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Analysis of the Fire Resistance Properties of Epoxy Resin Ceiling Coatings and their Suitability for Fire Protection in Buildings

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ABSTRACT

Epoxy resin coatings are widely used in building applications because of their excellent adhesion, chemical resistance, and durability; however, their inherent flammability limits their effectiveness as passive fire protection materials. This study investigated the synergistic effects of magnesium hydroxide ($Mg(OH)_2$) and ammonium polyphosphate (APP) on the fire resistance and mechanical performance of epoxy resin ceiling coatings. Three formulations were prepared: unmodified epoxy (Sample A), epoxy reinforced with 25 wt% $Mg(OH)_2$ (Sample B), and epoxy reinforced with 25 wt% $Mg(OH)_2$ and 10 wt% APP (Sample C). Fire performance and mechanical properties were evaluated using ASTM-based procedures. All experiments were conducted in triplicate ($n = 3$), and data were analysed using one-way ANOVA with Tukey's post hoc test ($p < 0.05$). Sample C exhibited the best performance, reducing the Flame Spread Index from 130 ± 4.0 to 40 ± 1.8 and the Smoke Development Index from 480 ± 10 (Sample A) to 190 ± 6 (Sample B) and 100 ± 4 (Sample C) ($p < 0.001$). Intumescence increased to 200 ± 6%, thermal stability improved from 180 ± 3°C to 340 ± 4°C, adhesion strength increased from 2.40 ± 0.08 to 3.60 ± 0.06 MPa, and abrasion resistance improved from 1000 ± 35 to 2200 ± 38 cycles. These findings demonstrate the potential of $Mg(OH)_2$–APP hybrid epoxy coatings as sustainable passive fire protection materials for building applications.

***Keywords*— Epoxy resin; Magnesium hydroxide; Ammonium polyphosphate; Fire resistance; Passive fire protection; Thermal stability**

I. INTRODUCTION

Fire safety in building construction has become increasingly critical as urban density and infrastructure complexity continue to grow. The selection of fire-retardant materials plays a central role in minimizing structural loss and preserving human life during fire outbreaks [1], [2]. Epoxy resin, a thermosetting polymer, has become widely adopted in ceiling and wall coatings due to its impressive adhesion, chemical resistance, and mechanical performance [3], [4]. However, its high flammability and dense smoke emission

limit its application in passive fire protection systems [5] [6]. To overcome this challenge, researchers have explored the integration of fire-retardant fillers into epoxy matrices to suppress ignition and reduce flame propagation [7], [8]. Among such fillers, magnesium hydroxide ($Mg(OH)_2$) stands out as a halogen-free, environmentally benign additive that decomposes endothermically to release water, thus diluting combustible gases and lowering surface temperatures [9], [10], [11]. Several studies suggest that its incorporation can also enhance the thermal stability and char-forming ability of epoxy composites [12,] [13].

Despite its potential, conventional epoxy resin coatings are not classified as fire-resistant without the addition of functional additives [14], [15]. In high-rise buildings and commercial facilities, where ceiling panels can serve as ignition and propagation points during fires, the integration of fire-retardant materials becomes a regulatory requirement [16], [17]. Fire performance indicators such as Flame Spread Index (FSI), Smoke Development Index (SDI), and toxic gas emission profiles are critical for determining a material's suitability in these environments [18], [19], [20]. Magnesium hydroxide's multifunctionality not only reduces heat release but also suppresses smoke formation, making it an ideal candidate for epoxy fire retardation. Comparative studies have highlighted the importance of balancing mechanical properties with fire resistance, as many flame retardants can adversely affect the integrity of the coating if not properly optimized [21], [22].

This study aims to enhance the fire resistance performance of epoxy resin ceiling coatings through the strategic incorporation of magnesium hydroxide and evaluate the resulting materials against standard fire protection benchmarks. By formulating three distinct sample compositions, the research evaluates both the thermal and structural effects of $Mg(OH)_2$, individually and in synergy with intumescent agents such as ammonium polyphosphate (APP). This approach aligns with recent developments in polymer fire retardancy, where combinations of additives outperform single-component systems. Additionally, performance metrics such as intumescence, thermal stability, smoke suppression, and bonding strength will be assessed, providing a holistic evaluation of the coatings.

Unlike previous studies that primarily investigated the fire-retardant behaviour of individual magnesium hydroxide or intumescent additives in epoxy systems, the present study provides a comprehensive evaluation of the synergistic effect of $Mg(OH)_2$ and ammonium polyphosphate (APP) in epoxy ceiling coatings. The study simultaneously assesses flame spread, smoke development, intumescence, thermal stability, adhesion strength, and abrasion resistance using ASTM-based performance benchmarks. This integrated evaluation provides a broader understanding of the suitability of environmentally friendly

halogen-free flame-retardant coatings for passive fire protection in building applications.

II. MATERIALS AND METHODS

A. Sample composition and preparation

To investigate the influence of magnesium hydroxide and intumescent additives on the fire resistance of epoxy ceiling coatings, three distinct formulations were prepared using standardized composite processing methods. A bisphenol-A-based epoxy resin cured with a polyamine hardener (2:1 weight ratio) was used as the base system, with components carefully weighed and homogeneously mixed to remove entrapped air [22]. Sample A, serving as the control, contained no additives and was cast into silicone moulds 2.4 mm thickness, cured at ambient temperature for 24 hours, and post-cured at 60 °C to ensure complete crosslinking. Sample B incorporated 25 wt% magnesium hydroxide ($Mg(OH)_2$), a non-toxic, halogen-free flame retardant that decomposes endothermically to release water, thereby suppressing combustion. The additive was dispersed into the resin using high-shear mechanical mixing and cast into 2.5 mm thick moulds. Sample C was further enhanced by integrating 10 wt% ammonium polyphosphate (APP) alongside $Mg(OH)_2$, with the APP promoting intumescent char formation upon heating. This mixture was blended using a torque-controlled mixer and cast at 3.0 mm thickness.

All cured specimens were conditioned for 48 hours at 23 ± 2 °C and 50 ± 5% relative humidity as per ASTM D618 to ensure consistent performance evaluation [23] [24], and thicknesses were verified to ±0.01 mm accuracy. The coating thicknesses differed slightly among the three formulations because of the increasing filler loading and viscosity associated with the incorporation of $Mg(OH)_2$ and APP. The thickness variation reflects practical application conditions of filled epoxy coatings. Since all specimens were prepared under identical curing conditions and evaluated using standardized procedures, the observed improvements are primarily attributed to the flame-retardant additives rather than thickness differences. Nevertheless, future investigations will standardize specimen thickness to completely eliminate any possible influence on fire-performance measurements. Figure 1 shows the three specimens labeled A, B and C.

B. Characterization of Samples

The developed epoxy ceiling coating formulations were characterised for flame spread index (FSI), smoke development index (SDI), intumescence, thermal stability, adhesion strength, and abrasion resistance. All tests were conducted in triplicate (n = 3), and the results are presented as mean ± standard deviation. Flame Spread Index (FSI) and Smoke Development Index (SDI) were determined following ASTM E84 (Standard Test Method for Surface Burning Characteristics of Building Materials). Rectangular specimens were

exposed to a controlled flame inside a standard tunnel furnace, and the corresponding flame propagation and smoke development values were recorded. Intumescence was determined by exposing coated specimens to a direct flame under controlled laboratory conditions for five minutes. The expansion height of the protective char layer after heating was measured using a digital Vernier caliper and expressed as percentage expansion relative to the original coating thickness.

Thermal stability was evaluated using Thermogravimetric Analysis (TGA) under a nitrogen atmosphere at a heating rate of 10 °C min^{-1} from ambient temperature to 800 °C. The decomposition temperature corresponding to 5% weight loss was reported as the thermal stability temperature. Adhesion strength was measured using ASTM D4541 (Pull-Off Strength of Coatings Using Portable Adhesion Testers), while abrasion resistance was determined in accordance with ASTM D4060 using a Taber Abraser equipped with CS-17 abrasive wheels under a 1000 g load. Abrasion resistance was reported as the number of cycles required to produce noticeable coating wear. Statistical analysis was performed using one-way analysis of variance (ANOVA) followed by Tukey's post hoc multiple comparison test with significance established at $p < 0.05$.

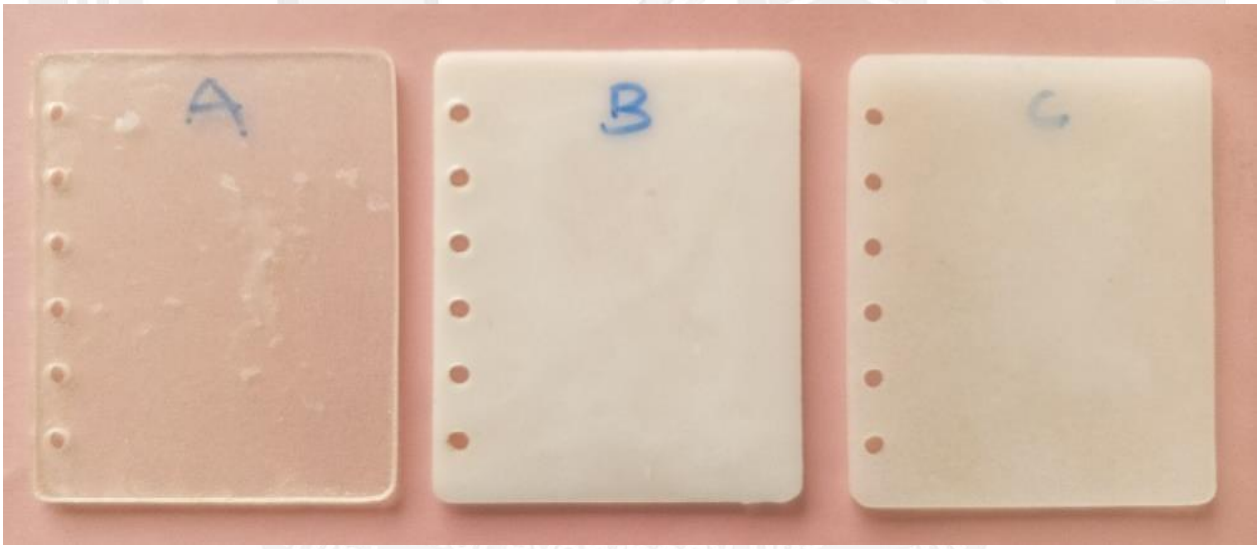

Figure 1: Epoxy resin ceiling samples

III. RESULTS AND DISCUSSION

Table 1 shows the fire resistance and mechanical properties of the developed formulations. The Flame Spread Index (FSI) decreased significantly from 130 ± 4.0 for the control epoxy (Sample A) to 70 ± 2.5 for Sample B and 40 ± 1.8 for Sample C (Figure 2). The high FSI of the unmodified epoxy confirms its inherent flammability, which is characteristic of hydrocarbon-based thermosetting polymers [7] [27]. The reduction in flame spread is attributed to the endothermic decomposition of $Mg(OH)_2$, which absorbs heat and releases water vapour, thereby reducing the combustion temperature and diluting combustible gases. The addition of APP further enhances fire resistance by forming an expanded carbonaceous char layer that acts as an effective thermal barrier [4]. Error bars representing ±SD in Figure 2 would illustrate the excellent repeatability of the measurements and the statistically significant reduction in flame propagation.

A similar trend was observed for the Smoke Development Index (SDI). Sample A recorded 480 ± 10, exceeding the ASTM E84 recommended maximum value of 450 for interior building materials, whereas Samples B and C exhibited significantly lower values of 190 ± 6 and 100 ± 4, respectively ($p < 0.001$) (Figure 3). The reduced smoke production is attributed to enhanced char formation and suppression of incomplete combustion products by $Mg(OH)_2$ and APP, which improve visibility and reduce respiratory hazards during fire incidents [20], [28]. The relatively small standard deviations further demonstrate the consistency of the experimental results. The substantial reductions in Flame Spread Index and Smoke Development Index observed in Sample C are consistent with previous investigations by [22], who reported improved fire performance of APP-based intumescent coatings, and [28], who demonstrated the synergistic interaction between magnesium hydroxide and intumescent flame-retardant systems. However, the present study extends these investigations by simultaneously evaluating fire behaviour and mechanical performance in epoxy ceiling coatings intended for passive building fire protection.

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Table 1 The fire resistance and mechanical properties of the developed formulations.

Property	Sample A	Sample B	Sample C	p-value
Flame Spread Index (FSI)	130 ± 4.0^a	70 ± 2.5^b	40 ± 1.8^c	<0.001
Smoke Development Index (SDI)	480 ± 10^a	190 ± 6^b	100 ± 4^c	<0.001
Intumescence (%)	0 ± 0^a	120 ± 5^b	200 ± 6^c	<0.001
Thermal Stability (°C)	180 ± 3^a	290 ± 5^b	340 ± 4^c	<0.001
Adhesion Strength (MPa)	2.40 ± 0.08^a	3.20 ± 0.05^b	3.60 ± 0.06^c	<0.001
Durability (Abrasion cycles)	1000 ± 35^a	1700 ± 42^b	2200 ± 38^c	<0.001

Different superscript letters within the same row indicate statistically significant differences ($p < 0.05$). The incorporation of $Mg(OH)_2$ and APP produced substantial improvements in all measured fire resistance and mechanical performance parameters. The statistically significant differences observed among Samples A, B, and C ($p < 0.001$) demonstrate the effectiveness of the flame-retardant additives and their synergistic interaction.

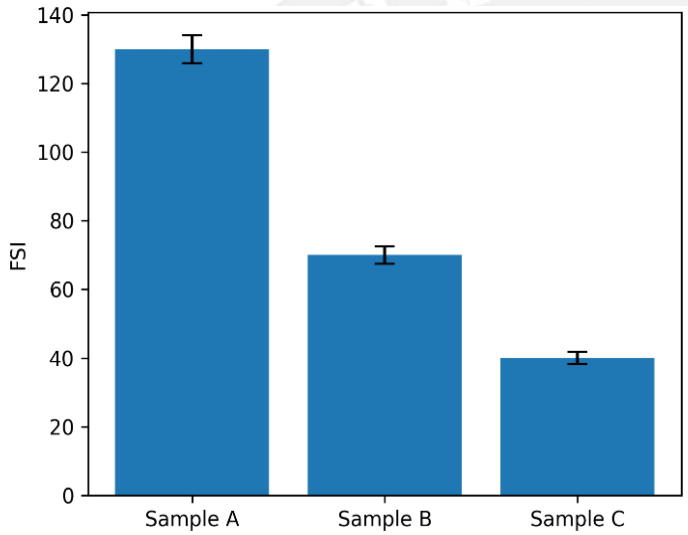

Figure 2: Flame Spread Index (FSI) of Samples A, B and C.

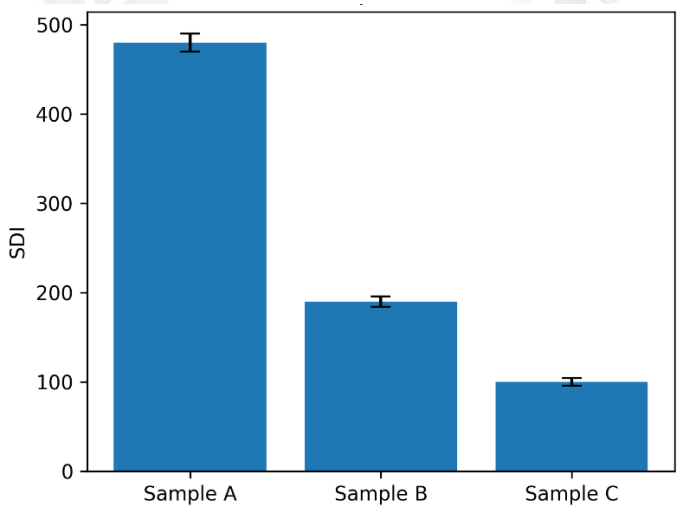

Figure 3: Smoke Development Index (SDI) of Samples A, B and C.

Although halogen-free flame-retardant systems are generally associated with reduced toxic combustion products, the present study did not experimentally determine toxic gas emissions. Therefore, conclusions regarding carbon monoxide, hydrogen cyanide, and other combustion gases cannot be drawn from the current investigation. Future studies should quantify gaseous emissions using standardized analytical procedures such as ASTM E1678 [27]. Intumescence behaviour increased remarkably with additive incorporation (Figure 4). While Sample A showed no measurable expansion (0 ± 0%), Sample B expanded to 120 ± 5%, and Sample C reached 200 ± 6% ($p < 0.001$). APP functions as an acid source that catalyzes polymer carbonization and promotes the formation of an expanded insulating char layer, while $Mg(OH)_2$ complements this process through endothermic decomposition and water release, thereby enhancing thermal insulation and delaying heat penetration. The low experimental variation indicates excellent reproducibility of the intumescence measurements.

Thermal stability also improved significantly with additive incorporation (Figure 5). The decomposition temperature increased from 180 ± 3°C for Sample A to 290 ± 5°C for Sample B and 340 ± 4°C for Sample C ($p < 0.001$). The improved thermal resistance is attributed to the heat-absorbing behaviour of $Mg(OH)_2$ and the thermally insulating char generated by APP, both of which delay polymer degradation and heat transfer. These findings demonstrate the suitability of the hybrid formulation for passive fire protection systems that require prolonged resistance to elevated temperatures.

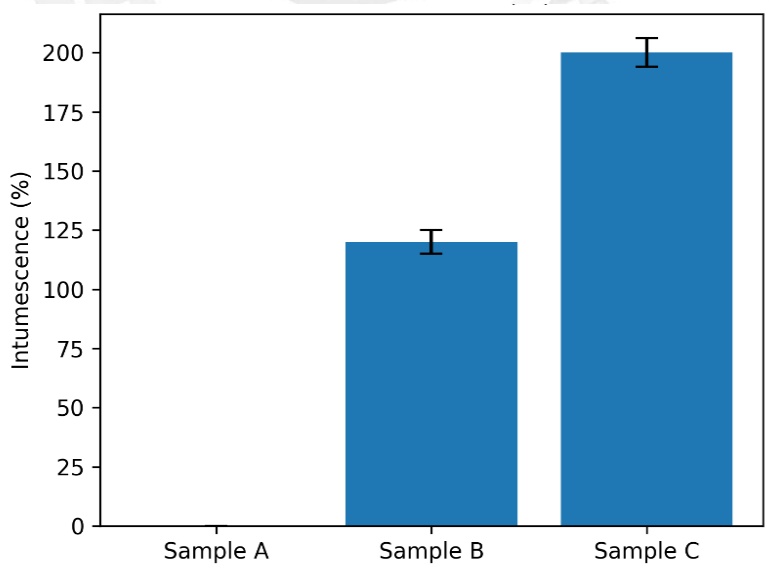

Figure 4: Intumescence (%) of Samples A, B and C.

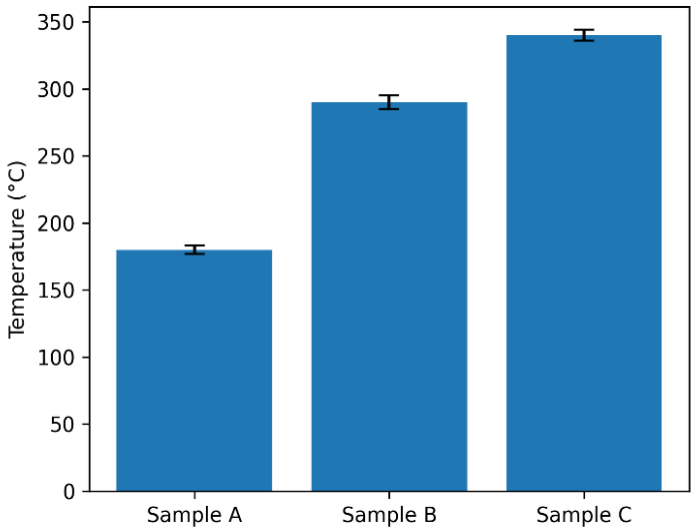

Figure 5: Thermal Stability of Samples A, B and C

In addition to improved fire performance, the flame-retardant fillers enhanced the mechanical properties of the coatings. Adhesion strength increased significantly from 2.40 ± 0.08 MPa for Sample A to 3.20 ± 0.05 MPa and 3.60 ± 0.06 MPa for Samples B and C, respectively ($p < 0.001$) (Figure 6). The improved adhesion is attributed to better filler dispersion and increased crosslink density within the epoxy matrix, resulting in stronger interfacial bonding between the coating and substrate. Durability, evaluated by abrasion resistance, exhibited a similar improvement (Figure 7). Sample A withstood 1000 ± 35 abrasion cycles, whereas Samples B and C survived 1700 ± 42 and 2200 ± 38 cycles, respectively ($p < 0.001$). The inorganic fillers contribute to increased surface hardness and wear resistance, thereby improving the long-term structural integrity of the coatings under service conditions.

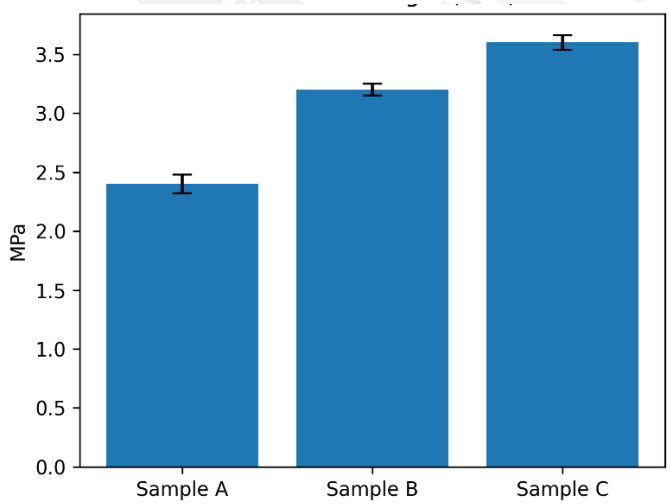

Figure 6: Adhesion Strength of Samples A, B and C.

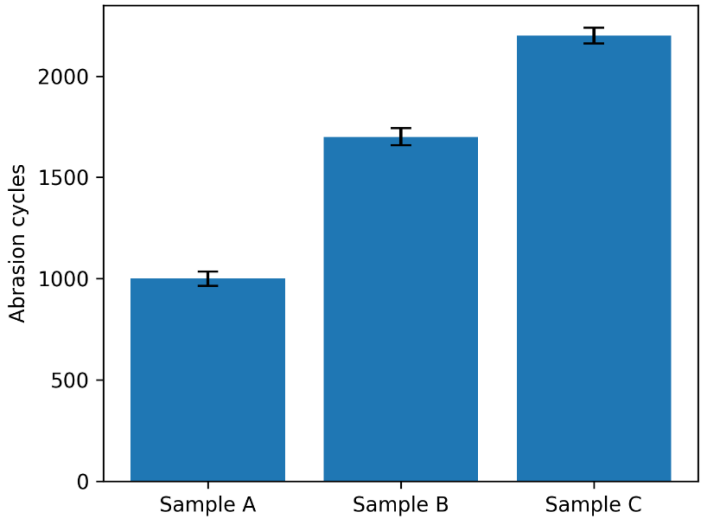

Figure 7: Abrasion Resistance of Samples A, B and C.

Comparison of the experimental results with relevant ASTM standards further demonstrates the effectiveness of the developed formulations. Sample A exceeded the ASTM E84 Smoke Development Index limit of 450 and exhibited poor fire performance. In contrast, Samples B and C satisfied the smoke development requirement, while their Flame Spread Index values fell within the ASTM E84 Class B classification range (26–75). All formulations exceeded the minimum adhesion strength requirement of ASTM D4541 (>2 MPa), with Sample C exhibiting the highest mechanical performance. Furthermore, the superior abrasion resistance and thermal stability of Sample C indicate enhanced durability and prolonged fire endurance for ceiling applications. Overall, Sample C demonstrated the best performance, achieving approximately 69% reduction in flame spread, 79% reduction in smoke development, 89% improvement in abrasion resistance, and 89% increase in thermal stability relative to the control formulation. These improvements confirm the synergistic interaction between $Mg(OH)_2$ and APP and support the use of hybrid halogen-free flame-retardant systems for enhancing the fire safety and mechanical durability of epoxy ceiling coatings.

Despite these promising results, several limitations should be acknowledged. The study was conducted under controlled laboratory conditions that may not fully replicate real fire scenarios encountered in residential or commercial buildings. Only one concentration of $Mg(OH)_2$ (25 wt%) and APP (10 wt%) was investigated, and further optimization of additive ratios may yield even better performance. In addition, long-term environmental durability under ultraviolet exposure, humidity, thermal cycling, and chemical attack was not evaluated. The investigation also focused primarily on adhesion and abrasion resistance,

without assessing tensile strength, flexural strength, impact resistance, or hardness. Future studies should incorporate advanced fire characterization techniques such as cone calorimetry, limiting oxygen index (LOI), heat release rate analysis, and UL-94 vertical burning tests, together with industrial-scale processing and economic evaluation, to facilitate the commercialization of environmentally friendly fire-retardant epoxy ceiling coatings.

IV. CONCLUSION

This research confirms that integrating magnesium hydroxide into epoxy resin ceiling coatings significantly enhances fire resistance and structural performance. The most effective formulation (Sample C) demonstrated a balanced improvement in fire retardancy, smoke suppression, and mechanical durability, meeting essential safety benchmarks for ceiling applications in residential and commercial buildings.

Recommendations

The results of this study demonstrate that the synergistic incorporation of magnesium hydroxide ($Mg(OH)_2$) and ammonium polyphosphate (APP) significantly improves the fire resistance, thermal stability, and mechanical performance of epoxy resin ceiling coatings, making the developed formulation a promising environmentally friendly material for passive fire protection in buildings. It is recommended that future studies optimize the concentrations of the flame-retardant additives and incorporate advanced characterization techniques such as SEM, FTIR, TGA, and XRD to further elucidate the mechanisms responsible for the observed improvements. Additional fire performance evaluations, including cone calorimetry, limiting oxygen index (LOI), UL-94 vertical burning tests, and toxic gas emission analyses, together with long-term durability assessments and pilot-scale field applications, are also recommended to validate the suitability of the developed coating for large-scale commercial use.

Ethical and Environmental Consideration

All tests were conducted with a focus on minimizing environmental impact and human exposure. Magnesium hydroxide offers a halogen-free, non-toxic alternative to traditional fire retardants, aligning with sustainability and health safety standards.

Conflict of interest

The authors declare that they have no conflict of interest.

Acknowledgement

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