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Comparative Analysis on Fire Performance of Wood Coated with Intumescent and Modified Intumescent Coating

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Abstract: ***This study presents a comprehensive evaluation of the fire performance of teak wood (Tectona grandis) coated with intumescent and modified intumescent coatings under controlled cone calorimeter testing at 50 kW/m² heat flux. Modified formulations incorporating synergistic additives—magnesium hydroxide (1 wt.%), boric acid (2 wt.%), and calcium carbonate (5 and 10 wt.%)—were systematically compared against uncoated wood and commercially available intumescent coatings. The modified coatings exhibited superior fire-retardant performance through multi-phase char formation comprising magnesium oxide, boron oxide, calcium oxide, and ceramic borate-phosphate networks. Key findings demonstrate substantial improvements: time to ignition increased from 10 seconds (uncoated) to 59 seconds (5% $CaCO_3$ formulation), representing a 490% enhancement. Total heat release decreased from 33.15 MJ/m² to 26.71 MJ/m² (10% $CaCO_3$), while smoke production rate and carbon monoxide emission were reduced by 37% and 35%, respectively. Thesynergistic interaction between inorganic fillers promoted endothermic decomposition, blowing gas generation, and formation of compact, thermally stable char structures with enhanced mechanical integrity and oxidation resistance. The study reveals critical formulation dependencies: 5% $CaCO_3$ optimizes ignition delay, while 10% loading provides superior heat suppression during sustained combustion. These findings advance the development of environmentally sustainable, halogen-free fire protection systems for structural wood applications, demonstrating practical applicability for timber construction where rapid fire spread poses significant life safety risks.***

Keywords: Fire Performance, Intumescent Coatings, Modified Intumescent Coatings, Magnesium Hydroxide, Boric Acid, Calcium Carbonate, Synergistic Effect, Char Expansion, Thermal Insulation, Fire Resistance, Fire Retardancy.

I. INTRODUCTION

Flame-retardant coatings represent an important research field in fire safety, as they provide effective passive protection for residential, industrial, and transportation infrastructures [1]. These coatings operate by delaying ignition, reducing flame spread, and limiting heat release, thereby reducing risks of catastrophic damage to property and human life [2]. Conventional intumescent coatings rely on theswelling of a polymeric matrix to form a char layer that insulates the underlying substrate from heat and oxygen [3]. However, their performance can be strongly influenced by environmental conditions and mechanical durability, requiring continuous improvements in their formulation [4]. A promising approach for improving the fire safety performance of intumescent coatings is the incorporation of inorganic fillers with high thermal stability. These additives can improve early flame suppression, enhance char strength, and contribute to long-term thermal insulation [5].Among such fillers, magnesium hydroxide ($Mg(OH)_2$) and calcium carbonate ($CaCO_3$) have attracted particular interest due to their abundance, environmental safety, and complementary flame-retardant mechanisms [6]. $Mg(OH)_2$ decomposes endothermically around 330–350 °C, releasing water vapor that dilutes combustible gases, cools the substrate, and delays ignition. In contrast, $CaCO_3$ decomposes above 700 °C, liberating CO_2 that suppresses flame propagation and reinforces the compactness of the char residue, improving thermal insulation during prolonged exposure [7,8]. In addition to these fillers, boric acid (H_3BO_3) has been identified as an effective synergistic additive, promoting char formation and producing a borate glassy layer that decreases oxygen and volatile gas permeability at high temperatures [9]. Despite its benefits, boric acid's inherent acidity can destabilize waterborne or alkaline polymer matrices; however, its neutralization with $Mg(OH)_2$ forms magnesium borates, which stabilize pH, improve pigment dispersion, and yield ceramic-like phases that enhance the mechanical integrity of the char [10]. The combined use of $Mg(OH)_2$, $CaCO_3$, and boric acid therefore represents a multifunctional strategy that strengthens both thermal shielding and structural durability of intumescent coatings [11]. Nevertheless, the use of high filler loadings often reduces the mechanical properties and adhesion of the coatings, highlighting the need for optimized low-content formulations [12].

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In this context, recent studies emphasize the importance of evaluating fire performance parameters such as heat release rate (HRR), mass loss rate (MLR), and time to ignition (TTI), as well as investigating chemical transformations through Fourier-transform infrared spectroscopy (FTIR) [13–15]. These methods provide a comprehensive understanding of how filler combinations influence both the flame-retardant efficiency and long-term stability of the coatings. To overcome the limitations associated with the direct use of boric acid in waterborne systems, a neutralization strategy was adopted. A solution of magnesium hydroxide ($Mg(OH)_2$) and boric acid (H_3BO_3) was prepared, leading to the formation of magnesium borate compounds that stabilize the pH of the system and reduce the detrimental acidic effects of boric acid on polymer matrices. These magnesium borates contribute additional ceramic-like phases during combustion, thereby reinforcing the char structure. Subsequently, calcium carbonate ($CaCO_3$) was incorporated into the mixture to enhance thermal insulation and char compactness.The prepared filler blend was then uniformly dispersed into an already marketed water-based emulsion, enabling the development of an environmentally sustainable intumescent formulation with multifunctional fire-retardant properties.

Based on these considerations, this paper we work to analyze the synergistic effect of $Mg(OH)_2$, $CaCO_3$, and boric acid in water-based intumescent coatings applied on structural wood substrates. Using cone calorimeter tests, the impact of these additives on HRR, MLR, and TTI is analyzed, while FTIR spectroscopy is employed to examine the chemical and structural changes of the char residue. The findings aim to demonstrate a sustainable pathway for developing multifunctional intumescent coatings with improved thermal protectection.

II. MATERIALS AND METHODS

A. *Materials*

Two kinds of fillers, magnesium hydroxide ($Mg(OH)_2$) and calcium carbonate ($CaCO_3$), were used as fire-retardant (FR) additives to improve the flame-retardant behavior of a water-based coating applied on structural wood. In addition, boric acid (H_3BO_3) was introduced as a synergistic agent.However, due to its inherent acidity, it was neutralized with $Mg(OH)_2$ to form magnesium borate compounds prior to incorporation. The prepared filler blend was then dispersed into an already marketed water-based emulsion to obtain the final coating formulation. Magnesium Hydroxide ($Mg(OH)_2$) was obtained as a high-purity grade material (CAS 1309-42-8), suitable for both laboratory and industrial applications (assay ≥99.5%) from National Fire Service College Laboratory, Nagpur, Maharashtra, India. Calcium carbonate, $CaCO_3$ was purchased from SRL Chemicals (Mumbai, India) as an extrapure grade powder (98 wt.% purity, CAS 471-34-1, molecular formula $CaCO_3$ and molecular weight 100.09 g/mol). Suitable for both laboratory and industrial use. And boric acid (H_3BO_3), was purchased from Actylis Laboratory Chemicals (CAS 10043-35-3, molecular formula H_3BO_3, molecular weight 61.83 g/mol). The product was supplied as a white crystalline powder (assay ≥99.5% by neutralization).

Wood was obtained from a local shop, wood type is Sagwan also known as Indian Teak Wood (Tectona grandis) and dimension was 100mm X 100mm X 15mm. Sagwan (Tectona grandis) woodwas selected as the substrate for testing the intumescent coatings due to its widespread use in structural and furniture applications, particularly in regions where durability and load-bearing performance are critical. Teak is known for its high density, natural oils, and dimensional stability, which make it a representative model for studying the fire-retardant performance of coatings on high-quality hardwoods. Also, its uniform grain structure and commercial availability ensure reproducible results during laboratory testing. Using sagwan wood allows the evaluation of the coating's effectiveness under realistic conditions relevant to structural and interior wood applications. Unlike steel substrates that require thermal insulation to maintain structural integrity, Sagwan mimics realistic fire exposure scenarios involving ignition, pyrolysis, and char formation. This makes it an appropriate and relevant substrate for evaluating the synergistic performance of hybrid flame-retardant coatings. The wood's surface characteristics also allow for meaningful investigation of coating adherence, expansion behavior upon intumescence, and mechanical durability under combined thermal and environmental stress.

B. *Coating preparation and characterization*

All coating batches were prepared in the laboratory by incorporating the previously discussed fillers into a commercially available water-based intumescent coating. The base coating composition was 37–46 wt.% water, 18–25 wt.% ammonium polyphosphate, 3–12 wt.% pentaerythritol, 7–13 wt.% melamine, and 4–35 wt.% other proprietary ingredients. Magnesium hydroxide ($Mg(OH)_2$) and boric acid (H_3BO_3) were first mixed in distilled water at 60 °C for 1 hour to form a neutralized magnesium borate compound ($Mg(B(OH)_4)_2$). Calcium carbonate ($CaCO_3$) was subsequently added to this mixture to complete the filler system. Two different samples were prepared:

- Sample 1: 2.12 g H_3BO_3 (2 wt.%) mixed with 1 g $Mg(OH)_2$ (1 wt.%), followed by 5 g $CaCO_3$ (5 wt.%).
- Sample 2: 2.12 g H_3BO_3 (2 wt.%) mixed with 1 g $Mg(OH)_2$ (1 wt.%), followed by 10 g $CaCO_3$ (10 wt.%).

Each filler blend was then incorporated into 100 g of the commercial intumescent coating to obtain the final formulations, which were applied on structural wood substrates using a BYK manual film applicator. The applied coating thickness was maintained at 1200 µm.

All samples were coded systematically to identify the filler composition and content. The codification scheme allows distinction between the different concentrations of $CaCO_3$ while keeping magnesium borate ($Mg(B(OH)_4)_2$).



Fig: Teak Wood

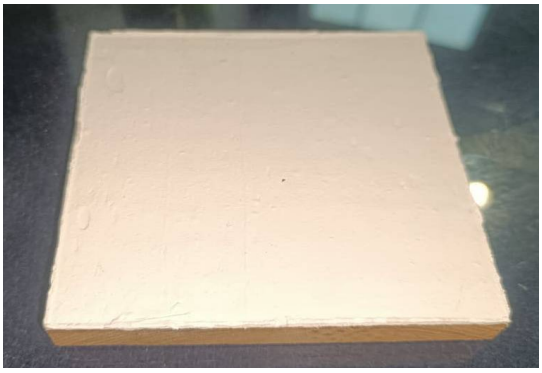


Fig: Teak Wood coated with Intumescent Coating

These coatings were subsequently used for fire performance evaluation using cone calorimetry, including measurements of heat release rate (HRR), mass loss rate (MLR), time to ignition (TTI), and FTIR characterization of the char residue.

Sample Code	Description
W	Uncoated wood.
IC	Wood coated with commercial intumescent coating.
S5	Wood coated with Sample 1 filler formulation (2% H_3BO_3, 1% $Mg(OH)_2$, 5% $CaCO_3$)
S10	Wood coated with Sample 2 filler formulation (2% H_3BO_3, 1% $Mg(OH)_2$, 10% $CaCO_3$)

C. Cone calorimeter operation

1) Cone Calorimeter Setup:

The cone calorimeter uses a cone-shaped radiant electrical heater as its primary heat source. The heater consists of a tightly wound electrical element in the form of a truncated cone, insulated with refractory fiber and encased in stainless steel. Irradiance on the specimen surface iscontrolled via thermocouples in contact with the heater, ensuring uniform heat flux across the exposed area.

A removable radiation shield protects the specimen prior to testing. This shield, constructed from non-combustible material, may be water-cooled with a matt black finish or reflective/ceramic, and is designed for quick insertion and removal.

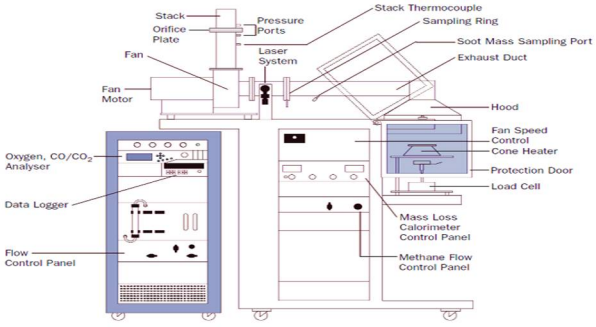


Fig 2 : Schematic Diagram of Cone calorimeter

The irradiance control system regulates heater output to maintain the preset thermal flux during calibration. Heat flux levels are verified using a Schmidt-Boelter type heat flux meter, calibrated against reference instruments.

The specimen holder is a stainless-steel square pan lined with refractory fiber insulation, designed to position the sample centrally beneath the heater and weighing device. A stainless-steel retainer frame secures the sample during testing.Specimen mass loss is monitored continuously using a precision weighing device with high accuracy and fast response.

The combustion gases are extracted by an exhaust system comprising a hood, fan, ducts, and an orifice plate flow meter. Gas mixing is promoted by a restrictive orifice, and samples are drawn via a ring sampler with multiple ports. Exhaust temperature is monitored by thermocouples, and flow is determined from pressure drop across the calibrated orifice plate.

The gas sampling system includes a pump, soot filter, cold traps, moisture and CO_2 removal stages, and supplies the oxygen analyzer. Oxygen concentration is measured by a paramagnetic oxygen analyzer, with corrections for pressure fluctuations, providing the basis for heat release rate calculation using oxygen consumption calorimetry.

Ignition is achieved via a spark igniter located above the specimen, and ignition time is measured by a calibrated electronic timer.For calibration, a methane diffusion burner with wire gauze ensures uniform flame, enabling verification of system accuracy against a known heat release rate.

All outputs include oxygen concentration, exhaust flow, thermocouple temperatures, and mass loss are recorded by a data acquisition system with high precision and one-second logging capability

2) Cone calorimetry test

CONE tests of the Wood sample were performed on a cone calorimeter following ISO 5660. For each test, (Length) 100 mm × (width) 100 mm × (height) 10 mm specimens were covered with aluminum foil, exceptthe upper surface, which was placed into a specific steel frame, the steel frame mounted horizontally on the loader, and then exposed to heat radiation of 50 kW/m^2. This heat radiation corresponded to a temperature of 617◦C on the upper test sample surface

The distance between the bottom surface of the cone heater and the specimen surface was adjusted to 25 mm.

III. RESULT AND DISCUSSION

A. Readings from cone calorimeter:

Srl no.	Sample ID	Heat Release Rate-max-$(HHR)_{Max}$	Total Heat Release (THR)	Mass Loss Rate (MLR)	CO Peak	SPR(m2/s)	T_{ig}
1	W	60.49 kW/m^2	33.15 MJ/m^2	0.0643 g/s	0.26	0.2569	10 sec
2	IC	67.01 kW/m^2	31.12 MJ/m^2	0.0616 g/s	0.19	0.1923	30 sec
3	S5	69.95 kW/m^2	30.60 MJ/m^2	0.0639 g/s	0.18	0.1687	59 sec
4	S10	66.75 kW/m^2	26.71 MJ/m^2	0.0538 g/s	0.17	0.1607	53 sec

Table : Reading obtained from Cone calorimeter for different specimen

B. Observation:

The results show clear differences in fire performance among uncoated, intumescent coated, and modified coated wood samples (containing boric acid, magnesium hydroxide, and varying calcium carbonate percentages).

Uncoated Wood (W) exhibits highest heat release rate (HRR), total heat release (THR), mass loss, CO peak, and smoke production rate (SPR), indicating the fastest and most intense burning. Starts burning quickly, with a time to ignition (T_{10}) of just 10 seconds, showing its lack of fire resistance.

Intumescent Coated Wood (IC) shows significant improvement over uncoated wood: lower HRR, THR, mass loss, CO, and SPR. Time to ignition is delayed to 30 seconds, demonstrating effective fire-retardant action of intumescent coating.

Modified Coated Wood with 5% $CaCO_3$ (S5), the addition of 5% calcium carbonate further lowers most combustion indices compared to IC: HRR, THR, mass loss, CO peak, and SPR all decrease. Time to ignition is 59 seconds, the highest among all samples, indicating maximum delay in ignition and best fire performance.

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Modified Coated Wood with 10% $CaCO_3$ (S10) with 10% calcium carbonate, HRR, THR, CO, and SPR are lowest among all samples, except mass loss which is slightly less than S5. Time to ignition is 53 seconds, still better than IC and W but not as high as S5, suggesting a slight decrease in fire retardancy at higher $CaCO_3$ loading, due to changes in coating structure by introduction of higher concentration of $CaCO_3$, which causes disturbance in the ratio of acid source, blowing agent and additive balance.

C. Images of charcoal residue after burning:

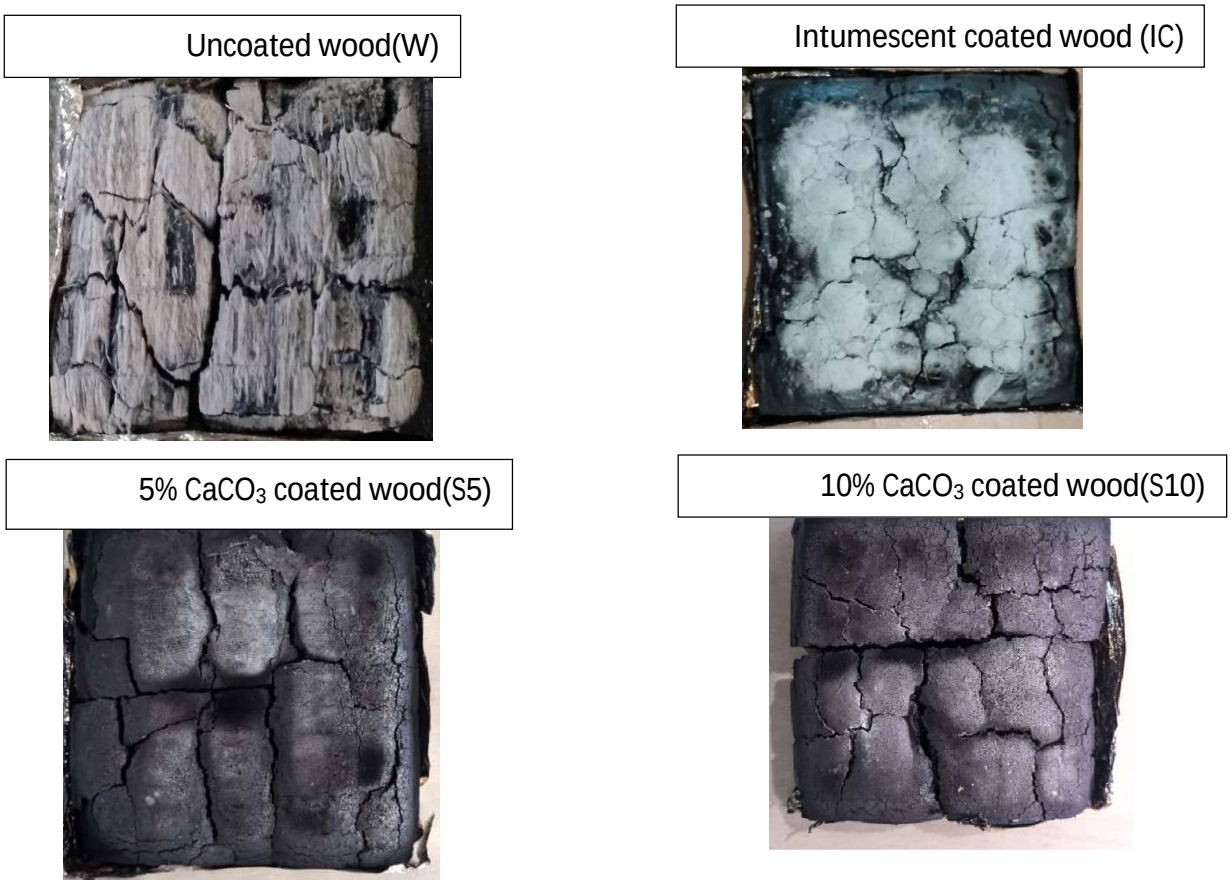


Fig : Wood specimen after burning

D. Discussion:

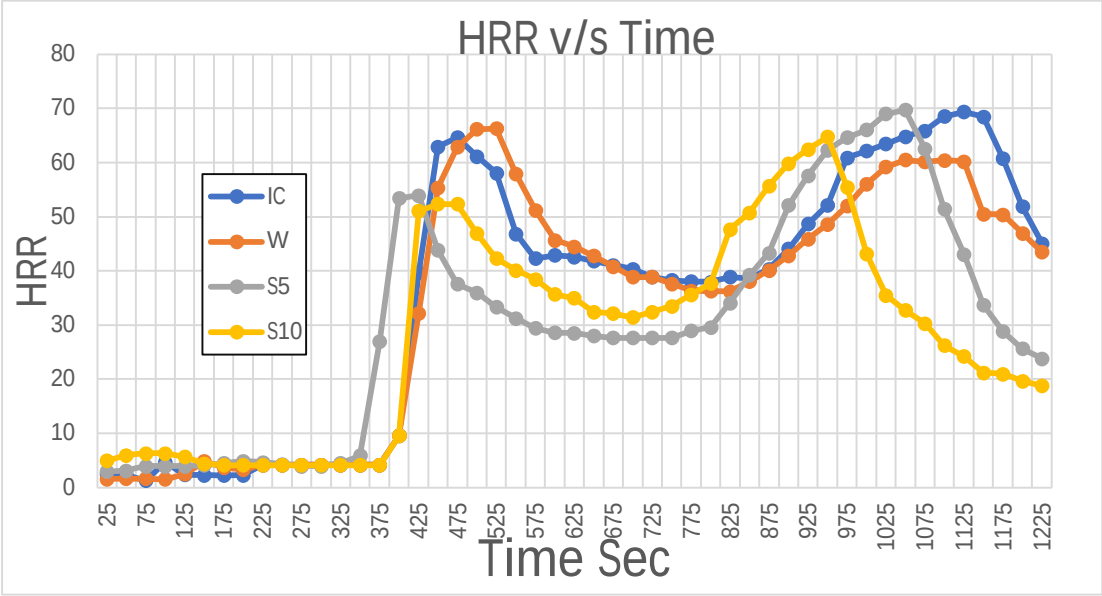
The cone calorimeter results demonstrate significant variations in fire performance among uncoated wood, conventional intumescent-coated wood, and modified intumescent coatings incorporating magnesium hydroxide, boric acid, and varying calcium carbonate loadings. Thesefindings revealimportant insights into the mechanisms by which synergistic fire-retardant formulations improve char formation and thermal protection under high heat flux conditions.

Fire Performance of Uncoated and Baseline Coated Wood:Uncoated wood (W) exhibited the poorest fire resistance, with the highest heat release rate (60.49 kW/m²), total heat release (33.15 MJ/m²), mass loss rate (0.0643 g/s), CO peak (0.26), and smoke production rate (0.2569 m²/s), combined with rapid ignition at just 10 seconds. This baseline performance reflects the inherent flammability of lignocellulosic materials, which undergo rapid thermal decomposition and combustion when exposed to the 50 kW/m² heat flux from the cone calorimeter. The application of a conventional intumescent coating (IC) resulted in substantial improvements, delaying ignition to 30 seconds and reducing HRR, THR, mass loss, CO, and smoke production. This enhancement is attributed to the classical intumescent mechanism, wherein the coating system comprising acid sources, char formers, and blowing agents undergoes a coordinated sequence of thermal decomposition, esterification, gas release, and char expansion. The expanding char layer acts as a physical and thermal barrier, insulating the underlying wood substrate from heat and oxygen while diluting combustible volatiles.

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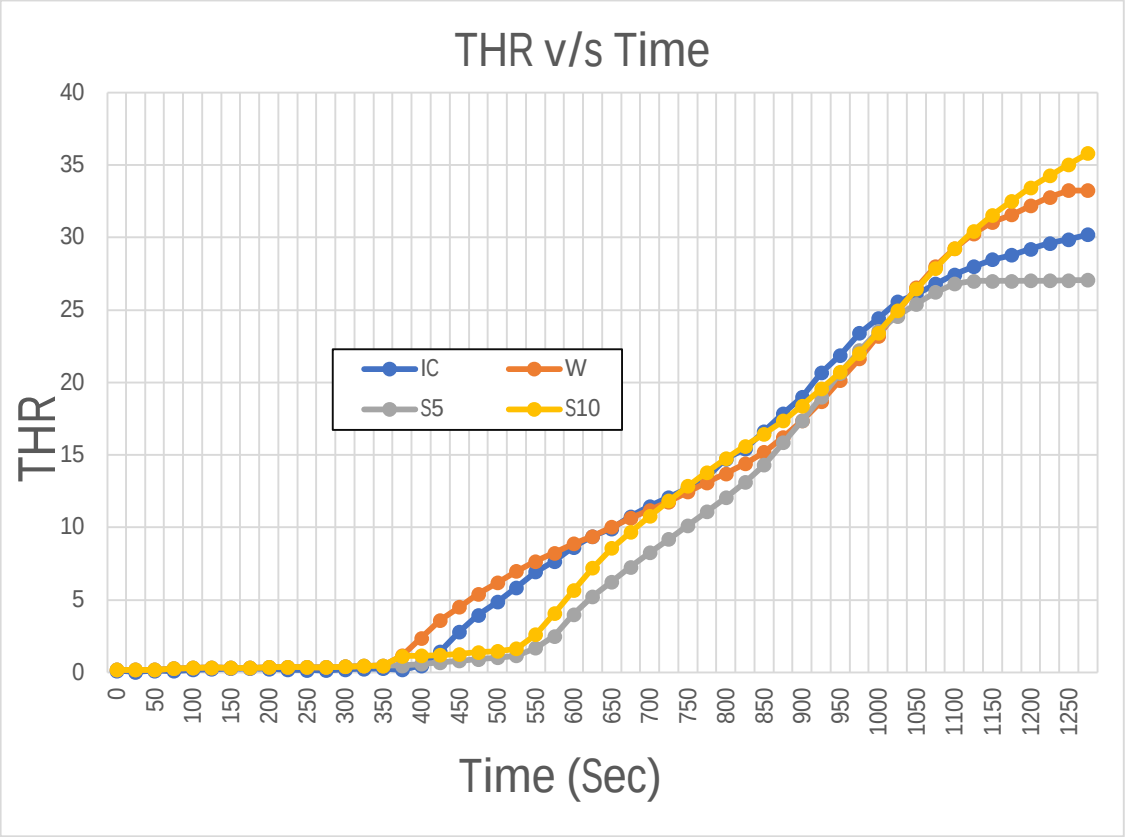
1) Enhanced Performance with Modified Coatings: The incorporation of modified fire-retardant systems based on the reaction products of magnesium hydroxide and boric acid, supplemented with calcium carbonate, yielded further improvements in fire performance. The pre-reaction of $Mg(OH)_2$ and H_3BO_3 at 40°C for one hour facilitated coprecipitation and surface association of borate species on magnesium hydroxide particles, creating a synergistic precursor system. Upon exposure to the extreme temperatures of cone calorimetry (~800°C), this system undergoes multiple endothermic decomposition reactions that significantly enhance fire retardancy. Magnesium hydroxide decomposes endothermically at approximately 340°C, releasing water vapor and forming magnesium oxide (MgO). This decomposition absorbs substantial heat from the flame zone while generating non-combustible gas that dilutes flammable volatiles and promotes char expansion. Simultaneously, boric acid dehydrates above 170°C to form boron oxide (B_2O_3), which acts as a glass-forming agent. The resulting vitreous boron oxide phase creates a protective glassy layer that binds the char structure, reduces permeability to heat and oxygen, and inhibits further oxidative degradation of the carbon residue. At elevated temperatures, the interaction between MgO and B_2O_3 can lead to the formation of magnesium borate phases (such as $Mg_3(BO_3)_2$ or MgB_2O_5), which contribute to the mechanical strength and thermal stability of the char layer. These ceramic-like phases provide a compact, continuous protective barrier that effectively shields the wood substrate from thermal attack.

2) Role of Calcium Carbonate as a Synergistic Filler:The addition of calcium carbonate as a mineral filler introduced further complexity and optimization to the fire-retardant system. At temperatures exceeding 700°C, $CaCO_3$ undergoes endothermic decomposition to calcium oxide (CaO) and carbon dioxide (CO_2). This decomposition absorbs additional heat and generates non-combustible gas, contributing to the blowing effect and char expansion. More importantly, calcium carbonate and its decomposition product CaO interact with phosphate species present in intumescent systems to form stable calcium phosphates and calcium polyphosphates (such asCaP_2O_6), which enhance char strength, compactness, andresistance to oxidative degradation. Research has demonstrated that the optimal ratio of $CaCO_3$ to acid sources iscritical for maximizing thermal insulation performance, with excessive filler loadingpotentially disrupting the balance of acid source, char former, and blowing agent. In the present study, the S5 formulation (5% $CaCO_3$) achieved the longest time to ignition (59 seconds) and exhibited substantial reductions in HRR, THR, mass loss, CO, and smoke production compared to both uncoated wood and baseline intumescent coating. This superior performance can be attributed to an optimal balance of components that facilitated efficient char formation, maximum expansion, and a compact protective layer with enhanced resistance to decomposition.



The S10 formulation (10% $CaCO_3$) demonstrated the lowest HRR (66.75 kW/m²), THR (26.71 MJ/m²), CO peak (0.17), and smoke production (0.1607 m²/s) among all samples. However, its time to ignition (53 seconds) was lower than that of S5, suggesting a trade-off in performance characteristics. This reduction in ignition delay at higher $CaCO_3$ loading may be explained by disturbances in the critical balance of intumescent components.

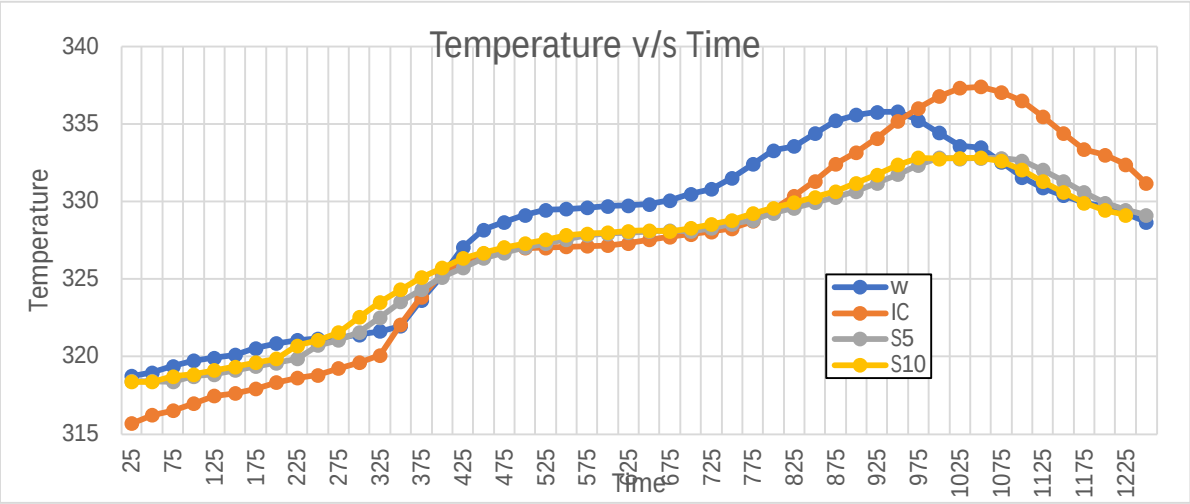
Excessive filler content can dilute the concentration of acid sources and blowing agents, potentially reducing the efficiency of esterification reactions and gas generation that drive initial char expansion. Additionally, higher filler loading may increase the viscosity of the incipient char, hindering its ability to expand and trap gases effectively during the early stages of intumescence.Nevertheless, the lower heat release and smoke production of S10 indicate that the increased $CaCO_3$ content provided superior thermal insulation and fire suppression once the char was fully formed. This suggests that while the initial intumescence may be slightly compromised, the resulting char possesses enhanced thermal mass, improved structural integrity, and better resistance to oxidative degradation at elevated temperatures.



3) Mechanism of Enhanced Fire Retardancy:The synergistic fire-retardant mechanism of the modified coatings can be summarized as follows: During exposure to the cone calorimeter's heat flux, the coating undergoes sequential thermal decomposition. Magnesium hydroxide and boric acid decompose endothermically in the temperature range of 170–340°C, absorbing heat and releasing water vapor. This initial phase cools the substrate and generates blowing gases that expand the softened coating matrix. Calcium carbonate decomposes at higher temperatures (>700°C), providing additional endothermic cooling and CO_2 blowing. The solid decomposition products of MgO, B_2O_3, CaO, accumulates to form a dense, multi-phase char structure. Boron oxide acts as a binder and vitrification agent, creating a glassy matrix that seals pores and reduces permeability. Magnesium and calcium oxides reinforce the char mechanically and chemically, forming stable ceramic phases that resist further oxidation and structural collapse. The combined effect is a thick, compact, and thermally stable char layer that effectively insulates the wood substrate, suppresses combustible volatile release, and reduces heat feedback to the combustion zone.

4) Char Formation and Structural Characteristics:The quality of char formation is a critical determinant of fire-retardant performance. Research has shown that compact, continuous char layers with minimal cracking and a closed cellular structure provide superior thermal insulation compared to fragile, lamina-like, or highly porous chars. The synergistic interaction between magnesium hydroxide, boric acid, and calcium carbonate promotes the formation of such high-quality chars by providing multiple mechanisms of char reinforcement: mechanical support from oxide particles, chemical cross-linking via borate and phosphate networks, and viscosity control through balanced filler loading.

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The formation of a compact basal layer at the char-substrate interface is particularly important for long-duration fire protection, as this layer resists oxidative degradation and maintains thermal insulation even as the outer char layers are consumed. The observed performance trends suggest that the S5 and S10 formulations successfully achieved this type of robust char structure, with S10 providing the most effective barrier to heat release and smoke generation once fully developed.

5) Optimization of Component Balance: The results underscore the importance of carefully balancing the ratios of acid source, char former, blowing agent, and filler in intumescent formulations. While increased filler loading generally improves char strength and thermal stability, excessive amounts can disrupt the delicate coordination of softening, esterification, and gas evolution that drives intumescence. The optimal filler concentration must provide sufficient thermal mass and char reinforcement without excessively diluting reactive components or increasing viscosity to the point where expansion is inhibited. In the this study, the 5% $CaCO_3$ loading appears to represent an optimal balance for maximizing ignition delay, while the 10% loading provides superior performance in terms of reducing heat release and smoke production during sustained fire exposure. This suggests that formulation optimization should consider the specific performance objectives whether maximizing time to ignition, minimizing peak heat release, or reducing toxic gas and smoke generation and adjust component ratios accordingly.

IV. CONCLUSION

This study successfully demonstrated the enhanced fire-retardant performance of modified intumescent coatings incorporating magnesium hydroxide, boric acid, and calcium carbonate on wood substrates under cone calorimeter testing at 50 kW/m² heat flux. The systematic investigation of four sample configurations uncoated wood (W), conventional intumescent coating (IC), and modified coatings with 5% (S5) and 10% (S10) calcium carbonate revealed significant improvements in fire safety parameters through synergistic chemical interactions.

The pre-reaction of magnesium hydroxide and boric acid at 40°C generated a reactive precursor system that, upon thermal exposure, provided multiple fire-retardant mechanisms including endothermic dehydration, blowing gas generation, and formation of protective ceramic-glass char structures. The integration of calcium carbonate as a mineral filler further enhanced performance through additional endothermic decomposition and char reinforcement, while creating complex interactions with phosphate species that improved char integrity and thermal stability.

The superior performance of the modified coatings is attributed to the formation of a multi-phase char structure comprising magnesium oxide, boron oxide, calcium oxide, and complex borate-phosphate ceramics that collectively provide thermal insulation, mechanical strength, and oxidation resistance. The synergistic interactions among these components create a compact, continuous protective barrier that effectively shields the wood substrate from thermal attack while suppressing combustible volatile release.

The observed trade-off between ignition delay and sustained fire suppression at higher filler loadings underscores the critical importance of component balance in intumescent formulations. While 5% calcium carbonate provides optimal ignition resistance, 10% loading offers superior performance during prolonged fire exposure.

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These findings contribute significantly to the development of environmentally sustainable fire protection systems for wood-based construction materials. The use of inorganic mineral fillers and the elimination of halogenated compounds align with contemporary environmental regulations while providing enhanced fire safety performance. The demonstrated effectiveness under high heat flux conditions suggests potential applications in structural fire protection, interior finishing systems, and other building applications where rapid fire spread poses significant life safety risks.

Future research should focus on long-term durability testing, weatherability assessments, and scaling up for commercial applications. Additionally, investigation of the coating system's performance under different heat flux conditions and fire exposure scenarios would provide valuable insights for developing comprehensive fire protection standards and application guidelines.

Key findings:

1) Substantial improvement in ignition resistance: Time to ignition increased from 10 seconds for uncoated wood to 59 seconds for the S5 formulation, representing a 490% improvement and demonstrating the effectiveness of the modified coating system in delaying fire initiation.

2) Significant reduction in THRR: All coated samples exhibited lower heat release rates, with S10 achieving the lowest maximum HRR of 66.75 kW/m² compared to 60.49 kW/m² for uncoated wood, indicating superior fire suppression capability during sustained combustion.

3) Enhanced smoke suppression and reduced toxic gas emission: CO peak values decreased from 0.26 for uncoated wood to 0.17 for S10, while smoke production rates were reduced by up to 37%, contributing to improved life safety through reduced smoke toxicity and visibility obstruction.

4) Optimal formulation of coating: The S5 formulation provided maximum ignition delay, while S10 demonstrated superior heat suppression and lowest total heat release (26.71 MJ/m²), indicating that formulation optimization can be tailored to specific fire protection objectives.

REFERENCES

[1] Viholainen N, Kylkilahti E, Autio M, Toppinen A. A home of wood: Consumer experiences of wooden building materials. International Journal of Consumer Studies. 2020 Nov;44(6):542-5

[2] Borisovich SA, Alexandrovich BA, Abdukadirovich MB, Maratovich AM, KuandykovichMZ, Rakhmetulin BZ. made Fire hazard and fire resistance of wooden structures. Springer International Publishing; 2023 Apr 6.

[3] Nazrun T, Hassan MK, Hasnat MR, Hossain MD, Ahmed B, Saha S. A comprehensive review on intumescent coatings: formulation, manufacturing methods, research development, and issues. Fire. 2025 Apr;8(4):155.

[4] Zou Y, Zhang Y, Li P, Qiao J, Wu Y, Li X, Zuo Y. Water-resistant, transparent, and highly efficient flame-retardant wood coating. Industrial Crops and Products. 2025 Jan 1;223:120061.

[5] Scionti G, Piperopoulos E, Atria M, Calabrese L, Proverbio E. Effect of magnesium hydroxide and aluminum hydroxide as thermal barriers on the flame-retardant behavior of acrylic-based coating. Coatings. 2023 Aug 28;13(9):1517.

[6] Mallick BN, Rana PK, Sahoo PK. Preparation of Starch-Based Bionanocomposite Hydrogel with Mica for Fire Retardancy. Advances in Polymer Technology. 2015 Dec;34(4).

[7] Ran Y, Ding J, Yang F, Bao Q, Zhu J, Du C, Tao P, Wang X, Zhang S, Yin W. A novel organic-inorganic composite flame-retardant coating with excellent compatibility provides superior flame retardancy and smoke suppression for wood. Industrial Crops and Products. 2025 Feb 1;224:120286.

[8] Popescu CM, Pfriem A. Treatments and modification to improve the reaction to fire of wood and wood based products—An overview. Fire and Materials. 2020 Jan;44(1):100-11.

[9] Lainioti GC, Koukoumtzis V, Andrikopoulos KS, Tsantaridis L, Östman B, Voyiatzis GA, Kallitsis JK. Environmentally friendly hybrid organic–inorganic halogen-free coatings for wood fire-retardant applications. Polymers. 2022 Nov 16;14(22):4959.

[10] Hussain A, Landry V, Blanchet P, Hoang DT, Dagenais C. Fire performance of intumescent waterborne coatings with encapsulated APP for wood constructions. Coatings. 2021 Oct 20;11(11):1272.

[11] Tsapko Y, Tsapko A, Bondarenko O. Effect of a flame-retardant coating on the burning parameters of wood samples. Восточно-Европейскийжурналпередовыхтехнологий. 2019(2 (10)):49-54.

[12] Kmeťová E, Kačíková D, Kačík F. The effect of intumescent coating containing expandable graphite onto spruce wood. Coatings. 2024 Apr 16;14(4):490.

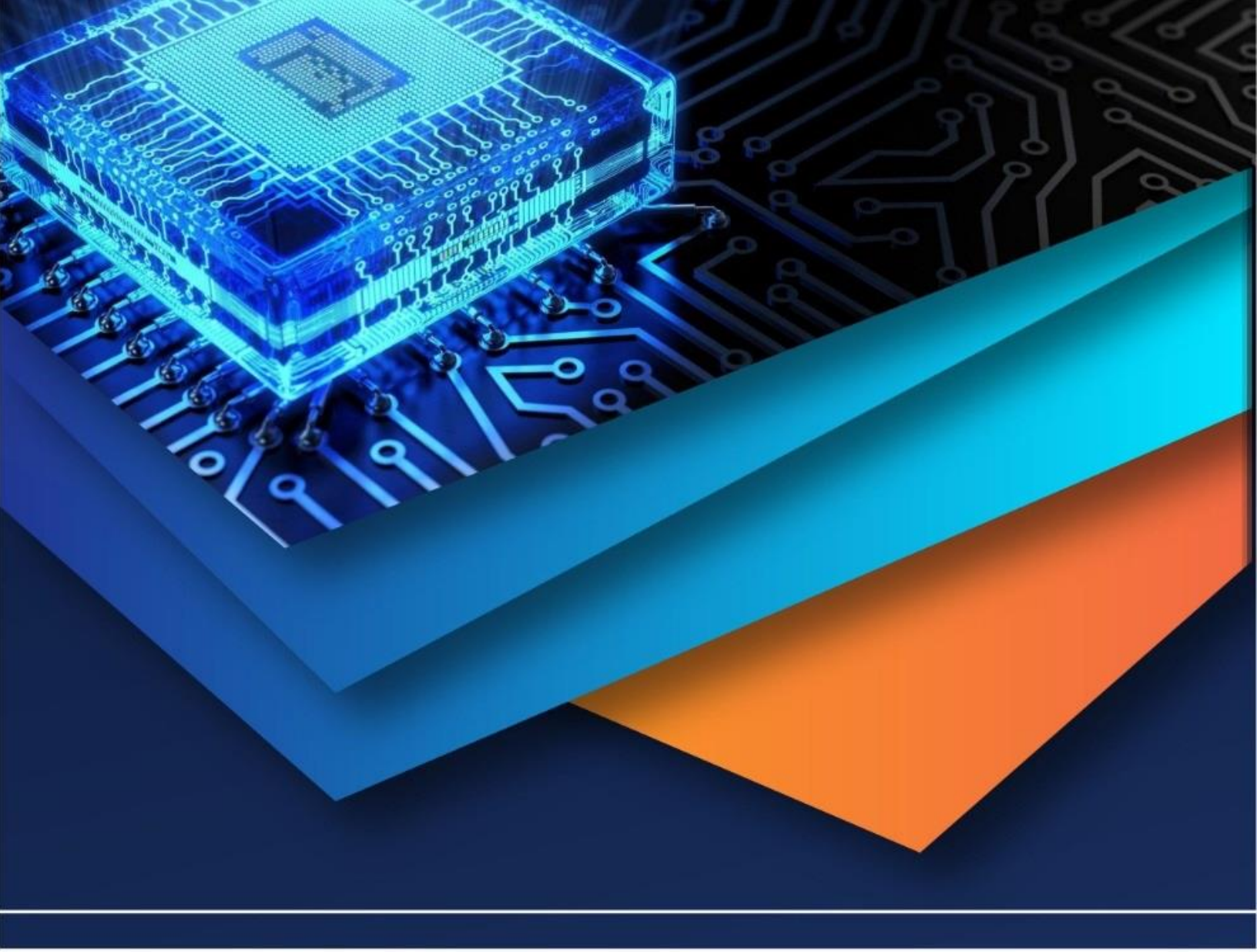
[13] IS 5509:2021 – Fire Retardant Plywood – Specification (BIS, India): Specifies requirements and test methods for fire-retardant plywood to limit flame spread and ignition.

[14] ISO 5660-1:2015 – Reaction-to-fire tests using heat flux calorimeter (Cone Calorimeter): Measures heat release rate, smoke, and ignition under controlled heat flux.

[15] ASTM E1354 – Heat and Visible Smoke Release Rates Using Oxygen Consumption Calorimeter: Determines heat and smoke release of materials under radiant heat.

[16] ASTM E84 – Surface Burning Characteristics of Building Materials (Steiner Tunnel Test): Evaluates flame spread and smoke development on material surfaces.

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