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A STUDY ON THE PHYSICAL PROPERTIES AND FLAME RETARDANT PERFORMANCE OF HIGH-CONCENTRATION BORON-BASED FLAME RETARDANT PB WITH AMINO RESIN ADDITIVES

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ABSTRACT: Flame-retardant particleboards were developed by incorporating a high-concentration boron-based flame retardant into amino resin systems. The flame retardant was introduced using a resin-mixing method with urea-formaldehyde (UF) and melamine-formaldehyde (MF) resins employed as carriers. The effects of the resin type, boron compound loading, and resin solid content on the physical and mechanical properties were systematically evaluated to identify the optimal manufacturing conditions. The results showed that the flame-retardant treatment had a minimal impact on the density and moisture content. However, the MF resins exhibited superior dimensional stability in regarding thickness swelling compared with the UF resins. All the specimens maintained a flexural strength exceeding 18.0 MPa, indicating sufficient mechanical performance. Although the flame-retardant particleboard achieved only an E-class rating under EN 13501-1, significant reductions in the charred area and after-flame time indicated improved flame retardancy. These findings confirm that boron-based treatment can enhance flame resistance without compromising the core physical and mechanical characteristics of the particleboard. This study supports the feasibility of using flame-retardant particleboards in interior construction and furniture applications. Future studies should focus on advancing flame-retardant formulations to achieve higher fire classification levels, assess long-term performance, and confirm environmental safety.

KEYWORDS: Flame-retardant, Boric acid, Borax, Combustion, Wood-based panel, Particleboard

1 – INTRODUCTION

Wood-based panels are widely used in architecture and interior design because of their affordability, versatility, and ease of processing. However, one of their major limitations is their vulnerability to fire and environmental degradation. In response to increasingly stringent fire safety regulations and the growing popularity of timber construction, the demand for flame-retardant wood materials, particularly for interior finishes and furniture, has increased significantly. Boron compounds, such as boric acid (BA) and borax (BX), are well known for their flame-retardant efficacy on wood surfaces. While BX reduces flame spread and promotes smoldering, BA suppresses smoldering but has a limited effect on flame spread. These compounds are often used in combination to achieve synergistic effects [1], [2], [3]. Despite these advantages, boron-based compounds suffer from low water solubility and high leachability under humid and wet conditions. Because they are not chemically fixed within the wood matrix, their long-term durability and effectiveness are significantly limited [3], [4]. To address these challenges, several studies have investigated the incorporation of boron compounds into polymeric adhesives to reduce the leachability and improve the durability. Traditionally, BA and BX have been used in solution form for wood and wood-based panels such as particleboard and MDF, while powder forms are more commonly applied in wood–plastic composites [5]. However, these conventional approaches still present challenges in achieving uniform distribution and long-term retention of the flame-retardant agents within the wood matrix. Among the various strategies, BA and BX have been blended with amino resins, such as melamine-

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formaldehyde (MF), urea-formaldehyde (UF), and melamine-urea-formaldehyde (MUF), for the fabrication of wood-based panels. These approaches have shown enhanced flame retardancy and improved mechanical performance in certain cases [6], [7], [8], [9]. Based on these findings, this paper proposes a novel approach to overcome the solubility and leaching limitations of conventional boron-based flame retardants by formulating high-concentration solutions of BA and BX. This solution was incorporated into particleboard using a resin-mixing method, with UF and MF resins serving as carriers. The objective was to enhance flame resistance while maintaining or improving the physical and mechanical properties of the board. This study evaluated the flame retardancy, dimensional stability, and mechanical strength of different resin types, boron loadings, and resin solid contents to determine the optimal manufacturing conditions. This study aims to increase the practical value of recycled wood materials, promote their use in sustainable construction and interior applications, and contribute to the development of durable, flame-retardant, wood-based products. Although this research focuses on non-structural particleboards, the formulation strategy—combining high-concentration boron-based flame retardants with amino resin systems—demonstrates strong potential for application in structural engineered wood products (EWPs), such as oriented strand board (OSB), laminated veneer lumber (LVL), and cross-laminated timber (CLT). Accordingly, this study provides a foundational basis for adapting flame-retardant technologies to structural-scale timber components, in response to increasing fire safety requirements in contemporary mass timber construction.

2 – MATERIALS AND METHODS

2.1 Flame Retardant

The preparation process of the boron-based flame retardant is illustrated in Fig. 1. The flame retardant was prepared by mixing BA (H_3BO_3) and BX ($Na_2B_4O_7 \cdot 10H_2O$) and dissolving the mixture in water at a high temperature of 90–95 °C to produce a boron compound solution. This solution, referred to as BAX, has a solid content of 40%. The BAX solution was subsequently mixed with amino resins, specifically UF and MF, each with a solid content of 70%, to prepare high-concentration boron-based flame retardants. These were designated as UBAX (UF + BAX) and MBAX (MF + BAX). The mixing ratios between the amino resin and BAX were optimized through preliminary experiments and set to 1:2 and 1:1.6. The viscosity of each additive was measured using a DV-E Viscometer (BROOKFIELD, USA). The properties of BAX and the carrier resins are listed in Table 1. The effects of the carrier resin type and BAX loading level on flame retardancy and physical properties were systematically evaluated.

Table 1: Physical Properties of the Carrier Resins and Flame-Retardant Components

Property	Type	Solid content (%)	Viscosity (cP)	pH
Carrier Resin	UF	69.6	820	8.2
	MF	70.6	280	8.6
Flame Retardant	UBAX	50.3	39.6	7.5
	MBAX	51.6	40.8	7.0

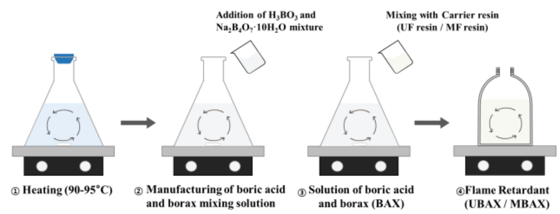

Figure 1. Preparation process of boron-based flame retardant

2.2 Fabrication of Flame-Retardant Particleboard

Conventional particleboards consist of a three-layer structure comprising surface–core–surface layers. As the surface layer is the most susceptible to combustion, this study focused on applying a flame retardant only to the surface layer to suppress flammable gas release and delay ignition. A single-layer board was fabricated using surface particles (40–60 mesh), which were oven-dried at 105 °C for 24 h to achieve a moisture content below 5%. An E1-grade UF resin with 60% solid content was used as the adhesive. The resin loading was 12% based on the oven-dry particle weight. A 20% ammonium chloride (NH_4Cl) solution was used as a hardener at 5% relative to resin solids. Additionally, 3% wax was added to enhance the water resistance. The surface particles were then mixed with the flame-retardant resin using a mechanical stirrer and physically agitated for 10 min to ensure a uniform coating. The coated particles were formed into a mat using a forming frame prior to hot-pressing. Boards were manufactured using a hydraulic single press at 50 ± 2 kgf/cm² and 180 °C, with a pressing time of 30 s/mm. The target density was 0.75 g/cm³, and the final board dimensions were 300 × 300 × 10 mm. The thickness of the particleboard was uniformly controlled by using a press stopper during pressing. The detailed flame-retardant treatment conditions, including the carrier resin type and BAX additive level, are summarized in Table 2. The flame-retardant particleboard manufacturing process is illustrated in Fig. 2.

Table 2: Flame-Retardant Treatment Conditions Based on Carrier Resin Type and BAX Content

Experiment	Resin type	Resin (%)	BAX (%)
Preliminary	UF	2	4 3.2
	MF	2	4 3.2
Main	MF	1 1.5 2	4 4 4

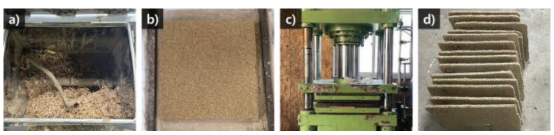

Figure 2. Particleboard manufacturing process: (a) Mixing with flame-retardant resin, (b) Mat formation, (c) Hot pressing, (d) Conditioning

2.3 Evaluation of Physical and Mechanical Properties

To determine the appropriate carrier resin, a preliminary test was conducted using UBAX and MBAX to fabricate flame-retardant particleboards. The physical properties were compared, and MF was selected as the optimal resin for subsequent tests. Boards were fabricated with MBAX contents of 1.0%, 1.5%, and 2.0% relative to the oven-dried particle weight, and a non-treated control group was used for comparison. All specimens were conditioned at room temperature for more than 2 d. The physical and mechanical properties were evaluated based on density, moisture content, thickness, swelling, bending strength, and formaldehyde emission. Thickness swelling was determined by submerging the specimens horizontally in water at (20 ± 1) °C for 24 h, followed by measuring the thickness after removing surface moisture. The bending strength was measured using a universal testing machine (UTM, HOUNSFIELD H50KS-0064, UK). The span length was set to the thickness of the specimen multiplied by 15, plus 50 mm, according to the ISO 16893:2016 standard. Formaldehyde emissions were determined using the desiccator method, in accordance with ISO 12460-4:2016 standard. All the tests were conducted according to the ISO 16893:2016 standard.

2.4 Evaluation of Flame-Retardant Performance

Prior to testing, the specimens were conditioned at (20 ± 2) °C and (65 ± 5)% relative humidity until equilibrium moisture content was achieved. The flame-retardant performance was evaluated using a 45 Degree Flammability Tester (FESTEC INTERNATIONAL Co., Ltd., Korea) equipped with a Meker burner. The specimens were mounted at 45° and exposed to a 65 mm flame for 2 min. The test was conducted in accordance with the Korean National Fire Agency standard (Notice No. 2022-29) and KS F 2819 (Standard Test Method for Incombustibility of Thin Materials for Buildings), both of which specify the performance thresholds for the charred area, char length, afterflame time, and afterglow time. To ensure accurate measurements, only the actual charred regions were measured, excluding the soot deposits. After testing, the specimen surface was lightly sanded using a sanding machine to remove the soot layer before the charred area and char length were assessed. The experimental setup for the flame-retardancy tests is shown in Fig. 3. These national criteria, along with international standards, such as ISO 11925-2 and EN 13501-1, are summarized in Table 3 for comparison. While ISO 11925-2 also employs a single-flame source, it focuses on determining whether the flame spread exceeds 150 mm, which is the threshold for the E-class classification under EN 13501-1. Based on these criteria, the relationship between flame-retardant content and performance was analyzed to identify the optimal formulation.


Figure 3. Test setup for flame-retardant evaluation using a 45 Degree Flammability Tester

Table 3: Comparison of Korean and International Flame-Retardant Performance Standards

Criteria	Korean Standard	ISO 11925-2 / EN 13501-1
Charred area	≤ 50 cm²	Not specified
Char length	≤ 200 mm	≤ 150 mm
Afterflame time	≤ 10 s	Recorded only (not used as a criterion)

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Afterglow time	≤ 30 s	Recorded only (not used as a criterion)

3 – RESULTS AND DISCUSSION

3.1 Effect of Resin Type and BAX Loading on the Physical and Flame-Retardant Properties of Particleboards

The physical, mechanical, and flame-retardant properties of the particleboards were evaluated based on the type of carrier resin, UF or MF, and the loading level of the boron-based flame retardant, BAX. The physical and mechanical properties of the treated boards, including density, moisture content, thickness, swelling, bending strength, and formaldehyde emission, are summarized in Table 4. The density remained consistent across all test conditions, indicating that BAX addition and resin type had minimal impact on board compaction. The moisture content slightly increased at a BAX loading of 4%, suggesting higher hygroscopicity owing to the boron compound. The thickness swelling decreased as the BAX content increased, reflecting improved dimensional stability compared with the untreated samples. The MF-treated boards exhibited approximately 13% less thickness swelling than the UF-treated boards. This enhanced water resistance may be attributed to the higher substitution rate of methylol ($-CH_2OH$) groups in MF resin, which contributes to the formation of a more stable cross-linked polymer network. The bending strength improved following the flame-retardant treatment. With the addition of 4% BAX, the bending strength increased by 130.2% to 146.1% compared with that of the untreated control. This enhancement is likely due to the improved bonding efficiency and internal cohesion facilitated by the amino resin matrices, particularly because BAX interacts with the adhesive system to reinforce the board integrity. The formaldehyde emission levels of all treated boards met the E1 emission standards specified in ISO 12460-4. However, the emissions were slightly higher than those of the untreated specimens, likely due to the use of formaldehyde-based carrier resins. This suggests the need for further formulation optimization to balance the flame performance and environmental safety. The flame-retardant performance results, including the afterflame time, afterglow time, charred area, and char length, are presented in Table 5. All treated samples satisfied the Korean fire safety criteria, showing afterflame times ≤ 1 s and afterglow times ≤ 10 s, with charred area and char length below regulatory thresholds. All the samples met the EN 13501-1 Class E classification. Compared with the untreated boards, the flame-treated specimens exhibited visibly reduced char formation. This may be attributed to the ability of boron compounds to inhibit the release of combustible gases, slow thermal degradation, and limit flame spread, as reported by LeVan and Tran [1].

Table 4: Physical and Mechanical Properties of Flame-Retardant Particleboards with Different Resin Types (Preliminary Test)

Sample	Physical and Mechanical Properties				
	ρ (g/cm^3)	MC (%)	TS (%)	MOR (MPa)	FE (mg/L)
C	0.75	6.67	17.82	9.73	0.5
UF-4	0.78	7.41	11.08	22.40	1.2
UF-3.2	0.78	7.37	12.33	18.59	1.5
MF-4	0.78	6.69	9.57	23.95	0.8
MF-3.2	0.80	6.57	10.81	18.86	1.1

Table 5: Flame-Retardant Performance of Flame-Retardant Particleboards with Different Resin Types (Preliminary Test)

Sample	Flame-Retardant Performance			
	After flame time (s)	After glow time (s)	Charred Area (cm^2)	Char length (cm)
C	0.7	8.1	34.13	7.0
UF-4	0.5	3.3	23.40	6.0
UF-3.2	0.8	2.7	22.05	6.0
MF-4	0.8	3.1	21.60	6.0
MF-3.2	0.5	3.5	22.50	6.0

3.2 Optimization of Manufacturing Conditions for MF-Based Flame-Retardant Particleboards

Based on the results of the preliminary study, MF resin was selected as the optimal carrier owing to its superior water resistance and dimensional stability. The BAX content was fixed at 4% (based on oven-dry particle weight), and the MF resin content was varied at 1.0%, 1.5%, and 2.0% to evaluate its influence on the board properties. The physical and mechanical results are summarized in Table 6. As the MF content increased, both water resistance and bending strength improved. The thickness swelling decreased by approximately 20.3% at 2.0% MF compared to that of the untreated control, whereas the bending strength increased by nearly 60%. However, the performance improvement between 1.5% and 2.0% was marginal, suggesting a plateau in the benefits of additional resin. This indicates that a 1.5% MF content may be sufficient to stabilize the board structure and moisture durability. Compared to the UF-treated boards in the preliminary study, the MF-treated boards achieved similar or superior performance at lower resin levels, highlighting higher bonding efficiency and durability of the MF. The reduced resin content also presents cost-effective and environmentally favorable manufacturing potential. The flame-retardant performances of composites with various MF contents are listed in Table 7. All treated samples met the flame-retardant performance criteria specified by the Korean National Fire Agency, exhibiting afterflame times ≤ 1 s and afterglow times ≤ 10 s. The charred area and char length also remained within the required thresholds. Additionally, all samples achieved a Class E classification under EN 13501-1. Compared to the untreated boards, the treated specimens exhibited visibly reduced char formation. This reduction may be attributed to the ability of boron compounds to inhibit the diffusion of combustible gases, thereby slowing thermal degradation and limiting the flame spread, as previously reported by Levan and Tran [1].

Table 6: Physical and Mechanical Properties of MF-Based Flame-Retardant Particleboards with Varying Resin Contents (Main Test)

Sample	Physical and Mechanical Properties				
	ρ (g/cm^3)	MC (%)	TS (%)	MOR (MPa)	FE (mg/L)
C	0.79	10.4	12.30	10.42	0.3
MF-1	0.82	11.7	13.72	13.83	0.7
MF-1.5	0.83	10.5	10.60	15.12	0.9
MF-2	0.82	11.2	9.81	16.59	0.8

Table 7: Flame-Retardant Performance of MF-Based Particleboards According to Resin Content (Main Test)

Sample	Flame-Retardant Performance			
	After flame time (s)	After glow time (s)	Charred Area (cm^2)	Char length (cm)
C	0.8	5.2	42.19	9.0
MF-1	0.8	2.6	21.09	6.3
MF-1.5	0.6	2.9	24.01	6.6
MF-2	0.9	2.8	23.70	6.5

4 – CONCLUSIONS

In this study, a high-concentration boron-based flame retardant was developed using amino resins (UF and MF) as carriers and applied to particleboard. The effects of the flame-retardant treatment on the physical, mechanical, and fire-related properties of the panels were systematically evaluated. The results confirmed that flame-retardant treatment improved the dimensional stability and moisture resistance while maintaining or enhancing the mechanical strength. Particleboards fabricated with MF resin exhibited better water resistance than those fabricated using UF resin, as indicated by the reduced thickness swelling. All specimens maintained a flexural strength above the quality standard and met the E1 formaldehyde emission limit, confirming their environmental safety. In terms of flame performance, all the treated boards met the Korean National Fire Agency's performance requirements and satisfied the EN 13501-1 Class E classification. The observed reduction in the charred area and char length further validated the enhanced flame retardancy effect. Notably, no significant difference in flame performance was observed across different resin dosage levels, indicating that effective flame resistance can be achieved with minimal resin addition. The optimized formulation of 2% MF resin and 4% BAX provided the best balance among flame retardancy, mechanical performance, and moisture durability. These findings offer practical insights into the design of flame-retardant particleboards that can be safely and efficiently used as nonstructural materials in building interiors, such as wall linings, ceilings, and furniture components. Furthermore, this approach helps mitigate the leachability of traditional boron-based flame retardants and contributes to the development of more durable and sustainable fire-safe wood products. Moreover, the demonstrated compatibility between boron-based flame retardants and amino resin systems indicates strong potential for extending this formulation to structural engineered wood products, such as OSB, LVL, and CLT. Future research should focus on optimizing the application method and evaluating the post-fire mechanical integrity of treated structural panels. In particular, achieving higher fire classification levels and improving long-term durability under real-world environmental conditions will be key to expanding the application of this technology to mass timber construction.

5 – ACKNOWLEDGEMENT

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