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DEVELOPMENT OF GEOPOLYMER SURFACE COATINGS WITH IMPROVED FIRE RETARDANCY AND ABRASION RESISTANCE – A SHORT REVIEW

This review highlights the recent advancements in surface coatings that are crucial for fire retardancy and abrasion resistance. Developments in fire-retardant coatings have introduced formulations that enhance thermal stability and improve combustion resistance. Simultaneously, innovations in abrasive materials focus on durable, high-strength, and heat-resistant compositions suited to demanding industrial applications. These trends reveal a growing need for sustainable, high-performance alternatives to traditional materials. Geopolymers are emerging as a promising solution, environmental compatibility, and superior performance to deliver coatings that excel in both fire protection and wear resistance. This review consolidates findings across fire protection and abrasive applications, emphasizing the role of geopolymer technology in developing coatings that can withstand both fire and mechanical wear. Future directions include optimizing geopolymer formulations to further enhance their resilience, making them adaptable to varied high-demand applications.

Keywords: Geopolymer; coating; abrasive; fire-retardant coating; geopolymer-based abrasive

1. Introduction

Coatings serve as protective layers on surfaces, enhancing durability, visual appeal, and resistance to environmental elements. In the context of fire safety, coatings play a fundamental role in preventing and slowing down the spread of flames, thereby reducing the risk of fire damage to structures. These coatings achieve their fire-retardant properties through various mechanisms, such as forming a protective char layer, undergoing endothermic reactions, or creating a thermal barrier that insulates the underlying material from heat [1-3]. With continuous advancements in fire safety materials, there has been a growing focus on improving the effectiveness of these coatings. By optimizing their formulation and application methods, fire-retardant coatings are now better equipped to withstand high temperatures and protect surfaces for longer periods, enhancing both safety and structural integrity.

1.1. Types of fire-retardant coatings

There are various types of fire-retardant coatings, each designed to cater specific materials and applications. For instance, intumescent coatings expand when exposed to heat, providing an additional protective layer. These coatings are commonly used in structural applications to prevent fires in steel since it will expand when heated, creating a protective char layer that shields the underlying material from high temperatures [2,4,5]. Besides that, cementitious coatings, another type of fire-retardant coating, are known for their robustness and ability to provide passive fire protection by forming a protective barrier that insulates the substrate from heat [2,6]. Next, water-based coatings, a subset of intumescent coatings, offer environmental benefits due to their low volatile organic compound (VOC) emissions. These coatings are typically easier to apply and dry quickly, making them convenient for construction applications [7,8]. Furthermore, composite coatings, combine different materials to enhance fire protection properties, often incorporating intumescent and other fire-retardant materials. The use of additives in composite

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coatings can significantly improve their performance by enhancing the intumescent behaviour and delaying heat transfer to the substrate [9].

1.2. Char layer formation in fire-retardant coatings

The term "char" refers to the carbonaceous protective layer that forms on the surface of an intumescent coating when exposed to heat or fire, as shown in Fig. 1. This layer plays a crucial role in passive fire protection, as it acts as a thermal and physical barrier, slowing down heat transfer and preventing material degradation [10,11]. The formation of the char layer is driven by a series of thermochemical reactions involving three key components: an acid source, a carbon source, and a blowing agent. Traditional intumescent coatings are designed based on this system, which is widely used due to its efficiency in forming a stable and insulating char layer.

1.2.1. Decomposition of the Acid Source

The first stage in char formation is the thermal decomposition of the acid source, typically ammonium polyphosphate (APP) which contains the elements nitrogen (N), hydrogen (H), phosphorus (P), and oxygen (O). When heated above 200°C until 300°C, APP decomposes into phosphoric acid (H_3PO_4) which act as catalysts for dehydration and cross-linking reactions.

$$(NH_4PO_3)_n \rightarrow nNH_3 + nH_3PO_4$$

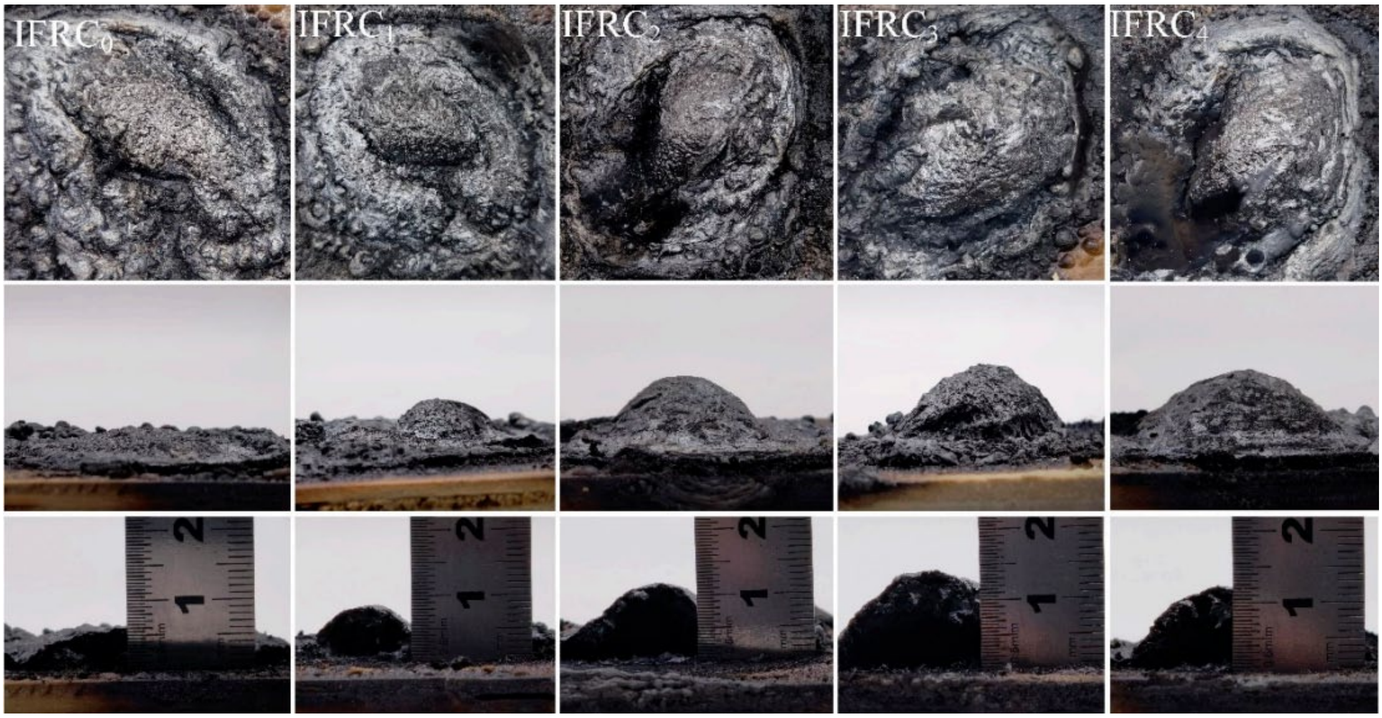

Fig. 1. Digital photographs of the char layers from IFRC0–IFR4 (55%-50% of IFR content) [20]

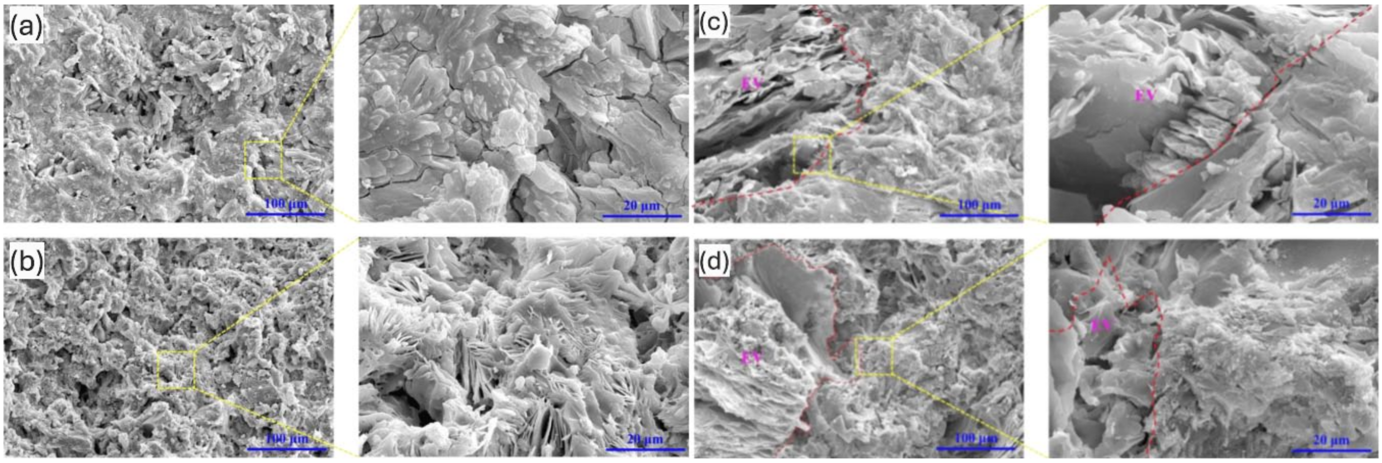

Fig. 2. SEM image of the fracture surface for MPC (a) at room temperature, (b) after fireproof test, SEM image of the fracture surface for MPC with 40% EV (c) at room temperature, and (d) after fireproof performance test [21]

Here, $(NH_4PO_3)_n$ represents ammonium polyphosphate, which decomposes to release ammonia (NH_3) and phosphoric acid (H_3PO_4). The released phosphoric acid plays a crucial role in promoting the dehydration and carbonization of the carbon source [12,13]. Fig. 2 shows the illustrates the chemical reaction pathway of ammonium polyphosphate and phosphoric acid under heating conditions.

1.2.2. Carbonization of the Carbon Source

The carbon source, commonly pentaerythritol ($C_5H_{12}O_4$), also known as PER or starch, serves as the primary char-forming agent. Under the catalytic influence of phosphoric acid, PER undergoes thermal decomposition and dehydration, forming a stable carbon-rich residue that contributes to char formation [14].

$$C_5H_{12}O_4 \rightarrow \text{Carbon char} + H_2O$$

This reaction removes water (H_2O) and promotes cross-linking between carbon structures, resulting in a more compact and thermally stable char. The efficiency of carbonization directly impacts the mechanical strength and thermal resistance of the char layer.

1.2.3. Expansion of the Char Structure

Simultaneously, the blowing agent, such as melamine (MEL), decomposes at elevated temperatures, releasing gases such as ammonia (NH_3), carbon dioxide (CO_2), and nitrogen (N_2). The gas evolution causes the softening carbonaceous residue to expand, forming a highly porous structure [15].

$$C_3H_6N_6 \rightarrow 3HCN + 3NH_3 + N_2$$

This reaction releases hydrogen cyanide (HCN), ammonia (NH_3), and nitrogen gas (N_2), which create a foamed, aerated char that significantly enhances thermal insulation. The expansion process is critical in ensuring that the char layer remains lightweight yet structurally robust to maintain fire resistance [11]. The char continues to cross-link and stabilize due to polymerization reactions, creating a strong, rigid, and heat-resistant barrier. Fig. 3 shows the schematic diagram of the char-forming process in a fire-retardant system involving APP and MEL derivatives.

1.3. Properties of geopolymers

Geopolymer coatings are emerging as a promising alternative due to their superior mechanical and thermal performance, as well as their lower environmental impact compared to traditional cement-based coatings [2,16,17]. Geopolymer is an inorganic polymer formed by the chemical reaction of aluminosilicate materials with alkaline activators such as sodium hydroxide (NaOH) and sodium silicate (Na_2SiO_3), forming a stable, interconnected polymeric structure [18,19]. This process, known as geopolymerization, results in a three-dimensional network structure that imparts high mechanical strength, thermal stability, and chemical resistance to the material [20-22]. Geopolymers are synthesized from raw materials like fly ash (FA), metakaolin (MK), and ground granulated blast slag (GGBS), which are abundant industrial by-products, making geopolymers a sustainable and eco-friendly alternative to traditional materials [23,24]. Geopolymers are increasingly recognized for exceptional thermal stability and fire resistance, making these materials promising for coatings in environments that demand high durability and fire protection.

1.3.1. Thermal stability and fire resistance

Geopolymers exhibit superior resistance to high temperatures compared to traditional materials like ordinary Portland cement (OPC). They can endure temperatures ranging from 1000°C to 1200°C, maintaining structural integrity and minimizing micro-crack formation up to certain temperature thresholds [25]. The aluminosilicate matrix in geopolymers contributes to the thermal stability, allowing to retain the mechanical properties

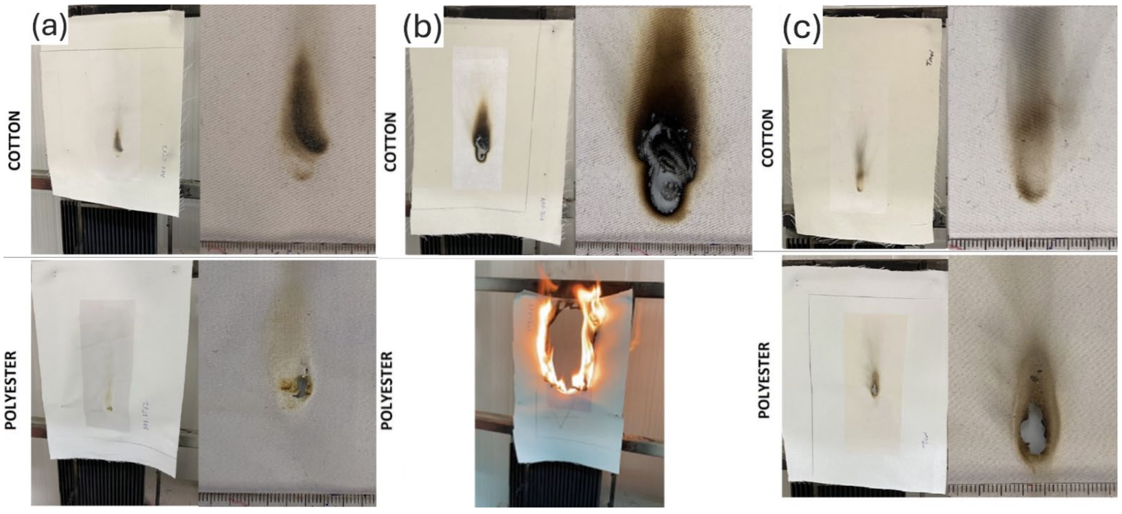

Fig. 3. Vertical flame spread tests performed on (a) FR-A, (b) FR-B, and (c) FR-C

such as compressive strength and elastic modulus at elevated temperatures. For instance, geopolymers show enhanced strength and modulus below 500°C, although deterioration occurs above this temperature due to chemical changes [26]. Geopolymers are used in applications requiring high fire resistance, such as in aerospace and construction industries. Their ability to withstand high temperatures without significant loss of mass or structural integrity makes them suitable for fire-resistant coatings and barriers [27,28]. In welding processes, geopolymers have been tested as insulating materials, demonstrating resistance to temperatures exceeding 3000°C without cracking or damage, showcasing their potential in high-temperature applications [29]. Additionally, geopolymers exhibit low thermal conductivity, helping slow down the transfer of heat. This feature is advantageous in scenarios where slowing the spread of fire is crucial, such as in building materials or protective coatings [30,31]. These attributes make geopolymers an excellent choice for fire-resistant coatings, providing durable protection in high-temperature environments.

1.3.2. Mechanical properties for abrasion resistance

The mechanical properties of geopolymers, including hardness, durability, and compressive strength, make them suitable for applications requiring abrasion resistance. Geopolymers exhibit notable hardness levels due to their dense microstructure, which is achieved through the polymerization of aluminosilicate materials. This hardness is crucial for resisting surface wear during abrasive contact, making geopolymers ideal for applications like grinding wheels and protective industrial coatings [32,33]. The use of FA in geopolymer coatings also has been shown to improve abrasion resistance, making them suitable for protective industrial coatings [34]. Durability is another defining characteristic of geopolymers. The durability of geopolymers is attributed to their cohesive structure, which provides high resistance to surface wear. This is particularly evident in harsh environments, such as marine settings, where geopolymer coatings have demonstrated superior performance compared to traditional cement-based coatings [35]. Furthermore, their compressive strength allows geopolymers to withstand heavy loads without substantial deformation or failure, making them suitable for structural applications that face both physical impact and frictional wear [33,36,37]. Together, these mechanical properties make geopolymers highly effective as coatings in settings that endure frequent abrasive forces, providing reliable surface protection and extending material longevity.

2. Challenges in modern applications of fire-retardant coatings

Fire-retardant coatings play a critical role in enhancing fire safety across various industries, including construction, aerospace, and automotive. However, despite their effectiveness, these coatings face several challenges that limit their applicability in modern, high-performance environments. One of the primary limitations is the high thickness and weight of traditional coatings, particularly cementitious formulations. While these coatings provide robust fire protection, their bulkiness makes them unsuitable for lightweight structures or applications where weight reduction is critical, such as in aerospace and high-rise buildings. For instance, cementitious coatings often require layers as thick as 10-20 mm to achieve adequate fire resistance, significantly increasing the overall weight of structures [2,6]. This limitation has spurred interest in thinner, lightweight alternatives such as intumescent and geopolymer coatings. Another significant challenge is the durability and environmental resistance of fire-retardant coatings. These coatings are often exposed to harsh conditions, such as UV radiation, moisture, and chemical exposure, which can degrade their performance over time. For example, water-based coatings, despite their low volatile organic compound (VOC) emissions and environmental benefits, are susceptible to degradation in humid environments, limiting their long-term durability [7]. Similarly, the cost and sustainability of fire-retardant materials remain a concern. Many coatings rely on synthetic or non-renewable materials, such as APP and MEL, which are not only costly but also have significant environmental implications. The production of these materials often involves high energy consumption and carbon emissions, raising questions about their long-term sustainability [38]. Additionally, toxicity and safety concerns associated with some fire-retardant materials pose significant challenges. For example, APP-based coatings, while effective, release toxic gases such as ammonia and phosphorus oxides during combustion, which can be hazardous in confined environments like ship interiors [39]. This raises safety concerns, particularly in applications where human exposure is unavoidable.

2.1. Future directions in fire-retardant coatings

Future research is expected to explore several innovative directions. One promising approach involves the incorporation of nanomaterials such as graphene oxide and layered double hydroxides (LDHs) to enhance the thermal stability and char-forming ability of coatings [8]. These nanofillers have shown potential in improving heat shielding performance while maintaining mechanical integrity. Additionally, the development of bio-based fire-retardant coatings presents an eco-friendly alternative to conventional formulations. Studies have investigated the use of natural additives such as starch, lignin, and chitosan to enhance fire resistance while minimizing environmental impact [40]. Another emerging trend is the integration of hybrid coating systems, where different fire-retardant mechanisms are combined to achieve superior performance. For instance, some studies have explored the use of geopolymer-based coatings with added intumescent layers to create multi-functional fire barriers [17,31]. Additionally, optimizing the structural composition of geopolymer coatings, such as adjusting the Al/Si ratio, has been found to influence their intumescence behaviour and insulation properties [41]. Advanced characterization techniques also play a crucial role in guiding future improvements. Real-time microstructural analysis using high-temperature SEM and in-situ XRD could provide deeper insights into how coatings degrade under extreme heat conditions [9]. TABLE 1 summarizes recent research on coatings for fire retardant, focusing on the types of coating, materials used, and key findings discussed in Section 2.1 – Recent Works on Fire-Retardant Coatings.

TABLE 1

Recent Works of Coatings for Fire Retardant

Authors	**Types of coatings**	**Materials**	**Key Finding**
Elpida Piperopoulos et al. [5]	Intumescent coating	1) Coating materials: Ammonium polyphosphate, pentaerythritol, and acrylic matrix.	Ammonium polyphosphate coating (APiC) effectively enhance fire resistance by lowering steel temperature and forming a consistent, protective char layer.
Feiyue Wang et al. [32]	Intumescent coating	1) Coating materials: Ammonium polyphosphate (APP), pentaerythritol (PER), and melamine (MEL). 2) Filler: Tungsten tailing particles (TTF), polypyrrole (PPY), and epoxy resin.	Adding polypyrrole-coated tungsten tailing particles to intumescent coatings could improve fire resistance and durability, offering a more effective and sustainable fire-retardant option.
Jianwei Cheng et al. [6]	Cementitious coating	1) Cement-based material. 2) Additives: FA, cellulose, emulsion, and aluminium hydroxide.	The optimized CFSCF composition may offer a strong, flexible, and effective flame-retardant coating, providing immediate flame extinguishing and enhance mechanical properties over time.
Xiaobing Dai et al. [33]	Cementitious coating	1) Magnesium phosphate cement (MPC), $NH_4H_2PO_4$. 2) Additives: Dead-burnt magnesia (MgO), expanded vermiculite (EV), and borax.	$NH_4H_2PO_4$-based magnesium phosphate cement (MPC) may be an effective binder for fire-retardant steel coatings, providing rapid setting, strong bonding, and excellent fire resistance with optimized thickness.
Onur Yilmaz et al. [7]	Water-based coating	1) Styrene-acrylic copolymer. 2) Inorganic filler: Disodium octaborate (FR-A) and zinc borate (FR-B). 3) Commercial waterborne fire-retardant product (FR-C).	The formulation with disodium octaborate (FR-A) may be more effective for enhancing fire resistance in textiles, especially cotton, by reducing flame spread and improving heat resistance when combined with a styrene-acrylic copolymer.
Kun-Yu Guo et al. [8]	Water-based coating	1) Ammonium polyphosphate (APP). 2) Graphene oxide (GO). 3) Silane.	Offer an effective fire safety solution by significantly reducing fire alarm response times and providing early warnings, enhancing protection against combustible material hazards.
Borys Mykhalichko et al. [9]	Composite coating	1) Epoxy resin (ED-20). 2) Curing agent: Polyethylenepolyamine (pepa). 3) Copper (II) hexafluorosilicate ($CuSiF_6$).	Coating with $CuSiF_6$ significantly enhance fire safety by lowering combustion temperature, reducing mass loss, and achieving high fire protection ratings with improved smoke suppression.
Qi Yang et al. [34]	Geopolymer coating	1) Geopolymer materials: MK and SF. 2) Activator: Sodium silicate solution (Betol 39T) and NaOH.	Geopolymers with low Al/Si ratios enhanced fire protection by promoting intumescence and effective heat insulation, whereas higher Al/Si ratios result in rigid structures with limited fire resistance.
Putri R. et al. [35]	Geopolymer coating	1) Geopolymer material: MK and SF. 2) Alkaline actiavtor: NaOH and water glass (WG). 3) Additives: Graphite (G) and mixture of diammonium phosphate-starch-urea (DSU).	Adding graphite enhances the fire resistance of geopolymer coatings without affecting intumescence, while the MSGD formulation (with diammonium phosphate, starch, and urea) provides effective fire protection, maintaining lower steel temperatures over time.
Mohd Salahuddin et al. [25]	Geopolymer coating	1) Geopolymer materials: FA, MK, and blast furnace slag. 2) Alkaline actiavtor: NaOH and Na_2SiO_3. 3) Additives: Rice husk ash (RHA).	Optimizing the RHA/AA ratio at 0.30 and NaOH concentration at 6 M may enhance the fire resistance and thermal stability of RHA-based geopolymer coatings.
Johan Sarazin et al.[11]	Geopolymer coating	1) Geopolymer material: MK and SF. 2) Alkaline actiavtor: NaOH and Na_2SiO_3. 3) Foaming agent: Hydrogen peroxide (H2O2) and cetylTrimethyl Ammonium Bromide (CTABr).	Incorporating H_2O_2 and CTABr into GP foam significantly enhance fire resistance, reduce steel temperature, and improve coating stability during fire exposure.
Ya Chao Wang et al. [36]	Geopolymer coating	1) Geopolymer materials: FA and GGBS. 2) Chemical activator: Sodium metasilicate nonahydrate, Na_2SiO_3.9H2O, sodium oxide and silicon dioxide (Na2O/SiO2), and potassium hydroxide (KOH).	Using 25 wt. % slag or FA in geopolymer coatings may greatly enhance flame resistance, with slag-based coatings particularly effective in reducing heat release and blocking heat and volatile transfer.
Faiz Uddin et al. [10]	Geopolymer coating	1) Geopolymer materials: Class F FA. 2) Alkaline activator: NaOH and KOH. 3) Additives: Carbon fiber (CF) and basalt fiber (BF).	FA geopolymer coatings, especially when reinforced with carbon or basalt fibers and applied in thicker layers, may provide strong adhesion and significantly enhanced fire resistance for timber.

2.2. Recent works of fire-retardant coatings

2.2.1. Intumescent coating

In intumescent coating category, a study led by Elpida Piperopoulos et al. [15] evaluated the intumescent capacity of ammonium polyphosphate-based coatings for fire protection in naval applications through experimental testing and mathematical modelling [5]. The coatings were formulated with APP, pentaerythritol, and an acrylic matrix, applied on ASTM A1008 carbon steel substrates. Three coating variations were tested which are the standard intumescent coating (iC), an enhanced coating with ammonium polyphosphate (APiC), and an uncoated control (uC). The APiC coating demonstrated superior insulation properties, reducing the back temperature of steel by up to 200 K compared to uncoated samples. Additionally, the mathematical model aligned well with experimental data, supporting its use for predicting intumescent growth. Notably, the APiC coating formed a thicker, more uniformly distributed intumescent char, up to 12.2 mm, significantly enhancing fire resistance. Nevertheless, the over usage of APP, a common fire-retardant ingredient, can release toxic gases when it breaks down at high temperatures. During a fire, it might release harmful fumes, like ammonia and phosphorus oxides, which could be dangerous if inhaled, especially in enclosed spaces like inside a ship.

Besides that, a research investigation conducted by Feiyue Wang et al. [42] examined the application of polypyrrole-modified tungsten tailing particles (PPY-TTF) to improve the flame-retardant properties, smoke mitigation capabilities, and durability against aging of intumescent fire-resistant coatings. The coatings included APP, pentaerythritol (PER), melamine (MEL), and fillers like tungsten tailings, polypyrrole (PPY), and epoxy resin. Results showed that adding 3 wt.% of PPY-TTF significantly boosted flame retardancy and reduced smoke, with a 10.7% decrease in mass loss and a 35.4% reduction in flame spread compared to coatings without PPY-TTF. In addition, PPY-TTF also improved durability by reducing issues like blistering and powdering. This approach provides an innovative use for tungsten tailings in fire-resistant materials. However, PPY-TTF can be challenging to prepare consistently, as the polypyrrole modification process requires precise conditions and specific equipment, potentially complicating and increasing the cost of large-scale production. Fig. 4 shows the digital photographs of the char layers with different content of intumescent flame retardant (IFR).

2.2.2. Cementitious coating

For cementitious coating, Jianwei Cheng et al. [6] introduced an innovative cement-based flexible spray coating designed specifically for flame retardancy in coal mines, with the objective of mitigating spontaneous combustion. This cementitious coating, labelled CFSCF, was formulated with a cement-based material and additives such as FA, cellulose, emulsion, and aluminium hydroxide. The study identified the optimal mix ratio as 11% FA, 1.6% cellulose, and 24% emulsion, achieving tensile strengths of 1.81 MPa, 2.15 MPa, and 2.53 MPa at 7, 14, and 28 days, respectively. Peak tensile strength reached 2.55 MPa after 28 days, with maximum elongation at break of 52.62% at 14 days, highlighting the coatings robust mechanical properties. Importantly, CFSCF demonstrated effective flame retardancy, extinguishing flames immediately upon removal from the source. Although post-fire microstructural analysis was conducted, a comparison with pre-fire microstructure was missing. Such analysis could further elucidate the effects of heat exposure on micro-scale properties like pore structure and crack formation, potentially enhancing our understanding of the materials performance under fire conditions.

Furthermore, Xiaobing Dai et al. [43] investigated a fire-retardant coating for steel based on magnesium phosphate cement (MPC) using $NH_4H_2PO_4$ as the main component, along with dead-burnt magnesia (MgO), expanded vermiculite (EV), and borax. The study aimed to develop a coating with high bonding strength and corrosion resistance. The MPC coating demonstrated rapid setting and strong bonding performance, achieving a tensile bonding strength of 0.6 MPa within 3 hours and 1.10 MPa at 28 days, which exceeds Chinese standards. Additionally, the coat-

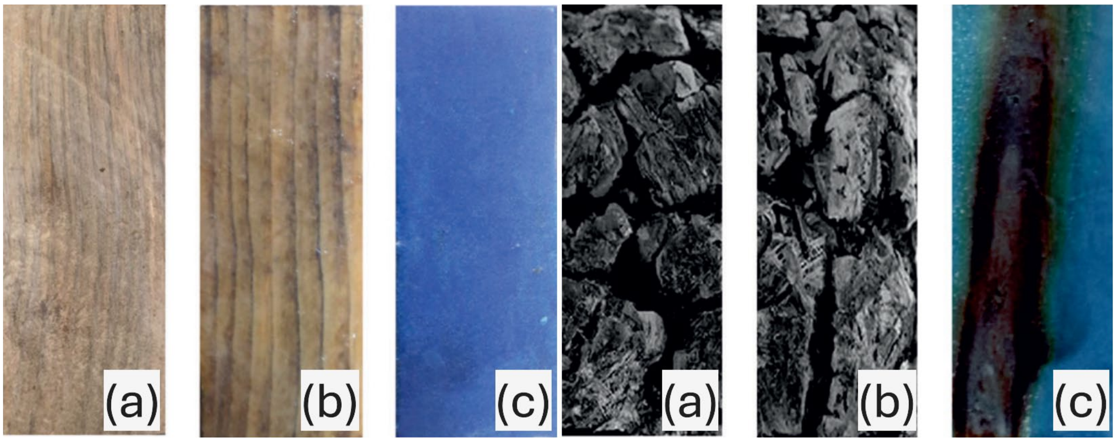

Fig. 4. Wood specimens before and after combustibility tests (a) with no coating, (b) coated with epoxy amine composite, and (c) coated with CuSiF6-modified epoxy-amine composite [9]

ing provided effective fireproof performance, with recommended thicknesses of 10 mm for paste applications and 4 mm for mortar containing 40% expanded vermiculite. However, ingredients like $NH_4H_2PO_4$ and borax can be costly and less widely available than materials like FA or regular cement. This could make MPC coatings expensive, especially for large projects. Fig. 5 shows the SEM image of the fracture surface for MPC before and after fireproof performance test with different temperatures.

2.2.3. Water-based coating

For water-based coating, Onur Yilmaz et al. [7] developed an eco-friendly, halogen-free waterborne hybrid coating to enhance the fire retardancy of textile fabrics using boron-based derivatives. The coating combines a styrene-acrylic copolymer and inorganic fillers, specifically disodium octaborate (FR-A) and zinc borate (FR-B), and was compared with a commercial fire-retardant product (FR-C). Among these, the formulation with disodium octaborate (FR-A) demonstrated superior fire resistance, significantly reducing flame spread and enhancing heat resistance, especially on cotton textiles. This research highlights the potential of combining boron derivatives with styrene-acrylic copolymers to achieve effective fire-retardant properties in textiles. Nonetheless, although the coating is halogen-free and water-based, boron compounds can have environmental and health implications. High levels of boron exposure can be toxic, and there may be concerns about its impact if the coated textiles are widely used, especially in applications where direct skin contact occurs. Fig. 6 shows the picture of cotton and polyester during the vertical flame spread tests performed.

In addition, Kun-Yu Guo et al. [8] developed a water-based hybrid coating aimed at making polyurethane (PU) foams both fire-resistant and super-hydrophobic, with rapid fire alarm response capabilities. The coating was formulated with ammonium polyphosphate (APP), graphene oxide (GO), and silane to achieve desired properties. The study found that these hybrid coatings significantly improved fire alarm response times, detecting heat within approximately 2.0 seconds and issuing an early warning at 11.2 seconds when exposed to 300°C. These results highlight the coatings potential as an effective solution for fire safety and prevention, particularly in reducing fire hazards

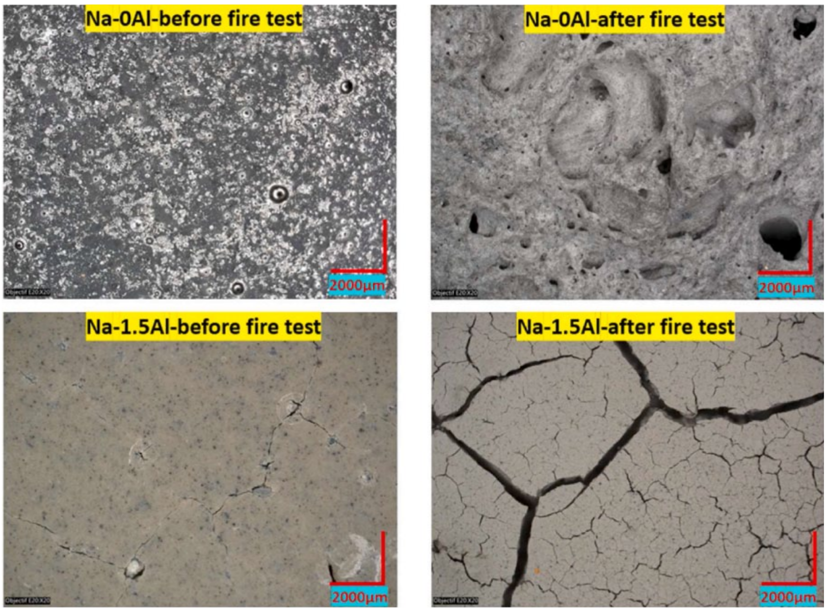

Fig. 5. Optical microscopy of GP from the surface [22]

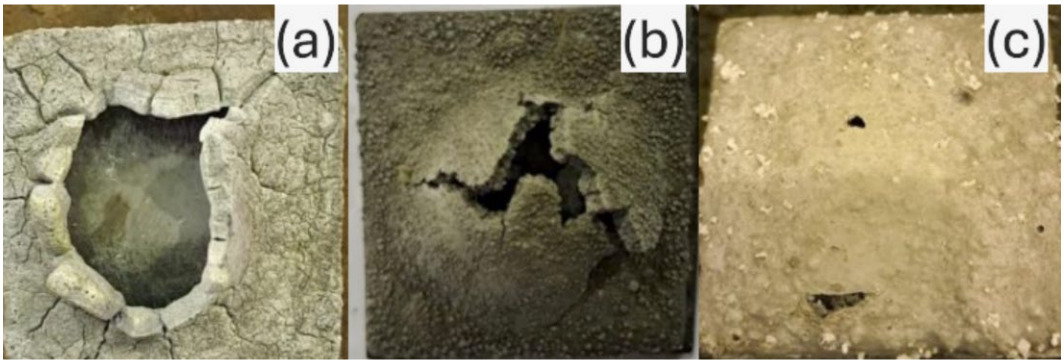

Fig. 6. The coated steel specimens after the fire test: (a) MK-silica fume geopolymer (MS), (b) MK-silica fume-graphite geopolymer (MSG), (c) MK-silica fume-graphite-DSU geopolymer (MSGD) [23]

associated with combustible materials. In contrast, although the study emphasizes an eco-friendly, water-based approach, using components like APP, GO, and silane treatments could increase material costs. These specialized ingredients might make the coating less affordable for large-scale projects.

2.2.4. Composite coating

For composite coating, a study by Borys Mykhalichko and Helen Lavrenyuk [9], a flame-retardant coating for wood was developed using an epoxy-amine composite modified with copper (II) hexafluoro silicate ($CuSiF_6$). This innovative coating aimed to enhance fire protection by incorporating materials like epoxy resin (ED-20), polyethylene polyamine as a curing agent, and $CuSiF_6$ as the primary fire-retardant component. The study found that the $CuSiF_6$-modified coating significantly reduced the combustion temperature and mass loss of the wood, classifying it as a "hardly combustible" material. Furthermore, the coating achieved a first group fire protection rating, effectively stopping combustion upon flame removal and significantly reducing smoke production. Fig. 7 shows the wood specimens before and after the combustibility tests. A limitation of the study is that the potential environmental impact and toxicity of copper (II) $CuSiF_6$ raise concerns regarding large-scale application, especially in indoor settings. $CuSiF_6$ contains fluoride ions, which can be hazardous in high concentrations, and copper ions, which may be toxic to aquatic life and could leach into the environment under humid conditions.

2.2.5. Geopolymer coating

For geopolymer coating, Qi Yang et al. [41] studied the impact of the aluminium-to-silicon (Al/Si) molar ratio on the fire resistance and intumescence of sodium-based geopolymers for steel protection. Using metakaolin (MK) and silica fume (SF) as geopolymer materials, activated by Na_2SiO_3 and NaOH, they tested Al/Si ratios of 0, 0.18, 0.36, and 0.54. Geopolymers with lower Al/Si ratios displayed strong intumescent behaviour, expanding to form hollow structures that effectively insulated heat, reducing the backside steel temperature by 347°C compared to uncoated steel. In contrast, higher Al/Si ratios (such as 0.54) resulted in rigid structures with minimal expansion, limiting fire protection due to shrinkage and cracking. Dynamic mechanical analysis indicated that lower Al/Si ratios promoted structural softening, enabling intumescence at around 100°C. However, while the study used basic microscopy to examine changes in the geopolymer structure after fire exposure, a more detailed analysis could provide clearer insights about the material behaves at high temperatures. Techniques like scanning electron microscopy (SEM) and X-ray diffraction (XRD) could reveal finer structural details and identify changes in bonding and phases. This would enhance understanding of the coatings durability and could lead to better fire-resistant formulations. Fig. 8 shows the optical microscopy of GP from the surface.

Besides that, Rena Yulia Putri et al. [40] examined the impact of graphite addition on the fire resistance of a MK-SF geopolymer coating for steel. The geopolymer formulation incorporated MK, SF, and alkaline activators (NaOH and water glass), with additives including graphite and a diammonium phosphate-starch-urea (DSU) mixture. The study found that graphite enhanced the coatings fire resistance but did not significantly influence its intumescent behaviour. Fire tests revealed that the MSGD sample, containing DSU, provided effective fire protection, maintaining the steels temperature at approximately 350°C after 30 minutes, whereas uncoated steel reached 500°C within just 14 minutes. Nevertheless, while the additives DSU is easy to prepare, cost-effective, and enhances thermal properties, DSU-based coatings might not be as durable in humid or wet conditions, which could affect long-term fire resistance. Fig. 9 shows the coated steel specimens after the fire test.

Next, Mohd Salahuddin et al. [31] investigated a rice-husk-ash (RHA)-based geopolymer coating designed to enhance fire-retardant and thermal properties. This coating incorporated geopolymer materials such as FA, MK, blast furnace slag, and alkaline activators (NaOH and Na_2SiO_3) with RHA as an additive. The study found that an RHA/activated alkaline solution (RHA/AA) ratio of 0.30 and a NaOH concentration of 6 M optimized the coatings thermal performance and structural integrity during fire tests. These parameters were shown to significantly impact the coatings fire resistance and thermal properties. Fig. 10

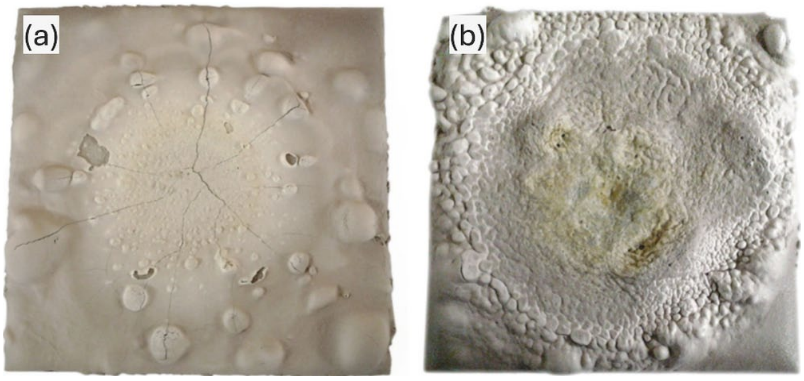

Fig. 7. Mild steel plate coated with geopolymer binder for samples (a) S5 (RHA/AA Ratio = 0.70) and (b) S7 (RHA/AA Ratio = 0.40) after fire-retardant test [24]

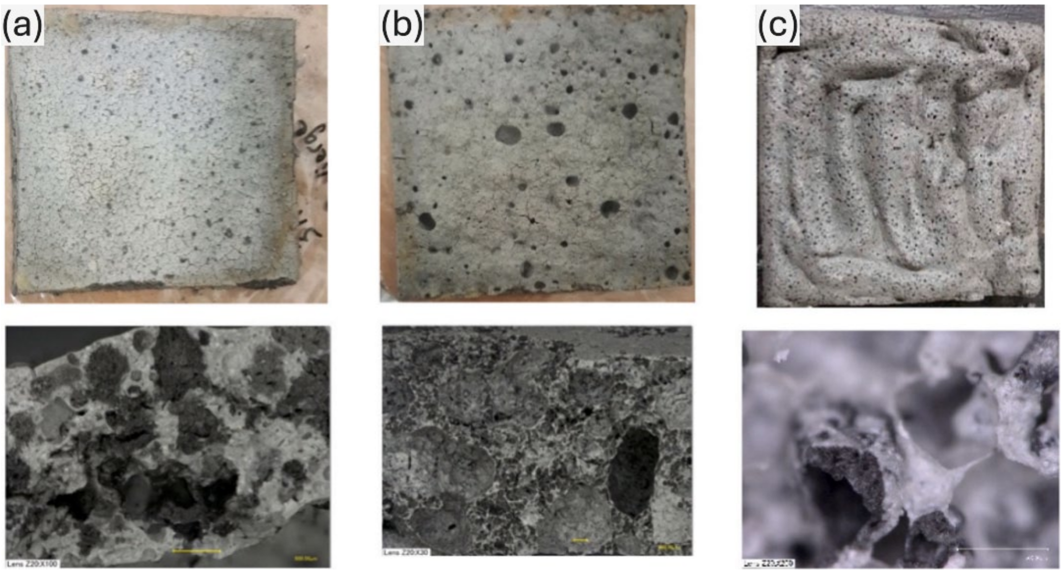

Fig. 8. Macrophotographs of GP foam coatings before and after fire test (a) H_2O_2 (0%w) CTABr (0%w), (b) H_2O_2 (0%w) CTABr (0.05%w), and (c) H_2O_2 (2%w) CTABr (0.05%w) [11]

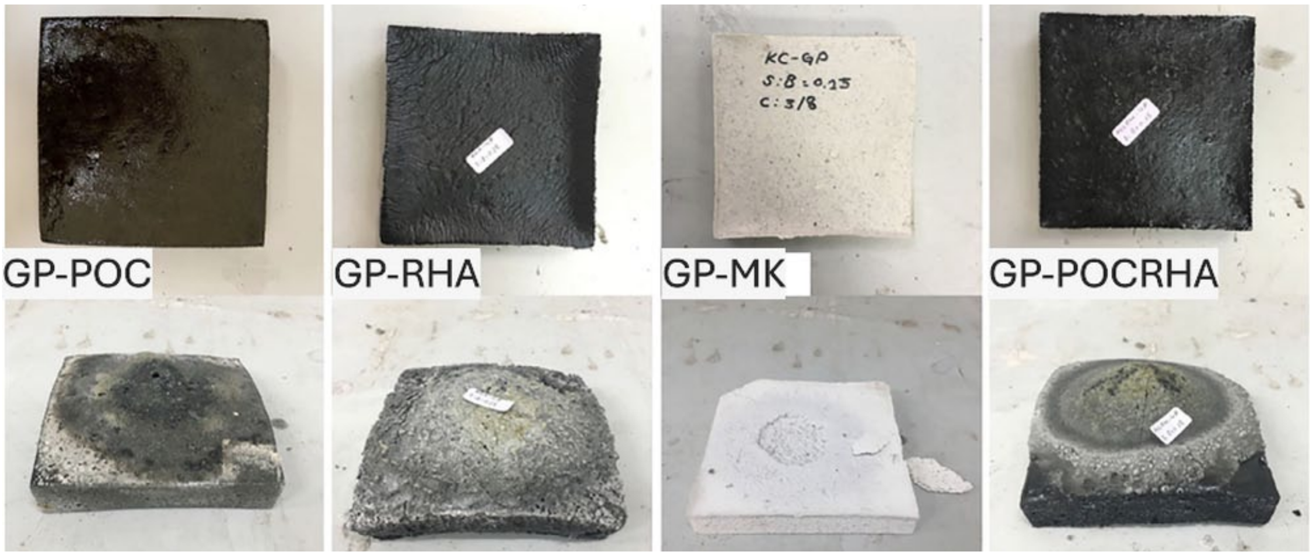

Fig. 9. The images of GP:POC, GP:RHA, GP:MK, and GP:POC-RHA before (top) and after (bottom) subjected to high temperature flame in flame exposure test [26]

shows the mild steel plate coated with geopolymer binder after fire-retardant test.

Moreover, Johan Sarazin et al. [17] investigated the flame resistance and thermal effectiveness of geopolymer foam coatings for protecting steel surfaces. The geopolymer formulation included MK, SF, and alkaline activators (NaOH and Na_2SiO_3), with hydrogen peroxide (H_2O_2) and cetyltrimethyl ammonium bromide (CTABr) as foaming agents and stabilizers. The study found that incorporating CTABr in the foam significantly enhanced fire resistance, reducing the back steel temperature by 251°C compared to 203°C for foams without CTABr. Additionally, the geopolymer coatings maintained structural integrity and did not detach from the steel during fire exposure. However, using only one thickness for the geopolymer foam coatings limits insights into how thickness affects fire protection and cost. Future studies should test different thicknesses to find the best balance between material use and insulation. Fig. 11 shows the macrophotographs of GP foam coatings before and after fire test.

Furthermore, Abdul Rashid M. et al. [44] evaluated the fire resistance, thermal stability, and surface morphology of composite coatings with geopolymer-based bio-fillers for application in structural insulated panels (SIP). The study tested different binders, including ordinary Portland cement (OPC), calcium aluminate cement (CAC), and an alkali-activated geopolymer (GP), alongside fillers such as palm oil clinker (POC), rice husk ash (RHA), and metakaolin (MK). Results showed that coatings with geopolymer binders, particularly those incorporating palm oil clinker (GP) and rice husk ash (GP), demonstrated superior fire resistance compared to coatings with traditional binders like OPC and CAC. Optimizing the coating formulation, including

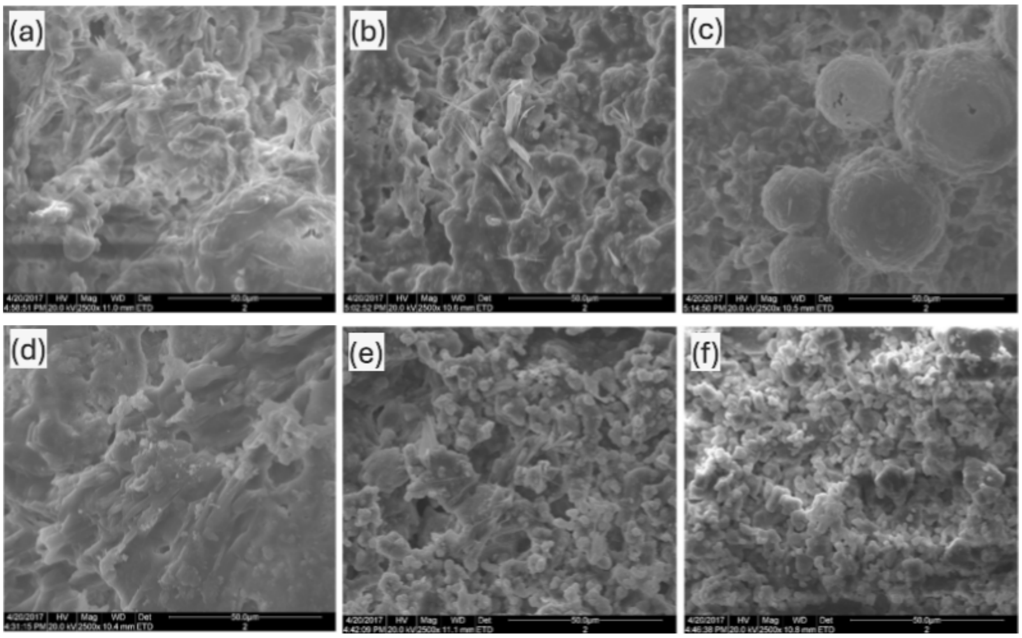

Fig. 10. Micro-morphology of samples with an amplification of 2500 after burning including (a) FA (4.73 g) Slag (0 g), (b) FA (7.88 g) Slag (0 g), (c) FA (11.03 g) Slag (0 g), (d) FA (0 g) Slag (3.15 g), (e) FA (0 g) Slag (6.30 g), (f) FA (0 g) Slag (9.45 g) [25]

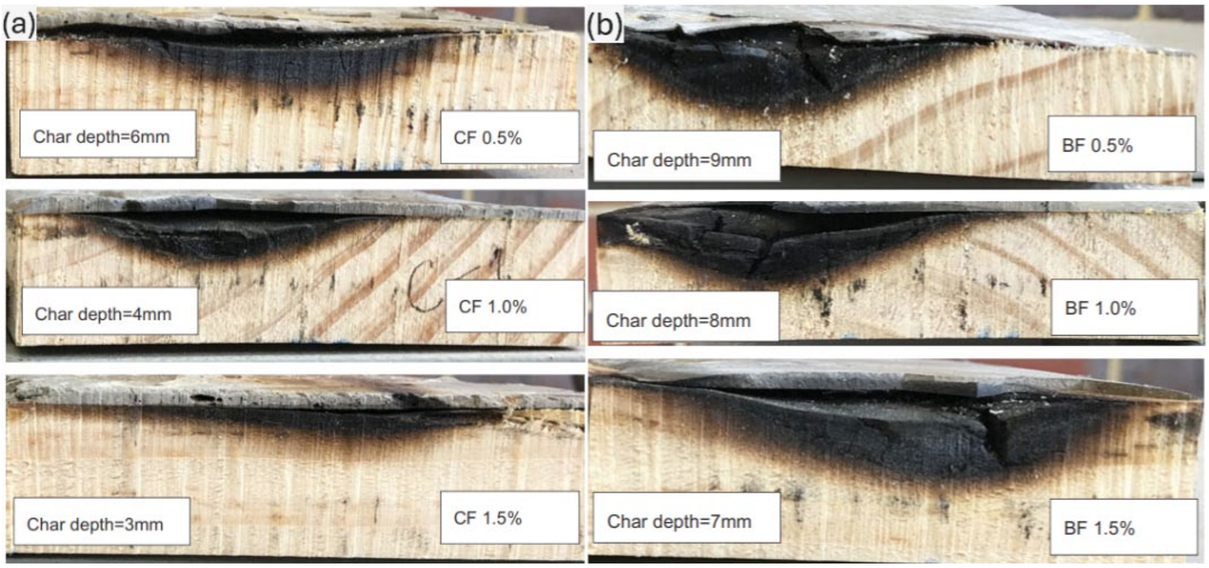

Fig. 11. (a) Char depths of timber coated with thick geopolymer coating containing CF and (b) BF [10]

thickness and the alkaline activator ratio, enhanced fire resistance, with GP achieving nearly 2 hours of protection during flame exposure. These findings highlight the critical role of binder and filler choices in improving the thermal stability and fire resistance of geopolymer coatings, positioning them as viable materials for SIP applications. Although multiple fillers were studied, combinations or varied proportions of these fillers were not tested, and further exploration of filler ratios could offer deeper insights into how different compositions influence fire resistance and other material properties. Fig. 12 shows the images of samples before and after the flame exposure test.

Then, Ya Chao Wang and Jiang Ping Zhao [45] explored the development of geopolymer composite coatings using either FA or GGBS to enhance flame resistance. The coating was activated with Na_2SiO_3 and potassium hydroxide (KOH), with varying contents of FA and GGBS. The study found that geopolymer coatings significantly improved flame resistance when used at optimal content levels, specifically 25 wt.% for either slag or FA. The slag-based coating demonstrated a 45.5% reduction in Peak Heat Release Rate (pHRR), while the FA-based coating reduced pHRR by 39%. The results indicated that slag-based geopolymers offered a strong blocking effect on the transfer of volatiles and heat due to their chemical activity in alkali conditions. However, the study focused solely on coatings with either slag or FA, without exploring potential synergistic effects from combining both materials. Testing mixed formulations, such as FA with moderate amounts of slag, could reveal an optimal balance for enhancing fire resistance by leveraging the workability of FA

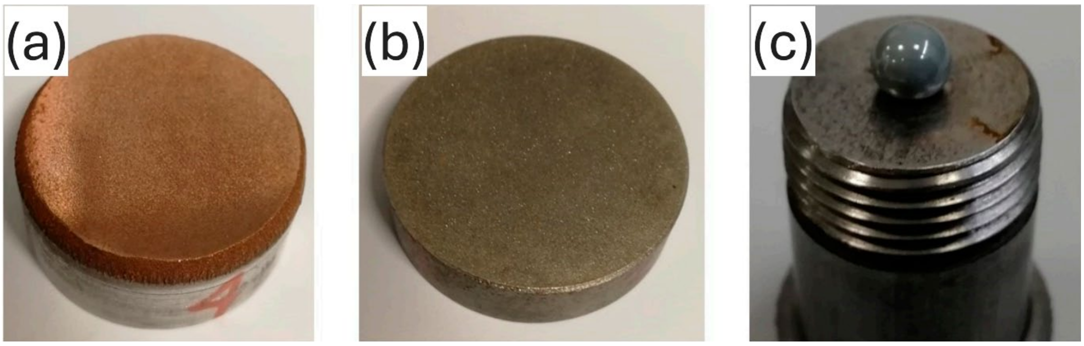

Fig. 12. Samples for testing: (a) DMMC, (b) D30, and (c) Si_3N_4 ball [38]

and the strength of slag. Fig. 13 shows the micro-morphology of samples with different content of FA and slag.

In addition, Faiz Uddin A.S. et al. investigated the fire resistance of FA-based geopolymer coatings for pine timber, activated with sodium (Na) and potassium (K) hydroxides. The study utilized Class F FA as the geopolymer base and included carbon fiber (CF) and basalt fiber (BF) as reinforcing additives. The coatings achieved bond strengths of approximately 0.90 MPa with Na and 0.85 MPa with K on smooth timber surfaces. Increasing the coating thickness from 2 mm to 4 mm resulted in a 35-45% reduction in char depth, while the addition of CF and BF further improved fire resistance, with CF yielding a 67-79% reduction in char depth. These findings highlight the potential of FA geopolymer coatings as effective fire-resistant materials for timber. However, the study lacks microstructural analysis post-fire exposure, which could offer valuable insights into structural changes in the geopolymer matrix and fibers under heat, thereby elucidating the materials failure mechanisms and resilience. Fig. 14 shows the char depths of timber coated with thick geopolymer coating containing CF and BF.

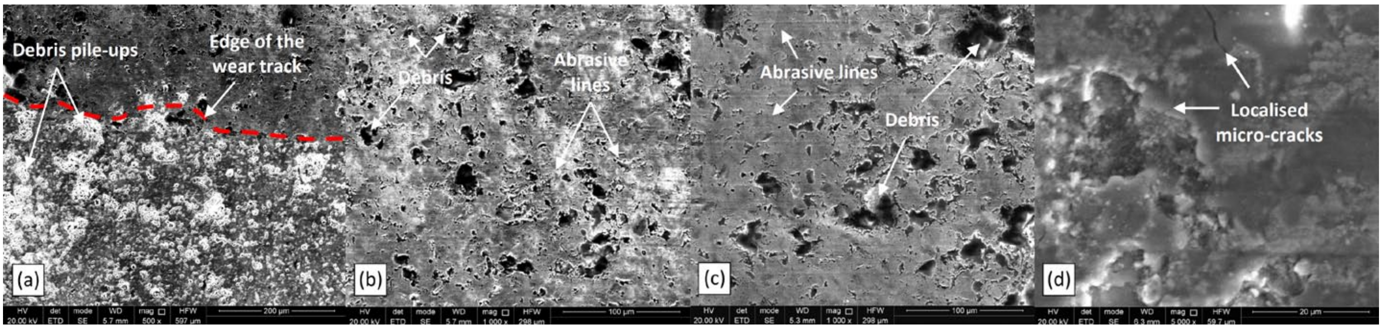

Fig. 13. SEM images of (a) debris formation at the edge of chromia coating wear track, (b) abrasion lines and particle generation within chromia coating wear track, (c) abrasion and particle generation within titania coating wear track and (d) micro-crack formation within titania coating wear track [40]

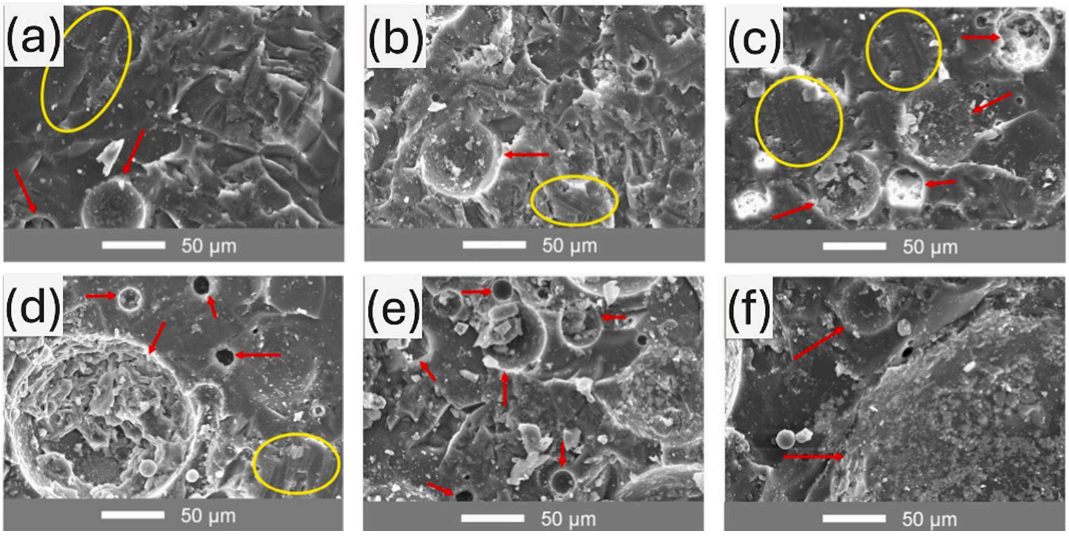

Fig. 14. SEM image after the abrasion test: a) without nano-WC particles, b) 1 wt.% addition, c) 2.5 wt.% addition d) 5 wt.% addition, e) 7.5 wt.% addition, and f) 10 wt.% addition [46]

TABLE 2

Recent Works of Abrasion-Resistant Coatings

Authors	Types of Coatings	Materials	Parameters	Key Findings
Filos et al. [38]	Metal coating	1) Abrasive particles: Synthetic diamond. – Used in two forms, as an electrodeposited coating (D30) and as part of a diamond-reinforced metal matrix composite (DMMC) coating. 2) Metal matrix components: Copper powder. 3) Substrate Materials: Aluminium alloy and cast iron.	1) Sliding speed. 2) Coating deposition on diamond particle density and granulometry.	1) D30 coatings with larger diamond particles result in higher wear rates and rougher surfaces, especially at higher sliding speeds. 2) DMMC coatings with finer diamond particles offer better wear resistance and smoother surfaces for controlled abrasion applications.
Savulyak et al. [39]	Alloy coating	1) Alloying compositions: Fe-Cr-Mo-V-C and Fe-Cr-B4C-Mo-C (contain iron, chromium, molybdenum, vanadium, boron carbide, and carbon). 2) Suspension Medium: Silicate Glue (Liquid Glass). 3) Substrate: Steel (Steel 45).	Chromium content in alloy compositions	1) Increasing chromium content from 2% to 10% improved hardness and wear resistance by forming complex alloyed carbides. 2) Addition of vanadium, molybdenum, and boron further enhanced wear resistance.
Georgiou et al. [40]	Ceramic-based coating	1) Ceramics: Chromia (95Cr2O3) and Titania (99TiO2) powders. 2) Bond coating: Nickel-aluminide layer for adhesion. 3) Substrate: Steel.	1) Abrasive sliding conditions using a pin-on-disk apparatus. 2) Varying coating thickness and friction force measurements.	1) Chromia and titania coatings showed strong wear resistance with abrasion as the main wear mechanism, demonstrating high durability under abrasive conditions. 2) Chromia coating showed higher friction fluctuations due to debris pile-up, while titania coating had smoother friction performance.
Çöpoğlu and Çiçek [41]	Glass-ceramic coating	1) Glass-ceramic matrix: Based on oxides in the SiO_2-Na_2O-B_2O_3-Al_2O_3-CaO system. 2) Reinforcement: Tungsten carbide (WC) nanoparticles. 3) Additives: Fe-Cr-Co pigment, clay, boric acid, sodium nitrite. 4) Substrate: Cast iron.	Various weight percentages of WC nanoparticles	1) Optimal performance at 2.5 wt.% WC, yielding lowest mass loss and minimal surface changes. 2) Higher WC ratios caused particle agglomeration, reducing abrasion resistance, indicating an optimal concentration for best results.
Schwarz P. et al. [42]	Metal matrix composite (MMC) coating	1) Matrix: X400CrVMo17-15-2 alloy. 2) Reinforcement: Fused tungsten carbide (FTC) and metallic carbide (MC). 3) Heat Treatment Media: Cryogenic treatment. 4) Substrate: S235JR steel.	Heat treatment: two routes with cryogenic treatment.	1) FTC-reinforced coatings showed highest abrasion resistance, reducing wear more than heat treatment alone. 2) Heat treatment improved hardness and wear resistance but was less effective than FTC. 3) Harder matrix in heat-treated coatings reduced wear groove size in scratch tests.
Novotny et al. [43]	Geopolymer coating	2) Geopolymer suspension ingredients: MK, aluminium hydroxide ($AlOH_3$), aluminium oxide (Al_2O_3), graphite, sodium silicate (water glass), phosphoric acid (H_3PO_4), isopropanol (iPrOH). 2) Substrate: Aluminum alloy EN-AW 6060 (AlMgSi0.5).	Composition of geopolymer suspensions.	1) Geopolymer coatings achieved high-quality layers on aluminum with thicknesses of 1.5-11 μm. 2) Al_2O_3 particles improved microhardness and reduced thermal expansion. 3) Graphite reduced microhardness, indicating softening effect.
Ariyanto et al. [44]	Geopolymer coating	1) Fibers for Reinforcement: Ramie (natural fiber), basalt, carbon, PVA, and steel fibers. 2) Geopolymer: FA 3) Alkaline activators: Na_2SiO_3 and NaOH. 3) Additives: SF 4) Testing Abrasives: Sand, steel balls.	Types of fiber reinforcement.	1) Geopolymer mortar with ramie fiber enhances abrasion resistance in hydraulic structures. 2) Ramie fiber reduces brittleness and improves durability. 3) Silica fume strengthens the matrix by filling voids and aiding chemical reactions.
Witzke et al. [45]	Geopolymer coating	1) Geopolymer Matrix: MK with 10% RHA. 2) Alkaline Activators: Na_2SiO_3 and NaOH. 3) Aggregates: Medium sand, granite gravel. 4) Abrasives for Testing: Dry sand, metallic spheres, aluminium oxide.	Testing methods: inorganic, hydraulic, deep abrasion, and natural wear exposure.	MK-based geopolymers with 10% RHA demonstrated excellent abrasion resistance, making them suitable for sustainable construction materials in areas with light traffic or hydraulic wear.

3. Overview of abrasion-resistant coatings

Abrasion-resistant coatings are essential for enhancing the durability and longevity of various materials and components across multiple industries. These coatings are designed to protect surfaces from wear and tear caused by friction and mechanical actions. The development and application of abrasion-resistant coatings involve various materials and techniques, each tailored to specific requirements and environments. TABLE 2 summarizes recent research on coatings for abrasion-resistant, focusing on the types of coating, materials used, and key findings discussed in Section 3.1 – Recent Works of Abrasion-Resistant Coatings.

3.1. Recent works of abrasion-resistant coatings

3.1.1. Metal coating

In the study by Filos et al. [46], new abrasive coatings were developed for grinding wheels aimed at processing silicon nitride (Si_3N_4) ceramic balls. The research focused on two types of synthetic diamond coatings, an electrodeposited coating (D30) with larger diamond particles and a diamond-reinforced metal matrix composite (DMMC) with finer particles embedded in a copper matrix. Findings indicated that the D30 coating, with its larger particles, resulted in higher wear rates and a rougher surface finish, especially at higher sliding speeds, making it suitable for applications requiring rapid material removal. In contrast, the DMMC coating provided a more controlled abrasion and smoother surface, better suited for applications demanding precision and durability. However, the study lacks advanced surface characterization techniques, such as SEM, which could have offered deeper insights into the microstructural of the coating. This limitation suggests that further studies could explore the microstructure in greater detail to optimize coating performance. Fig. 15 shows the samples that have been prepared.

3.1.2. Alloy coating

For alloy coating, Savulyak et al. [47] conducted a study on the structure formation and wear resistance of abrasion-resistant coatings, specifically alloy compositions of Fe-Cr-Mo-V-C and Fe-Cr-B4C-Mo-C applied to steel substrates. The objective was to investigate the effect of chromium content on the hardness and wear resistance of these coatings. Using silicate glue as a bonding medium, the alloy compositions were successfully applied to Steel 45. Key findings indicated that increasing the chromium content from 2% to 10% improved the hardness and wear resistance due to the formation of complex alloy carbides. Additionally, the addition of vanadium, molybdenum, and boron contributed to enhanced wear resistance, highlighting the effectiveness of these elements in strengthening the coating. Nevertheless, the study lacks consideration of environmental and safety concerns associated with elements like chromium and vanadium can be hazardous and pose environmental risks. Moreover, the study also lacks advanced surface characterization techniques like SEM, which would offer a deeper understanding of microstructural effects on wear resistance.

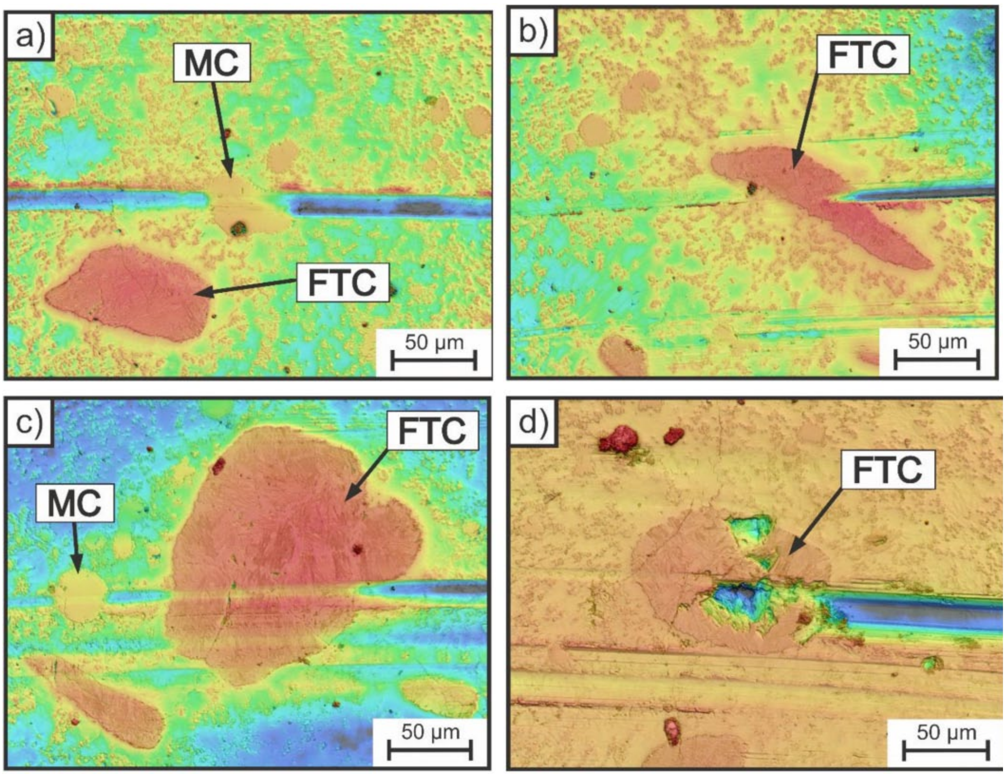

Fig. 15. LSM images of (a-c) regions with both FTC and MC particles, (b-d) focus on areas dominated by FTC particles [42]

3.1.3. Ceramic-based coating

For ceramic-based coating, Georgiou et al. [48] investigated the tribological performance of thermally sprayed ceramic coatings, specifically chromia (Cr_2O_3) and titania (TiO_2), under abrasive sliding conditions. The objective was to evaluate friction and wear characteristics of these coatings, which were applied to a steel substrate with a nickel-aluminide bond layer. Using a pin-on-disk apparatus, the study assessed performance under varying coating thicknesses and friction forces. Results indicated that both chromia and titania coatings displayed strong wear resistance, with abrasion being the main wear mechanism. Chromia exhibited higher friction fluctuations due to debris pile-up, whereas Titania provided smoother friction performance. Nonetheless, the study did not explore environmentally safer alternatives to chromium oxide, which is known to be hazardous and poses environmental concerns. Fig. 16 shows SEM images of the coating samples.

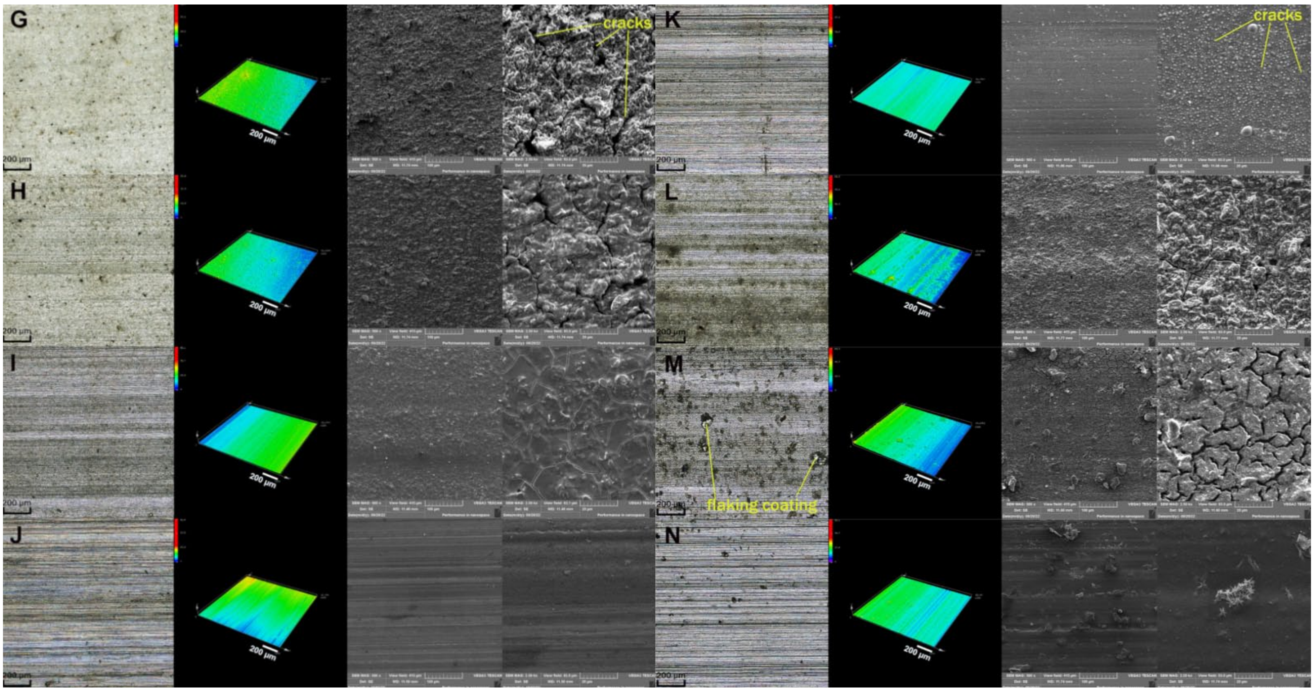

Fig. 16. SEM and CLSM analysis of the surface of G–N geopolymer suspensions [43]

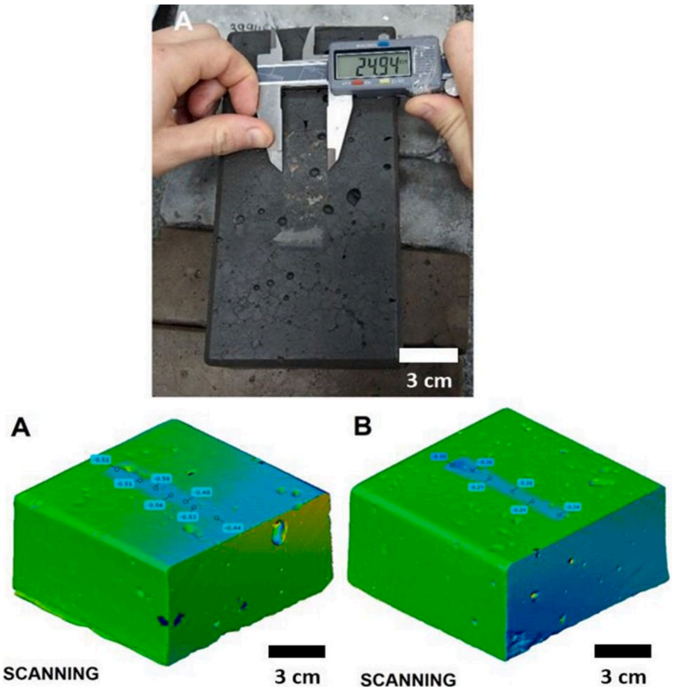

Fig. 17. Samples after the deep abrasion test: (A) 10% of RHA; (B) MK [45]

3.1.4. Glass-ceramic coating

Çöpoğlu and Çiçek [49] investigated the development of glass-ceramic coatings reinforced with tungsten carbide (WC) nanoparticles to improve abrasion resistance when applied to cast iron surfaces. The study focused on varying the weight percentages of nano-WC particles (1%, 2.5%, 5%, 7.5%, and 10%) in a glass-ceramic matrix composed primarily of oxides (SiO_2, Na_2O, B_2O_3, Al_2O_3, CaO). Additional additives, such as black pigment for color, clay for adhesion, boric acid as a flux, and sodium nitrite for corrosion resistance, were also included. Results demonstrated that a 2.5 wt.% concentration of nano-WC particles provided the best performance, with the lowest mass loss and minimal changes in surface properties during abrasion tests. Higher concentrations of WC caused particle agglomeration, which reduced abrasion resistance, indicating that 2.5 wt.% is likely the optimal concentration. Despite these findings, the study lacks analysis of other mechanical properties, such as hardness, fracture toughness, and adhesion strength, which are crucial for understanding the full durability of the coating under mechanical stress. Fig. 17 shows SEM image of the samples after the abrasion test.

3.1.5. Metal Matrix Composite (MMC) coating

Schwarz P. et al. [50] explored the influence of particle reinforcement and heat treatment on the wear resistance of inductively melted hard paint coatings, using a metal matrix composite (MMC) system. The study applied an alloy matrix (X400CrVMo17-15-2) reinforced with particles of fused tungsten carbide (FTC) and metallic carbide (MC) on an S235JR steel substrate. Heat treatment, including cryogenic treatment, was used to modify the matrix structure and enhance hardness and wear resistance. The findings showed that FTC-reinforced coatings achieved the highest abrasion resistance, outperforming coatings treated by heat alone. Heat-treated unreinforced coatings also displayed improved hardness and wear resistance, but not to the same extent as FTC-reinforced coatings. Additionally, coatings with a harder matrix due to heat treatment demonstrated reduced wear groove size in scratch tests. However, FTC's high cost and limited global availability may restrict its practical application in cost-sensitive industries, and the energy-intensive heat treatment process, particularly with cryogenic treatment, raises concerns about sustainability and environmental impact for broader applications. Fig. 18 shows the Laser Scanning Microscopy (LSM) images of the samples after the abrasion test.

3.1.6. Geopolymer coating

For geopolymer coating in the role of abrasion resistance, Novotny et al. [51] investigated the manufacture and characterization of alkali-activated MK-based geopolymer coatings, which were applied as brush-on layers on aluminium substrates (EN-AW 6060 alloy). The study focused on the different composition of geopolymer suspensions (G-N), including ingredients such as metakaolin as the base material, aluminium hydroxide ($AlOH_3$), nano-sized Al_2O_3 particles for enhancing microhardness, graphite as a softening agent, Na_2SiO_3 as a binder, phosphoric acid as a matrix modifier, and isopropanol as a solvent. The findings indicated that geopolymer coatings achieved high-quality layers with thicknesses ranging from 1.5 to 11 µm. Al_2O_3 particles contributed to improved microhardness and reduced thermal expansion, while graphite led to a decrease in hardness, acting as a softening agent. Nevertheless, the preparation process for these geopolymer materials may be somewhat complex where the use of nano Al_2O_3 particles requires additional precautions to prevent agglomeration, which could impact the quality and abrasion resistance of the coating. Fig. 19 shows the SEM and Confocal Laser Scanning Microscopy (CLSM) analysis of the samples surface.

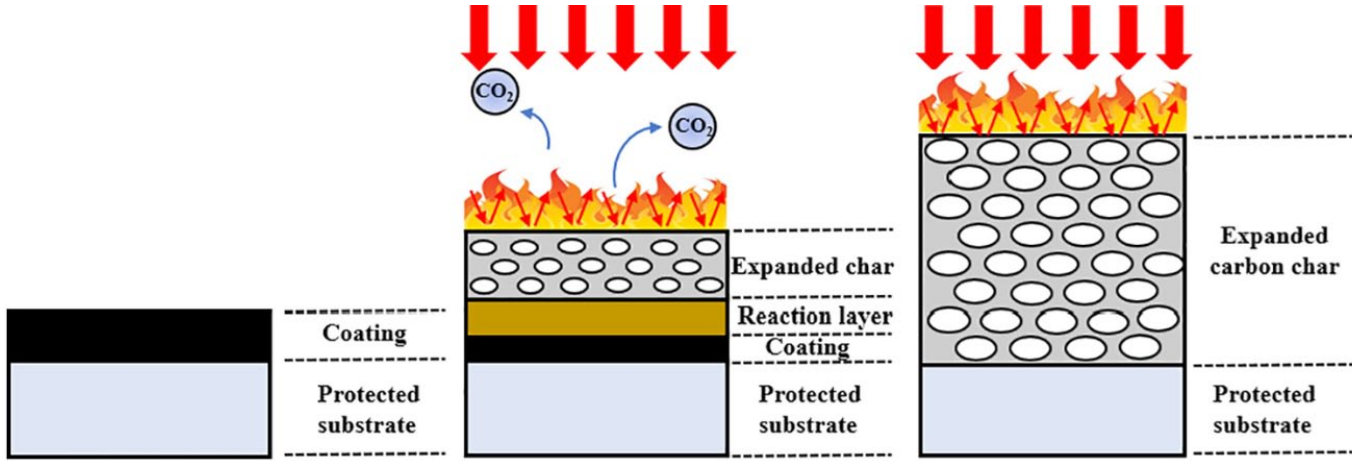

Fig. 18. Mechanisms of fire-retardant coating [14]

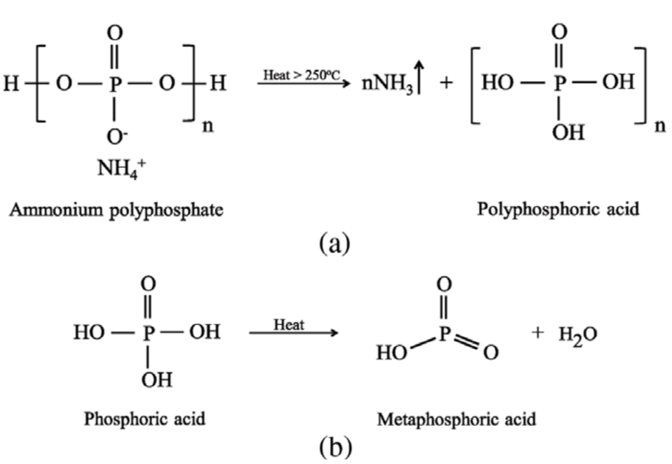

Fig. 19. APP thermal decomposition reactions: (a) decomposition of APP and (b) decomposition of phosphoric acid [13]

Besides that, Ariyanto et al. [52] conducted a review to discuss various abrasion testing methods and efforts to enhance abrasion resistance in hydraulic structures through the use of geopolymers and additional reinforcing materials. The objective of their study was to examine how fibers and other additives can improve the durability and abrasion resistance of geopolymers in demanding environments. The review included different types of fiber reinforcements such as ramie (a natural fiber), basalt, carbon, polyvinyl alcohol (PVA), and steel fibers. These fibers were selected for their unique properties which are ramie to reduce brittleness, basalt for durability, carbon for its high strength-to-weight ratio, PVA for bonding, and steel for impact resistance. The geopolymer matrix was composed FA with Na_2SiO_3 and NaOH. Additionally, SF was used as a pozzolanic additive to fill voids and improve matrix strength, while sand

and steel balls were employed in abrasion tests to simulate hydraulic wear conditions. Key findings indicated that ramie fiber and SF effectively enhanced abrasion resistance and mechanical durability in hydraulic applications. However, the review lacked advanced microscopic characterization techniques, such as SEM or XRD, which could have provided insights into fiber dispersion, crack propagation, and the crystalline structure of the geopolymer matrix, offering a deeper understanding of the composite's structural integrity and wear mechanisms.

In addition, Witzke et al. (2023) conducted a study to evaluate the abrasion resistance of MK-based geopolymer coatings, particularly focusing on their performance in both accelerated tests and natural wear conditions. The geopolymer matrix was developed using MK as the primary aluminosilicate precursor, with RHA used as a 10% replacement to enhance matrix density and abrasion resistance. Na_2SiO_3 and NaOH served as activators, while sand and gravel aggregates provided structural integrity. Various abrasive testing materials which are dry sand, metallic spheres, and aluminium oxide were used to simulate different abrasion conditions. The study found that MK-based geopolymers modified with 10% RHA exhibited excellent abrasion resistance, making them a sustainable and durable choice for construction materials, particularly in applications exposed to light traffic or hydraulic wear. However, the study's limitation was that it only tested a 10% RHA replacement level, exploring other ratios such as 5%, 15%, and 20% could help identify the optimal amount for maximum abrasion resistance without compromising other mechanical properties. Fig. 20 shows the samples after the deep abrasion test.

4. Summary and future works

This review provides a comprehensive analysis of recent advancements in fire-retardant and abrasion-resistant coatings, with a particular focus on sustainable and high-performance alternatives. Among the materials studied, geopolymer-based coatings stand out due to their excellent environmental sustainability, superior thermal stability, and mechanical strength. Geopolymers form a ceramic-like char at high temperatures, offering exceptional fire resistance, while their dense microstructure ensures remarkable abrasion resistance. Additionally, their ease of fabrication, low cost, and eco-friendly nature make them a promising alternative to conventional synthetic coatings.

Despite these advantages, several limitations must be addressed to fully realize the potential of geopolymer coatings. Challenges such as adhesion to metal substrates, resistance to moisture degradation, and long-term durability under cyclic thermal and mechanical stresses require further investigation. Moreover, the lack of standardized testing methodologies across studies hinders consistent performance evaluation, highlighting the need for unified protocols.

To advance the development of geopolymer-based coatings for fire-retardant and abrasion-resistant applications, future research should focus on the following areas:

1) Optimizing Geopolymer Formulations: Investigate the effects of varying the ratios of geopolymer precursors (e.g., fly ash, metakaolin, sodium silicate, and NaOH) to enhance adhesion, mechanical strength, and long-term performance. Explore the incorporation of additives such as nanomaterials or fibers to improve specific properties.
2) Curing Conditions and Adhesion: Study the impact of curing condition, such as temperature, humidity, and pressure on the structural integrity and bonding strength of geopolymer coatings on substrates like mild steel, aluminium, and composites.
3) High-Tech Fire and Mechanical Testing: Conduct advanced fire tests to evaluate the durability of geopolymer coatings under extreme conditions, including prolonged exposure to high temperatures and rapid thermal cycling. Perform mechanical tests, such as adhesion strength, abrasion resistance, and impact resistance, to assess performance in real-world applications.
4) Standardization of Testing Protocols: Establish standardized testing methodologies to ensure consistent and comparable performance evaluation across studies. This will facilitate the development of reliable and reproducible geopolymer coatings for industrial applications.

By addressing these research gaps, geopolymer-based coatings can be further optimized to meet the demanding require-

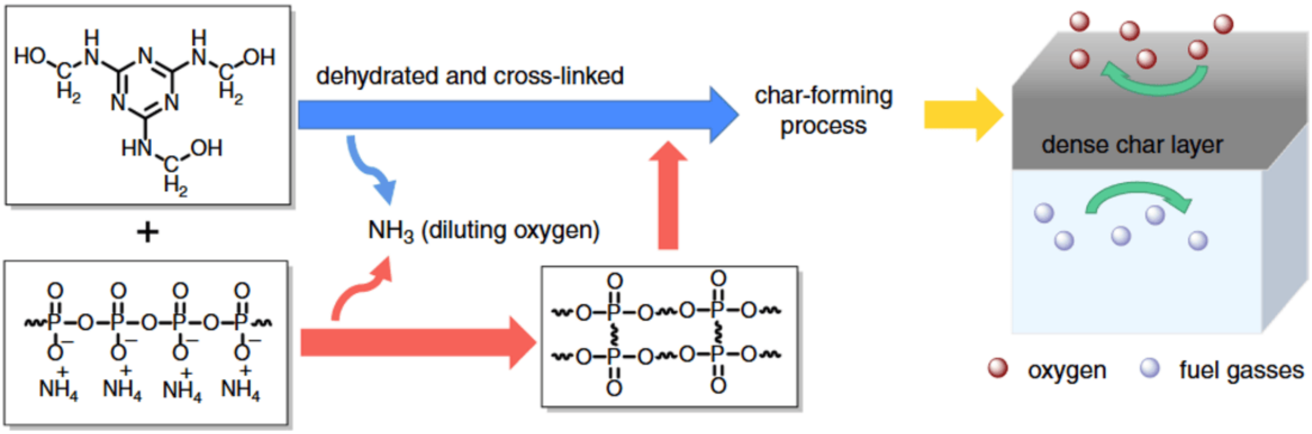

Fig. 20. Char formation mechanism involving APP and MEL derivatives [6]

ments of modern fire-retardant and abrasion-resistant applications, paving the way for their widespread adoption in industries such as construction, aerospace, and automotive.

Acknowledgement

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