INFLUENCE OF DIFFERENT VENEER SOAKING TECHNOLOGICAL FACTORS ON REACTION TO FIRE PERFORMANCE OF BIRCH PLYWOOD

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Abstract. A study of the influence of different technological factors on the reaction to fire performance of birch plywood made by the veneer soaking method was conducted and reported in this research paper. Technological parameters like the fire-retardant salt concentration level, temperature and soaking time were investigated to find the best technological parameters for manufacturing fire-retardant birch plywood. The aim of this work is to find the optimal technological parameters for manufacturing fire retardant birch plywood with the best possible reaction to fire class B-s1,d0 for wood-based products according to EN 13501-1. The soaking technology of each individual veneer before glueing was used for dry veneer soaking and wet veneer soaking by the diffusive impregnation method. A test plan matrix was created to find the relationship between the technological factors. The first experiment stage was investigation of fire retardant concentration and soaking time of reaction to fire performance of birch plywood at 20 °C temperature liquid. In the second experiment, the influence of fire retardant liquid heating was investigated by using three heating temperatures 30, 40 and 55 °C. Plywood samples were produced at an experimental scale using a laboratory press. Reaction to fire performance was measured by a single burning test method according to EN 13823, which is the main test method for evaluation of reaction to fire performance according to EN 13501-1. It was concluded that the duration of soaking and fire retardant concentration have an influence on the reaction to fire performance of birch plywood. 8 and 16 hour duration was discovered as insufficient duration, while duration more than 24 hours did not show any significant improvement. It was concluded that higher concentration levels significantly improve the fire retardant retention level in wood and heating also shows a positive impact on the fire protection level when temperatures do not exceed 50 °C .

Keywords: birch plywood, fire protection, fire retardants, soaking method, diffusive impregnation.

Introduction

The development of fire-retardant wood products has become a significant field in the wood processing industry. Construction products such as plywood face challenges in achieving an adequate level of fire protection due to the gluing technology, which prevents fire retardants from penetrating deeper than the first veneer layer in the plywood structure. Consequently, it is not possible to guarantee a homogeneous fire performance level for fire-retardant plywood produced using high-pressure impregnation of ready-made plywood. This conclusion was drawn from the investigation of the birch plywood high-pressure impregnation research project reported by Rudzīte and Bukšāns (2021) [1].

This study is a continuation of the research reported by Bukšāns and Kalniņa (2024), which aimed to develop a birch plywood fire-retardant treatment technology capable of achieving a B-s1,d0 reaction to fire classification according to EN 13501-1:2018. The conclusions from the first stage of the project indicated promising potential to achieve this classification using two specific technologies: dry veneer soaking and wet veneer diffusion impregnation. It was also concluded that further research was required to identify the optimal technological parameters, including fire-retardant solution concentration, temperature, and soaking time [2].

The immersion method is a simple and widely used wood impregnation technique where wood is submerged in a liquid solution (such as preservatives, fire retardants, or other chemical treatments) to enhance its properties. This method is commonly employed to increase wood durability and resistance to moisture, fire, insects, and decay. A state-of-the-art article on wood impregnation, published by Augustina et al. (2023), discusses the mechanisms of the impregnation process and its effects on wood properties. The authors concluded that wood impregnation processes have inherent limitations and that optimised impregnation parameters for each impregnating agent are required. They highlighted the importance of using catalysts, pressure, thermal factors, and compression to accelerate the impregnation process [3].

For the normal-pressure impregnation method by dipping, technological parameters – specifically fire-retardant solution concentration and temperature – were identified as the two main factors. An additional parameter, soaking time, must be investigated to develop an optimal treatment technology.

Jang E.S. and Kang C.W. (2023) investigated the wood impregnation process and the factors influencing wood retention levels. They concluded that pressure, temperature, and time all affect the impregnation process, with pressure being the most critical parameter. In their findings, temperature did not significantly influence the impregnation process compared to pressure and time [4].

The Wood Handbook provides a general description of wood preservation processes, including diffusion processes used for treating green or wet wood. These processes rely on waterborne preservatives that diffuse from the treating solution or paste into the water content of the wood [5].

Bekhta (2016) and Olesia (2016) investigated diffusion impregnation technology for the treatment of veneers using different fire retardants. Their research compared the capillary uptake method for dry veneers with the diffusion impregnation method for wet veneers. Olesia et al. (2016) explored the effects of different fire-retardant concentration levels, as well as the influence of duration and temperature on fire performance of birch plywood [6; 7].

The results indicated that capillary impregnation of dry birch veneers is the most effective method for achieving deep penetration of fire retardants. However, diffusion impregnation of moist veneers, compared to capillary impregnation of dry veneers, has several advantages: it results in less salt crystallisation on the veneer surface, a more homogeneous distribution of fire retardants throughout the veneer layers, and is more energy-efficient [6]. The fire protection class of plywood depends on retention of the fire retardant. A mathematical relationship between impregnation parameters (such as temperature, concentration of the impregnating solution, and duration of impregnation) and fire-retardant retention was established [7].

Some researchers are developing organic compound-based flame retardants for wood, positioning them as ecological solutions for fire protection. For example, while the study of polyelectrolyte complexes (PECs) for wood substrates is still in its early stages, their versatility and eco-friendly nature have already been recognised for fabric fire retardancy, as demonstrated by Soula et al. (2021). However, results obtained from cone calorimeter testing according to ISO 5660-1 do not show a sufficient level of fire protection for yellow birch wood to achieve a B class performance level, despite a significant improvement in combustion properties for PEC-treated samples compared to reference samples [8].

In addition to affecting fire performance, wood impregnation may also alter the hygroscopic properties of wood and its dimensional stability. For example, Popović et al. (2013) investigated the impregnation of ash wood with acetic acid and found that all treatments led to a decrease in the volumetric swelling of the wood. This effect was attributed to the reaction of acetic acid with hydroxyl (-OH) groups in the wood structure [9].

Certain fire retardants may contain active chemicals that react with the wood structure, potentially altering the physical and mechanical properties of wood products. Fire retardants based on inorganic salts pose the highest risk of increasing the hygroscopic properties of wood by raising its equilibrium moisture content.

A reduction in the mechanical properties of fire-retardant-treated wood was also reported by Demir (2017) when investigating plywood treated with varying concentrations of fire retardants. The study observed that as the solution concentration increased, the mechanical strength values decreased while the surface roughness values increased [10].

Kawalerczyk et al. (2023) investigated the influence of fire retardants on the physical and mechanical properties of birch plywood. They concluded that plywood manufactured from impregnated veneers exhibits decreased bonding quality and reduced formaldehyde emissions. However, the deterioration in shear strength was not as significant as in plywood bonded with urea-formaldehyde adhesive. Additionally, the study found that increasing the fire-retardant concentration led to a rise in the weight percentage gain (WPG) of the veneers [11].

This research work aimed to investigate the temperature and fire retardant solution concentration level influence on reaction to the fire performance level of birch plywood to develop a technology for the production of the highest fire performance level birch plywood. The work was planned in two stages. At the first stage, the scope was to find the optimal fire-retardant concentration level for the impregnation process of soaking dry veneers and diffusive impregnation of wet veneers in correlation with duration of the impregnation process. At the second stage, the impregnation temperature influence was investigated.

Materials and methods

The test plan includes three concentration levels of fire retardants done for birch veneer impregnation at room temperature 20 °C. Concentration levels 20%, 30% and 40% were investigated in impregnation duration 8, 16 and 24 h.

Temperature variables – 30, 40 and 55 °C performed at the second stage of the research work, when the best performing concentration level and impregnation time were established. Two technologies of veneer impregnation were investigated: 1) dry veneer soaking in a bath of fire retardant solution, identified with the abbreviation (S), 2) wet veneer diffusive impregnation in fire retardant solution, identified with the abbreviation (M). The research plan and samples variables identification is shown in Table 1.

Rotary-cut birch veneer with a thickness of 1.5 mm was used. Untreated birch veneers were used in the core layers for variables with fire-retardant-impregnated top veneers, which are identified by the abbreviation (2L), while plywood variables made entirely of impregnated veneers are identified by (AL). Wet veneer moisture content was expected to be average 80% and dry veneers sorted out with average moisture content about 10%. High accuracy moisture measurement by the drying-weighing method of individual veneers was not performed.

One type of fire retardant chemicals, fully approved and used in the EU market, was utilized in this study. This chemical is available in dry powder form and a necessary concentration of fire retardant liquid is achieved by mixing the powder with warm water. Concentration of fire retardant solution is calculated according to formula 1. This relationship is also used when the concentration level needs to be adjusted. First, the mass of the initial working solution is determined, followed by the concentration of the solution, which is measured using the drying-weighing method. This involves drying the collected sample at 103 °C and weighing before and after drying. Once the solution concentration is identified, the proportion of fire-retardant salt and water in the mixture is calculated. Based on these calculations, the required amount of water and fire-retardant powder is added to prepare the fire retardant mixture for a new cycle. This procedure was performed after each cycle, as dry wood absorbs the working solution, reducing its volume. During the diffusive impregnation process of wet veneers, the salt migrates from the fire retardant solution into the water within the wood cells, attempting to reach an equilibrium state. As a result, the salt concentration in the working solution changes with each treatment cycle, and it must be adjusted

$$Concetration = \frac{m_0}{m_1} \times 100\%, \tag{1}$$

where m_0 – dry mass of fire retardant powder, kg;
m_1 – total mass of fire retardant solution, kg.

The retention level of fire retardant in dry veneers was measured using a weighing method for each individual veneer before and after soaking. The retention level of fire retardant in wood expressed as% of dry fire retardant mass at wood mass on a dry basis, which was calculated using formula 1.

$$Atro / Atro = \frac{m_{Fr}}{m_w} \times 100\%, \tag{2}$$

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

Determination of the retention level of diffusive impregnation was found as inaccurate and impossible for this impregnation scale, where about 350 kg of fire retardant solution and about 140 individual veneers present in one batch.

To determine the effect of the impregnation temperature on fire reaction performance, the soaking tank was equipped with a heating system.

Table 1

Plywood variable identification and description

Identification	Concentration, % /duration, h	Temperature, °C	Impregnated plywood veneers	Average moisture content of veneers, %
*S-1-2L	40%/24 h	20	top 2 of 9	10
S-2-2L	40% /16 h	20	top 2 of 9	10
S-3-2L	40%/8 h	20	top 2 of 9	10
S-4-2L	30%/16 h	20	top 2 of 9	10
S-5-2L	30%/8 h	20	top 2 of 9	10
S-6-2L	30%/24 h	20	top 2 of 9	10
S-7-2L	20%/24 h	20	top 2 of 9	10
S-8-2L	20%/16 h	20	top 2 of 9	10
S-9-2L and S-9-AL	20%/8 h	20	top 2 of 9 and 9 of 9	10
S-10-2L and S-10-AL	40%/24 h	55	top 2 of 9 and 9 of 9	10
S-11-2L and S-11-AL	40%/24 h	40	top 2 of 9 and 9 of 9	10
S-12-2L and S-12-AL	40%/24 h	30	top 2 of 9 and 9 of 9	10
S-13-2L and S-13-AL	20%/24 h	40	top 2 of 9 and 9 of 9	10
M-1-2L	40%/24 h	20	top 2 of 9	80
*M-2-2L	40% /24 h	20	top 2 of 9	80
M-3-2L	40%/16 h	20	top 2 of 9	80
M-4-2L	40%/8 h	20	top 2 of 9	80
M-5-2L	30%/16 h	20	top 2 of 9	80
M-6-2L	30%/8 h	20	top 2 of 9	80
M-7-2L	30%/24 h	20	top 2 of 9	80
M-8-2L	20%/24 h	20	top 2 of 9	80
M-9-2L	20%/16 h	20	top 2 of 9	80
M-10-2L	20%/8 h	20	top 2 of 9	80
M-11-2L and M-11-AL	40%/24 h	55	top 2 of 9 and 9 of 9	80
M-12-2L and M-12-AL	40%/16 h	55	top 2 of 9 and 9 of 9	80
M-13-2L and M-13-AL	40%/24 h	40	top 2 of 9 and 9 of 9	80
M-14-2L and M-14-AL	40%/24 h	30	top 2 of 9 and 9 of 9	80
M-15-2L and M-15-AL	40%/48 h	55	top 2 of 9 and 9 of 9	80
* S1 and M2 samples were immersed in fire-retardant solution in the form of stacked plywood package, all other variables made by individual immersion of each veneer one by one.				

After impregnation, the veneers were dried using an industrial veneer roller dryer until they reached a moisture content of 3-6%. Nine-layer birch plywood samples were produced on an experimental scale (800 × 1000 mm) using a laboratory press, fully adhering to industrial-level bonding technology, resulting in 12 mm thick plywood after calibration. Phenol-formaldehyde resin adhesive was used for gluing. For each prototype variable, three test replicates were prepared, with each replicate consisting of four plywood panels measuring 500 × 750 mm. All samples were conditioned according to EN 13238:2010 until the constant mass criterion was met.

The reaction-to-fire performance was evaluated using the Single Burning Item (SBI) test method – EN 13823:2020, which is the primary method for assessing reaction to fire in accordance with the EN 13501-1:2018 standard. All samples were mounted directly onto a standard gypsum plasterboard substrate. The fire growth rate index (FIGRA0.2) and the total heat release in the first 10 minutes (THR_{600s}) were evaluated as the main factors for predicting the reaction-to-fire performance of plywood, as these parameters determine potential compliance with Class B requirements under EN 13501-1:2018.

Descriptive statistical analysis and histograms were used to evaluate veneer density and the retention level of the fire retardant. A correlation analysis between veneer density and fire retardant retention levels (Atro/Atro) was performed. The distribution of fire retardant within the veneers was assessed and compared with normal distribution curves. Reaction-to-fire test data were obtained for three replicates; therefore, average values and standard deviations were calculated. Comparative analysis and predictions of potential reaction-to-fire classes according to EN 13501-1:2018 were also conducted.

Results and discussion

At the beginning of the Latvijas Finieris AS project, Buksans and Kalnina (2024) concluded that all birch veneer samples soaked in a 20% fire retardant concentration failed to meet the protection level required for B class. This was attributed to the reduced fire retardant retention level in the veneers, leading to the establishment of a target to achieve a fire-retardant concentration level (Atro/Atro) above 20%.

By determining the sample mass, the distribution of wood density was analysed. The density of birch wood veneer was recorded from 530 to 770 kg·m^{-3}, as shown in the histogram in Fig. 1. Variations in wood density could be the cause of differences in impregnation concentration and plywood reaction to fire performance. Average density was 620 kg·m^{-3}, with Mode 644 kg·m^{-3}, and Median 621 kg·m^{-3}, and standard deviation of 55 kg·m^{-3}, determined from data of 917 samples.

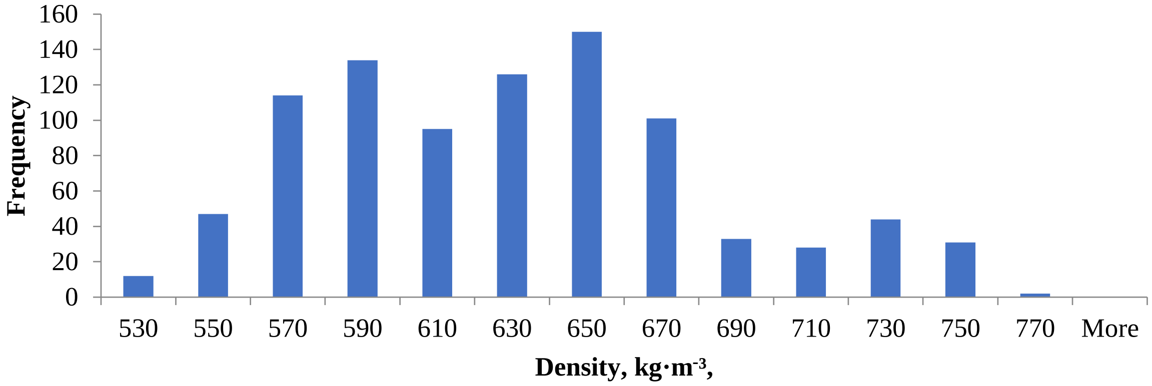

Fig. 1. **Histogram of individual birch veneer density analysed for all dry veneer amount**

Performing a correlation analysis between the veneer wood density and the fire retardant concentration level in the wood (Atro/Atro), a strong correlation (correlation coefficient 0.81) was found for sample group S11, which was selected as the best-performing in fire tests among all prototypes, as shown in Fig. 2. This can also be logically explained by the concept of wood porosity. The lower the wood density, the higher the porosity, the thinner the cell walls, and the greater the amount of liquid the wood can absorb.

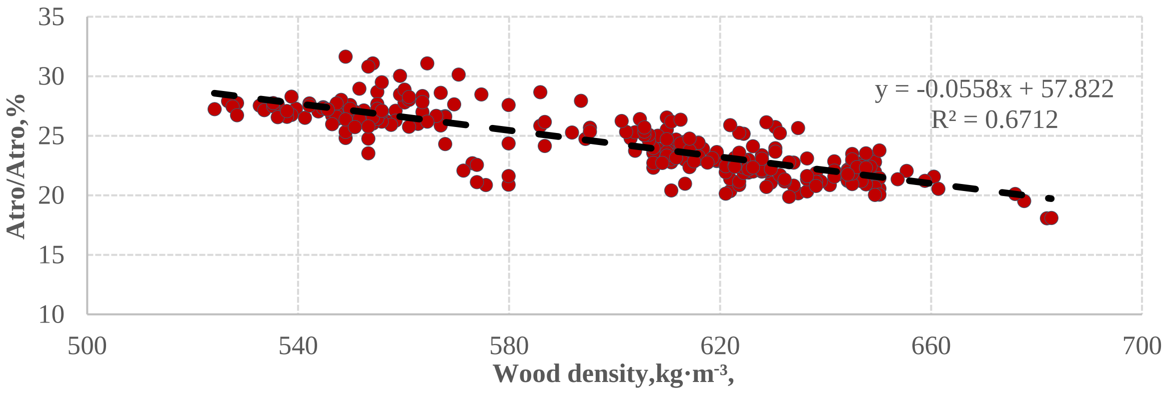

Fig. 2. **Wood density influence on fire retardant retention level (Atro/Atro) for sample group S11**

All sample variables of dry veneer soaking were evaluated for their fire retardant uptake, which was accurately determined by weighing each veneer before and after impregnation. The normative Atro/Atro level to be achieved was 15%, and all impregnation variables met this requirement, as shown in Fig. 3.

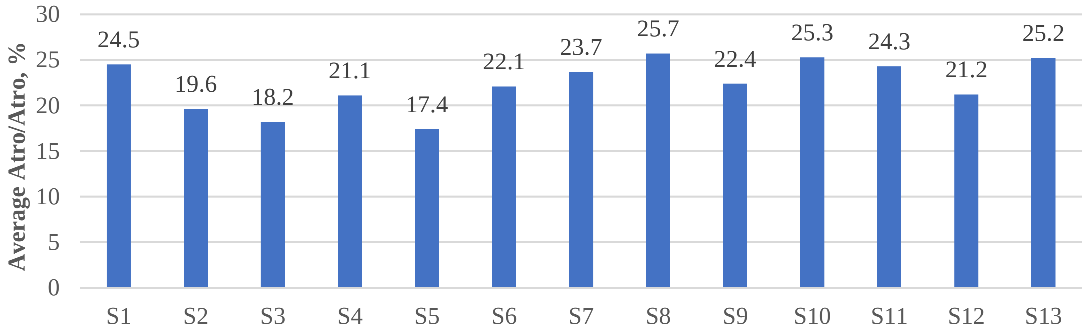

Fig. 3. **Fire retardant retention levels for all dry veneer soaking sample groups**

A more detailed analysis of the Atro/Atro level is presented for sample group S11, which was established as the best-performing variable after fire testing. The deviation ranged from 20% to 32%, depending on the density of each veneer with average Atro/Atro 24.3%, see Fig. 4.

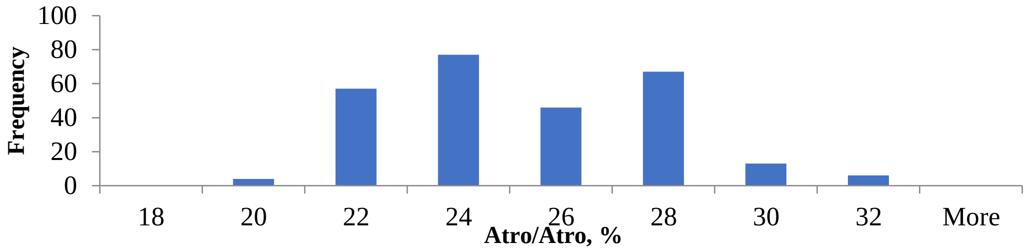

Fig. 4. **Histogram of fire retardant retention level in birch veneers of group S11**

All sample variations were tested in three repetitions to gain an understanding of performance consistency and repeatability. The main fire reaction performance indicators are the fire growth rate index (FIGRA0.2), shown in Fig. 5 for dry veneer soaking sample prototypes and Fig. 7 for wet veneer diffusive impregnated samples. The total heat release over 600 seconds (THR $_{600s}$), accordingly shown in Fig. 6 and 8. The boundary value for the B fire reaction class is marked as a red dash line. Samples located below these red lines have demonstrated the potential to meet the B fire reaction class requirements, and the blue colour bars were used to indicate B-s1,d0 compliant fire performance results in graphs.

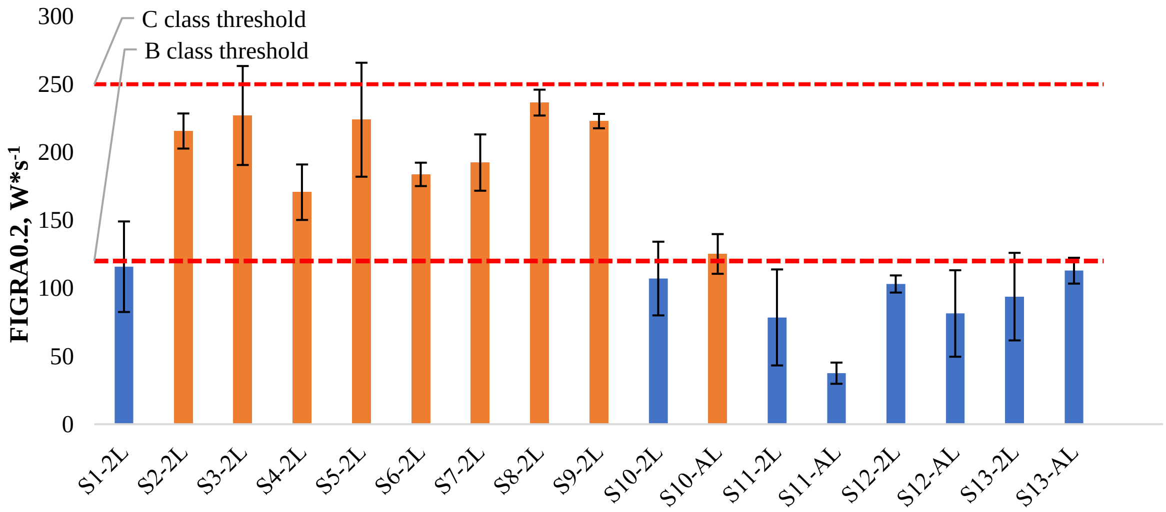

Fig. 5. **Fire growth rate index for fire retardant treated plywood variables produced by dry veneer impregnation**

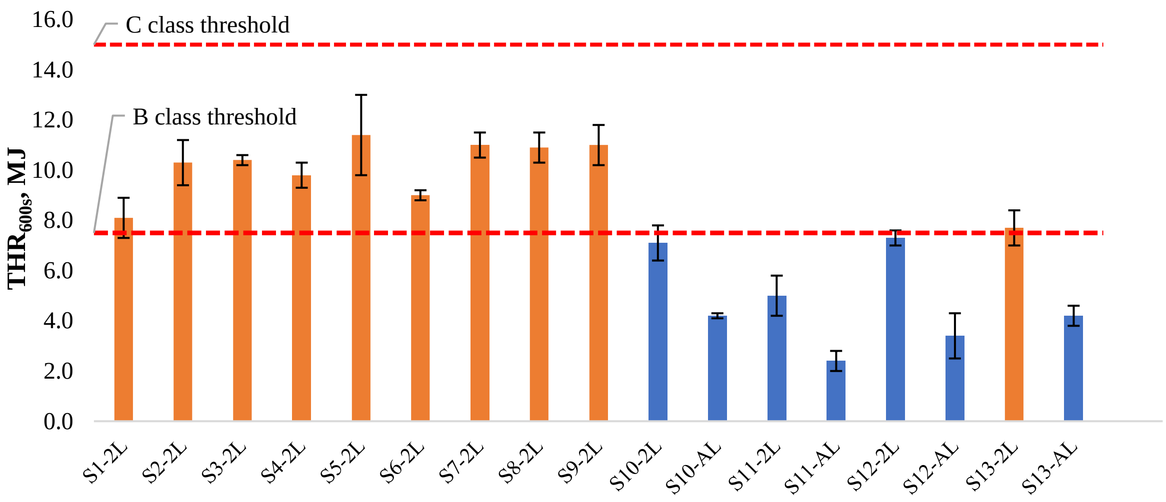

Fig. 6. **Total heat release in 600 s for fire retardant treated plywood variables produced by dry veneer impregnation**

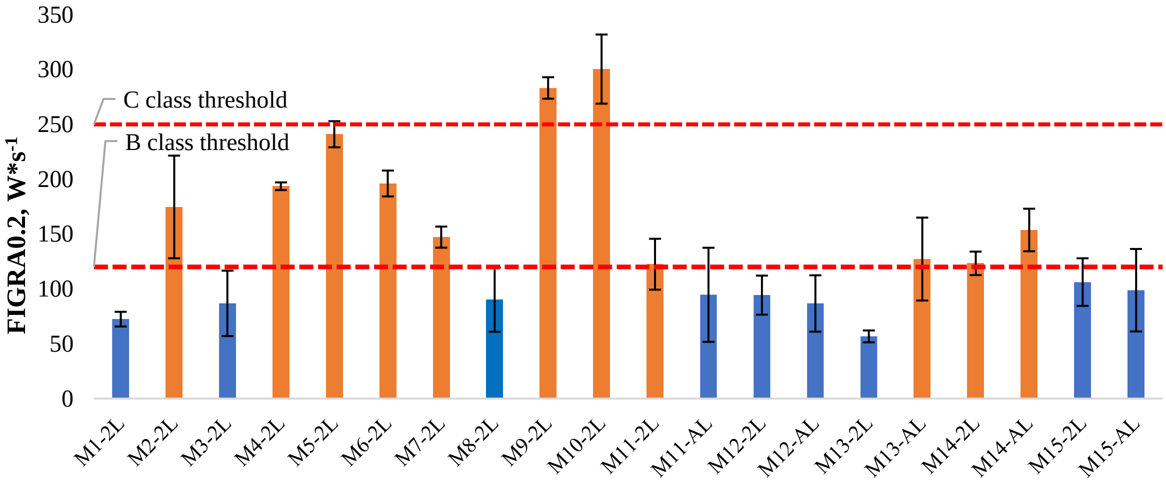

Fig. 7. **Fire growth rate index for fire retardant treated plywood variables produced by wet veneer diffusive impregnation**

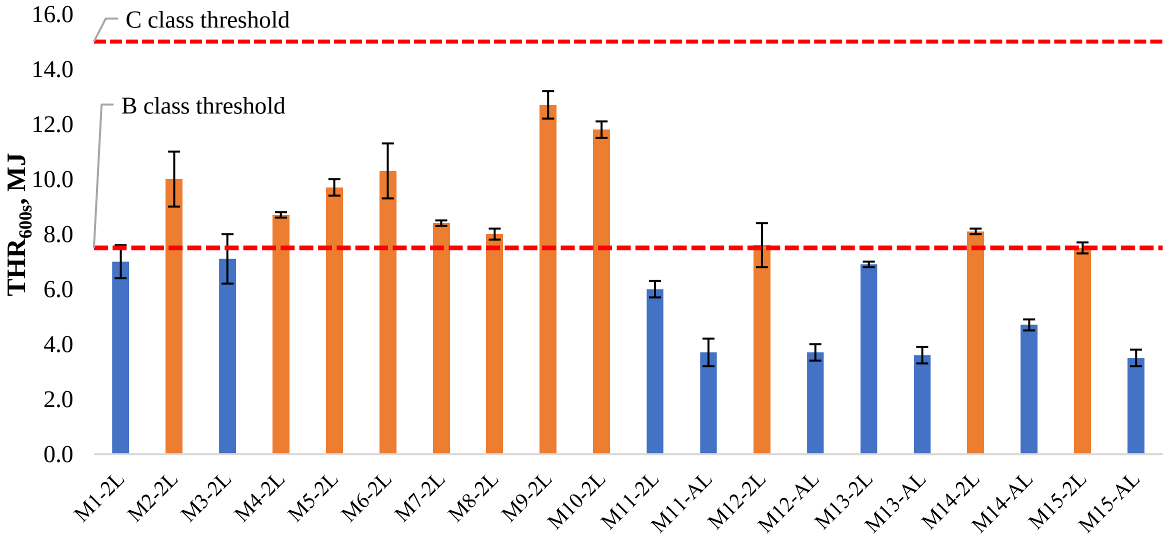

Fig. 8. **Total heat release in 600 s for fire retardant treated plywood variables produced by wet veneer diffusive impregnation**

In the first stage of the study, it was found that soaking duration of 8 hours for dry veneers yielded the poorest results across all concentration groups, and this time was considered insufficient for the impregnation solution to fully penetrate the entire veneer cross-section. Reaction to fire performance indicators showed less variation between replicates of 16 hour and 24 hour soaking times.

An increase in the concentration of the fire-retardant solution from 20% to 40% revealed a correlation between concentration and reaction to fire performance of plywood. However, the correlation was not linear, as increasing the concentration from 20% to 30% reduced the FIGRA0.2 index by only 5%, whereas increasing the concentration to 40% reduced the FIGRA0.2 index by 40%. From this, a hypothesis can be formed that a higher concentration of the fire-retardant solution will result in better performance in fire tests. However, it should be noted that concentrations above 40% are not recommended, as salt crystallisation may occur.

In the diffusion impregnation method for wet veneers, the solution concentration and exposure time play a much more significant role. This study confirms the hypothesis that a higher solution concentration and longer exposure time provide better reaction-to-fire performance. Wet veneer immersion for 24 hours showed the potential to achieve B-s1,d0 reaction to fire class indicators. However, the obtained results were very close to the B class limit for the THR_{600s} parameter, which can be explained by the fact that two veneer layers were considered insufficient for the fire protection required to achieve B class. Therefore, it was decided that, in the next stage of the study, a soaking time of 24 hours and the highest solution concentration of 40% would be used, focusing on determining the optimal temperature for the fire-retardant solution. The temperature of the fire-retardant solution during soaking significantly improved the reaction to fire performance indicators. In the dry veneer soaking technology, all three temperature groups – 30, 40, and 55 °C – provided results compliant with B-s1,d0 reaction to fire performance. In the diffusion impregnation technology for wet veneers, increased uncertainty was observed. In the dry veneer soaking technology, veneers soaked at a fire retardant solution temperature of 40 °C showed the best results. The FIGRA0.2 index of veneers soaked at 40 °C was 65% lower than at 55 °C and 53% lower than those soaked at 30 °C. Similar relationships were observed for both veneer layouts – with two surface veneer layers and the layout with all impregnated veneer layers.

The coating scheme with two impregnated veneer surface layers showed significantly poorer reaction to fire performance in the wet veneer diffusion impregnation technology compared to the layout with all impregnated veneer layers, where a difference of more than twofold was observed. This can be explained by the insufficient thickness of the fire protection top layer in the plywood layout. When using a temperature of 55 °C, increased water evaporation and a faint ammonia smell were observed. The veneers treated at this temperature also showed inconsistent test results; therefore, the use of this temperature is not recommended. It can also be hypothesised that the minimum number of impregnated veneer layers in the coating scheme is three, while maximum performance can be achieved by using a plywood layout made from all impregnated veneer layers. When the entire stack was immersed in the fire-retardant solution, the lowest performance of plywood was observed due to the wet veneers being packed very tightly, preventing the impregnation solution from reaching the inner layers of the stack. Therefore, the immersion of veneers should be organised using a one-by-one method or by placing a mesh layer between veneers to allow the fire-retardant solution to reach all veneers uniformly.

The poorest results were observed for the M9 and M10 sample groups, which involved veneer soaking at the lowest concentration of 20% and soaking times of 8 hours and 16 hours, both of which proved insufficient for the diffusion of impregnation. These two groups were classified in the D-s1,d0 fire reaction class, which corresponds to the standard plywood fire reaction class.

Conclusions

1. Impregnation duration of 24 hours was approved as the most sufficient time for soaking and diffusive impregnation, because 8 hours and 16 hours did not show sufficient fire protection level to reach B-s1,d0 class birch plywood, while 48 hour duration did not show better performance than 24 h duration.
2. Impregnation at 40 °C was approved as the most effective temperature because the fire-retardant solution temperatures 20 °C, 30 °C and 55 °C showed worse performance than 40 °C for both technologies, dry veneer soaking and wet veneer diffusive impregnation.

3. The morphological structure of birch wood affects the penetration of fire retardant into the wood and will influence the fire reaction performance. Retention control methods need to be found to ensure that each plywood board meets the declared properties. One method to ensure this is by creating a large safety margin for fire reaction criteria, guaranteeing that at least 95% of the production meets the B-s1,d0 class requirements.
4. The vacuum-pressure impregnation method technology was not covered by this study, which could significantly change both the absorption of fire retardant and the homogeneity of properties, as the high pressure will ensure maximal filling of cell cavities in such thin wood products as veneer. This technology can only be applied to dry veneer impregnation.

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Author contributions

Both authors have contributed equally to the study and preparation of this publication. Authors have read and agreed to the published version of the manuscript.

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