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Development of Low-Smoke, Eco-Friendly, Fire Retardant, Intumescent Coatings for GI and Steel Structures

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ABSTRACT

This study presents the development of eco-friendly intumescent coatings with reduced smoke emission. Water-based formulations were developed by adjusting the type of binder used (PVAc, PVAc-Epoxy) and incorporating a smoke suppressant filler (Zinc Borate) to enhance performance. Fire tests revealed that these coatings produced carbonaceous char layers over 70 times thicker than the original coating. Char morphology and composition were evaluated via SEM-EDS and TGA. The most effective formulation, comprising a water-based binder with 50 % epoxy and hardener, exhibited superior fire resistance, passing the BS 476 Part 5 ignitability test. It achieved a fire propagation index below 12 (BS 476 Part 6) and attained Class 1 surface flame spread (BS 476 Part 7). Smoke density (ASTM E 662) remained below critical thresholds specified by NFPA 230, with optical densities under 100 and 200 at 1.5 and 4 minutes, respectively. Formulation IC3 nearly satisfied non-combustibility criteria and maintained steel substrate temperatures at approximately 200 °C for 120 minutes in direct flame, demonstrating robust thermal insulation. Prog Color Colorants Coat. 19 (2026), 189-205© Institute for Color Science and Technology.

1. Introduction

Steel and Galvanised Iron (GI) (steel coated with zinc) are widely used in various industries, especially in building and infrastructure, due to their high strength, durability, increased resistance to corrosion and rust, and availability for structural frameworks, bridges, and facilities [1]. Under extreme situations, such as accidental fires, both steel and GI can lose significant strength. Steel frameworks begin to lose their structural integrity when exposed to temperatures exceeding 500 °C, which can lead to the collapse of buildings [2, 3]. Effective fire protection techniques must be employed to ensure occupant safety and minimize the risk of building collapse during fire incidents [4]. As a result, there has been a trend toward using more sustainable and environmentally friendly alternatives. One such approach is to utilize intumescent fire-retardant coatings (IFRCs), which are specifically developed to protect metallic constructions, such as steel and GI, from high-temperature exposure. This char reduces heat transfer to the underlying metal, allowing it to maintain structural integrity for a longer period and providing critical time for evacuation and firefighting efforts [5]. The use of IFRCs has become a necessary component of passive fire protection systems in current construction.

The effectiveness of an intumescent coating in producing this protective char is determined by its carefully designed chemical composition, which ensures optimal performance. A typical intumescent formulation consists of six main components: an acid donor, a carbon donor, a blowing agent (or expanding agent), a binder (often a thermoplastic resin), pigments,

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and fillers [6, 7]. Every component is essential to the intumescence process.

When heated, an acid donor, such as phosphoric acid, produces mineral acids that activate dehydration reactions with the carbon donor. The carbon donor, such as pentaerythritol, interacts with the released acid to form a persistent, carbon-rich char layer that serves as a thermal barrier. At high temperatures, the blowing agent decomposes, releasing non-flammable gases such as carbon dioxide, ammonia, and water vapour. These gases enable the binder to foam and expand, which aids in the creation of a thick, thermally insulating char layer [8]. The binder, typically a thermoplastic resin, holds the materials together and softens when heated, facilitating the expansion process and enhancing the mechanical strength and cohesiveness of the final char [9]. Additionally, pigments and fillers are used to improve the coating's fire resistance. They help to control the rate of expansion, strengthen the char structure, limit hazardous gas emissions, and improve the coating adhesion to the substrate [10].

Various studies have been conducted on the protection of steel structures using fire-retardant intumescent coatings [11-14]. Various inorganic fillers were added to the intumescent coating composition, enhancing the function of intumescent coatings [15-18]. The research investigated the impact of glass flakes (GF) on the performance of waterborne intumescent fire-resistant coatings (IFRCs). It was found that glass flakes significantly enhance the fire resistance and water durability of these coatings [19]. The research examined the incorporation of cenospheres (hollow alumino-silicate microspheres sourced from fly ash) as a filler in water-based intumescent fire-retardant coatings (IFRC) utilised on structural steel. The coatings containing cenospheres produced a stable and well-adhered char [20]. The study investigated the effectiveness of using nano-sized zinc borate (ZB) as a replacement for boric acid in intumescent fire-retardant coatings (IFRCs) applied to steel. The coating that demonstrated the best performance was IFRC-ZB3, which contained 3 wt. % zinc borate. After one hour of direct fire exposure, the steel temperature remained under 200 °C, as per the UL-1709 standard. The char produced exhibited an expansion of 8.25 times and maintained a compact and robust structure. Also, the carbon content within the char increased to 47.7 %, while oxygen levels decreased to 31.5 %. The notable reduction in gaseous products highlighted an improvement in fire resistance and a decrease in smoke generation [21]. Carbon nanomaterials, particularly graphene oxide and expandable graphite, work in conjunction with IFRC components to enhance fire resistance and promote environmental safety by minimizing smoke production [22]. Hence, many fillers that enhance the properties of IFRCs have been studied [23-27].

Resins are crucial components in intumescent coatings, as they serve as binders, holding all other materials together while also significantly contributing to the formation and expansion of the char structure after exposure to fire. They are critical in guaranteeing the homogeneity, adhesion, and mechanical strength of the final protective coating [28]. Intumescent coatings are generally classed according to the type of binder employed, which includes solvent-based, epoxy-based, and water-based formulations. Each variety has various advantages and disadvantages, depending on the intended application. Solvent- and epoxy-based coatings are renowned for their high adhesion, rapid drying times, and resistance to moisture and adverse weather conditions. These qualities make them ideal for outdoor applications and industrial settings. However, they have considerable disadvantages, including the release of poisonous gases and heavy smoke during burning, as well as the emission of volatile organic compounds (VOCs), which pose serious environmental and health concerns. In contrast, water-based intumescent coatings are a more sustainable and environmentally beneficial option. They contain fewer volatile organic compounds, are non-flammable, have a lower chemical odour, and are less expensive. Due to their safer chemical profile, these coatings are ideal for use in interior or confined space applications [29].

Furthermore, Epoxy-based waterborne coatings have gained popularity due to their multiple advantages. These hybrids have superior corrosion resistance, mechanical strength, and thermal insulation, making them ideal for fully exposed steel constructions in harsh settings [30]. For example, in unmodified PVAc/epoxy systems, the epoxy resin reacts with amine hardeners to form a crosslinked network, while PVAc remains as a separate phase. Phase separation occurs due to PVAc's incompatibility with the epoxy matrix, resulting in a two-phase structure that enhances toughness and reduces cure shrinkage. Physical blends combine the desirable properties of each polymer. For example, PVAc provides good adhesion to polar substrates and flexibility, while epoxy offers superior water resistance and durability. Physical blending enables the easy incorporation of polymers, such as PVAc, into epoxy emulsions or other water-based systems without requiring complex chemical reactions. This reduces viscosity and improves coating or adhesive processing. Their dual functionality-combining fire protection and anti-corrosion performance-makes them ideal for infrastructure applications such as bridges, offshore platforms, and industrial structures [31, 32]. A research investigation examined the impact of blending epoxy emulsion with self-crosslinked silicone acrylate (SSA) emulsion to create a mixed binder for water-based intumescent fire-resistant coatings designed for steel. The addition of 14 % SSA (by mass) notably enhanced both the fire protection and the foam structure of the coating [33].

Despite substantial studies on fire-retardant intumescent coatings and formulas, few studies have properly followed established fire testing techniques, such as those defined in the British Standards (BS 476) or India's National Building Code (NBC). These standards outline the critical performance criteria that coatings must meet to be practical and widely used in the industry. Adherence to such test techniques is critical not just for determining fire resistance but also for guaranteeing regulatory compliance and safety certification.

This study focuses on the preliminary development of fire-retardant intumescent coating formulations based on water-based binder and their performance in various standard test methods. This was achieved by comparing three coating compositions based on the addition of smoke suppressant fillers and varying the binder. Once the formulations were prepared, they underwent various characterization methods. Fire resistance was evaluated through standardised fire tests, including the British Standards BS 476 Part 5 for ignitability, BS 476 Part 6 for fire propagation index (FPI), and BS 476 Part 7 for surface spread of flame (SSF). Additionally, smoke density was measured using ASTM E 662, assessing optical densities at specified intervals. The thermal behaviour and char properties of the coatings were analysed using Thermal Gravimetric Analysis (TGA) to understand weight loss and composition changes with increasing temperature. Scanning Electron Microscopy (SEM) coupled with Energy Dispersive X-Ray Spectroscopy (EDX) provided insights into the morphology and elemental composition of the char formed during fire exposure.

2. Experimental

2.1. Materials

To create an efficient fire-protective formulation, a blend of fillers, binders, and flame-retardant additives was carefully chosen for this investigation. The main source of acid was Exolit AP 422, a high-performance ammonium polyphosphate supplied by Clariant (Germany). Pentaerythritol, serving as a carbon source, was purchased from Loba Chemie to supplement the intumescent system, while Molychem provided mela- mine, which acts as a blowing agent. To improve the coating's opacity and UV resistance, titanium dioxide (Ti-Pure R-902) from DuPont (USA) was added. To ensure optimal adhesion and effective film formation on the substrate, Exen Chem supplied a water-based polyvinyl acetate (PVAc) binder. To improve the coating's thermal stability and mechanical integrity, additional mineral fillers such as calcium carbonate and magnesium hydroxide, both obtained from Avarice, were added. Zinc borate, purchased from Fine Chemicals, was used as a multifunctional additive that acts as both a flame retardant synergist and a smoke suppressor.

2.2. Methods

2.2.1. Formation of fire-retardant intumescent coating samples

Three distinct intumescent coating formulations-IC1, IC2, and IC3-were developed, as shown in Table 1. Each formulation included a water-based PVAc binder, along with fire-retardant fillers and essential fire-retardant additives, each present in specified percentages. The solid components-additives and fillers-were allowed to mix in a ball mill for 20-25 minutes at 80 rpm. These components were thoroughly mixed with the polymer binder for 25-30 minutes with a stirrer to produce a consistent coating mixture. The main differences between the three formulations were the type and amount of binder employed, as well as the use of smoke suppressant fillers (Zinc oxide and an antimony salt) to improve fire resistance and reduce harmful gas emissions. The produced mixes were applied uniformly to mild steel and GI sheets, resulting in a constant coating thickness. After application, the coated samples were allowed to air-dry for 24 hours at

Table 1: Description of different compositions (wt. %).

Comp-osition	Binder Used	Smoke suppressant fillers (%)	Acid source (%)	Carbon source (%)	Blowing agent (%)	Fillers (%)	Binder+ solvent (%)
IC1	Water-based binder	0	21.95	13.72	13.72	12.89	37.37
IC2	Water-based binder	0.15	21.83	13.64	13.64	13.37	37.52
IC3	Epoxy-based waterborne	0.15	21.83	13.64	13.64	13.37	37.52

ambient temperatures to ensure appropriate film formation and adherence before being tested for fire and durability. The coating thickness in all the samples was measured using an Accuplus Ec-770s coating thickness gauge, DFT Meter. This formulation technique aimed to investigate the impact of binder content and additive selection on the thermal insulation performance, char stability, and smoke suppression capabilities of the coatings.

2.2.2. Characterisation

Microscopic examinations were performed using a Sigma 300 Carl Zeiss scanning electron microscope (SEM) equipped with an Oxford Instruments Energy Dispersive X-Ray spectroscopy system, operating at 20 kV. Samples were examined at magnifications of 1000× and 2500× to assess the microstructural features and elemental composition of the coating. Thermo-gravimetric analysis (TGA) was performed using a TGA55 thermal analyser manufactured by TA Instruments. The samples were loaded into crucibles and subjected to heating in an air environment at a flow rate of 20 mL/min. The temperature was gradually raised to a peak of 990 °C at a rate of 10 °C/min, reaching this maximum in 99 minutes. The TGA data enabled the assessment of weight loss across various temperature ranges.

2.2.3. Methods of evaluation of sample coatings

Various tests have been performed to evaluate the fire performance of the sample coatings, following the relevant parts of British Standard BS 476, including tests for non-combustibility (Part 4), ignitability (Part 5), fire propagation (Part 6), and surface spread of flame (Part 7) [34-38]. Also, the coating samples were evaluated with a preliminary test and Specific optical density as per ASTM E 662 [39]. Their standard methods have been discussed in the supplementary information.

3. Results and Discussions

3.1. Preliminary test

To evaluate the effectiveness of the fire protection provided by the intumescent coating samples, the thickness of the char layer that developed after the initial fire exposure test was closely monitored and quantified. Important markers of a coating's capacity to insulate the underlying substrate during fire exposure are the thickness and structural integrity (strength) of the ensuing char. Several trial coatings showed notable expansion-up to 70 times the initial coating thickness-during the water-based coating formulation optimisation phase. However, as Figure 1 illustrates, these samples frequently developed weak or fragile char layers that were susceptible to disintegration under minimal mechanical stress, thereby impairing their protective role. The chosen formulations, IC1, IC2, and IC3, were coated and evaluated to solve this problem. Under conditions of flame exposure, these compositions generated char layers that demonstrated significant expansion and excellent structural strength, as shown in Figure 2. As seen in Figure 3, the observed char thicknesses for IC1, IC2, and IC3 were roughly 40 mm, 30 mm, and 35 mm, respectively. Upon examination, the three samples showed strong, coherent char layers that did not crumble or break. Because they produce adequate amounts of protective char with dependable mechanical strength, a crucial component for protecting steel substrates during fire incidents, the results thus show that these coatings are efficient in providing fire resistance.

Figure 1: Preliminary test of a sample during optimisation of coating composition with 70 times swelling and low char strength.

Figure 2: Preliminary test results- char layer formed for samples IC1, IC2, and IC3.

Figure 3: Preliminary test results- char layer thickness for samples IC1 (40 mm), IC2 (30 mm), and IC3 (35 mm).

3.2. SEM analysis of char residue

Figure 4 shows the SEM images of the samples IC1, IC2, and IC3. A uniform, expanded, and IFRC-forming porous char is created at high temperatures, providing effective thermal insulation and barrier properties. The porous/foam-like structure shown in the images is caused by the expansion of the expanding agent, which creates an insulating barrier by trapping air. The rough, flaky structure in images depicts the carbonised matrix, which is obtained from a carbon source.

The images of sample IC1 describe a compact and dense structure characterised by aligned platelet or flake-like formations set within a porous matrix. This suggests the presence of reinforced char that may include additives such as titanium dioxide. Such a composition likely contributes to enhanced mechanical stability and provides effective resistance against gas and heat penetration. Additionally, it may indicate the presence of a well-expanded, protective intumescent char that enhances its protective qualities. Sample IC2 exhibits a loosely arranged, sponge-like formation with large, uneven cavities and a coarse surface. The flaky structure formed allows heat flow between the flakes. While it shows significant expansion, it may possess reduced char strength. This suggests that the addition of

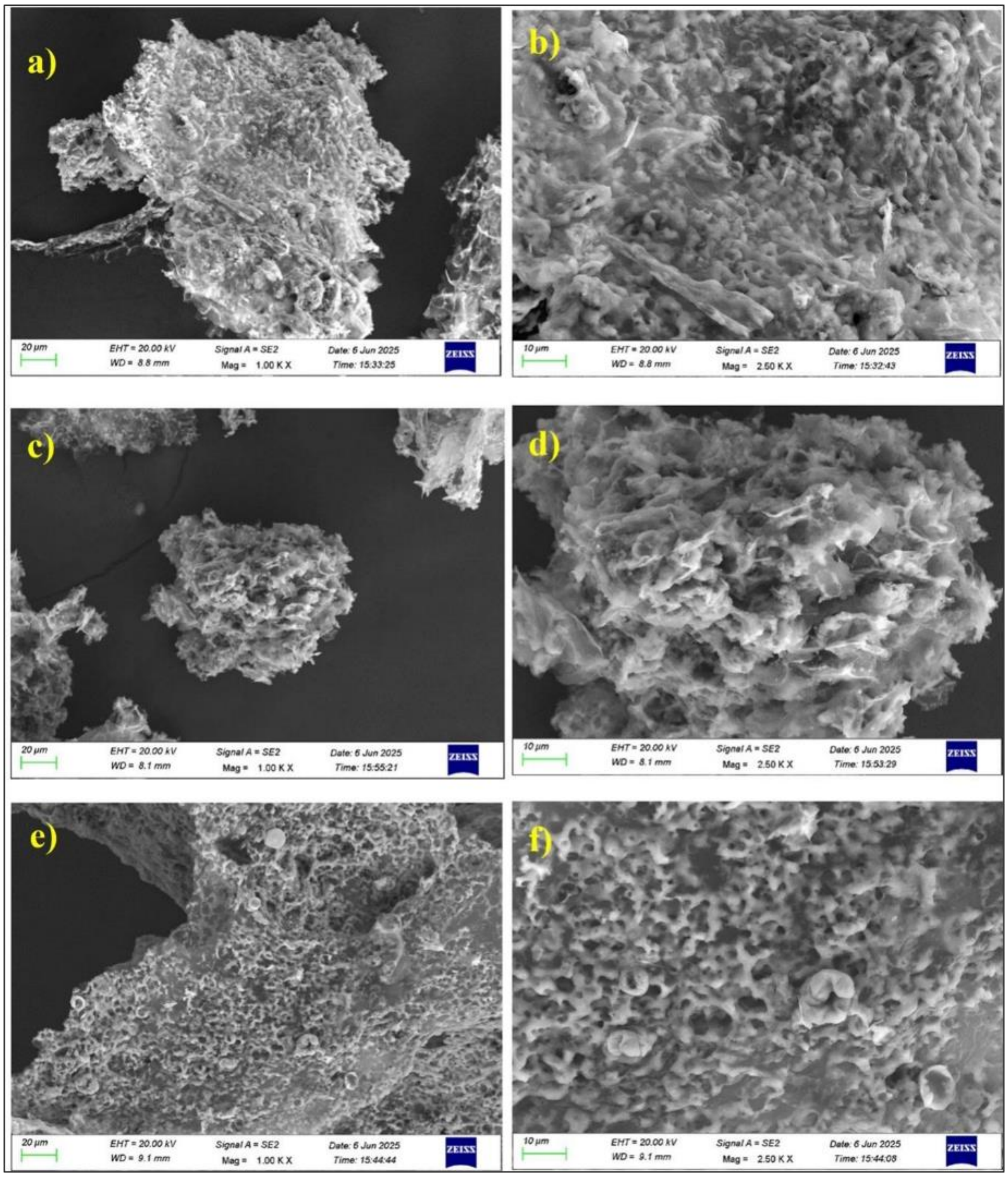
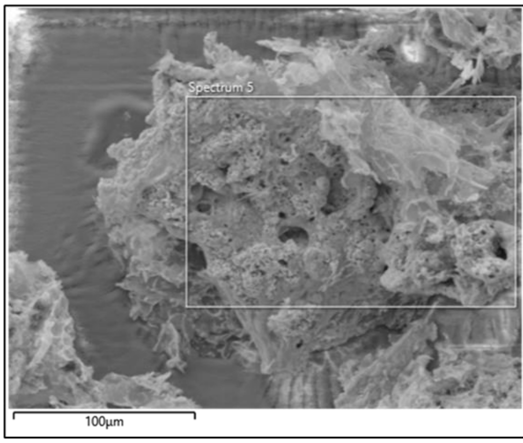


Figure 4: SEM images of the samples- a), b) IC1, c), d) IC2 and e), f) IC3.

smoke suppressants reduces the strength of the char but efficiently inhibits smoke emission. The IC3 sample exhibits a more compact and dense structure compared to IC1 and IC2, confirming more efficient insulation. Uniform, closed-cell, bubble-like, cohesive, uninterrupted matrix appearance traps gases inside cells, which acts as a thermal insulator. Such a structure is primarily formed through controlled foaming and expansion during the intumescence process. Hence, rounded, continuous, and cell-like structures form an ideal structure for efficient thermal insulation and fire resistance.

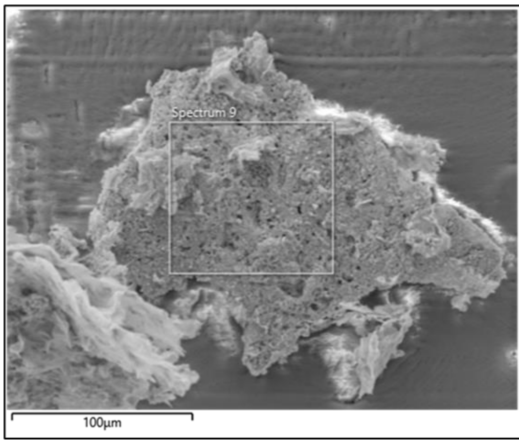
3.3. EDS analysis of char residue

Figures 5, 6, and 7 show the elemental composition in the char layer of samples IC1, IC2, and IC3. The distribution of these elements throughout various regions indicates a blend of both carbon-rich and mineral-rich char, which is beneficial for providing both insulation and structural protection when exposed to fire. It can be observed that the char layer formed by a water-based IFRC shows more Oxygen and Titanium, whereas the char of the IC3 sample, which is made up of epoxy-based waterborne binder, shows more Carbon content. EDS demonstrates that carbon (C) and oxygen (O) are retained in the char, indicating effective carbonisation and strong oxidation resistance. The consistent presence of Oxygen (O), Titanium (Ti), Phosphorus (P), and Carbon (C) across all three spectra confirms that these elements are incorporated and retained in the char residue. Phosphorus (P) is a key component of intumescent systems, often sourced from ammonium polyphosphate or similar flame-retardant additives, playing a crucial role in enhancing char formation and thermal stability. Titanium (Ti) likely originates from titanium dioxide (TiO_2), which is widely used as a pigment and synergistic agent to enhance the char and improve its thermal resistance. IC2 exhibits the highest levels of oxygen and phosphorus while having the lowest carbon content. This indicates a greater degree of oxidation and a char that is more mineral-rich and less organic in this area. In contrast, IC3 has the highest carbon content, which suggests a more carbon-dense char that is advantageous for insulation and barrier properties.



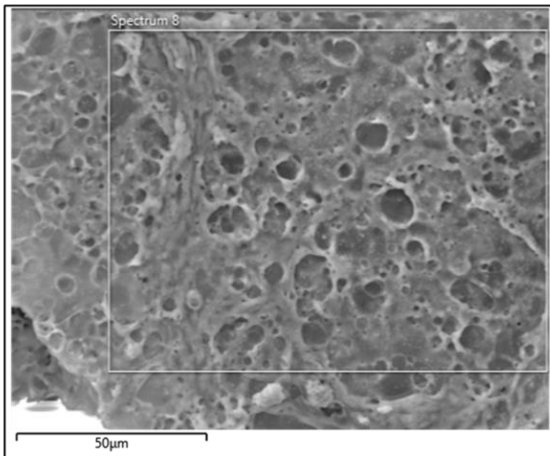
Spectrum 5	
Element	Wt%
O	33.6
Ti	22.6
P	16.8
C	20.9

Figure 5: EDS analysis of sample IC1.



Spectrum 9	
Element	Wt%
O	46.5
Ti	20.2
P	18.8
C	6.8

Figure 6: EDS analysis of sample IC2.



Spectrum 8	
Element	Wt%
C	29.2
O	27.6
P	22.2
Ti	16.8

Figure 7: EDS analysis of sample IC3.

3.4. Thermo-gravimetric analysis (TGA)

When the samples reach temperatures of 900-990°C, most of their organic material is removed, resulting in residual inorganic ash. The observed volume expansion during the intumescence stage decreases as the protective char is consumed in the presence of oxygen; however, mineral fillers contribute to a stronger residue.

Figure 8 shows the TGA of the fire-retardant intumescent coating samples IC1, IC2, and IC3, respectively, which demonstrates a multi-phase decomposition process. The initial mass reduction occurring below 150 °C is attributed to the evaporation of moisture. Key thermal events between 250 and 650 °C are associated with the decomposition of blowing agents and acid sources, characterized by pronounced exothermic peaks that indicate the formation of char.

The TGA curve, shown in green, illustrates how the sample loses weight as the temperature increases. Region I (~30-150 °C) exhibits a small mass loss (~1-2 %), which is likely due to the evaporation of moisture or solvent. Region II (~200-400 °C) exhibits significant mass loss due to the decomposition of organic compounds, including APP, Melamine, and PVAc. Region III (~450-650 °C) exhibits continued major mass loss (~30–35%), indicating the final decomposition of the polymeric backbone and the formation of insulating char through the reaction between the acid source and the carbon source, characterized by carbonisation. Above this, most of the volatile components have been decomposed, and a stable char residue has been formed, which is indicated by the small change in mass loss or plateau in region IV (~700 to 950 °C). At nearly 990 °C, the percentage of the original mass remaining was 36 % in IC1, 38.05 % in IC2, and 35.78 % in IC3. Although the residual mass percentage for samples IC1 and IC2 was found to be higher than that of IC3, IC3 is more effective as an FRIC due to its char structure and the char's effective stability, which is a crucial factor for thermal protection.

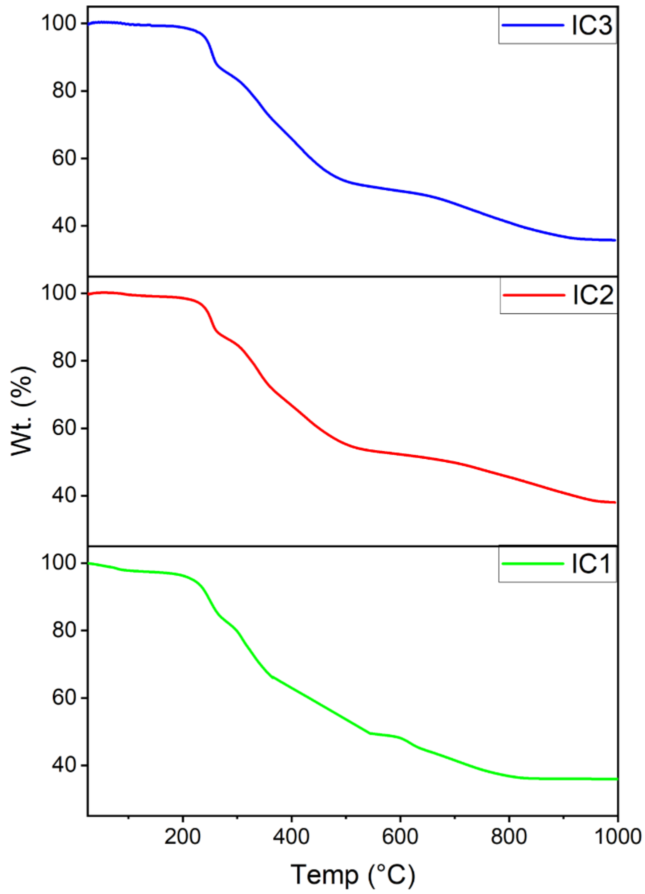


Figure 8: TGA plots for the samples IC1, IC2, and IC3.

3.5. Ignitability evaluation as per BS 476 Part 5

None of the coated samples showed any obvious flame on their surface after the ignition source was removed during the test. According to the conventional categorisation, all three samples-IC1, IC2, and IC3-were therefore categorised as "Not Easily Ignitable," and the letter "P" was used to represent their performance. Additionally, as shown in Figure 9, the char thickness that developed during the test was approximately 35 mm in each sample. Under direct flame exposure, the coating's efficient thermal shielding capabilities are demonstrated by the thick, stable char that consistently forms on all samples. Consequently, all the evaluated samples were determined to be efficient and in compliance with Ignitability evaluation standards, based on the lack of ignition as well as the development of a protective char layer.

3.6. Fire propagation index as per BS 476 Part 6

The FPI values determined for samples coated with IC1, IC2, and IC3 in this investigation were 0.2, 1.6, and 2.5, respectively. The coatings' adherence to fire safety regulations was confirmed by the fact that all values were much below the typical upper limit of 12. Furthermore, as shown in Figure 10, char thicknesses of 40, 40 and 35 mm were noted for samples IC1, IC2, and IC3, respectively. These significant char deposits show a high degree of thermal protection and insulation against flame exposure. Figure 11's temperature-time plots for every sample display a distinctive pattern: a spike in temperature during the early phases of char development, followed by a slower rate of increase once the protective char layer had completely formed. Once the intumescent layer is developed, this behaviour shows how the coating can stabilize thermal conditions and restrict heat transfer. In summary, the findings demonstrate that all three coating samples met the requirements outlined by the Fire Propagation Index (BS 476 Part 6) evaluation technique and were successful in preventing the spread of fire.

Figure 9: Char thickness of samples IC1 (35 mm), IC2 (35 mm), and IC3 (35 mm) in the Ignitability evaluation test.

Figure 10: Fire propagation index evaluation results for samples IC1 (40 mm), IC2 (40 mm), and IC3 (35 mm)

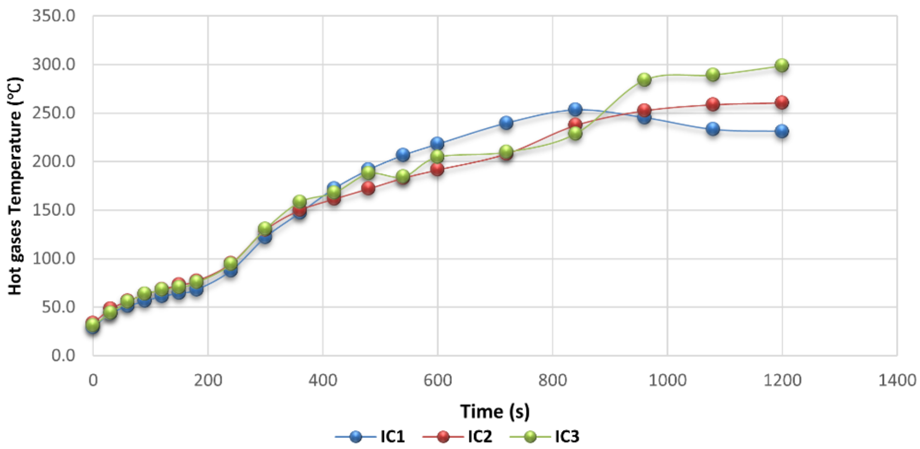


Figure 11: Time-temperature plot for samples IC1, IC2, and IC3 based on FPI evaluation.

3.7. Surface spread of flame of products as per BS 476-Part 7

A crucial test for categorizing materials according to the rate and degree of flame spread across their surfaces after ignition is the surface spread of flame evaluation. Every coating sample used in this investigation-IC1, IC2, and IC3-was examined for the surface spread of flame under controlled circumstances. None of the samples exhibited any discernible flame spread, according to the test results; therefore, they met the requirements for Class 1, the highest fire performance certification. During testing, visual inspection revealed partial coating separation in samples IC1 and IC2, as shown in Figures 12 and 13, despite all samples passing the evaluation. Although this detachment did not cause flames to spread, it may have an impact on the long-term stability of fire protection in harsh environments. The use of epoxy as a binder in the water-based coating matrix is a significant formulation enhancement, as highlighted by the lack of such detachment in IC3. This improved binder composition enhanced the coating's adhesion to the galvanized steel substrate, demonstrating that the choice of binder is crucial for the mechanical endurance and fire resistance of intumescent coatings.

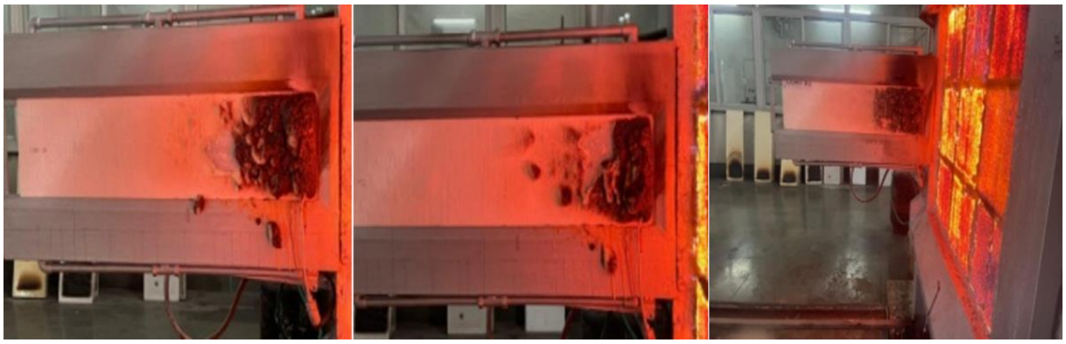


Figure 12: Surface spread of flame results- Char layer during test for samples IC1, IC2 and IC3

Figure 13: Surface spread of flame results- Char layer after test for samples IC1, IC2 and IC3.

3.8. Specific optical density as per ASTM E 662

The specific optical density (Ds) evaluation of the coated materials was carried out to determine their potential contribution to smoke generation during combustion. The maximum specific optical density (Dm) values for samples coated with formulations IC1, IC2, and IC3 were calculated as per standardized testing procedures and are summarized in Table 2. All measured values were found to be well within the acceptable limits, i.e., Dm less than 100 at 1.5 minutes and less than 200 at 4 minutes, indicating compliance with the required fire safety standards. Following the test, char layers ranging in thickness from 20 to 30 mm were observed across the samples, as shown in Figures 14 and 15, indicating effective thermal insulation. The specific optical density-time curves for the samples are depicted in Figure 16. The Ds value of IC2 was lower than that of IC1, while IC3 exhibited the lowest Ds value among all samples, demonstrating the incorporation of smoke suppressant fillers. The greater performance of IC3, which had the lowest Ds, demonstrates its improved smoke suppression capacity.

Furthermore, as shown in Figure 17, when exposed to both radiant heat flux and flame, the Ds values of IC2 and IC3 were found to be higher than those of IC1, indicating a link between thermal breakdown behavior and flame exposure. It can be assumed that smoke suppressant fillers primarily function in the condensed phase, forming a molten protective barrier on the surface during combustion. This barrier inhibits the emission of smoke by trapping volatile breakdown compounds. However, due to the limited activity in the gas phase, some flammable breakdown products may still ignite, resulting in ongoing smoke evolution. These findings are consistent with prior research, indicating that condensed-phase mechanisms are primarily responsible for the smoke reduction reported in these coatings [40].

Figure 14: Specific optical density evaluation- Non-flaming mode- char thickness for samples IC1(20 mm), IC2 (20 mm), and IC3 (20 mm).

Figure 15: Specific optical density evaluation- Flaming mode- char thickness for samples IC1(30 mm), IC2 (20 mm), and IC3 (20 mm).

Table 2: Specific optical density values for samples IC1, IC2, and IC3.

Composition	Sample	Non-flaming	Flaming
IC1	Dm (max) value-	46	32.9
	Dm (1.5 min)	6.6	17.3
	Dm (4.0 min)	26	25.2
IC2	Dm (max) value-	42.8	37.8
	Dm (1.5 min)	10.6	8.4
	Dm (4.0 min)	26.3	17.7
IC3	Dm (max) value-	26.5	38
	Dm (1.5 min)	7.5	17.5
	Dm (4.0 min)	18.3	30.6

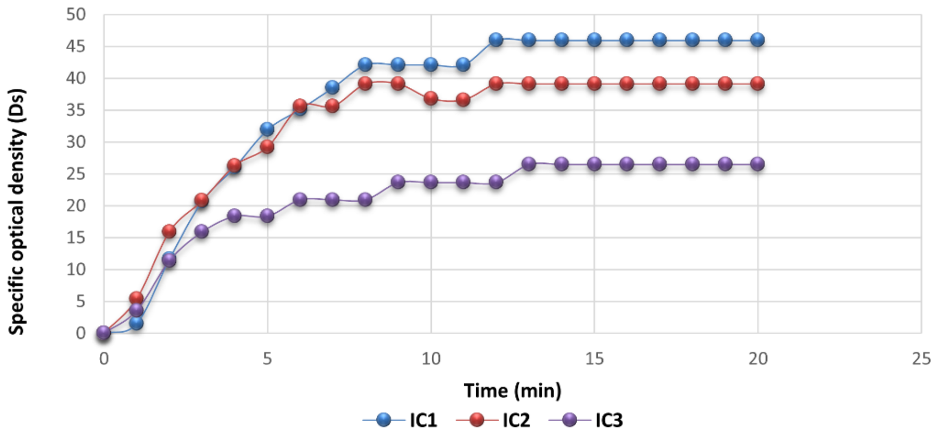


Figure 16: Specific optical density (Ds) curve of the coatings - Non-Flaming mode.

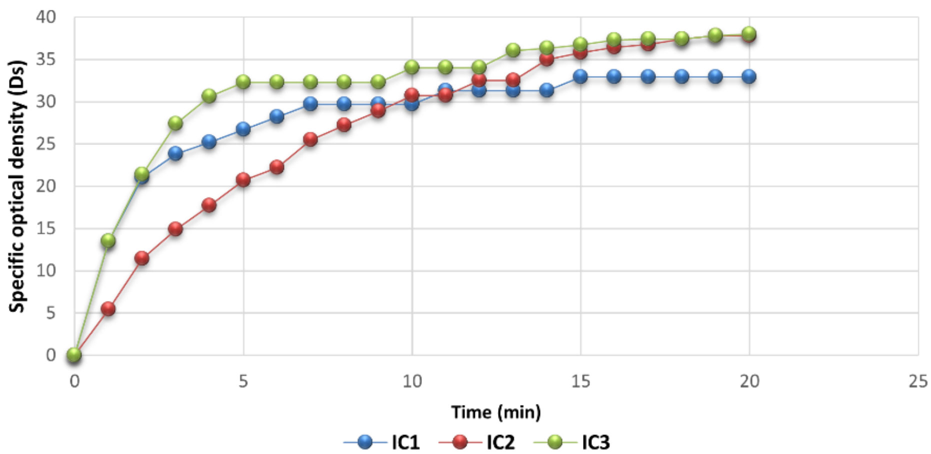


Figure 17: Specific optical density (Ds) curve of the coatings - Flaming mode.

3.9. Non-combustibility test as per BS 476-Part 4

The non-combustibility test was used to determine whether the coating materials have behaviour that precludes persistent burning or considerable thermal deterioration at high temperatures. Samples coated with formulations IC1, IC2, and IC3 were analysed using standard criteria, and the key findings are presented in Table 3. Figure 18 illustrates the post-test condition of the samples. Based on the collected data, the flame duration for IC3 was less than 10 seconds, and for IC1, no flame was observed, which was within the standard limit. However, IC2 had a flame time of approximately 20 seconds, which was significantly above the threshold. In terms of mass loss, all samples remained below permissible limits, registering values less than 50 %, with IC1 displaying the least and IC3 demonstrating the most mass loss, as illustrated in Figure 19. The furnace temperature rise-another key parameter-was found to be the lowest for IC3, indicating that the material released less heat, as illustrated in Figure 20. Specifically, IC3 exhibited a temperature rise of approximately 70 °C, which is modest and indicative of good thermal resistance. Sample IC3 meets normal non-combustibility standards, with a flame duration of ~2 seconds, mass loss < 50 %, and restricted temperature rise in the furnace. These findings suggest that IC3 exhibits more stable thermal performance and a lower propensity for combustion, thereby bolstering its potential as a fire-resistant intumescent coating in passive fire prevention applications.

Table 3: Observations from the non-combustibility evaluation for samples IC1, IC2, and IC3.

Composition	Sample	Non-flaming	Flaming
IC1	Dm (max) value-	46	32.9
	Dm (1.5 min)	6.6	17.3
	Dm (4.0 min)	26	25.2
IC2	Dm (max) value-	42.8	37.8
	Dm (1.5 min)	10.6	8.4
	Dm (4.0 min)	26.3	17.7
IC3	Dm (max) value-	26.5	38
	Dm (1.5 min)	7.5	17.5
	Dm (4.0 min)	18.3	30.6

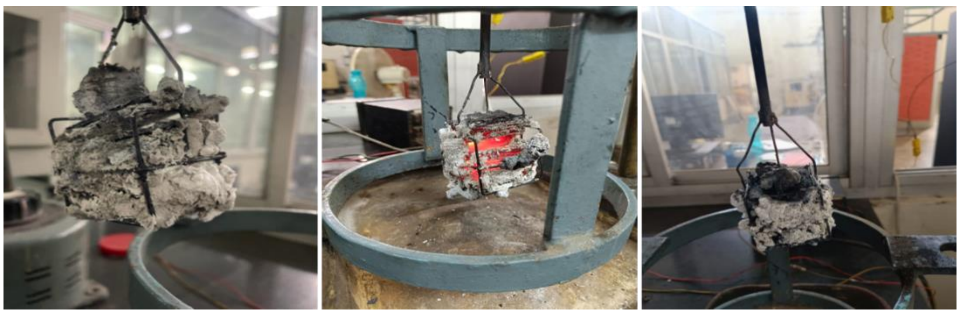


Figure 18: Samples IC1, IC2, and IC3 after non-combustibility test.

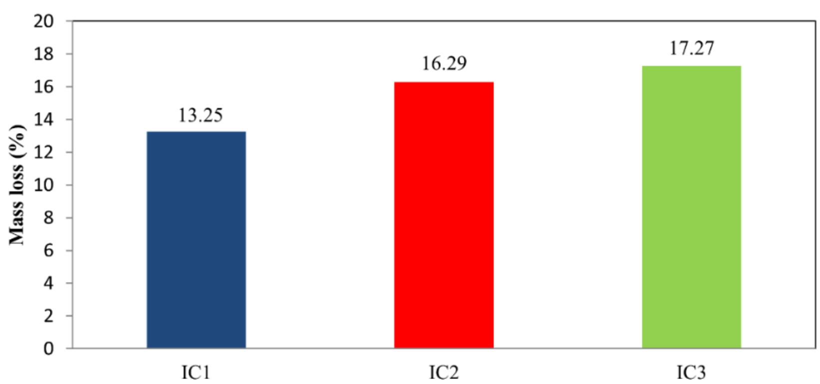


Figure 19: Mass loss of samples IC1, IC2 and IC3 in Non-combustibility evaluation.

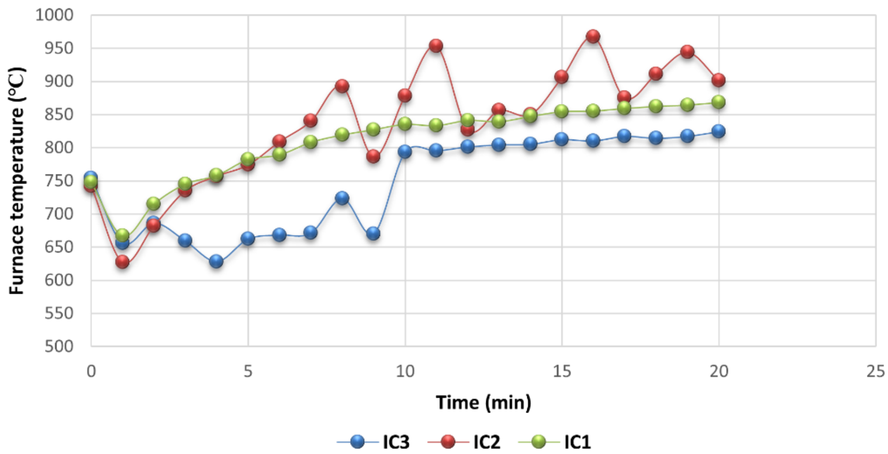


Figure 20: Time-temperature plot for samples IC1, IC2, and IC3 in Non-combustibility evaluation.

Table 4 presents the compiled evaluation results of the standardized tests mentioned above. Among the tested formulations, IC3 demonstrated the most promising fire performance. It formed a stable and sufficient char layer during initial fire exposure and was classified as 'Not Easily Ignitable' based on ignitability tests. A Fire Propagation Index (FPI) below 12 indicated a low rate of heat release. In the Surface Spread of Flame test, IC3 achieved a Class 1 rating, as no flame spread was detected. Additionally, it generated minimal smoke, with specific optical density values remaining below 100 at 1.5 minutes, and nearly satisfied the non-combustibility criteria, as evidenced by its short flaming duration, acceptable mass loss, and minimal furnace temperature rise.

3.10. Heat insulation test

The fire exposure test was conducted under controlled conditions designed to simulate a hydrocarbon fire scenario. The heat source was a liquefied petroleum gas (LPG) Bunsen burner, which consistently produced a flame temperature of 950 to 1000 °C. The burner was positioned 7 cm from the surface of the intumescent coating applied to the steel substrate. To assess the coating's thermal insulation ability, real-time temperature monitoring was carried out for 120 minutes. The I-section steel substrate, measuring 305 mm in width, 125 mm in flange thickness, 250 mm in depth, and 7 mm in web thickness, was coated with formulation IC3. A thermocouple was securely affixed to the steel's flame-exposed surface to measure heat transmission through the coating, resulting in accurate and localized temperature measurements. The temperature was measured at one-minute intervals during the experiment to capture the coating's dynamic thermal activity. Figure 21a illustrates the experimental setup, and Figure 21b shows the temperature gun used to verify that the flame temperature remained within the 950-1000 °C range. As shown in Figures 21c and 21d, the temperature at the steel surface was measured and cross-validated using both the thermocouple and the temperature gun.

Table 4: The overall effectiveness of the samples in the evaluations.

Sample	Time of Flaming (s)	Mass loss (%)	Rise in temperature (°C)	
			Furnace	Sp. Centre
IC1	No flame	13.25	120	187
IC2	20	16.29	225	163
IC3	2	17.27	70	31

Figure 21: Heat insulation test (a) setup, (b) flame temperature measured with temperature gun, (c) thermocouple temperature measurement and (d) temperature measured with temperature gun at the back surface of the sample.

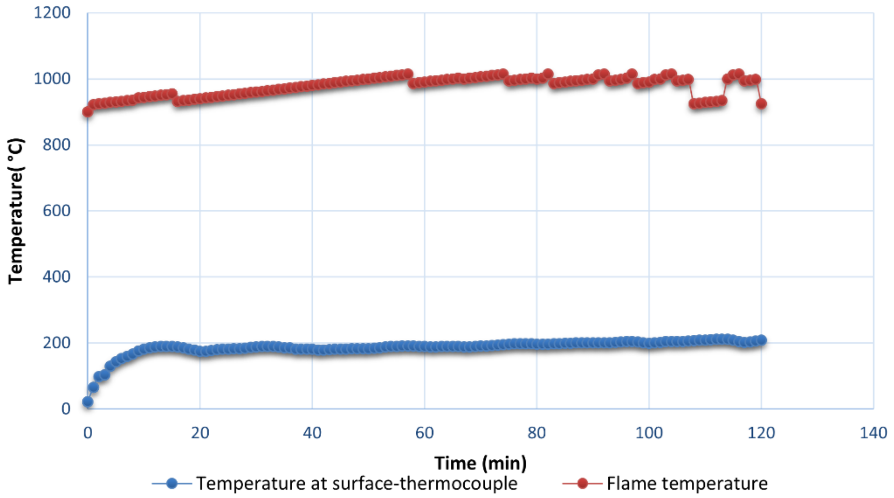


Figure 22: The temperature of the sample was measured using a thermocouple at the back surface of the sample.

Additionally, as Figure 22 illustrates, the temperature recorded on the coated steel surface remained relatively steady at approximately 200 °C during the exposure duration. This long-lasting temperature plateau demonstrates the IC3 intumescent coating's potent thermal barrier qualities. The coating may have undergone a sustained intumescent reaction, resulting in the formation of a protective char layer that significantly decreased heat conduction to the steel substrate, as indicated by its consistent insulating performance. In actual fire situations, where structural integrity must be preserved for prolonged periods to permit safe evacuation and firefighting operations, this delayed heat transmission is crucial.

4. Conclusion

This study successfully developed and tested three water-based, fire-retardant intumescent coatings, with IC3 demonstrating the most promising performance. IC3 produced a stable and expanded char layer under flame exposure, was classified as 'Not Easily Ignitable,' had a Fire Propagation Index (FPI) below 12, and showed no surface flame spread (Class 1 rating). Importantly, IC3 generated little smoke (specific optical density <100 at 1.5 min), nearly satisfied the non-combustibility criterion, and provided excellent thermal insulation by maintaining steel substrate temperatures near 200 °C for 120 minutes under direct flame. Compared to the other formulations, IC3 offered superior fire resistance, good substrate adhesion, and environmental compatibility. Additionally, blending PVAc with epoxy resins contributed to improved toughness and flexibility of the coatings without loss of adhesion. Overall, these results confirm the feasibility of developing effective water-based intumescent coatings for structural fire protection. Further evaluation under additional standard fire tests and real-world fire conditions is recommended to validate their large-scale performance.

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