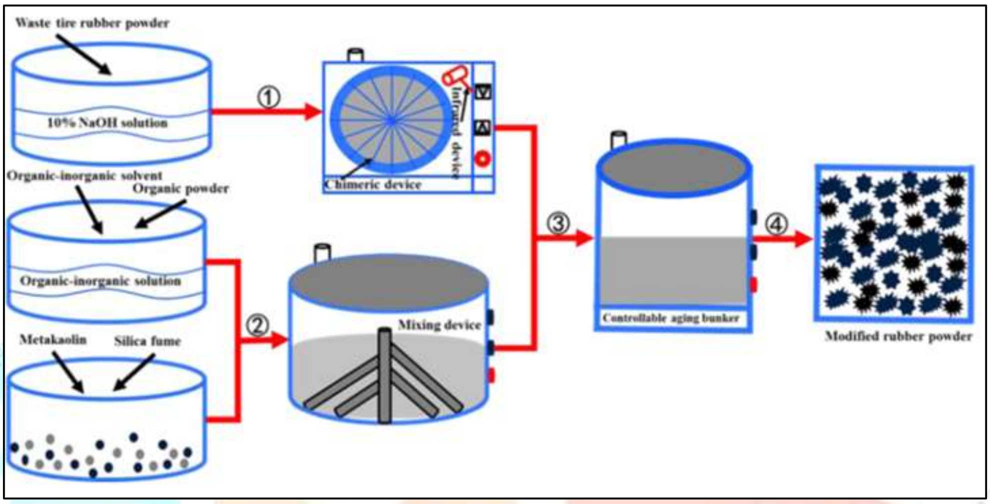

Figure 4: Steps of Modification of Rubber Particles [50]

3.3 Effect of Rubber Incorporation on the Mechanical Properties of Cementitious Composites

The incorporation of crumb rubber (CR) as a partial replacement for fine aggregates has been widely reported to influence the mechanical performance of cement mortars and concrete, with the magnitude of the effect strongly dependent on replacement level, rubber treatment, and the presence of supplementary reinforcement. In general, increasing rubber content leads to a reduction in compressive strength, elastic modulus, and tensile strength, primarily due to the low stiffness of rubber particles, increased porosity, and the formation of a weak interfacial transition zone (ITZ) between rubber particles and the cementitious matrix [22–24,26].

Several studies have shown that mechanical performance can be preserved at low replacement levels. For instance, flexural strength was maintained at crumb rubber contents up to approximately 4%, while compressive strength and dynamic modulus were preserved only at lower replacement ratios (≤ 2%) [22]. Similarly, replacement levels in the range of 3–5% were reported to provide an optimal balance between fresh-state performance and hardened mechanical properties, limiting strength degradation while benefiting from reduced density and improved ductility [23]. In this regard, it was further reported that the incorporation of crumbed tyre rubber at volume fractions up to 5% results in negligible changes in the ultimate strength and elastic modulus of concrete, indicating that low rubber contents can be accommodated without compromising structural performance [51]. Beyond these thresholds, mechanical properties deteriorate progressively with increasing rubber content [24].

The degradation in mechanical performance has been consistently attributed to increased air void content, higher total porosity, and poor rubber–cement bonding, which promote stress concentration and premature crack initiation under loading [24,25]. Nevertheless, several mitigation strategies have proven effective in alleviating strength loss. The incorporation of fiber reinforcement, particularly natural fibers such as coconut fibers and hybrid fiber systems, significantly improved crack-bridging capacity and reduced strength deterioration in rubberized mortars and concretes [25]. In addition, surface modification of rubber particles has been shown to markedly enhance mechanical performance. Polydopamine-treated rubber reduced porosity, refined pore size distribution, and eliminated interfacial gaps, resulting in substantial improvements in compressive and flexural strength compared to mixes containing untreated rubber [26].

Beyond conventional strength metrics, rubberized cementitious composites have demonstrated enhanced durability-related performance when rubber particles are properly modified. Studies comparing crumb rubber concrete (CRC) and modified crumb rubber concrete (MCRC) reported significant improvements in freeze–thaw resistance, chloride penetration resistance, and carbonation performance for MCRC, with modified rubber particles acting as elastomeric stress-regulating inclusions within the concrete matrix [50]. These findings highlight that, although rubber incorporation generally compromises strength, appropriate mixture optimization, surface treatment, and hybrid reinforcement strategies can effectively balance mechanical performance with enhanced durability, ductility, and thermal functionality.

3.4 Behaviour of Rubberized Cementitious Composites under Elevated Temperatures

The behaviour of rubberized mortars and concrete under elevated temperatures has been extensively investigated, particularly in terms of thermal insulation efficiency, residual mechanical performance, and resistance to fire-induced damage. Several studies have confirmed that the incorporation of crumb rubber significantly enhances the thermal insulation capacity of cementitious composites. For instance, rubberized rendering mortars exhibited reductions in thermal conductivity of up to 57% at rubber contents of 6%, while maintaining inherent non-combustibility [22]. However, intermediate replacement levels (2–4%) were reported to provide the most balanced performance, offering effective crack control and deformation capacity while maintaining sufficient bond strength to meet technical requirements [22].

Despite these thermal advantages, rubber incorporation generally leads to increased strength degradation at elevated temperatures. Studies on rubberized geopolymer concrete reported a higher percentage of compressive strength loss compared to reference mixes at all temperature levels [19]. At temperatures exceeding 600 °C, limited strength recovery was observed due to the polymerization of unreacted crystalline phases; however, this effect was less pronounced in rubberized systems owing to rubber decomposition, which generated additional voids and elevated internal pore pressure, thereby promoting cracking [16,22]. At 800 °C, rubberized specimens typically developed hairline cracks associated with moisture loss, evaporation, and degradation of the binder's chemical structure [16].

A key advantage of rubberized composites under fire exposure is their enhanced resistance to explosive spalling. The thermal degradation and volatilization of rubber particles create interconnected pressure-relief pathways, facilitating the escape of internal water vapor and significantly reducing the risk of sudden spalling [17,52]. The use of fine rubber particles was shown to further improve residual resistance to thermal cracking and deformation, particularly at temperatures above 400 °C [17]. While rubber inclusion generally increased total mass loss, the associated reduction in spalling risk represents a critical safety benefit under fire conditions. Below 400 °C, rubberized mortars often exhibited improved residual strength, whereas exposure beyond 600 °C resulted in pronounced internal degradation driven by microcrack expansion and pore coalescence [17]. These internal damage mechanisms can be effectively monitored using ultrasonic pulse velocity (UPV) measurements, which serve as a reliable indirect indicator of mass loss and strength degradation.

Hybrid mitigation strategies combining rubber particles with fiber reinforcement have demonstrated particularly promising performance at elevated temperatures. Rubberized geopolymer mortars incorporating polypropylene fibers exhibited enhanced toughness, crack resistance, and deformation capacity under combined mechanical and thermal loading [18]. Notably, the synergistic use of crumb rubber (≈20%) and fibers (≈1%) increased flexural toughness by up to 27.5% compared to fiber-only systems, while significantly improving thermal insulation through reductions in thermal conductivity and diffusivity of approximately 40% and 50%, respectively [18]. Similar trends were observed in OPC-based rubberized concrete incorporating steel fibers, where improvements in toughness and splitting resistance under high temperatures were consistent with previously reported findings [29]. Nevertheless, post-fire assessments generally indicated reduced compressive and splitting strength in rubberized concrete compared to reference mixes, although overall thermal performance remained comparable [20].

Overall, the available literature indicates that rubberized mortars and concrete exhibit a distinctive thermal response characterized by improved insulation performance and enhanced resistance to explosive spalling, albeit at the expense of reduced mechanical strength at high temperatures. These characteristics make rubberized cementitious composites particularly attractive for fire-protective and energy-dissipating applications, especially when combined with fiber reinforcement or used as sacrificial protective layers. A summary of key studies investigating the behaviour of rubberized mortars and concrete under elevated temperatures is presented in Table 1.

Table 1: Studies Reported Behaviour of Rubberized Composites Subjected to Elevated Temperature.

Ref.	Composite type	Rubber particle size	Replacement ratio	Elevated temperature	Measurements	Main findings
[19]	Fly ash-based GPC	Rubber fibres (2–4 mm wide and up to 22 mm long)	10% by weight	200-400-600-800°C for 2 hrs	Changes in the weight, compressive strength, density, and microstructure	The percentage of compressive strength loss was greater for rubberized geopolymer concrete than for control concrete at all temperatures.
[17]	GPM contains 60% GGBFS and 40% fly ash	0.27, 0.83, 1.7, and 4 mm	5% by weight	25-200-400-600-800°C	Surface observation, compressive and flexural strength, mass loss, ultrasonic pulse velocity, and microstructure change	Fine rubber particles reduced deformations and crack propagation at high temperature.
[18]	fly ash-based GPM	0-1, 0-3, 4, and 0-4 mm	0, 10, 20, 30% by volume	---	Workability, unit weight, mechanical and thermal properties	Decrease in the mechanical strength with enhancement of ductility and failure behaviour.
[20]	OPC concrete	0–0.8, 0.8–2.5, 2.5–4.0, 4.0–7.0, and 7.0–9.5 mm	0, 5, 10, 15%	400-600-800°C for 1 hr	Slump, density, compressive strength, and splitting tensile strength	The thermal behaviour of rubberized concrete and reference concrete was roughly similar.
[53]	OPC concrete	0.85-1.40 mm	4, 8, 12, and 16% by volume	25-200-400-600°C for 2 hrs	compressive strength, Stiffness, stress-strain curves, and toughness	Higher contents of CR led to a higher decrease in compressive strength and stiffness, but toughness and spalling resistance were enhanced.

SUMMARY AND CONCLUSIONS

This review paper critically examined the performance of geopolymer-based and rubberized cementitious materials as protective systems for fiber-reinforced polymer (FRP) strengthening applications under elevated temperatures. The study focused on comparing their thermal behaviour, damage mechanisms, residual mechanical performance, and suitability as fire-protective layers. Based on the synthesis of the available literature, the following key conclusions can be drawn:

- Geopolymer concrete and mortars exhibit superior fire resistance compared to conventional OPC-based materials, owing to their stable aluminosilicate network, low chemically bound water content, and interconnected pore structure, which collectively enhance thermal stability and reduce explosive spalling.
- The thermal performance of geopolymer systems is highly dependent on precursor composition and activator chemistry, with fly ash–based and potassium-activated geopolymers generally showing better strength retention and fire resistance than slag-rich or sodium-activated systems at elevated temperatures.
- Rubberized cementitious composites demonstrate excellent thermal insulation and spalling resistance, primarily due to rubber volatilization and the formation of pressure-relief pathways; however, these benefits are accompanied by a reduction in mechanical strength, particularly at high rubber contents and temperatures above 600 °C.
- Low to moderate rubber replacement ratios provide an effective performance trade-off, where enhanced ductility, deformation capacity, and crack control can be achieved without severe degradation of mechanical properties, making such systems suitable for protective rather than load-bearing applications.
- Hybrid mitigation strategies, including the use of fiber reinforcement and surface-modified rubber particles, significantly improve the overall performance of rubberized and geopolymer systems by mitigating crack propagation, enhancing toughness, and partially compensating for strength loss.
- From an application perspective, geopolymer materials are more suitable as fire-resistant structural or load-bearing protective layers, whereas rubberized mortars are particularly effective as sacrificial, insulating, and energy-dissipating layers for protecting FRP-strengthened reinforced concrete members under fire exposure.

FURTHER STUDY

Future research should address key gaps related to the performance of geopolymer-based and rubberized cementitious materials as fire-protective layers for FRP-strengthened structures. In this context, the following research directions are recommended:

– Investigation of thermo-mechanical compatibility and bond behaviour between FRP systems and protective layers under elevated temperatures.

– Assessment of the influence of rubber content, particle size, surface modification, and fiber reinforcement on residual strength, cracking, and spalling resistance after fire exposure.

– Development and evaluation of hybrid geopolymer–rubber protective systems to balance thermal insulation and mechanical integrity.

CONFLICT OF INTEREST

The authors have no financial interest to declare in relation to the content of this article.

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