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ORIGINAL ARTICLE

Assessment of fire-retardant treatments and their impact on the fire performance and bonding properties of aspen and silver birch veneers

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Abstract

Plywood is a valuable material that offers superior properties compared to solid wood. However, like solid wood, its poor flammability limits its suitability for various applications. This study investigates the impact of distinct types of fire retardants (FRs), designated as B, P, and U, as well as various application techniques—roller coating, spraying, and impregnation—on the bond strength and fire performance of aspen and birch veneers. A lap shear test (LST) was conducted to compare the bond strength of veneers bonded with a newly developed lignin-substituted phenolic formaldehyde (LPF) resin against a conventional formaldehyde resin (PF) to evaluate the effects of FR treatments. The results indicated that FR retention was significantly higher with impregnation and, overall, with aspen veneers than birch, except for aspen veneers treated using the spraying method with P-FR. The P-FR exhibited strong and consistent performance with birch veneers, irrespective of the treatment method. Notably, P-FR roller-coated aspen, with an FR retention of 9.5% and an ignition time of 11 s, demonstrated the best overall reaction to fire performance. With a basic protection duration of 52 s and a thermal decay time of 157 s, this combination demonstrated improved thermal resistance. The LST further revealed that FR treatments significantly impacted birch veneers, which experienced a 30–48% decrease in shear strength with PF resin relative to untreated veneers. The LPF resin was incompatible with birch veneers when treated with P-FR formulated from a protic ionic liquid. For aspen, the overall decrease in shear strength was 40%, but with B- and U-FR treatments, the reductions reached 38% and 50%, respectively—much higher than the decreases observed in birch (25% and 37%) relative to control samples. These findings provide valuable insights into the effects of fire retardants on new resins, though further research is necessary for comprehensive validation.

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1 Introduction

Due to advancements in technology, engineered wood panel products (wood composites) have been developed and adapted for a wide range of purposes. Wood composites such as plywood, particleboard, and blockboard are commonly used as nonloadbearing components in applications such as wall partitioning, flooring, and ceiling construction (Samani and Khali 2016). As a result, plywood comprising thin layers of wood veneer that are glued together with the grain direction of each layer perpendicular to that of the adjacent layers gains significance as an essential engineered wood product. Plywood outperforms solid wood in dimensional stability, uniform strength, and resistance to splitting and cracking. It is a practical and cost-effective choice for achieving the necessary functionality in furniture, construction, and automotive applications (Demir, Aydin, and Ozturk 2014). Currently, two main types of adhesives are extensively used in plywood production, depending on whether the intended application is interior or exterior: urea-formaldehyde (UF) and phenol-formaldehyde (PF). PF adhesives are used for plywood suitable for exterior conditions and contact with moisture, while UF resins are used for interior plywood applications where lower moisture interactions are guaranteed. However, recent developments have seen developments of biobased binders such as lignin in processes known as lignin phenolation, demethylation, and methylolation (Ghorbani et al. 2016) as a sustainable substitute for phenol (Klašnja and Kopitovic 1992). Lignin is abundantly available, inexpensive, and environmentally friendly (Younesi-Kordkheili and Pizzi 2018). In the production of plywood, both softwoods like spruce and pine and hardwoods like birch are commonly used raw materials. In the Baltic region, hardwoods are particularly abundant, with birch (Betula pendula Roth) being the most prevalent wood species employed for plywood manufacturing. While birch accounts for 24% of all hardwood in the region, alder (*Alnus gluinosa*) and aspen (*Populus tremula*), which together comprise 23%, remain underutilized. The drive for sustainable wood utilization and the desire to valorise natural resources have spurred interest in exploiting these underutilized hardwood species. A study by Heikko et al. (2020) investigated the use of alder and aspen veneers as plywood core materials by replacing birch veneers under various lay-up configurations. Their findings demonstrated that these underutilized wood species can be successfully employed in the veneer-based products industry if appropriate lay-up designs are implemented. Additional studies by (Akkurt et al. 2022) and (Rohumaa et al. 2021) have further explored the potential of incorporating underutilized wood species like alder and aspen into plywood production.

Plywood will find much significance and wide adaptation as a building construction or automobile design material if it can achieve the construction product regulation (CPR) with regards to fire resistance and mechanical properties (Alao et al. 2024). In the case where single or combined lay-up of underutilized wood such as aspen/alder and birch can achieve more sustainable outcomes, emphasis should be placed on the best approach to achieving the necessary reaction to fire resistance. According to Kawalerczyk et al. 2019; incorporating FR into individual veneers can achieve comprehensive fire protection, but this approach may have detrimental impacts on the mechanical properties and bonding performance of the plywood. For instance, Cheng and Wang (2011), reported a 25% reduction in bond strength for plywood with FR-treated poplar veneers bonded with PF resin. Notably, the extent of plywood strength reduction depends on the specific type of FR chemical used and the application method employed. To achieve strong bonding for veneers treated with FR, the veneer's surface must remain penetrable and wettable by adhesive following treatment. Therefore, extensive research is still warranted to optimize the fire performance of plywood.

Hence, this study investigates three types of fire retardants (B, P, and U) and the most suitable application method (spraying, brushing, and impregnation) on the reaction to fire performance and bond strength (shear strength) of veneers from birch (*Betula pendula* Roth) and aspen (*Populus tremula* L.). As earlier discussed, birch and aspen are chosen for this study as the popular hardwood species in Baltic regions with the former the most common wood species used in plywood production in northern Europe (Akkurt et al. 2022), and the latter, an underutilized wood species with promising properties due to its lightweight and porosity. The FR treatments was examined with reaction to fire performance veneer samples with dimensions of $100 \times 100 \times 1.5$ mm^3. The conventional PF and more sustainable lignin substituted phenolic resins were applied to determine the implications of the FR treatments on the bonding properties of the veneers. This study hypothesizes that wood species, fire retardant (FR) type, and application method all influence the FR retention and fire performance of wood veneer-based products. Additionally, the investigation extends to the performance of the FR and veneer with a newly developed lignin-substituted phenolic formaldehyde (LPF) resin, an aspect not previously explored.

2 Materials and methods

2.1 Materials

2.1.1 Fire retardants (FR) and veneers

The research was designed primarily to examine three industrially available fire retardants (FR), one of which is novel and has recently been developed for plywood modification. To create an unbiased and non-promotional perception about the FR's used, the terms P, B and U have been used to identify the FRs. Three application techniques were studied using veneers of aspen and birch. A total of 60 samples were prepared for the test. The veneer thickness was roughly 1.5 mm, which is a standard used in the plywood industry for the fabrication of plywood. The size of the test samples was 100 mm × 100 mm, which was cut originally from veneer sheets of 800 mm × 450 mm. The experimental design is shown in Table 1.

The pH of the veneers measured using a Seven Compact S210 pH meter that the birch veneers present a pH of about 4.9 while that of aspen veneers was 5.1. Table 2 presents some information regarding the FRs. The wet retention target of all the FR's was 240 g/m^2 ($\pm$10). As previously noted, two resin formulations were considered in the study.

Table 1 Experimental design

Wood species	Fire retardant treatment	Treatment method Impregnation (I) | Spraying (S) | Roller coating (*R*)	Sample label		
Birch (Bir)	Control (C)	Untreated	Bir-C		
	P FR	P FR+I P | FR+S P | FR+R	Bir-**P**-I	Bir-**P**-R	Bir-**P**-S
	B FR	B FR+I | **B** FR+S | **B** FR+R	Bir-**B**-I	Bir-**B**-R	Bir-**B**-S
	U FR	U FR+I | **U** FR+S | **U** FR+R	Bir-**U**-I	Bir-**U**-R	Bir-**U**-S
Aspen (Asp)	Control (C)	Untreated	Asp-C		
	P FR	P FR+I | P FR+S | P FR+R	Asp-**P**-I	Asp-**P**-R	Bir-**P**-S
	B FR	B FR+I | **B** FR+S | **B** FR+R	Asp-**B**-I	Asp-**B**-R	Bir-**B**-S
	U FR	U FR+I | **U** FR+S | **U** FR+R	Asp-**U**-I	Asp-**U**-R	Bir-**U**-S

Table 2 Properties of the fire retardants (FR)

FR chemical	Form	Details	Application procedure
P	Ready to use water-based solution	A novel protic ionic liquid (ILs)-based FR. It is composed of an aqueous solution of bisphosphonate acid, an alkanol amine, and optionally an alkaline agent (solid content: 44.9%). pH: 5.76	More suitable for roller coating. But can be designed for any application method including brushing, soaking and vacuum impregnation.
U	Ready to use water-based solution	A non-halogenated phosphate compounds designed for wood modification (boards, beams, etc.), Glulam and CLT (solid content: 38.9%). pH: 5–6	Brush, spray, roller. Impregnation is not necessary but can be used in autoclave.
B	Solute prepared by mixing 1 kg to 4400 ml of water.	A non-toxic FR, made from ingredients that occur naturally in fruits and vegetables or are found in nature in their elemental form (solid content: 13.7%). pH: 7.46	Any of the possible application methods but spraying and impregnation have been commonly used.

Formaldehyde based adhesive from PL: phenol adhesive (resin (14J021); hardener (24J662)) and a lignin substituted phenol formaldehyde (LPF) adhesive (resin (14W451); hardener (EXPH 9500). Both resins were obtained from Prefere Resins Finland Oy (Hamina, Finland). These resins were used to examine the effect of the FR treatment on bonding properties of the veneers.

2.2 Methods

2.2.1 Veneer treatment with FR

The 1.5 mm-thick veneers were obtained from birch (*Betula pendula* Roth) and aspen (*Populus tremula L.*) logs by peeling with a rotary peeling lathe (Model 3HV66; Raute Oyj, Finland). Sampling approach for the examined FRs is such that at least one test piece (100×100 mm^2) was sampled from the beginning, middle, and end of peeled veneer strips. No specific attention was given to heartwood or sapwood composition. However, this methodology provides a better representation of results, aligning with plywood industry practices. Prior to the FR-impregnation treatment the 100×100 mm^2 veneer sheets (Fig. 1a) were re-dried in the oven at 103 °C until constant weight. The veneers were stacked in a rack (Fig. 1b) and treated in an autoclave (Fig. 1c) (diameter: 270 mm; depth: 540 mm) at 0.65 bar for 15 min. In the case of spraying (S) and roller coating (R), aspen (990 mm x 412 mm) and birch (848 mm x 423 mm)

(a) (b) (c)

Fig. 1 (**a**) Veneer sample, (**b**) stacking of the veneers; (**c**) samples in the autoclave

Table 3 Estimated veneer density before and after treatment (values in bracket represent standard deviation)

	Aspen			Birch		
	S	R	I	S	R	I
Control	511.90(25)	508.97(25)	491.07(25)	621.42(10)	626.12(10)	614.13(9)
U	533.57(31)	517.75(11)	573.93(27)	640.03(8)	633.39(31)	674.40(10)
Control	521.13(25)	524.89(25)	496.13(25)	616.63(10)	615.49(10)	608.07(10)
B	527.69(10)	533.44(22)	527.47(27)	624.27(7)	616.01(5)	649.60(9)
Control	524.04(25)	522.74(25)	477.73(25)	592.04(22)	623.80(22)	620.67(22)
P	571.10(31)	573.04(31)	630.93(34)	676.57(20)	654.34(21)	725.40(31)

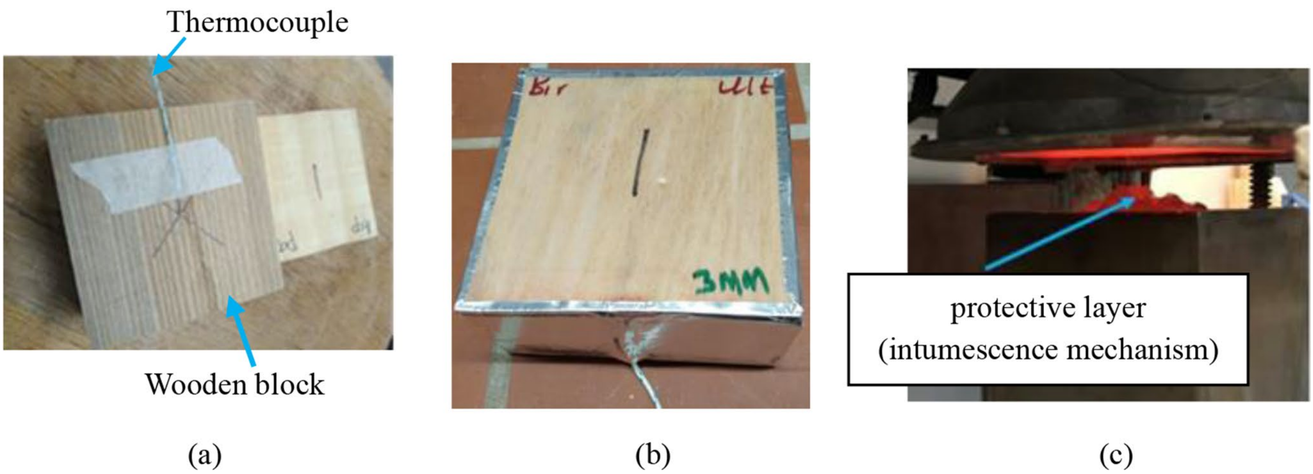

Fig. 2 (**a**) wooden block with thermocouple, (**b**) sample set-up; (**c**) sample in a sample holder under radiant heat

were treated with FR using a spread rate of 240 ± 10 g/m^2. Only one face of the veneers was treated. Table 3 presents the density of the untreated and FR-treated birch and aspen veneers.

2.2.2 Evaluation of reaction to fire properties

The reaction to fire of the samples was evaluated using a cone heater of a calorimeter in accordance with ISO 5660-1 2015. Three replicates were examined for each batch of samples at an exposure of 25 mm from the radiant surface. A birch wooden block (100 mm × 100 mm × 45 mm) was used as part of the setup to evaluate the ability of the veneers to mitigate flame spread to the wood (basic protection (T_{Pt})). This approach to examine reaction to fire has been applied in past studies (Alao et al. 2024; Liblik 2023; Kallakas et al. 2019). The arrangement incorporated a 0.25 mm type K thermocouple (Pentronic AB, Vastervik, Sweden) placed at the centre (Fig. 2a), between the veneer sample and the timber block (Fig. 2b) and secured with aluminium tape. The reaction to fire test (Fig. 2c) measured and recorded the time to ignition of the veneers and the length of time to effectively protect the wooden block from thermal decomposition, which corresponds to the T_{Pt}. Achieving a critical temperature of 270 °C was essential to determine T_{Pt}. The test was halted immediately upon veneer degradation, exposing the underlying solid wood. This resulted in variability in the exposure time, which is dependent on the properties and treatments of the veneers to achieve the protection limit. Hence, the residual mass was not considered as part of the analysis.

2.2.3 Evaluation of veneer bonding properties with single lap shear test

The adhesion test was performed according to EN 205 standard. Two drops of 6.3 µl Phenol formaldehyde (PF) and lignin phenol formaldehyde (LPF) adhesives, corresponding to a spread rate of 126 g/m^2 were applied to a surface area of 5 mm × 20 mm on overlapping veneer strips with dimensions of 20 mm × 150 mm (Fig. 3). Test samples were prepared using a two-post manual hydraulic press (Carver (model C)), Carver Inc. Wabash, IN, USA). In the case of PF binder, the samples with adhesive were pressed using a pressure of 2 MPa and temperature of 130 °C for 355 s and for LPF adhesive, the pressing duration was 510 s. The difference in press duration is because LPF has a lower reactivity compared to PF binders. The samples were conditioned to 65% relative humidity at a constant temperature of 20 °C before lap shear test with a Zwick Roell Z050 universal mechanical testing machine (Zwick GmbH & Co.KG, Ulm, Germany). The test rate of 1 mm/min was used.

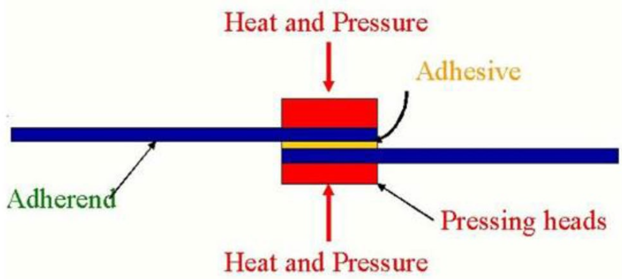

Fig. 3 Image describing the test method of the single lap shear test sample

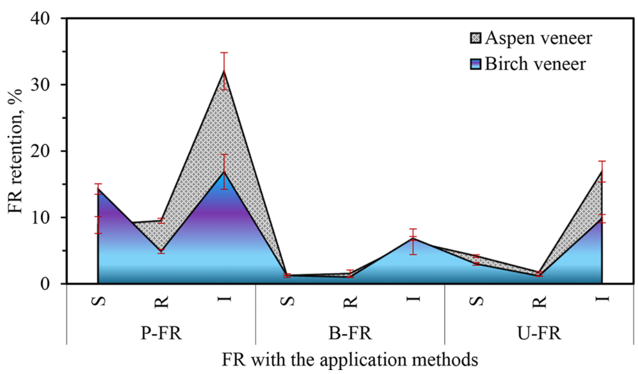

Fig. 4 Comparison of the average dry FR retention in the sprayed, roller coated and impregnated aspen and birch veneers

2.2.4 Statistical analysis

The results of the fire performance parameters and lap shear tests were statistically analysed using a one-way ANOVA test with a significance level (α) of 0.05.

3 Results and discussion

3.1 Retention rate of the FR in treated veneers

Figure 4 demonstrates that the fire retardant (FR) treatments resulted in varying levels of retention within the veneers. The trend was such that impregnation (I) > spraying (S) > roller coating (R). This trend was more consistent for both veneered-wood species treated with high solids content FRs (P- and U-FR). In the case of B-FR both spraying and roller coating achieved somewhat similar outcome for aspen veneers, but for birch, spraying achieved 20% more retention than roller coating. The lower uptake of flame retardants (FRs) using roller coating, compared to spraying, may be attributed to the accumulation of the FR solution on the veneer surface. This accumulation likely results from an initial high deposition that quickly saturates the surface pores, preventing further penetration. Overall, the retention of FRs is relative to their solid content, with P-FR demonstrating the highest retention, followed by U-FR and B-FR, respectively. The low retention observed with B-FR is due to its lower solid content, which means fewer active FR salts are available to fill the pores in the wood veneers. This leads to difficulties in penetration and issues with surface adhesion. It should be noted that this does not necessarily imply that the performance of the FR will be undesirably impacted as FRs have diverse mechanisms of action. The uptake of B-FR and all other FRs improved significantly with impregnation since, as previously mentioned, the entire veneer volume was treated, and impregnation typically forces the FR deeper into the veneers. Aspen wood exhibited higher FR retention (p-value with CI of 0.05 < 0.00), retaining 46.3% and 27.3% more than birch when impregnated with P-FR and U-FR, respectively. These differences may also be due to variations in cell wall structure. Aspen has a higher porosity and lower density, with its anatomical structure featuring larger and more numerous vessels that facilitate the movement of impregnating solutions. Moreover, the chemical composition of aspen wood may also contribute to its superior impregnability, especially with the high solid content FRs. In the case of B-FR impregnation, particularly with a significantly lower retention of 32% compared to birch (p-value = 0.005), this might be due to the lower lignin content of aspen, which can impede the diffusion of impregnating agents. Lignin can interact with various chemicals, hindering the penetration of impregnants, which causes a reduction in the effectiveness of the treatments. Furthermore, the open cell structure of aspen may result in the FR primarily filling the cell cavities, which can inhibit diffusion into the cell walls. Additionally, the diffusion of impregnating agents in aspen wood is expected to decrease when the agents have a lower solids content. This is because, even though the low solids content of the flame retardant (FR) initially leads to lower viscosity, which may enhance penetration, it can also restrict the diffusion of the agent deep into the wood. This can induce a lower concentration gradient, the driving force for diffusion.

3.2 Reaction to fire test results (basic protection time (Tpt) and decay time (Tdecay)

Figure 5 demonstrates that the fire retardant (FR) treatments improved thermal stability with better T_{pt} and T_{decay} for both aspen and birch veneers, regardless of the examined application method. However, the result was not so promising with U-FR. The outcome also indicates that B-FR would likely be more compatible with aspen if applied via spraying than impregnation or roller coating, even though the highlight in the subsequent section already indicates that the retention of B-FR was higher for the other two application methods. This observation highlighting a contrast between

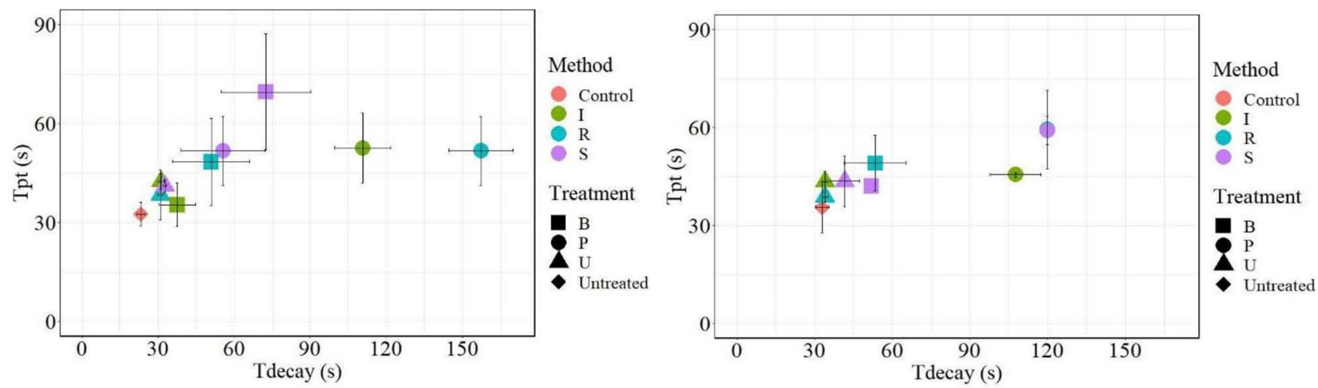

Fig. 5 The T_{pt} and T_{decay} of untreated compared to batches treated by impregnation (I), roller coating (R), and spraying (S) with P, U, and B fire retardants for (**a**) aspen and (**b**) birch veneers

FR retention and fire performance, underscores the need for further analysis due to the complexities of FR interactions with wood. Regardless, P-FR generally performed well with aspen, offering the best results with roller coating and impregnation treatments. The longer thermal decay time observed with roller coating compared to impregnation might be due to the higher initial density of the roller-coated aspen veneer (522 kg/m³) compared to the veneers used during impregnation (478 kg/m³). This could also be because the formulation of the FR is more compatible with roller coating. For birch, the performance of B-FR was like U-FR, offering only slightly notable improvements in fire performance compared to untreated birch. While P-FR produced better results, suggesting that all application methods are potentially suitable. The general observation is that higher FR retention does not necessarily translate into a better reaction to fire performance.

When comparing the outcome between the two wood species, denser birch should benefit more from deeper penetration offered by impregnation, but this treatment produced the same outcome for both types of wood veneers, which might be due to the higher dry FR retention in aspen. Considering veneers without FR treatment, the T_{decay} for birch was longer than that of aspen (p-value = 0.01), which is also a density factor of the, since the density of a material influences the reaction to fire properties (White 1984). Higher-density wood like aspen is reported to have a slower charring rate (Li et al. 2024). The charring rate is also influenced by the wood's chemical characteristics (Friquin 2011). High cellulose and hemicellulose content provide more fuel for combustion, with lignin being more resistant and thermally stable (Belouadah et al. 2024). Consequently, birch, typically having higher lignin content than aspen (Tullus et al. 2014), exhibits slower thermal decay.

Figure 6 presents the veneer residues and time to ignition (TTI). TTI is a parameter that indicates the level of fire performance and depends on wood species (chemical composition), density, moisture content, grain orientation, fire retardant treatment (kind, quantity, and application technique), dispersion, and retention. There is a lack of a clear trend between TTI and the application method relative to FR retention. This may be due to complexities like chemical interactions of FR and wood components, as well as the sensitivity of the test method. Untreated birch results are consistent with prior observations, displaying TTI result consistent with prior observations, achieving TTI that is longer (p-value = 0.001) than aspen. The observed trend of delayed TTI generally persisted following FR treatment. However, in most cases, the differences in TTI do not correspond to the outcomes obtained for T_{pt} and T_{decay}. For both aspen and birch veneers, treatment with P-FR, regardless of the application method, constantly produced higher or, in some cases, similar TTI compared to B- and U-FR. However, P-FR displayed higher variability within the measured samples, which might be because of the higher solids content impacting the uniform coverage or penetration of the FR. TTI was similar for both B-FR and U-FR, except in the case of impregnation, where U-FR demonstrated a 40% delay in TTI.

For aspen veneers treated with any FR type, impregnation resulted in a slight increase in TTI compared to other application methods. Like aspen, birch exhibited no significant changes in TTI with P and B-FR treatments, regardless of the application method. Interestingly, spraying caused the most delayed TTI for both P and B-FR. For U-FR, impregnation resulted in a delayed TTI (p-value = 0.01) compared to spraying and roller coating, although the delay was less pronounced than with P and B-FR. The two wood types show no marked differences in veneer residues relative to the FR treatments. As mentioned initially, the test aimed to examine T_{pt} and was concluded as soon as the veneer degradation reached and exposed the underlying wood block. Hence, the test duration varied depending on when the T_{pt} is achieved as well as when the wood block appears visibly

Fig. 6 Veneer residues (values represent TTI) after exposure to 50 kW/m^2 radiant heat from cone heater of a cone calorimeter

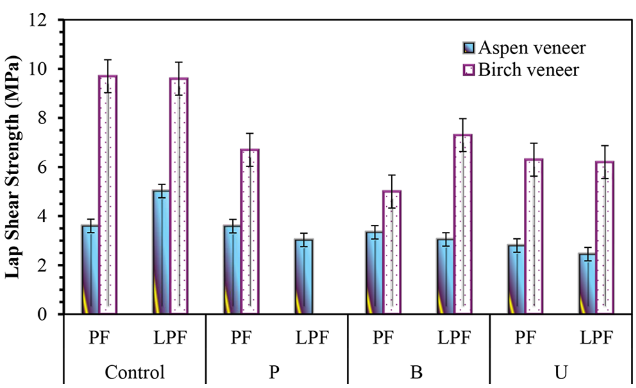

Fig. 7 LPF and PF Lap shear strength test results of the aspen and birch veneers, including with P, U and B FR treatments

damaged. However, treatment with P-FR consistently displayed lower thermal decomposition across all application methods, likely due to its higher FR retention, leading to slower decomposition.

3.3 Lap shear strength test results

To study lap shear strength, impregnated veneers were used due to the high retention content observed with this treatment. To design this test, the nature of LPF was considered with regards to the impact of lignin on reactivity (Ghorbani et al. 2016). In this regard, LPF generally has lower reactivity and thus requires longer curing time than phenolic resins, depending on the substitution levels. Hence, the pressing time used with LPF was almost two times more than applied with PF adhesive. This press time was achieved by conducting trial tests and can be observed from the results of the control samples (Fig. 7), that the variation in pressing time was adequate to achieving similar results for the studied adhesives. For reference, it is essential that the lap shear strength is at least 3 MPa to achieve the requirements of ANSI/HPVA HP-1 standard for plywood (Frihart et al. 2009). For the birch controls it can be noticed that the type of resin did not affect the shear strength. Similar observation is noted for U-FR batches. Interestingly, comparison of PF and LPF veneers treated with B-FR, shows the latter achieved 32% higher shear strength, which was 25% lower than that of the control veneer. However, for the P-FR treatment, many LPF bonded samples experienced failure when mounted on the tensile testing machine causing failure before testing. The lower shear performance of LPF adhesives compared to conventional PF adhesives is often due to the complexities in the structure of lignin, which can hinder its uniform reactivity with formaldehyde, leading to incomplete polymerization and weaker intermolecular forces (Younesi-Kordkheili and Pizzi 2021; Lawoko et al. 2021). While a longer press duration may mitigate this effect in some cases (as seen with control samples), achieving comparable shear strength to PF can be challenging, especially with the incorporation of FR treatment. Such incompatibility, especially in the case of P-FR treated birch veneers, might have arisen due to the higher viscosity of LPF (4000–8000 mPa·s (20 °C) compared to PF (250–400 mPa·s (20 °C). Besides, the combination of highly retained P-FR in the birch veneer in relation to its low porosity may have limited resin penetration, potentially resulting in the bonding incompatibility. This explanation is further buttressed by the fact that the B-FR-impregnated birch veneers, with the lowest retention, produced the best compatibility with LPF, achieving of all the samples in this group, the lowest decrease (25%) in shear strength compared to the control. All birch veneers exhibited significantly higher shear strength than aspen veneers, indicating a generally better performance. Among aspen samples, the LPF control group significantly outperformed ($p\text{-value}=0.001$) all other groups, achieving a shear strength of 5 MPa, which was 28% higher than the PF variant and 38 to 50% more than the FR-treated batches. There was no significant difference observed for all LPF-bonded aspen ($p\text{-value}=0.07$) compared to the FR treatment, nor for the PF-bonded batches ($p\text{-value}=0.37$), nor when both resin types were analysed together ($p\text{-value}=0.2$). Considering the limits for decorative plywood test (HP-1), all the aspen veneer groups, except for the U-FR treated samples achieve the standard value.

The overall result highlights that FR treatments decrease veneer shear strength, especially more significantly ($p\text{-value}<0.05$) for birch in the case of PF-resin compared to aspen. While asides incompatibility of P-FR-treated birch veneers with LPF, the aspen was more impacted by the FR treatment than birch. The decrease in shear strength with FR treatments aligns with findings from others (Bekhta et al. 2016; Kawalerczyk et al. 2019). Notably, while B- and P-FR treatments significantly reduced or caused the failure of birch shear strength, U-FR treatment had no significant impact on shear strength for either resin type. This suggests that performance differences may also be linked to FR composition and to the interaction between these factors and wood's inherent properties in addition to retention. According to Kawalerczyk et al. (2019), the negative impact of FR treatment on wood could potentially be related to changes in veneer pH, which is itself a factor in the wood characteristics and FR formulation. Aspen and birch typically have different initial pH values, 4.0–5.0 and 4.5–5.5, respectively, that could contribute to the observed substantial discrepancies in the outcome of the lap shear strength tests involving the FR treatment.

4 Conclusion

This study explored the effectiveness of fire retardant (FR) treatments applied to veneers from two wood species: underutilized aspen and the more commonly used birch in the plywood industry. Additionally, it compared the performance of conventional phenol-formaldehyde (PF) adhesives with an alternative of lignin-substituted phenolic (LPF). By investigating the relationship between PF, LPF and FR treatments and assessing aspen as a possible sustainable source for plywood production, the study specifically sought to close a knowledge gap.

The results suggest that aspen veneers demonstrate a superior capacity for FR uptake, with the impregnation method proving to be the most effective for FR deposition. The highest retention observed was 32%, achieved with P-FR applied to aspen veneers by impregnation. However, it is essential to note that this high retention did not necessarily correlate with improved reaction to fire performance. The most effective combination, yielding the most consistent results across both wood veneer types, was P-FR applied via roller coating, which had approximately 3.5 times less retention than the impregnation method.

The study examining the effects of fire-retardant (FR) impregnation on bond quality found that, while the shear strength of the veneer declined with FR treatment, all birch groups treated with FR—excluding the P-FR and LPF groups—met the ANSI/HPVA HP-1 standard requirements for veneer shear strength in plywood applications. In other words, P-FR-impregnated and LPF-bonded birch veneers showed the most significant incompatibility, with failures occurring before the mechanical tests. Likewise, the U-FR aspen groups, bonded with PF and LPF, did not fulfil these stipulations with performances below 3 MPa. The reduction in veneer bond strength when using conventional resin (PF), relative to FR treatment, was notably more for birch (30 to 48%) than for aspen (0 to 22%), suggesting that aspen could play an important aspect for improving plywood fire properties.

These findings open an exciting avenue for future research indicating that achieving optimal fire resistance with minimal effects on bond strength could require designing fire-retardant plywood in a novel format utilizing FR-treated aspen veneers for their excellent FR uptake and limited impact on bonding, in combination with untreated birch veneers in the core. This strategy effectively harnesses the strengths of both wood types: aspen's high FR retention and birch's superior bonding properties.

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Declarations

Competing interests The authors declare no competing interests.

Declaration of generative AI and AI-assisted technologies in the writing process Authors declare the use of artificial intelligence (AI) in improving grammar in the writing process. During the preparation of this work the author(s) used [google Gemini] to [search for applicable literature and improve spelling and grammatical structure]. After using this tool, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the publication.

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