

Study and Assessment of Fire Resistance Enhancement in Concrete Using Additive Material: Review Paper

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Abstract - This comprehensive review integrates recent evolution in the development of fire-resistant concrete and mortar materials, focussing the addition of inventive additives, fibers, and geopolymers technologies. The studies focuses the advanced fire resistance, mechanical performance, and durability of geopolymer concrete (GPC) in comparison to traditional Ordinary Portland Cement (OPC), with GPC revealing little cracking, spalling and better residual strength at higher temperatures. The integration of silica-fume, metakaolin, fly-ash and polypropylene fibers remarkably increases thermal insulation, decrease spalling, and enhance overall structural strength when exposed to fire. Hybrid systems integrating carbon nanotubes and polypropylene fibers indicate synergetic benefits adjusting fire safety with post fire structural stability. Furthermore advanced composite panels containing basalt fiber reinforced geopolymers and geopolymer coatings shows lightweight, high-temperature resistant solutions suitable for fireproofing and tunnel protection. The review emphasize the importance of performance-based, risk-informed design strategies, using advanced fire modelling and material innovations to enhance safety, sustainability, and resilience in fire prone structures. Overall, the addition of fibers, geopolymers, and composite materials shows a promising pathway toward safer, more durable, and environmentally sustainable fire-resistant construction materials.

Keywords: Spalling, Metakaolin, Polypropylene, Fire Resistance

INTRODUCTION

The developing demand for fire-resistant construction materials has performed extensive research into increasing the thermal stability, structural integrity and safety of concrete and mortar systems under high temperature conditions. Conventional Ordinary Portland Cement (OPC) concrete is widely used, shows major limitations when exposed to fire including spalling, cracking and decrease in strength, which negotiate structural safety. To address these objection, current advancements have emphasized on adding creative materials such as geopolymer fibers and cement based materials to improve fire resistance and durability. Geopolymer concretes, specifically those based on metakaolin and fly ash have emerged as promising alternatives due to their inherent non-combustible property, lower environmental impact and better performance at higher temperatures. These materials shows slight cracking and spalling keeping

structural integrity even when exposed to temperatures more than 1200°C. Additionally, the incorporation of fibers such as polypropylene, basalt, and carbon nanotubes (CNTs) has shown to relieve spalling by generating pore channels and increasing micro structural stability thereby refining fire resistance and post-fire mechanical properties. Additionally, evolved composite panels and coatings utilizing geopolymer matrices reinforced with fibers or added with insulating materials shows lightweight, high-temperature resistant solutions fit for various applications including tunnel protection and fire resistance panels. The synergetic use of combined systems integrating Carbon nano tube and Poly Propylene fiber increase the strength of every component maintaining fire safety with durability. This analysis emphasizes modern growth in fire resistant construction materials emphasizing the role of geopolymer fibers and innovative composites. It shows the trade offs, performance benefits, and design strategies essential to optimize safety, sustainability and resilience in fire-prone structures. The addition of these advanced materials and performance based approaches marks a major step toward safer, more durable, and environmentally sustainable construction practices.

REVIEW OF LITERATURE

A. Gil, F. Pacheco, R. Christ, F. Bolina, K. H. Khayat, and B. Tutikian

This study assessed the fire performance of three precast concrete panel types under ISO 834 fire conditions, divulging significant differences in their structural behavior. The prestressed concrete (PC) panel accomplished catastrophic omission after just 18 minutes, characterized by explosive shattering that demolished the top section and bare tendons, preceded by 5mm of displacement. The polypropylene fiber-reinforced concrete (RC-PPF) panel signified a superior performance, remaining the entire for 240-minute exposure with only quite shattering, superficial cracking, and 94mm distort, though its insulation limits were come to nearly at 140 minutes. Micro scale investigation disclose that while melted polypropylene fibers generated additional heat transfer pathways, they successfully stopped explosive spalling by making pressure-relief channels. Post-fire examinations displayed the PC panel suffered entire top section loss, the RC panel had prominent rebar exposure, while the RC-PPF continued structural integrity with only surface damage. Although all panels blocked flame penetration, the PC panel

lossed structurally before reaching insulation requirements. These observance showed that RC-PPF panels gives maximum fire resistance and structural strength, with fiber modification demonstrating particularly successful at stopping explosive shattering in spite of slightly decreased insulation performance, making them the most preferable choice for fire-resistant precast concrete uses.

Mohammad R. Irshidat 1, Nasser Al-Nuaimi, Mohamed Rabie

Current development in fire-resistance construction materials shows the potency of combining creative composites, fibers, and geopolymers to increase safety and durability. RC-PPF panels reveal higher structural fire resistance but little less insulation performance contrast to old PC panels, which are insufficient under fire subjection. Including polypropylene (PP) fibers into concrete stops explosive shattering by melting at around 160°C, producing pore channels that promote steam escape, while also keeping strength during fire subjection with least long-term durability result at a 0.5% volume fraction. When mixed with carbon nanotubes (CNTs), these composite systems further enhance high-temperature strength, crack resistance, and micro scale structural strength, keeping up to 49% of compressive strength at 600°C compare to 33% in plain concrete. Geopolymer concretes, mainly those related to metakaolin and fly ash, show increased fire resistance up to 700–800°C, with least cracking and spalling, and surpassed ordinary Portland cement (OPC) in remaining strength and environmental impact. Auxiliary, geopolymer coatings and basalt fiber-reinforced geopolymers gives lightweight, durable, and high-temperature resistance solutions able to withstand up to 1200°C, keeping structural strength and micro scale structural stability after temperature cycling. Adding silica fume at 10% amplifies mechanical strength and fire resistance by compressing the matrix, reducing thermal conductivity, and reaching a remarkable fire ratings. Overall, addition of fibers like PP, CNTs, geopolymers and modern composites remarkably enhance fire resistance, structural strength, and feasibility, showing a step toward objective-based design and multi layered protection method for high-risk, fire-related applications.

Jadambaa Temuujin a,b,*, William Rickard a, Melissa Lee a, Arie van Riessen a

Recent fireproofing agents face critical restraint : cement-based coating are heavy and susceptible to spalling, while intumescent paints demean under moisture and CO₂ exposure. Geopolymer-based coatings offer a auspicious substitute merging cementitious longevity with lightweight flexibility. Studies shows that metakaolin-based geopolymers, generated with commercial sodium silicate, form firm coatings when optimise for Si/Al (2.5) and Na/Al (1) ratios. Experiment shows that less water-to-cement ratios (0.41) makes dense, high-performance coatings able to resist 1100-1200°C flames without debonding. These coatings reveal superior water resistance (<5% absorption) and keeps structural strength through zeolitic phase crystallization at 1000°C. Contrasting to traditional choices, geopolymer coatings provide fine applications, good moisture resistance, and industrial

adaptability. Although, higher water content conception shows boost porosity and cracking potential, recommending need for fiber reinforcement. The MK-0.41 mixture come out as optimal, showing outstanding adhesion, compressive strength, and thermal stability. Upcoming research should address long-lasting weathering effects and thermal cycling performance. These outcomes place geopolymer coatings as feasible solutions for shielding steel structures in fire-susceptible environments, surpassing normal systems in key performance indicators while remaining viable to produce.

Van Su Le 1,*, Petr Louda 1,Huu Nam Tran 2,Phu Dong Nguyen 3, Totka Bakalova 1,Katarzyna Ewa Buczkowska 1,4 and Iva Dufkova 1

Basalt fiber-reinforced geopolymer foams (BGFs) consider as a durable and high-performance alternative to traditional fire resistance materials, integrating the environmental advantages of geopolymers with improved mechanical and thermal properties. Geopolymers have been used in concrete significant for low CO₂ emissions and magnificent fire resistance, with foam variants providing both insulation and structural support. Integration of basalt fibers and geopolymers addresses limitations related to high-temperature performance failure. Studies indicates that BGFs exhibit complex and variable thermal behavior: density reduces maximum of 400°C, then increases sharply at 1200°C due to heat exposure; water absorption peaks at 200°C and balance at higher temperatures. The mechanical strength of geopolymers and BSFs has little effect up to 600°C, with enhancement of over 100% in compressive and flexural strength. Structural study of concrete reveal stable crystalline phases (leucite, Akermanite) and basalt-derived minerals that provide to high-temperature stability. The fire resistance testing shows basalt fiber significantly surpass conventional materials, extending protection times for wood and steel structures from minutes to over two hours, particularly with the high basalt fiber composition, which sustain integrity below 900°C with nominal surface damage. These findings validate BGFs as effective, lightweight, and sustainable fireproofing solutions suitable for construction and industrial applications.

Alan Richardson, Urmil V Dave (2008)

Polypropylene (PP) fibers enhance the fire behaviour of concrete essentially by reducing explosive spalling during intense heat exposure. When heated at 160°C, PP fibers melt, generating micro-channels that permit steam to escape, thereby helping internal pressure and averting the explosive crack of the concrete surface. This pore-inducing action supports surface integrity and decreases surface cracking. Introduction of PP fibers has been shown to somewhat increase residual strength after fire exposure, with excellent performance noticed at around 0.5% volume addition. Although, the melting of fibers can guide to a slight reduction in post-fire strength, but overall, PP fibers are observed to be an effective and economical solution for increasing fire resistance in concrete structures

Abdelmelek Nabil, Éva Lublóy (2017)

Using variable amount of metakaolin increases the fire resistance of concrete by enhancing its thermal stability and decreasing spalling during intense heat exposure. Metakaolin, as an additional cementitious material, solidify the concrete matrix, increases secondary hydration, and enhance cohesive property, which together contribute to better performance under fire exposure. Experimental studies demonstrate that integrating metakaolin up to definite percentages (e.g., 3-12%) can remarkably increase residual strength after exposing up to 800°C and decrease the chance of spalling and surface damage. Higher metakaolin content generally result in improved thermal resistance, making concrete more resistant and safer in fire-prone environments.

HY Zhang, V Kodur(2014)

The evolution of metakaolin-fly ash based geopolymers focus to create eco-friendly cementitious materials with increased fire resistance. These geopolymers influence the high-temperature stability of fly ash and the mechanical strength of metakaolin. Studies shows that while MK-based geopolymers carry out well at ambient temperatures, they are liable to cracking and strength reduction under intense heat. In contrary to, fly ash-based geopolymers reveal better high-temperature performance, keeping structural integrity and decreasing spalling during fire exposure. Evolving optimized MK-FA blends involves compensating these properties to produce durable, fire-resistant materials suitable for structural applications. Fire resistance of geopolymer concrete generated from Elazığ Ferrochrome slag. This study revealed that geopolymer concrete, mainly with river sand, shows better performance than OPC concrete at elevated temperatures. Compressive strength enhanced at 100 °C and 300 °C, with a peak at 300 °C, but lowered drastically at 700 °C. Water absorption decreased barely up to 300 °C, then increased due to excessive heat. No significant cracks appeared, but SEM (Scanning electron microscopy) showed micro cracks, mainly in OPC and crushed sand geopolymer. Overall, geopolymer concrete appeared better fire resistance and withhold more strength than OPC concrete.

Salmabanu Luhar , Demetris Nicolaides and Ismail Luhar (2021)

The fire resistance behaviour of geopolymer concrete (GPC) shows major advantages compared to traditional OPC concrete. GPC is naturally non-combustible and shows superb thermal stability up to temperature range of 700–800°C, with slight degradation and reduced spalling behaviour. Its inorganic matrix allows it to resist high temperatures without substantial cracking or loss of structural integrity, unlike OPC concrete which suffers from critical spalling and cracking at high temperatures. The pore structure and microcrystalline phases establish during high-temperature exposure, such as leucite and kaliophyllite, provide to its refractory properties and thermal stability. Additionally, GPC sustain higher residual strength post-fire, making it a optimistic material for fire-resistant applications, particularly in tunnel linings and structural fire protection scenarios.

Konstantinos Sakkas^{1,2}, Stergiani Kapelari¹, Dimitrios Panias¹, Pavlos Nomikos².

This study researches on Potassium-based metakaolin geopolymer has shown significant possibilities as a passive fire protection material, mainly for tunnel linings and structural components prone to extreme heat conditions. Researches shows that such geopolymers can bear temperatures till 1350°C, preserving structural integrity and giving effective thermal insulation. Fundamental mechanisms contain low thermal conductivity (around 0.21 W/m·K), that helps to reduce heat transfer, and the formation of refractory crystalline phases such as leucite and kaliophyllite during intense heat exposure, which increases stability. In addition to, the geopolymer's microstructure experience favourable mineral transformations, and its less porosity (approximately 29%) reduces water absorption and spalling risks under heat exposure. The surface temperature remains below critical thresholds (e.g., 220°C), and the material experience no spalling inspite of intense heating, signifying excellent durability and adhesion. These properties maintain the appropriateness of potassium-based metakaolin geopolymers for passive fire protection in particular infrastructure.

Hassan Suiffi, Anas El Malik , Fatima Majid

This study shows how inclusion of polypropylene (PP) fibers in concrete mixture enhances its fire resistance and long-term endurance. The main outcome by adding 0.5% PP fibers by volume considerably enhances fire resistance by decreasing spalling under intense heat exposure. When exposed to 600°C for 6 hours, concrete with 0.5% PP fibers showed a residual compressive strength reduction of only 24.25%, in contrast to 36.58% in plain concrete. This enhancement is primarily because of the melting of PP fibers (approx 160°C), which generates interconnected pores or micro-channels that promote vapor escape, thereby soothing internal pressure and avoiding explosive spalling. Regarding durability, the addition of PP fibers causes a significant enhancement in porosity (13.2% - 13.8%) and permeability but these changes are small and do not considerably compromise the concrete's chemical fire resistance and long-lasting performance. Collectively the inclusion of PP fibers provides a cost-effective and experimental method to increase fire resistance without affecting durability.

Alexandros Sofianos, Michal Sejnoha*, Miroslav Broucek

This study shows the experimental analysis of fire resistance in concrete with changing fly ash composition shows that fly ash increases the material's thermal integrity and spalling resistance under intense heat exposure. Concrete panels reinforced with polypropylene fibers and protective surface layers showed improved temperature control and decreased spalling contrast to plain concrete. Especially, panels with polypropylene fibers demonstrated better surface temperature management and less surface damage during fire testing although they still showed some structural weakening at core temperatures up to 1125°C. Fly ash contributes to reduced permeability and pozzolanic activity that helps in limiting internal temperature rise and microcracking but alone it is not

sufficient for overall fire protection. A layered approach including fly ash, fibers, and surface protection is suggested for superb fire resistance in tunnel lining applications.

Chen Ding a, Kaixi Xue b, Hongzhi Cui a, Ziqing Xu b , Haibin Yang a

This study researches on fire resistance of silica fume insulation mortar showcase its potential as a heat insulating and fire-resistant material. Silica fume contains SiO_2 (approx 90%) increases the mortar packing density, and secondary hydration promoting to boost mechanical strength and thermal properties. Experimental result shows that incorporating 10% silica fume enhances compressive strength by 12.1% and reduces thermal conductivity by approximately 3.5%, also significantly improves fire resistance. Mortars with this dosage experience reduced mass loss during intense heat exposure (up to 1010°C), with a 28.3% decrease and achieve a Class A1 (non-combustible) fire rating. The densification effect of silica fume decreases cracking and spalling during fire and making it a promising sustainable alternative for fireproofing applications.

Gabriel Alexander Khoury -Imperial College, London, UK

Author focuses that current conventional fire resistance methods often fall short in exactly predicting how structures execute under real fire situations. Instead, extensive, competency based, risk informed approach is suggested, incorporating structural response analysis, material behaviour, and advanced fire modelling for more accurate design. Concrete's intrinsic fire resistance depends on its low thermal conductivity and high thermal mass, but in modern time it's required call for additional strategies. These comprise increasing element thickness, using specific design concrete blends with fly ash, silica fume, or slag to decrease spalling and maintain strength, and make sure proper reinforcement detailing with sufficient concrete cover. Protective coatings can provide extra safety, but the key to optimum fire resistance lies in integrating material upgradation, structural design, and advanced modelling. This study increases the fire resistance and safety of structures.

W.Y. Hung and W.K. Chow

Mixing polypropylene (PP) fibers to concrete increases fire resistance predominantly by melting at around 160°C , generating micro-channels that permit internal vapor to disappear and thus prevent eruptive spalling, while only less affecting durability due to slightly increases in porosity and permeability. The study commends using a 0.5% volume of PP fibers for optimum fire performance without adjusting the concrete's durability. Although PP fibers enhance spalling resistance and remaining strength after high-temperature subjection, they may decrease some mechanical properties after fire, mainly as fibers melt and form channels for vapor liberate. integrating PP fibers with other materials like carbon nanotubes (CNTs) can further enhance the combine overall performance, with CNTs increasing strength and thermal stability at high temperatures, and PP fibers furnishing fire safety through pore formation. comprehensively, PP fibers are

an productive, profitable solution for enhancing concrete's fire resistance with minimal influence on durability.

S. Alehyen, M. Zerzouri, M. ELalouani, M. EL Achouri, M. Taibi

Study emphasize excellent fire resistant of fly ash-based geopolymer (FA-GP) in contrast to normal Portland Cement. Temperature stability tests using Differential Scanning Calorimetry depicted that FA-GP keeps structural integrity up to 800°C , while OPC starts to decrease due to the decomposition of calcium silicate hydrate (C-S-H) and portlandite. Upon subjection to high temperatures (600°C , 800°C , and 1000°C), FA-GP trial samples hold on to their shape, reveals no visible cracks, and underwent less weight loss. In compares to, OPC samples grows surface spalls at 600°C and were completely damaged at 1000°C . FTIR analysis showed that FA-GP keeps its attributes Si-O-Al gel structure after heating, while OPC exhibits decomposition of the C-S-H gel. XRD analysis verified the formation of balanced crystalline phases like albite and nepheline in FA-GP after heat subjection, which imparted to its enhanced heated resistance. SEM images assisted these findings, exhibiting a denser and more compact microstructure in FA-GP after heating, with no microcracks or unreacted fly ash particles. The frittage and incomplete melting at high temperatures supported ill pores, further increasing the material's fire resistance. comprehensively, the geopolymer's ceramic-like behaviour and balance micro nanostructure at high temperatures make it highly fire-resistant and preferable for high-temperature applications in construction.

Francis N. Okoye a, Satya Prakash a, Nakshatra B. Singh

Research highlights the higher performance of fly ash-based geopolymer concrete containing the composition of 20% silica fume (SF) in contrasted to old OPC concrete. When bared to aggressive environments for 90 days, OPC concrete suffer from severe depletion, losing 60% of its compressive strength in 2% sulfuric acid (H_2SO_4) and 25% in 5% sodium chloride (NaCl) solutions. In contrast, geopolymer concrete with 20% SF shows exceptional durability, showing least strength 20 % decrease in acidic conditions and less degradation in chloride when comes in contact while keeping complete structural stability with invisible erosion. This performance stems from its denser small structure featuring N-A S-H and C-A-S-H gels, which exhibit nearly 25% lower permeability than OPC concrete. In cost effective, geopolymer concrete offers advantages, costing about $\$45/\text{m}^3$ in contrasted to $\$60/\text{m}^3$ for OPC in the Indian market - a 25% minimal cost. Each tonne of fly ash used in production not only production 2.5 m^3 of concrete but also provides one carbon credit, while the producing process reduces CO_2 emissions by 80-90% in contrast OPC production. The material's superior acid and chloride resistant, mixed with its environmental benefits (utilizing industrial waste and removing high-temperature processing), make it prominently suitable for harsh environment infrastructure projects. Further studies are required to determine the ideal SF content (5-30% range) and access performance under more chemical concentrations ($>2\% \text{ H}_2\text{SO}_4$, $>5\% \text{ NaCl}$), but present evidence sharply developed

geopolymer concrete as a technically up to date, cost-effective, and maintainable alternative to old OPC.

Weidong Dai 1 and Yachao Wang

Alkali-activated geopolymer binders shows extraordinary fire resistance, keeping structural strength up to 1200°C, far excelling Portland cement's abilities. Experiment on ternary SF/slag/FA (denote by wt%) prominent geopolymers performance improvement: bending strength enhance by 8.8% (105.6 MPa) at 150°C and 14.1% at 108.6 MPa at 500°C, while rupture and bending strength reaches 5.6 MPa after 1200°C comes in contact - five times greater than FA systems. Micro stage structural analysis discloses that the SF's important role in decreasing porosity from 20.93% to 13.47% and reducing median pore diameter from 6.4 nm to 5.6 nm, while elevate formation of thermostable gehlenite and labradorite phases above 850°C. Temperature analysis proves that it increases stability, with DTG peaks transferring from 128°C to 135°C and weight loss endpoints increasing from 166°C to 185°C. At less than 850°C, SF increases stability through pore volume optimization (25% increase in 0.2-3µm range) and denser gel formation, while above 850°C, its melting property creates a viscous phase that enables crack blunting and maintains structural integrity despite 6.9-9.4% volume shrinkage. While these geopolymers shows superior performance beyond cement at 600°C defect point, challenges remain in fully specify gel structures and forming execution standards. The study shows that careful SF content can balance increased durability below 850°C with controlled high-temperature behaviour, positioning geopolymers as modern fire-resistance construction materials with 832°C temperature stability.

Nabil Abdelmelek1, Eva Lubloy1

It has been proved that the analytic range of temperature subjections for the mechanical stability decrease between 400 and 800 °C . Hertz examined concrete containing 14–20% of SF renewal to cement mass, results ensured that concrete containing SF is mostly prone to cracking and spalling at elevated temperatures. OPC, SF, MK, and FA materials are used in experimental program. FA is most important for paste performance, otherwise, the application of over the desirable replacement may decrease the mechanical and durability properties. The bending strength values for all compositions are differing between 2 to 11 MPa. Results depict that the presence of SF and FA comparatively increases the flexural results of HCP compared to the results of the reference composition. The most favourable substitution of MK has shown a best heat tolerance than the favourable substitution of SF and FA, this could be due to the physical properties and chemical constituents of MK such as angular shapes of particles and most content of Al₂O₃ and S . It was assessed that the MK concrete suffered a high major loss of extensive strength and absorbent related durability than FA, SF, and OPC concrete after coming contact to increased temperatures. In extend, explosive cracking was seen in two of normal and high stability.

Eung-Mo An, Young-Hoon Cho, Chul-Min Chon, Dong-Gyu Lee, and Sujeong Lee

This study evaluates the synthesis of fire-resistant geopolymer materials using refused fly ash which is generated from a thermal power plant. Geopolymers were created by mixing this ash with alkali activators and targeting Si:Al in ratios of 1.5, 2.0, and 3.5. The compressive strength and fire performance of each and every blend were examined prior and post heating to 900°C. The sample with a Si:Al ratio of 1.5 indicates the highest fire resistance, in which the strength increasing from 29 MPa to 41 MPa. This composition also showed nominal thermal expansion and shrinkage. Fire resistance testing exposed the mortar with a ratio of 1.5 which sustained over 2 hours at 1050°C with nominal heat propagation (74°C on the cold side). The availability of thermally stable crystalline phases like nepheline and zeolite contributed to an increase in performance. The Lower Si:Al ratios produced more compact gel structures and better densification after sintering. Microstructural and XRD testing confirmed fewer pores and stronger crystalline transitions in the 1.5 ratio sample. The 3.5 ratio samples faced more degradation due to higher silicate content and contraction. These outcomes show geopolymer composition significantly affects mechanical and thermal stability. The study promotes using recycled fly ash for sustainable, fire-resistant construction is good. Overall, geopolymer with a Si:Al ratio of 1.5 demonstrated the best fire resistance performance even without adding fiber reinforcement.

CONCLUSION

The comprehensive assessment shows the advancements in increasing the fire resistance, thermal performance, compressive strength and structural integrity of concrete and composite materials through the combination of inventive additions and supplementing strategies. Materials such as geopolymer, silica fume, basalt fibre reinforced geopolymer, metakaolin, fly ash, & polypropylene fibers. This shows high fire resistance properties, decreased spalling, minimum cracking, & better remaining strength at maximum temperatures. The combine use of fibers, nanomaterials like CNTs, and evolved geopolymer formulations extend promising solutions for fire proof applications, mainly in tunnel linings, fire resistant panels, and structures components. comprehensively, Taking layered approaches that incorporate these materials and design strategies can predominantly increase safety, viability, and performance in fire proof construction, cover the way for more prompt structure in high risk areas.

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