IMPROVEMENT OF REACTION TO FIRE PERFORMANCE FOR WOOD RIBBON PANELS MADE OF ASPEN OR THERMALLY MODIFIED ASPEN WOOD LAMELLAS

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Abstract. A study of technological factors influencing the reaction to fire performance of acoustic panels made of aspen *(Populus tremula L.)* and thermally modified aspen wood lamellas was conducted and reported in this research paper. Aspen wood lamellas with a cross-section of 30 × 25 mm were used as ribbon elements for acoustic panel manufacturing. High-pressure vacuum impregnation technology at an industrial impregnation plant was applied with a target fire-retardant retention level of 50 $kg \cdot m^{-3}$. Each lamella was weighed before and after impregnation to determine the achieved retention level and an analysis of natural retention distribution in wood was done. Retention was expressed on an Atro/Atro basis, and impregnated lamellas were grouped into three retention level categories - low, medium, and high - to establish the relationship between retention level and reaction to fire performance. The aim of this work was to evaluate the influence of the fire-retardant retention level on the reaction to fire performance of impregnated aspen and thermally modified aspen wood ribbon elements used in acoustic panels. Reaction to fire performance was assessed by measuring FIGRA (Fire growth rate index), THR_{600s} (Total heat release in 600 s duration), and smoke production parameters using the single burning item test method according to EN 13823, which is the main test method for reaction to fire classification according to EN 13501-1. It was concluded that the fire-retardant retention level has a significant influence on the reaction to fire performance of aspen wood lamellas. An increase in retention level from 8 to 16 Atro/Atro for aspen wood resulted in a change of fire class and led to approximately a twofold reduction in both FIGRA and THR_{600s} values, as well as a noticeable increase in smoke production was observed, but for thermally modified aspen wood FIGRA and THR_{600s} were observed four times less for high concentration vs low.

Keywords: aspen wood, thermally modified wood, acoustic panels, fire retardant impregnation, reaction to fire performance.

Introduction

Wood is widely used in modern interior architecture due to its aesthetic qualities, sustainability, and favourable acoustic performance. In recent years, wood ribbon and slatted panels have become popular as decorative and acoustic solutions for wall and ceiling applications. These systems typically consist of narrow wooden lamellas mounted on backing materials, creating cavities that enhance sound absorption. However, the increasing use of wood in interior applications also raises concerns regarding fire safety and reaction-to-fire performance, as wood is a combustible material that can contribute to fire growth and heat release during fire events.

The fire behaviour of wood materials is governed by their thermal degradation processes, which include dehydration, pyrolysis, and the release of volatile combustible gases that support flaming combustion. During heating, wood decomposes primarily into char, combustible gases, and tar compounds, and the rate of these processes significantly affects ignition and flame spread characteristics [1]. Because untreated wood readily ignites and contributes to heat release, improving its fire performance is essential for applications in buildings where stricter fire classification requirements apply.

One common approach to improving the fire performance of wood is the use of flame-retardant treatments, particularly those based on phosphorus and nitrogen-containing compounds. Such chemicals modify the thermal degradation pathway of wood, promoting char formation and reducing the release of flammable volatiles. Phosphorus-based flame retardants are particularly effective because they catalyse dehydration reactions in cellulose and hemicellulose, leading to the formation of a protective carbonaceous char layer [2]. Nitrogen–phosphorus systems can also release non-combustible gases during decomposition, which dilute combustible gases in the flame zone and further inhibit combustion [3].

Among the different flame-retardant technologies, intumescent systems have received considerable attention. These systems form a swollen insulating char layer when exposed to heat, protecting the underlying substrate and slowing heat transfer. Studies have shown that wood impregnated with bio-based or intumescent flame retardants can significantly reduce peak heat release rates and total heat release during combustion [4]. Similarly, organic–inorganic mixed intumescent formulations have been shown to enhance the fire resistance of coatings by producing stable char structures that act as thermal barriers [5].

Another widely used method for improving the fire performance of wood-based materials is chemical impregnation. Pressure impregnation allows flame-retardant chemicals to penetrate deep into the wood structure, ensuring more uniform protection compared to surface treatments. Impregnation of wood-based panels with inorganic salts such as borates or bicarbonates has been shown to significantly reduce mass loss, flame spread, and heat release during combustion while maintaining acceptable mechanical properties [6]. Previous studies have also demonstrated that pressure-impregnated wood can exhibit substantially reduced heat release and slower fire growth due to enhanced char formation [7].

Several studies have focused on the reaction-to-fire performance of treated wood products used in building applications. For example, high-pressure impregnation combined with protective coatings has been shown to improve the reaction-to-fire classification of birch plywood used in interior applications [8]. Improvements in fire performance have also been achieved through alternative treatment methods such as plywood veneer soaking prior to panel manufacturing, which enhances the distribution of flame retardants within the wood structure [9]. These approaches demonstrate the potential of chemical treatments to produce wood-based materials capable of meeting more stringent fire safety requirements.

The geometry and surface treatment of wood panels can also influence their fire behaviour. Acoustic wood panels often contain perforations, grooves, or cavities that can modify heat transfer and airflow during combustion. Experimental studies have shown that such surface modifications can affect ignition behaviour, flame spread, and smoke production, highlighting the importance of evaluating the fire performance of acoustic panel systems [10].

Early research on fire-retardant wood products also emphasised the importance of developing eco-efficient, high-performance fire-protected timber materials for demanding building applications. The InnoFireWood project demonstrated that properly treated wood products can achieve improved fire performance while maintaining environmental and mechanical performance characteristics [11].

Despite significant progress in the development of flame-retardant wood products, there is still limited information regarding the fire performance of slatted or ribbon-type acoustic panels manufactured from impregnated wood lamellas. These systems present specific challenges due to their geometry, open surfaces, and potential airflow paths, which may influence combustion behaviour. While the relationship between fire-retardant retention and fire performance is generally known, the present study provides new insights for a specific application – ventilated wood ribbon acoustic panel systems produced under industrial conditions.

Therefore, the objective of the present study is to investigate the effect of high-pressure impregnation with ammonium phosphate-based fire retardants on the reaction-to-fire performance of aspen *(Populus tremula L.)* and thermally modified aspen wood lamellas intended for decorative and acoustic ribbon panels used in wall and ceiling applications. The scope of this research was focused only to panels reaction to fire performance and acoustic properties were not under the scope of this work. Thermally modified aspen wood was included in the study due to the benefits of dimensional stability and colour variance of decorative panelling. The study aims to evaluate how fire-retardant retention levels at high-pressure impregnated aspen wood influence the fire behaviour of the acoustic wood ribbon panelling and to assess its potential for improving the reaction to fire performance to B-s1,d0 fire class according EN 13501-1 [12].

Materials and methods

Materials. Two types of wood materials were used in the study 1) unmodified aspen wood (A) and 2) thermally modified aspen wood (TmA). Aspen wood from the species *Populus tremula* was selected due to its common use in interior decorative and acoustic panel applications and as this is the specific wood species in 4PLUS Ltd factory. The thermal modification of aspen wood sawn timber was done at 190 °C temperature schedule, which was produced through a controlled high-temperature modification schedule in an industrial kiln located in an EU country. The authors did not participate in the thermal modification process, and the modification schedule of aspen wood was not in the scope of this investigation. Wood lamellas were prepared from sawn timber boards with a cross-section of 30 mm width and a thickness of 25 mm and planed surface quality, corresponding to the dimensions commonly used in wood ribbon acoustic panels for wall and ceiling installations. Prior to impregnation, the average moisture content of the unmodified aspen wood was approximately 10% measured by the drying-weighting method, whereas the thermally modified wood had a lower moisture content of approximately 6%, which is typical for thermally treated wood materials.

Fire retardant treatment. The lamellas were treated with an industrial fire-retardant formulation based on ammonium phosphate. The fire-retardant solution had a concentration of 12.4% which was recommended to be used by the manufacturer of a specific industrial fire-retardant solution.

Impregnation was performed using vacuum–pressure impregnation technology at an industrial-scale impregnation facility located in an EU country. Controlled target of modification schedule was the retention level, which was reached at 4.6 bar pressure for aspen wood and 1.6 bar for thermally modified aspen wood. The treatment cycle phase under pressure duration for both was selected 12 min. This process allowed the fire-retardant solution to penetrate the wood structure to achieve effective chemical retention. Prior to treatment, each lamella was weighed with an accuracy of 0.1 g to determine its initial mass and all additional cross-sectional dimensions were measured with an accuracy of 0.1 mm for every single lamella width and thickness, giving the density calculation of wood before impregnation. Following the impregnation process, the samples were weighed again using the same measurement accuracy to determine the fire-retardant uptake and retention level. After treatment, the impregnated lamellas were kiln-dried in 4PLUS Ltd industrial kilns at drying schedules developed for aspen wood to remove excess moisture and stabilise the treated material before further processing. The retention level of fire retardant in wood was measured using a weighing method for each individual lamella. The retention level of fire retardant in wood - Atro/Atro (A_a/B_a) expressed as% of dry fire-retardant mass at wood mass on a dry basis, which was calculated using formula 1. Assigned minimal target retention level Atro/Atro expected to be 10%.

$$A_a / B_a = \frac{m_{Fr}}{m_w} \times 100\%, \tag{1}$$

where m_{Fr} – dry mass of fire retardant (A), kg;
m_w – dry mass of wood (B), kg.

The term Atro/Atro typically refers to the ratio of oven-dry weight (Atro weight) of fire retardant to the oven-dry weight of the wood after impregnation. This ratio helps determine how much of the fire retardant has been absorbed by the wood relative to its dry mass.

Panel manufacturing. After drying, the impregnated wood lamellas were used to manufacture wood ribbon acoustic panels. The lamellas were mounted onto fire-retardant impregnated wooden crossmembers with a centre-to-centre spacing of 50 mm using mechanical fitting elements made of steel. Panel production was carried out in a factory environment using industrial woodworking machinery, ensuring consistent manufacturing conditions. The lamellas used in the panel assemblies were not coated with any additional surface treatments or fire protective coatings, allowing the fire performance to be evaluated based solely on the fire-retardant impregnation treatment.

Samples were grouped in 3 retention level groups marked as Low (7…8%), Mid (12%) and High (16…17%) and for each retention level sample group, three test samples were manufactured.

Conditioning of test specimens. The finished panel assemblies were transported to a fire testing laboratory, where the specimens were conditioned prior to testing according to EN 13238. Conditioning was conducted at a temperature of 23 ± 2 °C and relative humidity of 50 ± 5% until constant mass was reached – mass loss in 24 h ≤ 0.1%.

Reaction to fire testing. The reaction-to-fire performance of the wood ribbon panels was evaluated using the Single Burning Item (SBI) test method in accordance with EN 13823. This test method is widely used in Europe to assess the fire behaviour of construction products installed in wall and ceiling configurations. For each retention level sample group, three replicate specimens were tested. The panel assemblies were installed on a calcium silicate backing board, which served as the substrate during testing. The system was tested as a ventilated construction, reflecting typical installation conditions for acoustic wood ribbon panel systems, see Fig. 1.

Fig. 1. **EN 13823 test sample of wood ribbon panel of aspen (a; b) and thermally modified aspen (c; d) wood before and after the test**

Statistical analysis. The retention level of the fire retardant in the wood lamellas was analysed using both descriptive and inferential statistical methods. Descriptive statistics, including mean, median, standard deviation, and variance, were calculated to characterise the distribution of retention values. In addition, 95% confidence intervals were determined for the mean values to quantify the uncertainty associated with the estimates. The distribution of retention data was evaluated using histogram analysis to assess variability and data dispersion. The relationship between fire-retardant retention level and wood density was analysed using Pearson correlation and linear regression analysis, and the strength and significance of the relationship were expressed using the correlation coefficient (*r*), confidence intervals, and corresponding p-values. Differences in reaction-to-fire performance parameters (FIGRA and THR_{600s}) between retention level groups (low, medium, high) and between material types (unmodified aspen and thermally modified aspen) were evaluated using analysis of variance (ANOVA) and independent sample t-tests, where appropriate. Statistical significance was assessed at a level of $\alpha = 0.05$, and exact *p*-values are reported in the Results and discussion section.

Results and discussion

The retention level of fire retardant expressed on an Atro/Atro basis was statistically analysed for aspen and thermally modified wood lamellas with a cross-section of 30×25 mm following high-pressure impregnation. A total of 466 measurements were included in the dataset for aspen wood lamellas and 500 samples for thermally modified aspen wood.

The mean retention value for aspen wood was 11.19% (Atro/Atro) with a standard error of 0.20, indicating a relatively precise estimate of the population mean due to the large sample size. The median value was slightly higher 12.31% suggesting that the central tendency of the data is somewhat shifted toward higher retention values. The standard deviation of 4.38% and variance of 19.14 indicate a moderate dispersion of retention values within the sample. The range of values was 20.56%, with the minimum measured retention of 0.86% and a maximum value of 21.42%, demonstrating substantial variability in chemical uptake among the lamellas. A very similar statistical distribution of fire retardant can also be observed for a batch of thermally modified aspen wood lamellas, see Fig. 2.

Correlation analysis was performed to evaluate the relationship between the fire-retardant retention level and wood density (see Fig. 3). A scatter plot was used to present individual sample values and visualise data variability and dispersion. The analysis indicated no meaningful linear relationship between wood density and fire-retardant retention. The Pearson correlation coefficients were $r = 0.05$ for unmodified aspen and $r = 0.004$ for thermally modified aspen, with both associations being statistically non-significant ($p > 0.4$). These results suggest that variations in wood density do not explain the observed variability in retention for either type of wood lamella.

This finding contrasts with the conclusions reported by Bukšāns and Kalniņa (2024), who observed a strong correlation between wood density and retention level in their experiments on birch wood impregnation. The difference between the two studies may be explained by the impregnation methodology used.

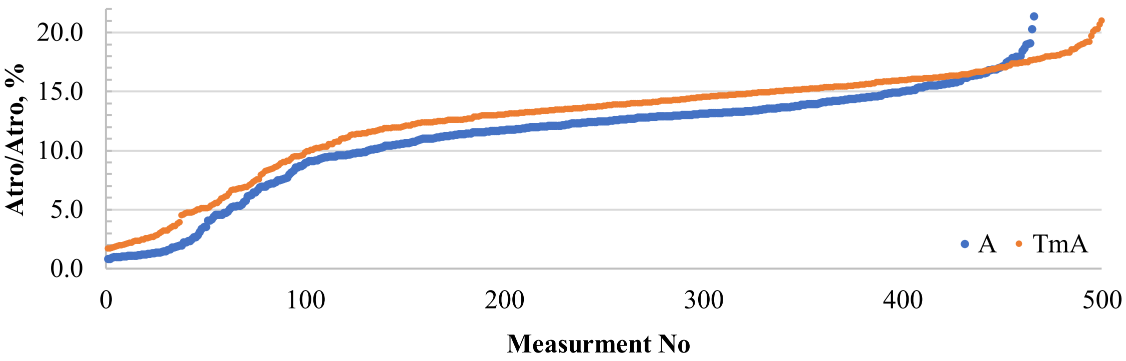

Fig. 2. **Fire retardant retention level - Atro/Atro for aspen and thermally modified aspen wood ribbon panels**

In the study conducted by Bukšāns and Kalniņa, the treatment was carried out using a veneer soaking method under atmospheric pressure, whereas the present study employed vacuum–pressure impregnation technology. The latter method enables substantially higher chemical uptake, and in the present study, differences in retention of more than tenfold between individual wood lamellas were observed. This study results highlight a technological problem of uneven distribution of impregnation chemicals in wood structure, which cannot be correlated with the porosity factor within the same wood species and is more related to the morphological structure of wood and the conditions of wood cell pits and torus after kiln drying of wood. A comparison between unmodified aspen and thermally modified aspen revealed that the proportion of lamellas failing to reach the minimum target retention level was higher in the thermally modified group. This behaviour can be attributed to the effects of thermal modification on wood structure and chemistry. Thermal treatment is known to reduce wood permeability due to pit closure (aspiration), degradation of hemicelluloses, and changes in cell wall structure, which collectively limit liquid penetration. The authors have unproven hypotheses that the uneven retention level at high-pressure impregnation technology strongly depends on the wood species factor.

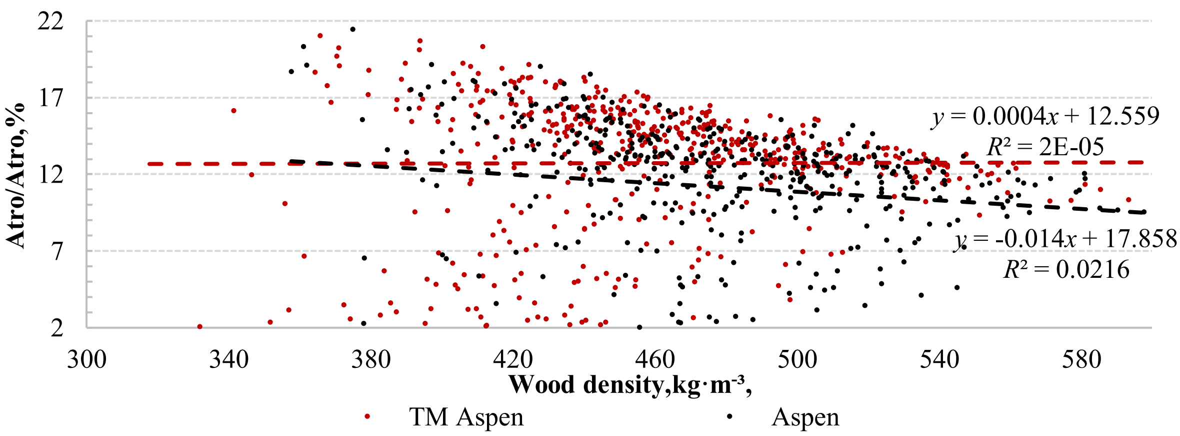

Fig. 3. **Wood density influence on fire retardant retention level (Atro/Atro) for aspen and thermally modified aspen wood**

The reaction-to-fire test results were evaluated using two main parameters: FIGRA (Fire Growth Rate Index) and THR_{600s} (Total Heat Release during the first 600 s). A comparison between the different fire-retardant retention levels – low, medium, and high – is presented in Fig. 4 and 5. The evaluation aims to compare the mean fire performance and corresponding confidence intervals of each product configuration with the threshold values for reaction-to-fire classes B and C. The results were compared with the reference unmodified aspen wood ribbon panel, which is indicated in orange. The red dashed lines represent the borderline values for classes B and C according to the requirements of EN 13501-1. At the highest retention level of approximately 17% (Atro/Atro), the closest performance to class B was achieved for both unmodified aspen and thermally modified aspen wood ribbon panels. A strong correlation between fire retardant retention level and reaction-to-fire performance parameters was observed for both product variants, indicating an approximately linear relationship between the retention level and improved fire performance.

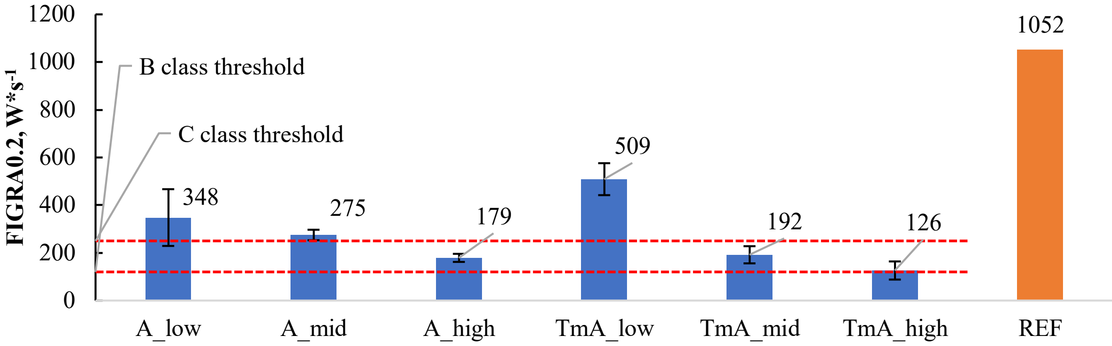

Fig. 4. **Fire growth rate index for fire-retardant-impregnated aspen and thermally modified aspen wood ribbon panels**

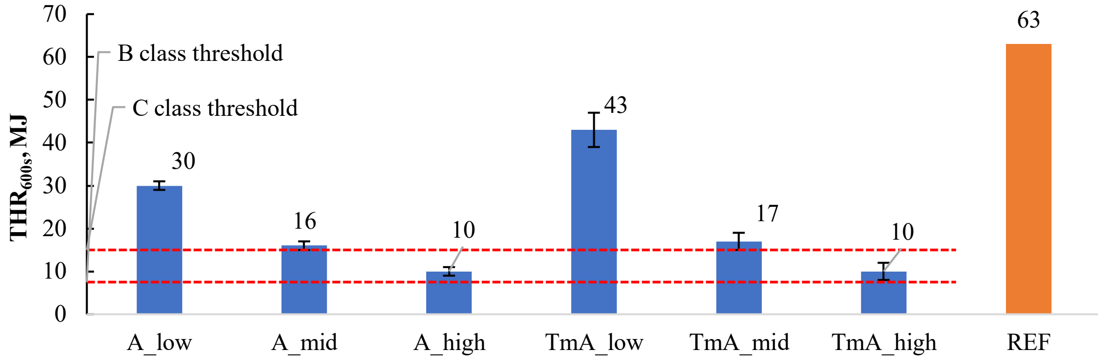

Fig. 5. **Fire growth rate index for fire-retardant-impregnated aspen and thermally modified aspen wood ribbon panels**

Thermally modified wood in the low retention samples group showed 46% higher average FIGRA and 43% higher average THR_{600s} values compared to unmodified aspen. Statistical analysis showed that the difference in FIGRA values between thermally modified and unmodified aspen wood panels was not statistically significant ($p = 0.13$), despite higher mean values observed for thermally modified wood. In contrast, $THR_{600}s$ values were significantly higher for thermally modified aspen ($p = 0.02$). This can be explained by the large variance in individual FIGRA measurements. Due to the limited sample size ($n = 3$), the statistical power of the analysis is low, and the results should be interpreted with caution.

This behaviour can be explained by the effects of thermal modification on wood structure and chemistry. Thermal treatment leads to degradation of hemicelluloses, reduction in equilibrium moisture content, and increased hydrophobicity, which reduces the ability of the wood to absorb and retain aqueous fire-retardant solutions. In addition, thermal modification alters the thermal degradation behaviour of wood, which may result in less effective char formation at insufficient fire-retardant concentrations. As a consequence, at low retention levels, the fire-retardant system is not sufficient to compensate for these changes, leading to higher heat release and faster fire growth compared to unmodified aspen wood. These observations are consistent with previously reported studies showing that phosphorus-based fire retardants promote dehydration reactions and char formation, thereby reducing the release of combustible volatiles during pyrolysis (Rowell and Dietenberger, 2013; Jiang et al., 2010), while thermal modification is known to alter wood permeability and chemical composition, affecting both impregnation efficiency and fire behaviour (Hansen-Bruhn and Hull, 2023).

Although the FIGRA values approached the borderline required for class B, the $THR_{600}s$ values remained too high, exceeding the class B limit by approximately 3 MJ. This indicates that, despite the significant improvement achieved through fire-retardant impregnation, additional fire protection measures are required in order to meet the class B performance criteria according to EN 13501-1.

One potential approach to further reduce both the FIGRA index and THR_{600s} values is the application of a protective top coating on fire-retardant-impregnated wood surfaces. While impregnated fire retardants primarily act by reducing the combustibility of wood and promoting char formation, an intumescent coating system can provide an additional protective mechanism. When exposed to heat, such coatings expand to form an insulating char layer, which slows heat transfer to the wood substrate, delays ignition, and reduces the rate of heat release during combustion.

The combined use of fire-retardant impregnation and intumescent surface coatings may therefore represent an effective strategy for achieving the required reaction-to-fire performance for wood ribbon panel systems used in interior applications.

The results of this study demonstrate that vacuum–pressure impregnation of aspen wood lamellas with ammonium phosphate-based fire-retardants significantly improves the reaction-to-fire performance of wood ribbon acoustic panels. The improvement in fire performance was reflected by substantial reductions in the FIGRA and THR_{600s} parameters compared with the untreated reference system. These findings are consistent with the general understanding of the fire behaviour of chemically treated wood materials described by Roger M. Rowell and Mark A. Dietenberger, who reported that phosphorus-based fire retardants modify the thermal degradation pathway of wood by promoting dehydration reactions and char formation, thereby reducing the release of combustible volatiles during pyrolysis.

However, the novelty of the present study lies in its focus on a specific and previously under-investigated wood product system – wood ribbon acoustic panels – and their reaction-to-fire performance under realistic installation conditions. Unlike flat wood-based cladding or panel systems, ribbon-type panel constructions introduce additional influencing factors, including open geometry, increased surface area, cavity effects, and potential airflow behind the panel system. These characteristics can significantly affect heat transfer, flame spread, and smoke development during fire exposure. Therefore, the results of this study highlight the practical challenges of achieving the desired reaction-to-fire classification using conventional fire-retardant impregnation treatments, even when the general relationship between retention level and fire performance is well established. The findings demonstrate that, for such complex panel systems, fire performance cannot be predicted solely based on material-level properties, but must also consider system-level behaviour and installation configuration. These findings are directly relevant for industrial production and certification of acoustic wood panel systems.

Conclusions

1. High-pressure impregnation with ammonium phosphate-based fire retardants significantly improved the reaction-to-fire performance of aspen wood ribbon panels, increasing the classification from class E for untreated panels to classes D, C, or B, depending on the achieved fire-retardant retention level.
2. Approximately 80% of the wood lamellas achieved the target fire-retardant retention level, while the remaining 20% fell below the specified threshold. This variability is likely related to differences in wood anatomical structure and permeability, including pit aspiration and reduced liquid transport pathways, as well as the influence of drying and impregnation process parameters on fire-retardant uptake.
3. Fire retardant treatment resulted in a substantial reduction in key reaction-to-fire performance parameters. The FIGRA parameter decreased 3 to 8 times, while the THR_{600s} value was reduced by 2 to 6 times compared with the reference system made from unmodified aspen wood lamellas.
4. Despite the significant improvement in fire performance, none of the tested retention levels enabled the wood ribbon panel systems to achieve the target reaction-to-fire classification of B-s1,d0.
5. The results demonstrate a strong, statistically significant correlation between fire-retardant retention level and key reaction-to-fire performance parameters. For unmodified aspen wood, the Pearson correlation coefficients were $r = 0.75$ for FIGRA and $r = 0.98$ for THR_{600s}, while for thermally modified aspen wood, the coefficients were $r = 0.92$ for FIGRA and $r = 0.96$ for THR_{600s}. Based on these findings, a fire-retardant retention level of approximately 20% (Atro/Atro) is estimated to be necessary to achieve class B performance according to EN 13501-1 for the tested system.

6. Further optimisation of the impregnation process is required to improve treatment uniformity and achieve the target retention levels. In addition, the combination of fire-retardant impregnation with intumescent coating systems may be a promising approach for achieving the B-s1,d0 reaction-to-fire classification required for demanding interior applications.

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Author contributions

Conceptualisation, K.G. and E.B.; methodology, E.B. and K.G.; formal analysis, E.B.; investigation, E.B.; data curation, K.G. and E.B.; writing original draft preparation, E.B.; review and editing, K.G. and E.B.; visualisation, E.B.; project administration, K.G.; funding acquisition, K.G. All authors have read and agreed to the published version of the manuscript.

References

[1] Rowell R. M., Dietenberger, M. A. Chapter 6: Thermal properties, combustion, and fire retardancy of wood. In: Second edition of the Handbook of Wood Chemistry and Wood Composites, Roger Rowell, Editor, by CRC Books, 2013, pp. 127-149.

[2] Jiang, J., Li, J., Hu, J., Fan, D. Effect of nitrogen phosphorus flame retardants on thermal degradation of wood. Construction and Building Materials Vol. 24, Issue 12, December 2010, pp. 2633-2637.

[3] Seo, H. J., Hwang, W., and Lee, M. C. Fire properties of Pinus densiflora utilizing fire-retardant chemicals based on borated and phosphorus (I) – combustion characteristics, BioRes. 12(3), pp. 5417-5427.

[4] Li L., Chen Z., Lu J., Wei M., Huang Y., Jiang P. Combustion Behavior and Thermal Degradation Properties of Wood Impregnated with Intumescent Biomass Flame Retardants: Phytic Acid, Hydrolyzed Collagen, and Glycerol, ACS Omega 2021 6 (5), pp. 3921-3930.

[5] Ma, L.; Song, Q.; Dong, F.; Yang, H.; Xia, Z.; Liu, J. Effect of Organic–Inorganic Mixed Intumescent Flame Retardants on Fire-Retardant Coatings. Coatings 2024, 14, 1034.

[6] Pedieu, R.; Bentis, A.; Riedl, B.; Wang, X.-M.; Deng, J.; Braghiroli, F.L.; Koubaa, A. Enhancing Fire Resistance and Mechanical Properties of Wood Strand Boards by Impregnation with Sodium Bicarbonate and Sodium Borate. Polymers 2025, 17, 2943.

[7] Hansen-Bruhn I., Hull T.R., Flammability and burning behaviour of fire protected timber, Fire Safety Journal, Volume 140, 2023, 103918.

[8] Rudzīte S., Bukšāns E. Impact of High-pressure Impregnation and Fire Protective Coatings on the Reaction to Fire Performance of Birch Plywood. Rural Sustainability Research. 45, 2021. pp. 65-75.

[9] Buksans E., Kalnina I. Improvement of reaction to fire performance of birch plywood by veneer soaking method. Engineering for Rural Development. 23, 2024. pp. 460–466.

[10] Gašparík, M., Kytka, T., Bezděková, M. Influence of Surface Treatment of Wood-Based Acoustic Panels on Their Fire Performance. Fire 2026, 9, 67.

[11] Östman, B., Tsantaridis, L., Mikkola, E., Hakkarainen, T., Belloni, K., Brumer, H., & Piispanen, P. (2006). Innovative eco-efficient high fire performance wood products for demanding applications: Final report for Vinnova-Tekes project InnoFireWood. SP Rapport, No. 30.

[12] CEN/TC 127 Fire safety in buildings. Fire classification of construction products and building elements - Part 1: Classification using data from reaction to fire tests. EN 13501-1:2018.

[13] CEN/TC 127 Fire safety in buildings. Reaction to fire tests for building products - Building products excluding floorings exposed to the thermal attack by a single burning item. EN 13823:2020.