Fire Safety Performance of Radiata Pine-magnesium-laminated (RML) Board for Building Material

Eun-Suk Jang,[a,c] Seok-Un Jo,[b] and Hee-Jun Park,[b,*]

In this study, the Radiata pine-magnesium-laminated (RML) board was proposed to develop wood materials with flame retardancy. The 45° flammability test, cone calorimeter test, gas toxicity test, single burning item (SBI) test, and Steiner tunnel test were performed to confirm the flame-retardant performance of RML. For RML with 80 to 150 g/m^2 of flame retardant applied, the carbonized area in the flammability test was 44.3 to 35.0 cm^2; in the cone calorimeter test, the total heat release (THR) was 5.4 to 6.2 MJ/m^2, and the time to stopped behavior of white lab mice was 857s, which surpasses the standard for semi-noncombustible materials in Korea. The RML was Class A2 based on EN 13823 (2020) in the SBI test and Class A based on ASTM E84-21a (2022) in the Steiner tunnel test. In conclusion, RML showed excellent flame-retardant performance. The thin wood veneer absorbs the flame retardant easily, and the magnesium board is a semi-noncombustible material. Accordingly, it was confirmed that an RML board could be a commercial wood-based building material with satisfactory flame retardancy.

DOI: 10.15376/biores.20.3.5620-5632

Keywords: Fire safety performance; Radiata pine; Magnesium-laminated board; Total heat release; Single burning item

*Contact information: a: Research Institute of Human Ecology, College of Human Ecology, Jeonbuk National University, Jeonju 54896, South Korea; b: Department of Housing Environmental Design, College of Human Ecology, Jeonbuk National University, Jeonju 54896, South Korea; c: Sambo Scientific Co., Ltd., R&D Center, Seoul 07258, South Korea; *Corresponding author phjun@jbnu.ac.kr*

INTRODUCTION

One of humanity's most pressing global challenges is the imperative to curtail greenhouse gas emissions and address climate change (Erickson 2017; Jang and Kang 2023a). Among greenhouse gas emissions, the construction industry is a significant contributor, generating substantial amounts of CO_2 primarily attributable to embodied and operational energy consumption (Chai *et al.* 2022).

The production of cement and metal building materials emits the highest levels of greenhouse gas. In contrast, wood, as a building material, can sequester carbon dioxide and requires less energy for its utilization and disposal (Abed *et al.* 2022; Linkevičius *et al.* 2023). Therefore, incorporating wood into construction practices can significantly contribute to energy efficiency and conservation within the industry (Cordier *et al.* 2022).

Wood is a renewable, non-toxic, and safe building material that humans have used since prehistoric times (Deng *et al.* 2022; Jang and Kang 2023b). Wood has attractive physical properties as a building material and provides emotional stability to the human body with pleasant scents and colors (Schreiner *et al.* 2020; Jang and Kang 2022a).

Magnesium is a lightweight material that can help reduce energy consumption during the construction process and reduce maintenance costs by reducing the structural load of the building. Magnesium has high recyclability and consumes less energy during recycling, attracting attention as a sustainable building material. Magnesium is also a non-combustible material (Wang *et al.* 2020).

However, cellulose, hemicellulose, and lignin, the major constituents of wood, are highly flammable (Deng *et al.* 2023), which is one of the biggest disadvantages of wood as a building material. Fire safety in buildings poses a significant threat to humans. Therefore, wood materials used for building should have improved fire resistance through the application of flame retardants (Mali *et al.* 2022).

Flame retardant coatings can be easily applied using spraying, brushing, or rolling methods (Hu and Sun 2021). When exposed to flames, the coating expands, creating a thick, porous charred layer on the wood surface, effectively slowing heat transfer (Hao and Chow 2003). This protective layer shields the wood from high temperatures and prevents prolonged exposure to oxygen, thus offering enhanced fire protection. Flame retardant coating treatment is the fastest and most convenient method that can be applied to already-built wooden buildings or ancient wooden cultural assets (Devi and Sharma 2019).

The vacuum pressure impregnation process is a treatment technology in which vacuum and pressure inject a flame-retardant solution into wood material (Zheng *et al.* 2022). Fire retardants can be applied to the inside of wood, which improves fire protection compared to coating treatments (Yun *et al.* 2017; Li *et al.* 2021).

However, while fluid can permeate well in the wood fiber direction, radial and tangential sections have very low permeability (Jang *et al.* 2020). Therefore, various heat treatment or chemical methods must be introduced to solve the impermeability of wood (Kang *et al.* 2018; Jang and Kang 2019, 2022b, 2023a; Popescu and Pfriem 2020). In addition, through drilling and incising on the outside of the wood, physical pretreatment must be applied to allow better penetration of flame retardant into the wood (Jang *et al.* 2024). However, these methods cannot be applied to a completed construction (Islam *et al.* 2014; Fukuta *et al.* 2022).

The authors used thin veneers on the outside of a magnesium board core to overcome these drawbacks. The thin veneer has the advantage of being able to absorb flame retardants only with coating treatment, and the magnesium board interior is non-combustible (Wang *et al.* 2020). The authors thought this combination would be a building material that complemented wood's advantages and disadvantages. The research team confirmed in a preliminary study that the veneered magnesium board had excellent adhesive strength similar to that of plywood and did not emit harmful substances (Park and Jo 2020), which indicates that veneered magnesium board could serve as a building material. The authors selected Radiata pine, a very common tree species in Korea, as the veneer species and named this material Radiata pine-magnesium laminated (RML) board.

The Ministry of Land, Infrastructure, and Transport of Korea prepared an administrative rule called "Fire Retardant Performance of Building Finishing Materials and Fire Spread Prevention Structural Standards" (MOLIT 2020). According to the notification, flame-retardant, semi-flammable, and non-combustible materials are classified as follows based on fire safety. Non-combustible materials are materials that do not burn, and when a fire occurs, they do not burn and release almost no heat. Semi-noncombustible material must not exceed 8 MJ/m^2 in total heat release for 10 min after the start of the cone calorimeter heating test by Korean Industrial Standard KS F 1SO 5660-1 (2015), and the maximum heat release rate for 10 min must not exceed 200 KW/m^2 continuously for more than 10 s. In addition, according to the Korean Industrial Standard KS F 2271 (2016) gas toxicity test result, it is stipulated that the average duration of action of laboratory rats should be longer than 9 min. Finally, flame-retardant materials are materials that do not burn easily, and the fire spreads more slowly than general combustible materials. Flame-retardant materials must have a total heat release of 8 MJ/m² or less for 5 minutes, and the maximum heat release rate must not exceed 200 kW/m² for more than 10 seconds.

Even materials with fire retardant treatment cannot be used as building materials in Korea if they do not pass this fire safety standard. Therefore, the authors investigated whether flame retardant-treated veneered magnesium board met these criteria. Our goal was to have the RML board achieve a semi-combustible rating. In addition, the gas toxicity test, single burning item (SBI) test, and Steiner tunnel test were performed to determine whether the product satisfies various international standards for flame retardant products. Table 1 is a summary of KS F ISO 5660-1, EN 13823 (SBI test), and ASTM E84 (Steiner Tunnel Test).

Table 1. Comparison with KS F ISO 5660-1, EN 13823, and ASTM E84

Item	KS F ISO 5660-1	EN 13823 (SBI Test)	ASTM E84 (Steiner Tunnel Test)
Standard Name	Reaction to fire tests — Heat release, smoke production and mass loss rate	Reaction to fire tests for building products — Building products excluding floorings exposed to the thermal attack by a single burning item	Standard Test Method for Surface Burning Characteristics of Building Materials
Main Purpose	Measures heat release rate (HRR), smoke production during combustion	Simulates real fire scenarios to assess fire reaction of wall materials	Evaluates surface flame spread and smoke development characteristics
Specimen Size	100 mm x 100 mm or 100 mm x 50 mm	1500 mm x 1000 mm	7.3 m (24 ft) long, 0.5 m wide
Test Conditions	Uses a cone calorimeter with radiant heat (e.g., 35 kW/m²)	30 kW burner ignition at corner of wall setup	Horizontal tunnel setup, flame applied at one end
Evaluation Metrics	HRR (Heat Release Rate) THR (Total Heat Release) Smoke production Mass loss rate	FIGRA (Fire Growth Rate Index) THR600s Smoke Growth Rate (SMOGRA) Flaming droplets Flame spread distance	Flame Spread Index (FSI) Smoke Developed Index (SDI)

Application Scope	Basic material-level heat and smoke testing	Fire reaction classification for interior wall materials (Europe)	Fire behavior classification of wall and ceiling materials (USA)
Classification Basis	No direct classification (used with other standards)	Used for Euroclass rating (A1 to F)	Used for NFPA classification (Class A, B, C)

EXPERIMENTAL

Specimens

Figure 1 shows a schematic diagram of the RML board in this study. Magnesium board (thickness 3 mm) was placed as a core, with face and back sides of radiata pine wood veneer (thickness 1.6 mm) and laminated.

The magnesium board was supplied by Jiahui Mgo Board, China. The authors received information about the physical properties of the magnesium board from the manufacturer: a density of 0.90 g/cm^3, a moisture content of 13%, a thermal conductivity of 0.1 W/(mk), and a modulus of rupture of 183.6 kgf/cm^2 (Park and Jo 2020). Radiata pine veneers were supplied by Beautiful Wood in Korea. The average air-dried density of the veneers was 0.45, and the moisture content was 12.8%. Here, a flame retardant whose main component is ammonium polyphosphate (solid content: 25%) was coated three times at 40 to 160 g/m^2 and dried for one week at room temperature (approximately 23 °C) and a humidity of 40 to 50%. The authors used EVA (Ethylene Vinyl Acetate) resin to bond veneer to magnesium board and pressured 7 kgf/cm^2 for 12 h at room temperature.

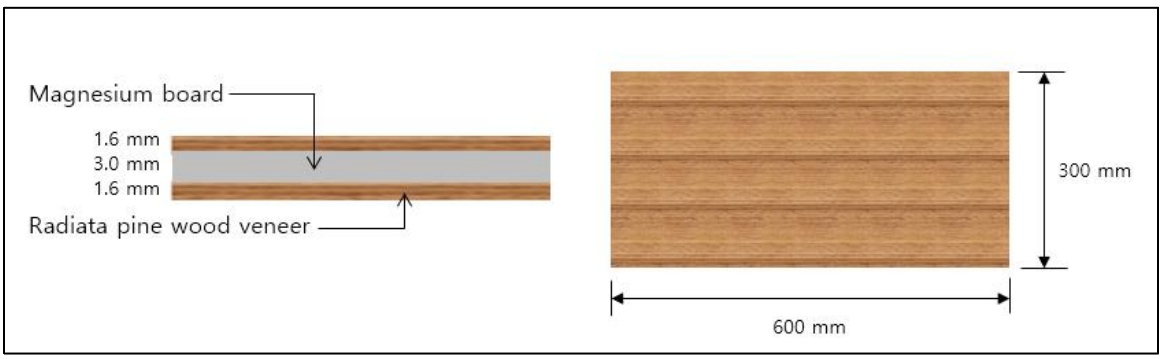

Fig. 1. Schematic diagram of RML board

45° Flammability Test

The 45° flammability test was conducted according to the Korea National Fire Agency (NFA) notification "Performance certification of flame-retardant products and technical standards for product inspection" (NFA 2022). The RML board was fixed at an angle of 45° from the floor, and the flame for heating was set at a length of 65 mm from the floor. The heating time by flame was 2 min. Afterward, the carbonized part of the RML board was brushed with a soft brush, and the carbonized area and length were measured.

Cone Calorimeter Test

The heat release rate test was performed using a cone calorimeter tester (Park *et al.* 2006) according to KS F ISO 5660-1 (2015) (Fig. 2). The authors quantitatively collected the ignition time, heat release rate, mass loss rate, and smoke gases from the cone calorimeter. The total heat release (THR) was calculated from the amount of oxygen consumed during combustion per unit mass. The authors wrapped all sides of the specimen except the top in aluminum foil. The applied heat flux was kept constant at 50 kW/m^2 during the heating process. The distance between the heater and the sample surface was 25 mm.

From the results of the 45° flammability test according to the amount of flame retardant applied, it was confirmed that the carbonization area was less than 50 cm^2 when 80 g or more retardant was applied, which passed the notification standards of the National Fire Service. Considering the difference in flame retardant absorption depending on the part of the wood, it was thought that 120 g/m^2 would pass this standard more reliably. Accordingly, all fire safety tests, including the cone calorimeter test, were conducted with material from application of 120 g/m^2 of retardant. The cone calorimeter tests were performed by Korea Conformity Laboratories (Seoul, Korea).

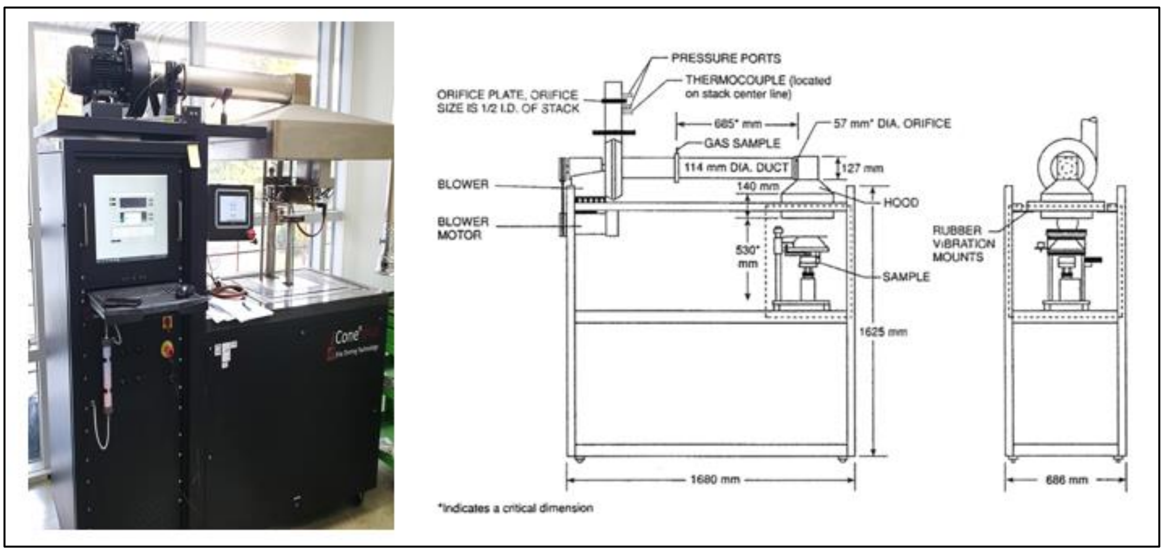

Fig. 2. Schematic diagram of cone calorimeter tester (Park *et al.* 2006)

Gas Toxicity Test

The gas toxicity test was performed according to the KS F 2271 (2016) standard. Three holes with a diameter of 25 mm were drilled through the specimen. The specimen was heated for 3 min with an LP gas burner and then heated again with an electric heating wire for 3 min. Air was supplied only during heating, and the supply amount was 3 L/min by the primary supply device of the heating furnace and 25.0 L/min by the secondary supply device. Gas discharge by the discharge device of the test box was performed only during heating, and the discharge rate was 10 L per minute. The exhaust gas temperature was measured using a prescribed thermocouple and thermometer. At this time, eight rats were placed into the experiment. The rats' behavior stop time was measured during the 15 min experiment, and the result was calculated by averaging the measured time per rat (Rie 2014, 2015).

All animal subjects were involved in the study in strict accordance with the guidelines set forth by the Institutional Animal Care and Use Committee (IACUC) of Jeonbuk National University. Furthermore, all procedures involving animals complied with the relevant legal frameworks, including the Animal Protection Act of South Korea and the Guide for the Care and Use of Laboratory Animals published by the National Institutes of Health (NIH).

SBI Test

The SBI test was performed according to EN 13823 (2020), which is a testing method used to evaluate the fire behavior of building products when subjected to thermal exposure from a single burning item, typically a propane gas burner. The test specimen was placed on a trolley inside a frame, and an exhaust system was positioned beneath it. During the test, the specimen's response to the burner was closely monitored (Fig. 3).

The classification parameters included in the SBI output are fire growth rate index (FIGRA), lateral flame spread (LFS), and THR. Additionally, the smoke growth rate index (SMOGRA) and total smoke production (TSP) were calculated. From this, fire safety performance is classified into four groups (Lowden and Hull 2013).

Fig. 3. SBI test procedure

Steiner Tunnel Test

The Steiner tunnel test was performed as described in ASTM E84-21a (2022). The sample was mounted on a removable top lid inside the Steiner tunnel, and a flame was spread along the entire length of the sample accompanied by a controlled airflow (Fig. 4). The sample burning progress could be observed through the sight glass installed on the side of the tunnel. The surface burning behavior of a material is measured by its flame spread index (FSI) and smoke development index (SDI).

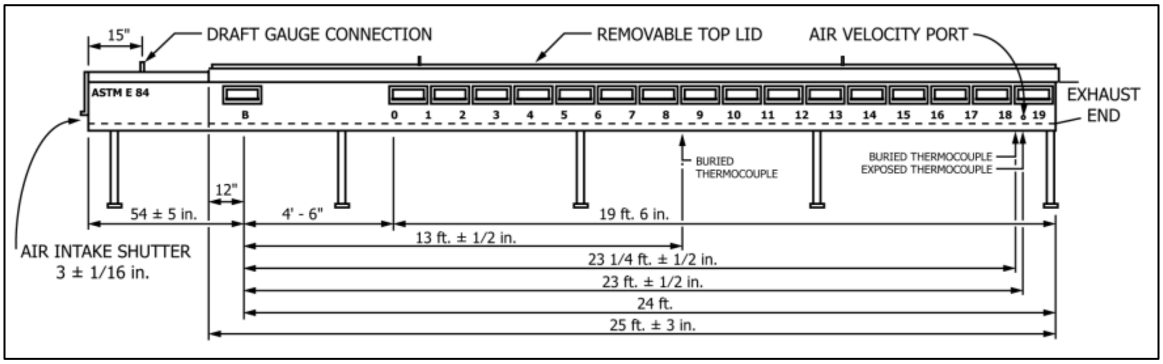

Fig. 4. Schematic diagram of a Steiner tunnel (ASTM E84-21a, 2022)

RESULTS AND DISCUSSION

45° Flammability Test

Figure 5 shows the results of the 45° flammability test. According to the NFA, the flame-retardant performance of wood is specified such that the carbonized area must be less than 50 m^2 after heating for 120 s. After applying flame retardant to RML, the carbon area was 44.3 cm^2 for 80 g/cm^2, 35.1 cm^2 for 120 g, and 35.0 cm for 150 g/m^2. As there was no difference in flame retardant performance with application of 120 g and 150 g/m^2 of retardant, application of 120 g/m^2 of flame retardant to the RML board was optimal.

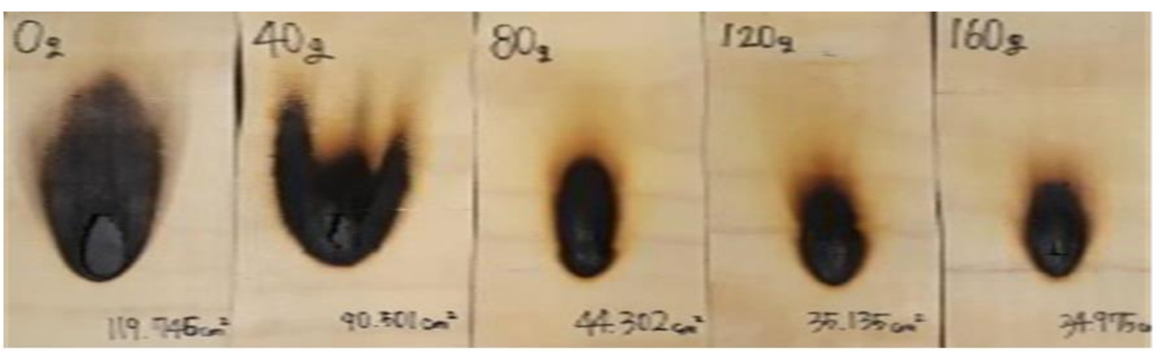

Fig. 5. The results of 45° flammability test

Cone Calorimeter and Gas Toxicity Test

Table 2 provides the results of cone calorimeter and gas toxicity tests for 120 g/m^2 flame-retardant coated RML board. According to the notice of the NFA, for semi-noncombustible material, the total heat released for 10 min under the heating condition of 50 kW/m^2 should not exceed 8 MJ/m^2, and the heat release rate should not exceed 200 kW/m^2 for more than 10 seconds.

According to the NFA, the average behavioral suspension time after 15 min of observation of laboratory rats exposed to the combustion gas generated by heating flame-retardant material for 6 min should be greater than 9 min. The THR of the flame-retardant coated RML board was 6.2 to 6.5 MJ/m^2. In addition, the time to stop the behavior of white lab mice was an average of 869.5 seconds, which met the standards of the NFA.

Table 2. Results of Cone Calorimeter and Gas Toxicity Test

Test	Number	Results	Unit	Criteria	Standard
THR	1	6.2	MJ/㎡	≤ 8 MJ/㎡	KS F ISO 5660-1 (2015)
	2	5.5			
	3	5.4			
Time to stopped behavior of white lab mice	1	14:42	m.s	≥ 9 min	KS F 2271 (2016)
	2	14:17			

Lu *et al*. (2021) impregnated melamine phosphate (MEL) and amino trimethyl phosphonic acid (AP) in Northeast poplar (*Populus girinensis* Skv.) individually or simultaneously to improve the flame retardancy of the wood. They conducted a treatment process on northeastern poplar wood samples by first reducing the pressure in the impregnation tank to -0.15 MPa for 30 min. Afterward, a solution was drawn into the tank under negative pressure. Subsequently, the tank was pressurized to 1.0 MPa for 3 h using an air compressor. The solution was then extracted and removed from the tank. The treated wood samples were retrieved, thoroughly washed with distilled water, and dried in an oven at 105 °C for 3 h. We compared the flame-retardant performance investigated in this previous study with that of the RML board.

The flame-retardant performance of the RML board was superior to MEL- and/or AP-treated wood. Although wood is a naturally porous material, penetration mainly occurs in the cross-section, and penetration in radial and tangential sections is difficult. Therefore, it is difficult for the flame retardant to penetrate deep into the wood, even with pressure impregnation. However, the thin veneer applied to the RML board easily absorbs flame retardant. In addition, magnesium board, which is the core material, is basically a material with excellent flame-retardant performance.

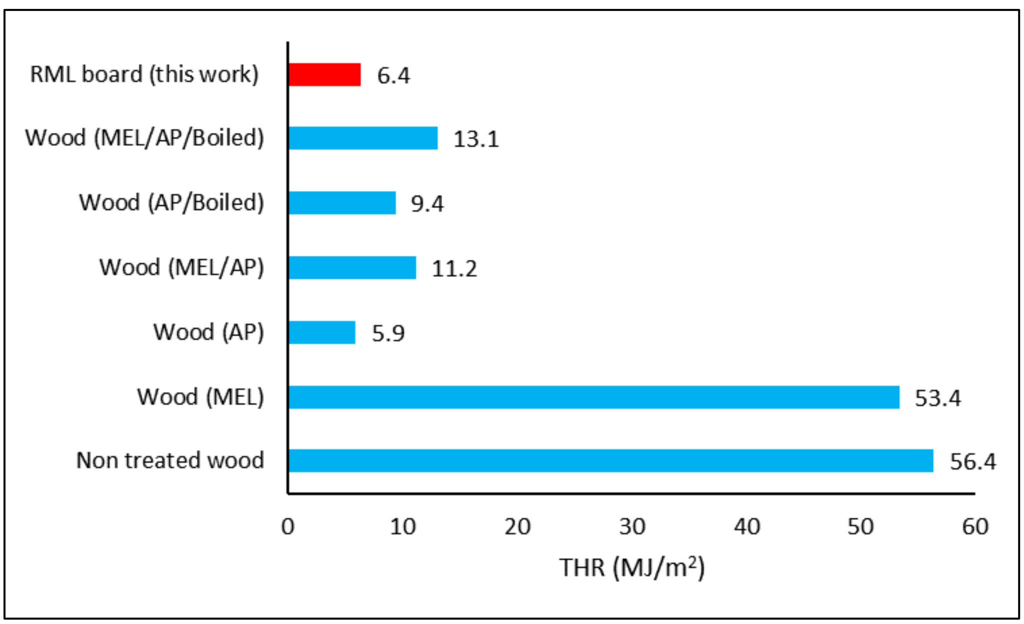

Fig. 6. Comparison of flame-retardant performance of treated wood (Lu *et al*. 2021) and RML board

SBI Test

EN 13501-1 applies a total of 4 tests (Noncombustibility, Gross calorific value, SBI test, Small flame test). This study performed only the SBI test. Table 2 provides the results of the SBI test. EN 13823 (2020) classifies the fire resistance performance grade according to FIGRA, THR, and LFS into four stages. The highest flame-retardant performance grade is class A2. The $FIGRA_{0.2MJ}$ of the flame-retardant RML board was 34.1 to 71.6, significantly lower than that of the A2 class standard of 120. Further, the THR_{600s} is specified as less than 7.5, but that of the flame retardant-treated RML board was only 0.3 to 2.2, which indicates that the flame-retardant performance of treated RML board meets European standard EN 13823 (2020).

Table 2. Results of SBI Test

Test	Number	Results	Unit	Criteria (Class A2)	Standard
$FIGRA_{0.2MJ}$	1	64.8	W/s	120 or less	EN 13823 (2020)
	2	71.6			
	3	34.1			
THR_{600s}	1	2.2	MJ	7.5 or less	
	2	3.3			
	3	0.3			
LFS	1	None	-	None	
	2	None			
	3	None			

Steiner Tunnel Test

Figure 3 provides the Steiner tunnel test results. ASTM E84-21a (2022) specifies Class A, the highest flame-retardant grade, as an FSI of 25 or less and an SDI of 450 or less. The FSI and SDI of the flame retardant-treated RML board were only 20, confirming that the board meets the USA flame retardant material standard.

Table 3. Results of Steiner Tunnel Test

Test	Number	Results	Unit	Criteria (Class A)	Standard
FSI	1	20	-	25 or less	ASTM E84-21a (2022)
SDI	1	20	-	450 or less	

CONCLUSIONS

1. Flame retardant-treated RML boards have passed international standards as flame retardant products in cone calorimeter, gas toxicity, SBI, and Steiner tunnel tests.
2. The flame retardant-treated RML boards showed superior flame-retardant performance compared to wood impregnated with flame retardant.

3. The RML board with flame-retardant performance can be used as a commercial building material such as wall cladding, ceiling panels, flooring, and interior finishing materials.

ACKNOWLEDGEMENTS

This research was funded by the R&D Program for Forest Science Technology in Korea (FTIS-RS-2024-00400728).

Author Contributions

E. S. Jang: First author, Conceptualization, Methodology, Experiment, Data analysis, Writing - original draft, and Writing - review and editing, S. U. Jo: Co-author, Experiment, Data analysis and Writing - review and editing, H. J. Park: Corresponding author, Conceptualization, Supervision and Writing - review and editing. All authors read and approved the final manuscript.

REFERENCES CITED

Abed, J., Rayburg, S., Rodwell, J., and Neave, M. (2022). "A review of the performance and benefits of mass timber as an alternative to concrete and steel for improving the sustainability of structures," *Sustainability* 14(9), Article number 5570. DOI: 10.3390/su14095570

ASTM E84-21a (2022). "Standard test method for surface burning characteristics of building materials," ASTM International, PA, USA.

Chai, S. Y. W., Ngu, L. H., How, B. S., Chin, M. Y., Abdouka, K., Adini, M. J. B. A., and Kassim, A. M. (2022). "Review of CO_2 capture in construction-related industry and their utilization," *International Journal of Greenhouse Gas Control* 119, Article number 103727. DOI: 10.1016/j.ijggc.2022.103727

Cordier, S., Blanchet, P., Robichaud, F., and Amor, B. (2022). "Dynamic LCA of the increased use of wood in buildings and its consequences: Integration of CO_2 sequestration and material substitutions," *Building and Environment* 226, Article number 109695. DOI: 10.1016/j.buildenv.2022.109695

Deng, C., Liu, Y., Jian, H., Liang, Y., Wen, M., Shi, J., and Park, H. (2023). "Study on the preparation of flame retardant plywood by intercalation of phosphorus and nitrogen flame retardants modified with Mg/Al-LDH," *Construction and Building Materials* 374, Article number 130939. DOI: 10.1016/j.conbuildmat.2023.130939

Deng, C., Liu, Y., Xu, J., Li, X., Wen, M., Duan, X., and Park, H. (2022). "Fire retardant performance of sugi and hinoki treated with phosphorus and nitrogen fire retardant," *Wood Research* 67(6), 941-952. DOI: 10.37763/wr.1336-4561/67.6.941952

Devi, K. S., and Sharma, T. D. (2019). "Innovations in conservation of heritage museums and libraries from fire hazards," *Sustainable Materials and Structures for Civil Infrastructures (SMSCI2019)* 2158(1), Article ID 020005. DOI: 10.1063/1.5127129

EN 13823 (2020). "Reaction to fire tests for building products - Building products excluding floorings exposed to the thermal attack by a single burning item," European Committee for Standardization, Brussels, Belgium.

Erickson, L. E. (2017). "Reducing greenhouse gas emissions and improving air quality: Two global challenges," *Environmental Progress & Sustainable Energy* 36(4), 982-988. DOI: 10.1002/ep.12665

Fukuta, S., Nomura, M., Kurisaki, H., and Okamura, H. (2022). "Application of laser micro incisions in the fire-retardant treatment," *European Journal of Wood and Wood Products* 80, 255-258. DOI: 10.1007/s00107-021-01752-9

Hao, J., and Chow, W. K. (2003). "A brief review of intumescent fire retardant coatings," *Architectural Science Review* 46(1), 89-95. DOI: 10.1080/00038628.2003.9696967

Hu, X., and Sun, Z. (2021). "Nano CaAlCO3-layered double hydroxide-doped intumescent fire-retardant coating for mitigating wood fire hazards," *Journal of Building Engineering* 44, Article ID 102987. DOI: 10.1016/j.jobe.2021.102987

Islam, M. N., Ando, K., Yamauchi, H., Kamikawa, D., Harada, T., Khalil, H. A., and Hattori, N. (2014). "Impregnation of laser incised wood of Douglas fir and Japanese cedar by dipping (passive impregnation) in solutions of copper azole (CuAz-B) and a fire retardant (PPC)," *Holzforschung* 68(3), 353-360. DOI: 10.1515/hf-2013-0140

Jang, E.-S., Jo, S.-U., and Park, H.-J. (2024). "Effect of grooving pretreatment on flame retardant vacuum-pressure impregnation performance of full-size timbers," *Journal of Wood Science* 70(1), Article number 57. DOI: 10.1186/s10086-024-02172-y

Jang, E.-S., and Kang, C.-W. (2019). "Changes in gas permeability and pore structure of wood under heat treating temperature conditions," *Journal of Wood Science* 65(1), Article number 37. DOI: 10.1186/s10086-019-1815-3

Jang, E.-S., and Kang, C.-W. (2022a). "Can the physical properties of wood samples be predicted from photographs displayed on a monitor?," *Wood Research* 67(5), 888-894. DOI: 10.37763/wr.1336-4561/67.5.888893

Jang, E.-S., and Kang, C.-W. (2022b). "An experimental study on changes in sound absorption capability of spruce (*Picea sitchensis*), Douglas fir (*Pseudotsuga menziesii*), and larch (*Larix kaempferi*) after microwave treatment," *Journal of Wood Science* 68, Article number 2. DOI: 10.1186/s10086-021-02010-5

Jang, E.-S., and Kang, C.-W. (2023a). "Effect of steam explosion treatment on impregnation of three species of softwoods: North American spruce, Korean pine, and Japanese larch," *BioResources* 18(1), 1454-1464. DOI: 10.15376/biores.18.1.1454-1464

Jang, E.-S., and Kang, C.-W. (2023b). "Effects of pressure and temperature on wood impregnation–focusing on larch (*Larix kaempferi*) and Korean pine (*Pinus koraiensis*)," *BioResources* 18(2), 3208-3216. DOI: 10.15376/biores.18.2.3208-3216

Jang, E.-S., Yuk, J.-H., and Kang, C.-W. (2020). "An experimental study on change of gas permeability depending on pore structures in three species (hinoki, Douglas fir, and hemlock) of softwood," *Journal of Wood Science* 66(1), Article number 78. DOI: 10.1186/s10086-020-01925-9

Kang, C.-W., Li, C., Jang, E.-S., Jang, S.-S., and Kang, H.-Y. (2018). "Changes in sound absorption capability and air permeability of Malas (*Homalium foetidum*) specimens after high temperature heat treatment," *Journal of the Korean Wood Science and Technology* 46(2), 149-154. DOI: 10.5658/WOOD.2018.46.2.149

KS F 2271 (2016). “Testing method for gas toxicity of finish materials of buildings,” Korean Agency for Technology and Standards, Seoul, Korea.
KS F ISO 5660-1 (2015). “Reaction-to-fire tests — Heat release, smoke production and mass loss rate — Part 1: Heat release rate (cone calorimeter method) and smoke production rate (dynamic measurement),” Korean Agency for Technology and Standards, Seoul, Korea.
Li, C., Zhou, X., Yang, C., Yu, L., Li, H., Mountain, E. I. M., and Fei, B. (2021). "Effects of different flame retardant treatments on the combustibility of bamboo filament," *Wood Research* 66(2), 255-266. DOI: 10.37763/wr.1336-4561/66.2.255266
Linkevičius, E., Žemaitis, P., and Aleinikovas, M. (2023). "Sustainability impacts of wood-and concrete-based frame buildings," *Sustainability* 15(2), Article number 1560. DOI: 10.3390/su15021560
Lowden, L. A., and Hull, T. R. (2013). "Flammability behaviour of wood and a review of the methods for its reduction," *Fire Science Reviews* 2, Article number 4. DOI: 10.1186/2193-0414-2-4
Lu, J., Jiang, P., Chen, Z., Li, L., and Huang, Y. (2021). "Flame retardancy, thermal stability, and hygroscopicity of wood materials modified with melamine and amino trimethylene phosphonic acid," *Construction and Building Materials* 267, Article ID 121042. DOI: 10.1016/j.conbuildmat.2020.121042
Mali, P., Sonawane, N., Patil, V., Lokhande, G., Mawale, R., and Pawar, N. (2022). "Morphology of wood degradation and flame retardants wood coating technology: An overview," *International Wood Products Journal* 13(1), 21-40. DOI: 10.1080/20426445.2021.2011552
MOLIT 2020-1053 (2020). “Fire retardant performance of building finishing materials and fire spread prevention structural standards,” Ministry of Land, Infrastructure and Transport, Sejong, Korea.
NFA 2022-28 (2022). “Performance certification of flame retardant products and technical standards for product inspection,” NFA, Seoul, Korea.
Park, H.-J., and Jo, S.-U. (2020). "Evaluation of physical, mechanical properties and pollutant emissions of wood-magnesium laminated board (WML Board) for interior finishing materials," *Journal of the Korean Wood Science and Technology* 48(1), 86-94. DOI: 10.5658/WOOD.2020.48.1.86
Park, S.-Y., Kim, D.-H., and Im, H.-S. (2006). "The experimental study for the combustion-property of sandwich panels using ISO 5660 cone calorimeter," *Fire Science and Engineering* 20(4), 33-41.
Popescu, C. M., and Pfriem, A. (2020). "Treatments and modification to improve the reaction to fire of wood and wood based products—An overview," *Fire and Materials* 44(1), 100-111. DOI: 10.1002/fam.2779
Rie, D.-H. (2014). "A research of grain size analysis of particulate matter in fire effluent," *Fire Science and Engineering* 28(6), 8-12. DOI: 10.7731/KIFSE.2014.28.6.008
Rie, D.-H. (2015). "A research of risk assessment for urethane fire based on fire toxicity," *Fire Science and Engineering* 29(2), 73-78. DOI: 10.7731/KIFSE.2015.29.2.073
Schreiner, L., Karacan, B., Blankenagel, S., Packhaeuser, K., Freiherr, J., and Loos, H. M. (2020). "Out of the woods: Psychophysiological investigations on wood odors to estimate their suitability as ambient scents," *Wood Science and Technology* 54, 1385-1400. DOI: 10.7731/KIFSE.2014.28.6.008

Wang, X., Shao, D., Ejeromedoghene, O., Qian, K., Kandawa-Schulz, M., Song, W., and Wang, Y. (2020). "Preparation and study of fireproof materials with high-waterproof performance," *Polymer Engineering & Science* 60(7), 1474-1481. DOI: 10.1002/pen.25394

Yun, H., Li, K., Hu, C., and Tu, D. (2017). "Adsorption and fixation of soluble fire retardancy in *Populus russkii* and *Cunninghamia lanceolata*," *Wood Research* 62(2), 253-260. DOI: 10.5555/20173180886

Zheng, J., Zhu, G.-Q., Tong, Y., and Meng, F.-M. (2022). "Application and analysis of a flame retardant treatment method for wood structure buildings," *Fire Science and Technology* 41(3), 356-358.

Article submitted: January 24, 2025; Peer review completed: March 15, 2025; Revisions accepted: May 19, 2025; Published: May 22, 2025.
DOI: 10.15376/biores.20.3.5620-5632