

Horizontal flame spread of flame-retardant-treated Japanese cedar (*Cryptomeria japonica*) exterior siding material

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(Received 22 September 2025)

Abstract: The primary objective of this study was to determine whether in-house-developed flame-retardant-treated cedar could serve as an exterior material, not only by meeting the fire-resistance criteria of the cone calorimetry test, but also by demonstrating dependable performance under realistic fire conditions. The results of the cone calorimetry test indicated that the material met the established criteria for total heat release and peak heat release rate, validating its classification as a quasi-noncombustible material. Furthermore, the ASTM E84 Steiner tunnel test was conducted to evaluate the performance of the flame-retardant cedar siding under conditions that simulated real fire scenarios more closely. Flame propagation exhibited a delayed onset and progressed gradually from 2.5 ft to 5 ft over 10 min, indicating restrained flame spread. Concurrently, smoke development remained negligible throughout the test, which is critical for maintaining visibility and minimizing exposure to toxic combustion byproducts. Post-test examination revealed minimal structural degradation, with no evidence of cracking or penetration beyond superficial charring, suggesting that the material retained its physical integrity even under elevated thermal stress. Collectively, these findings confirm that the flame-retardant cedar siding meets the requirements for an ASTM E84 Class A rating and functions as a reliable exterior cladding material capable of enhancing occupant safety in fire scenarios.

Keywords: Flame retardant; quasi-noncombustible performance; siding material; cone calorimeter; Steiner tunnel test

Introduction

In recent years, the construction industry has increasingly emphasized eco-friendliness and sustainability, leading to a steady increase in the demand for wood as a building material (Mergel et al. 2024; Jang et al. 2025a). Wood has a natural texture, aesthetic appeal, and excellent insulation properties. Its carbon storage capacity renders it a sustainable building material (Emre Ilgin and Karjalainen 2022; Jang and Kang 2022; Leszczyszyn et al. 2022; Blanchet et al. 2024).

However, wood has a fatal flaw: its inherent flammability. In the event of a fire, wooden structures can spread flames more easily than concrete structures, causing damage to life and property (Lowden and Hull 2013; Hansen-Bruhn and Hull 2023).

Therefore, flame-retardant treatment technology is essential to ensure the safety of wood materials in buildings (Liang et al. 2023; Gao et al. 2024). According to the Korean Ministry of Land, Infrastructure, and Transport (MOLIT) Notification No. 2020-1053 (MOLIT 2020), flame-retardant treatment is legally required for exterior materials used in high-rise buildings in Korea.

Flame retardants used in wood materials typically consist of phosphates, borates, and nitrogen-based compounds. These compounds react with heat to form a carbon layer on the wood surface or inhibit combustion (Chen et al. 2021; Wu et al. 2021).

Common flame-retardant treatment methods for wood include surface coating and vacuum-pressure impregnation. Vacuum-pressure impregnation allows flame retardants to deeply penetrate the porous structure of wood, providing more reliable fire-retardant than coatings (Jang et al. 2024a; Jang et al. 2024b; Jo et al. 2024; Holeček et al. 2025; Jang et al. 2025b).

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The easiest method for evaluating the fire-retardant properties of wood after flame-retardant treatment is cone calorimetry. The cone calorimetry test is a laboratory test based on KS ISO 5660-1 (Korean Agency for Technology and Standards 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). Small specimens ($100 \times 100 \text{ mm}^2$) are exposed to a constant radiant heat flux. The test measures quantitative indicators such as the heat release rate (HRR), total heat release (THR), mass loss rate (MLR), time to ignition (TTI), and smoke production rate (SPR).

Recently, research has been actively conducted on various chemical compositions and treatment technologies for enhancing the flame retardancy of wood. The performance of flame-retardant-treated timber is evaluated using a cone calorimeter.

Wu et al. (2021) conducted a cone calorimetry analysis to assess the combustion behavior of plywood treated with flame retardants. Their findings demonstrated substantial reductions in key fire-related metrics. The treated specimens exhibited reductions of 63.7%, 91.9%, and 53.7% in the average HRR, THR, and effective heat of combustion, respectively. Additionally, the smoke production and toxic gas emissions were significantly mitigated, with the total smoke output, carbon monoxide generation, and oxygen consumption reduced by 76.8%, 85.0%, and 91.9%, respectively. The flame-retardant plywood also exhibited improved fire-resistance indices, including a fire growth index of $3.454 \text{ kW} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$ and a fire performance index of $0.136 \text{ s} \cdot \text{m}^2 \cdot \text{kW}^{-1}$.

Jo et al. (2024) conducted cone calorimetry experiments to examine how variations in the solid content of flame-retardant impregnation (SCFI) influenced THR in Korean larch and Japanese cedar. Through simple linear regression analysis, they determined that achieving the flame-retardancy threshold of 8 MJ/m^2 required SCFI levels of 93.9 kg/m^3 for larch and 144.6 kg/m^3 for cedar. These findings provide a quantitative basis for defining the optimal impregnation dosage necessary to meet the fire safety standards for both wood species.

Zhang et al. (2025) performed cone calorimetry experiments on pinewood samples treated with various flame-retardant additives to quantitatively analyze the combustion characteristics according to heat-flux variations. They found that complex flame retardants, such as DOPO, TPP, and $(\text{NH}_4)_2\text{HPO}_4$, promoted sample decomposition and reduced the surface temperature, thereby inducing ignition delay. Significantly enhanced

flame-retardant performance was observed, particularly under radiant heat conditions of 25 and 30 kW/m^2 . Treated samples exhibited ignition delay times at least 1.5 times longer than untreated samples, along with reductions in MLR, THR, oxygen consumption, and CO/CO_2 emissions.

These studies have demonstrated that the cone calorimetry test is useful for quantitatively assessing the fundamental combustion characteristics of wood, highlighting the importance of advancing flame-retardant treatment technologies to ensure the fire safety of buildings. However, the specimen size used in the cone calorimetry tests was limited, and complex variables such as the material installation method, structural connections, ventilation conditions, and material interactions were excluded.

In particular, measurement device errors and reproducibility issues in tests performed in high-temperature environments can lead to quantitative discrepancies with actual fire situations. These limitations suggest that although the cone calorimetry test is suitable for understanding the basic combustion characteristics of materials, it is insufficient for evaluating the fire safety of buildings (Bray et al. 2023; Jang et al. 2024a).

Meanwhile, the ASTM E84 Standard Test Method for Surface Burning Characteristics of Building Materials (ASTM International 2024)—a representative flame-retardancy test stipulated in the U.S. Building Code—evaluates the surface burning characteristics of materials in a 7.6-m-long tunnel-type device called the “Steiner tunnel.” Test specimens are installed on the tunnel ceiling and exposed to a 79-kW gas burner at one end under forced ventilation for 10 min. The measurements include the Flame Spread Index (FSI) and Smoke Developed Index (SDI), which indicate the flame retardancy rating of a material (Class A, B, or C). The ASTM E84 test uses large specimens to reflect the actual installation conditions of building materials (ASTM International 2024). It comprehensively evaluates flame spread and smoke development, making a substantial contribution to ensuring building fire safety.

Therefore, the objective of this study was to evaluate the fire performance of flame-retardant-treated cedar siding using both the KS F ISO 5660-1 cone calorimeter test (Korean Agency for Technology and Standards 2015) and the ASTM E84 Steiner tunnel test (ASTM International 2024). This approach was not intended to diminish the value of cone calorimetry in flame-retardancy assessment, but rather to complement it with ASTM E84 testing, which provides additional insights under more realistic fire conditions.

Materials and methods

Sample preparation

We obtained heat-dried cedar (*Cryptomeria japonica*), used as exterior building siding, from Gaonwood, Co., Ltd. in Jeonju, Korea. The timber was standardized to be 21 mm thick, 151 mm wide, and 2,500 mm long. Our previous research indicated that grooved wood significantly increased chemical uptake and improved fire retardant performance by increasing the surface area (Jang et al. 2024a). Therefore, we grooved the surface of the cedar siding, as shown in Figure 1.

Flame retardant

The inorganic non-halogenated flame retardant employed in this study was independently developed and patented by our research team (Park 2013). The primary components of flame retardants are diammonium phosphate (DAP), ammonium polyphosphate (APP), anhydrous borax, and water. The solids content of the flame retardant was 27%.

This formulation leveraged the complementary effects of phosphorus- and boron-containing compounds, which, when exposed to heat, facilitated the development of both a protective char layer and an intumescent barrier. These layers functioned as physical shields, significantly limiting the penetration of oxygen and thermal energy.

Vacuum-pressure impregnation process

The cedar-siding samples underwent vacuum-pressure impregnation to ensure the deep penetration of the flame retardant. Initially, the samples were placed in an impregnation chamber, where they were subjected to a vacuum of -0.1 MPa using a vacuum pump for approximately 3 min. This process removed air from inside the chamber and on the wood surface, facilitating the penetration of the flame retardant.

Subsequently, the flame-retardant solution was introduced into the chamber for >10 min. The system was then pressurized to approximately 1.5–1.7 MPa and maintained under this condition for 60 min to ensure thorough diffusion of the flame retardant into the wood pore structure. Following the pressure phase, the flame retardant was extracted from the chamber within 10 min, and the specimen was again subjected to vacuum conditions (-0.1 MPa) for an additional 10 min to remove the residual surface solution and promote uniform distribution.

The final solids content of the flame retardant within the cedar siding was 162 ± 11 kg/m³. According to prior cone calorimetry testing conducted by our research group, cedar wood achieves

the required flame-retardant performance threshold when impregnated with a minimum of 144.6 kg/m³ of flame retardant (Jo et al. 2024). Therefore, the authors predicted that the treated specimens would satisfy the necessary criteria for fire-retardant.

To stabilize the chemical treatment and moisture levels, the impregnated wood was air-dried under controlled laboratory conditions ($20 \pm 3^\circ\text{C}$, $60 \pm 5\%$ relative humidity) for approximately four weeks. After drying, the moisture content was approximately 12%, as determined using an electronic moisture meter (model: Testo 606-1, Testo SE & Co. KGaA, Germany), indicating its suitability for further thermal performance evaluation (Jo et al. 2024; Lardet et al. 2024).

Cone calorimetry test

The quasi-noncombustible performance of the cedar-siding samples was evaluated in accordance with the MOLIT notification criteria based on the KS F ISO 5660-1 (Korean Agency for Technology and Standards 2015) cone calorimetry test method (MOLIT 2020).

Three specimens with dimensions of 100 mm × 100 mm and a moisture content of 12% were prepared. Each specimen was exposed horizontally to an external heat flux of 50 kW/m² using a cone heater. Heat release rate (HRR), total heat release (THR), mass loss rate (MLR), time to ignition (TTI) were recorded continuously during the 10-min exposure. Post-test observations included an assessment of physical damage, such as cracking, melting, or penetration, in accordance with quasi-noncombustible material performance requirements.

To qualify as a flame retardant, materials must meet stringent criteria under thermal stress: the THR must remain below 8 MJ/m² during the initial 5 min of exposure, the peak HRR must not exceed 200 kW/m² for at least 10 continuous seconds, and the specimen must show no signs of structural compromise, such as cracking, perforation, or melting, after 5 min of heating.

In comparison, quasi-noncombustible materials are subject to slightly different standards. They must maintain a THR under 8 MJ/m² over a 10-min heating period, maintain a peak HRR below 200 kW/m² for a minimum of 10 s, and exhibit no critical damage, breach-like cracks, or melt-through after 10 min of thermal exposure.

These differences in the threshold values reflect stricter fire safety requirements for quasi-noncombustible materials. In this study, the cone calorimetry test was conducted by Korea Conformity Laboratories (KCL, 7, Nambusunhwan-ro 319-gil, Seocho-gu, Seoul).

Steiner tunnel test based on ASTM E84

The cone calorimetry test was performed by applying radiant heat to a small test specimen (100 mm × 100 mm). By contrast, the Steiner tunnel test involved a real fire test on actual wood (21 mm thick, 151 mm wide, and 2,500 mm long), allowing a more detailed investigation into the fire safety of the occupants.

Surface burning characteristics of the flame-retardant-treated cedar siding were assessed using the ASTM E84 standard test method (ASTM International 2024). This method evaluates the FSI and SDI of building materials under controlled fire-exposure conditions. The test lasted 10 min, during which the FSI was determined by calculating the area beneath the curve of the flame tip position over time. Cement board yielded an FSI of zero, whereas red oak served as a reference material with a normalized value close to 100.

The SDI was computed by multiplying the ratio of the area under the light absorption curve over time to that for a standard heptane pan fire by 100.

The ASTM E84 standard (ASTM International 2024) evaluates flame-retardant-treated materials according to their FSI and SDI values. The materials were classified into three classes: Class A, Class B, and Class C. Class A represents the highest flame retardancy, with an FSI between 0 and 25 and an SDI below 450. Class B represents an FSI between 26 and 75, whereas Class C corresponds to a higher flame spread potential, with an FSI between 76 and 200. The SDI must remain below 450 for all classes.

Figure 2 shows the Steiner tunnel. Nineteen observation windows were placed at 300 mm intervals in a 7.5 m-long tunnel, each of which recorded the position of the flame front over time. The FSI was then calculated using these data.

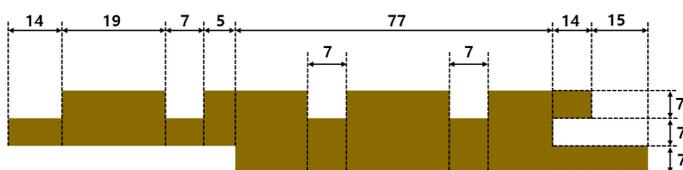


Figure 1. Schematic of the cedar siding material with grooves (unit: mm).

The Steiner tunnel furnace was preheated to a minimum brick temperature of 65.6°C and then cooled to 40.6 ± 2.8°C. The specimen was mounted horizontally on the ceiling, with the exposed surface facing downward toward the ignition source. A protective fiber cement board was placed behind the specimen to shield the tunnel cover. Airflow was maintained at 1.22 m/s through a tunnel. The specimens were preheated for 2 min prior to ignition. Two burners delivering a combined heat output of 89 kW were ignited and operated continuously for 10 min.

The flame propagation was tracked visually along the tunnel length by an observer. Smoke density was measured using a photometric system installed in the exhaust duct. The laboratory environment was maintained at a temperature of 22.2°C and a relative humidity of 40%. Specimen moisture content was 12%. In this study, the Steiner tunnel test was conducted by KCL.

Results and discussion

Cone calorimetry test

Cone calorimetry tests were conducted on three individual cedar-sided specimens to assess their fire-safety performance. Table 1 presents the THR per unit area for cedar sidings. All values were below the regulatory threshold of 8 MJ/m².

Our previous study (Jo et al. 2024) proposed a regression model that predicted the THR would remain below 8 MJ/m² when the SCFI exceeded 144.6 kg/m³, provided the flame retardant was impregnated into cedar. In this study, the SCFI was approximately 162 kg/m³, and the measured THR was <8 MJ/m². These results are consistent with the values predicted by the existing regression model and can be interpreted as an experimental confirmation of the model's reliability and applicability.



Figure 2. Steiner tunnel tester at KCL.

Table 1. Cone calorimetry test results for the cedar siding material.

Test item	Test results			MOLIT notification criteria
	Rep 1	Rep 2	Rep 3	
THR per unit area (8 MJ/m ²)	7.7	1.6	5.1	≤8 MJ/m ²
Time exceeding 200 kW/m ² HRR continuously (s)	0	0	0	≤10 s
Presence of harmful fire-related factors in test specimen	None	None	None	Should be none

In addition, none of the samples exhibited a continuous HRR exceeding 200 kW/m² for >0 s, satisfying the criterion of ≤10 s. Furthermore, no harmful fire-related factors were detected in the specimens.

These consistent results across all three samples demonstrated that the cedar-siding material maintained stable thermal behavior under high-temperature conditions and met the required standard of quasi-noncombustible performance.

Results of Steiner tunnel test

Figure 3 illustrates the flame spread and smoke development behavior of flame-retardant-treated cedar siding under the ASTM E84 Steiner tunnel test (ASTM International 2024). The flame spread curve (black line with circular markers) indicated delayed ignition, initiating at approximately 4.5 min, followed by a gradual increase in flame propagation from 2.5° to 5° over the 10-min test duration. This slow and limited flame spread indicated effective thermal insulation and combustion resistance.

By contrast, the smoke-developed curve (blue line) remained nearly flat and close to 0% obscuration throughout the test period, suggesting minimal smoke generation. This is a critical safety feature because lower smoke production corresponds to better visibility and lower risk of inhaling toxins during fire events.

Figure 4 shows the cedar-sided specimens before (a) and after (b) the ASTM E84 Steiner tunnel test (ASTM International 2024). The untreated surface of the flame-retardant cedar siding (a) appeared clean and structurally intact, with uniform coloration and no visible damage. This baseline condition highlighted the initial integrity of the material before thermal exposure. Image (b) shows the post-test condition, where the specimens exhibited significant charring and surface blackening, indicative of exposure to elevated temperatures and combustion. Despite visible discoloration, the absence of deep cracks, perforations, or melt-throughs confirmed the structural resilience of the material under fire conditions.

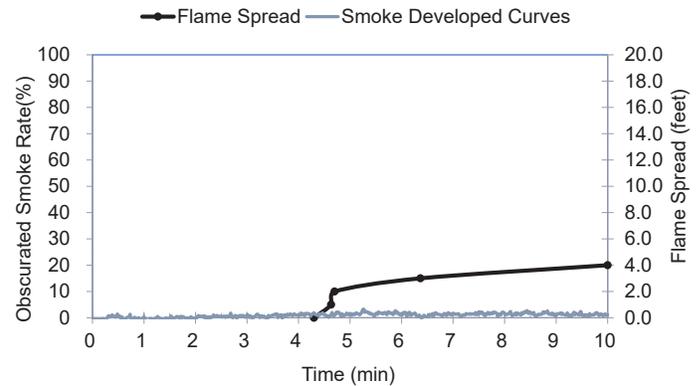


Figure 3. Flame spread and smoke suppression characteristics of the flame-retardant-treated cedar siding under the ASTM E84-24 test (ASTM International 2024).

These visual observations aligned with the quantitative data shown in Figure 4, where the flame spread remained limited (rising gradually from 2.5° to 5° over 10 min), and the smoke development was minimal throughout the test. Photographic and graphical evidence both demonstrated that the flame-retardant treatment mitigated fire propagation and smoke emission, producing a quasi-noncombustible material suitable for exterior applications.

Table 2 presents the FSD and SDI values obtained in this study, which satisfied the ASTM E84 Class A rating. These results indicated that the cedar siding material performed well in terms of securing visibility and safety in actual fire situations. The above results confirmed that cedar siding qualifies as a Class A fire-retardant material according to ASTM E84 standards (ASTM International 2024) and has sufficient quasi-

Table 2. FSI and SDI results for the cedar siding material subjected to the ASTM E84 Steiner tunnel test.

Index	Value	ASTM E84 Classification Criteria
FSI	10	Class A: 0–25
		Class B: 26–75
		Class C: 76–200
SDI	10	Class A: <450



Figure 4. Photographs of cedar siding specimens before (a) and after (b) Steiner tunnel testing.

noncombustible performance as an exterior building material. However, further weathering tests will be required to verify the ability of this system to perform in outdoor exposures.

Taken together, these results demonstrate that the treated cedar siding exhibited stable combustion behavior, suppressed rapid flame propagation, and significantly limited smoke emissions. These characteristics confirm its suitability as a quasi-noncombustible exterior material compliant with the ASTM E84 Class A standards (ASTM International 2024). In future work, we plan to conduct durability testing on flame-retardant-treated cedar siding exposed to weathering.

Conclusions

This study evaluated the fire safety performance of a cedar exterior siding material manufactured via vacuum/pressure impregnated with a flame retardant. Cone calorimetry tests based on KS F ISO 5660-1 (Korean Agency for Technology and Standards 2015) indicated that the flame-retardant-treated cedar siding material met the THR and HRR standards, confirming its applicability as a quasi-noncombustible material. In addition, it received a Class A rating in the ASTM E84 test (ASTM International 2024), which simulates real-world fire conditions. This indicates that flame-retardant-treated cedar

siding is a reliable building material that can ensure occupant safety, even in emergency fire situations. This research provides a crucial technical foundation for the development of eco-friendly, high-performance exterior materials and can contribute to sustainable building designs. Further tests to assess performance of the system in exterior exposures are planned.

Acknowledgments

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

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