IMPROVEMENT OF REACTION TO FIRE PERFORMANCE OF BIRCH PLYWOOD BY VENEER SOAKING METHOD

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Abstract. This research paper presents a study on improving the reaction to fire performance of birch plywood. Birch plywood finds wide application in various industries, particularly in construction, where it is used for decorative panelling, structural purposes, and panels with acoustic properties. However, one obstacle to the standard use of plywood in these applications is its reaction to fire performance. In many countries, fire safety regulations require plywood products to comply with B-s1,d0 class standards. The objective of this research was to elevate the natural reaction to fire performance level of birch plywood from D-s1,d0 to B-s1,d0 class, as per EN 13501-1:2018 standards. To achieve this goal, were investigated the highest level of fire protection technology available. The approach involved fire impregnation technology, wherein each individual veneer was soaked in two different fire-retardant solutions before gluing. Two soaking technologies were explored, with veneers being dried in industrial veneer dryers after impregnation. Plywood samples were produced at an experimental scale using laboratory press but adhered fully to industrial-scale gluing technology. The reaction to fire performance was evaluated using the single burning item test method prescribed by EN 13823:2020, which is the primary method for assessing reaction to fire performance according to EN 13501-1:2018 standard. The research yielded a potential fire protection technology capable of achieving B-s1,d0 compliant birch plywood. Both dry veneer soaking and wet veneer soaking technologies showed promise in achieving the desired reaction to fire performance. However, several technological aspects, such as the type of fire retardant, liquid concentration level, temperature, and the soaking time, need to be fine-tuned for optimal results.

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

Introduction

Birch plywood is valued for its strength, versatility, and aesthetic appeal, making it a popular choice in construction, furniture manufacturing, and other industries. However, its inherent flammability poses significant risks in the event of fire, necessitating effective fire-retardant treatments to enhance its fire resistance properties. Most fire retardants work by preventing the access of oxidizing agents (for example, air containing oxygen), but they can also affect the ratio of flammability or upgrade flammability parameters and characteristics of the impregnated material being protected [1]. Fire-retardant treatments for wood can be classified into two general classes: 1) impregnated into the wood or incorporated into wood composite products, and 2) applied as paint or surface coatings [2]. Combinations of impregnation and surface coatings can also be used to achieve better surface quality.

The improvement of the reaction to fire performance level of birch plywood has been the focus of authors for more than a decade, during which various fire protection options have been investigated. However, these will not be discussed in this paper. Surface impregnation methods have shown insufficient protection for achieving good fire resistance in birch plywood, as it is not possible to penetrate chemicals deeper than the top layer, which varies significantly in thickness due to the calibration process. Additionally, the glue line typically blocks any chemical penetration deeper than the first veneer. Authors have explored numerous solutions involving intumescent coatings, which are dependent on the thickness of the coating layer. However, a drawback of this technology is poor surface quality due to thick coating layers and lack of resistance against moisture and water influence. The results of these investigations by the authors have not been published yet.

A comprehensive investigation into the influence of high-pressure impregnation on the real reaction to fire performance was conducted by Rudzīte and Bukšāns (2021), concluding that it is not possible to ensure an even distribution of fire retardants in a batch of impregnated birch plywood. Depending on the spot of flame application to a large-scale panel, it was found that there can be varying performance levels of D, C, and B classes within a single sheet of 12 mm plywood. Another problem related to the high-pressure impregnation of ready-made birch plywood specimens is the change in their geometrical form [3].

In recent years, authors have focused on other fire protection technologies that offer the greatest potential for plywood products. One such technology involves impregnating veneers with fire retardant before the gluing process. While this approach has many disadvantages, it boasts one significant advantage over all other technologies – the even and deep distribution of fire protection chemicals throughout the entire plywood cross-section. This characteristic may yield the highest possible non-combustibility rate for plywood products.

There is not a lot of research done in this field, but some researchers have made valuable contributions to the development of this technology. Most closely related to this paper topic are the works of Bekhta (2016) and Olesia (2016), where different fire retardants were used to impregnate veneers through capillary uptake and diffusive impregnation methods for wet veneers. The work was conducted using a comparatively low concentration level of 20% aqueous solution, and the sample size was only 250 by 250 mm. The double immersion method was employed, with the first immersion at a high temperature of 80-90 °C for a duration of 30 minutes, followed by 40 minutes at 20 °C solution. Five different fire retardants were investigated for birch veneers, and it was concluded that the best results were achieved by using di-ammonium phosphate and ammonium sulphate fire retardants, while sodium dichromate, ferrous sulphate, and ammonium chloride solutions were also tested. Fire properties were evaluated using the test method GOST 16363-98 [4].

Specific attention was directed towards the diffusion impregnation method, which offers several benefits compared to the dry veneer soaking method. Olesia et al. (2016) conducted research on diffusive impregnation of birch veneers, exploring different fire-retardant concentration levels, as well as investigating the influence of duration and temperature on the fire performance of birch plywood [5]. Fire testing was conducted according to EN ISO 11925:2011. Unfortunately, this test method does not allow for the determination of the reaction to fire class according to EN 13501-1. The main test method for these purposes is EN 13823. However, this paper provides valuable information about fire retardant absorption content in relation to various variables.

Kawalerczyk (2023) conducted impregnation of dry birch veneer in potassium carbonate and urea solution for 1 hour. The experiments were carried out at the laboratory scale, and the fire-retardant weight percentage gain was determined independently from the solution composition and concentration. It was concluded that a higher weight percentage gain is achieved with a higher concentration of the fire-retardant solution [6]. Additionally, the optical, physical, and mechanical properties of the veneers were investigated, although these aspects were not directly related to the authors' research topic.

Demir (2017) conducted research on the immersion of poplar and pine wood veneers in three different fire retardant concentration solutions: 5%, 7%, and 10%. It was found that all mechanical strength values of panels produced using veneers treated with fire retardant chemicals were lower than those of control panels. Furthermore, with an increase in the solution concentration, the mechanical strength values decreased, while the surface roughness values increased [7]. Both of these research works indicate the side effects of fire retardant treated plywood products, which need to be taken into consideration.

Pingli (2021) studied the thermogravimetric behaviour of flame-retardant plywood prepared from eucalyptus, birch, and poplar, revealing that poplar plywood exhibited the highest thermostability. The results of the EN 13823 test were consistent with those of the Limit Oxygen Index test and thermogravimetric analysis. Both tests indicated that the tree species significantly affected the flame-retardant properties of the plywood, with birch and poplar exhibiting a trend line compliant with class B heat release rate standards [8].

Materials and methods

This research was planned as a technology screening experiment, where numerous variables were investigated, with each variable having only one test replicate. Therefore, it is not possible to evaluate factors such as repeatability and reproducibility, nor is it possible to establish statistically approved relationships between the variables. Nevertheless, the experiment was designed to evaluate a significant number of variables for the veneer soaking technology and to predict potential reactions to fire for each variable.

Two chemicals, fully approved and used in the EU market, were utilized in this study and will be referred to in this paper as FR1 and FR2. Both chemicals are salt-based inorganic compounds containing active compounds such as phosphates and ammonium groups. However, the full chemical composition of these fire retardants is not known to the authors as it is considered a commercial secret. Two different concentration levels of fire retardants were used at room temperature: 20% and 40% for fire retardant FR1, and 20 and 50% for FR2, which represented the highest possible concentration level of the specific product. Dry veneer soaking and wet veneer soaking using the diffusive impregnation method were utilized. 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 as its possible only by destructive method and intended to not be a highly important factor due to veneer further soaking.

The fire retardant plywood variables created and tested are described and identified 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. For samples FR1-10, the top three layers were glued from impregnated 1.5 mm thickness black alder wood veneers, while FR1-11 utilized 1.5 mm white alder for the top layers. The retention level of fire retardant in dry veneers was measured using a weighing method for each individual veneer before and after soaking. Prototypes FR1-7, FR1-8, and FR1-9 were made with a special surface activation additive comprising 0.5% of the impregnation liquid to improve the liquid capillary uptake in wood. The retention level determination for wet veneers was calculated after measuring the concentration level of the fire-retardant liquid before and after diffusive impregnation. 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.

$$Retenitionlevel = \frac{m_{Fr}}{m_w} \times 100\%, \tag{1}$$

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

Seventy-two veneers were prepared for each variable to produce five plywood samples measuring 500 by 750 mm with a thickness of 12 mm. After impregnation, the veneers were dried using an industrial veneer roller dryer until reaching a moisture content of 3-6%. Subsequently, the plywood samples made of nine veneer layers with a thickness of 12 mm were glued using phenol-formaldehyde resin glue at a laboratory-scale press measuring 600 by 900 mm. The glue used was taken from a standard birch plywood production line, and pressing parameters were set up in accordance with those of a standard plywood production line.

Plywood samples were tested without thickness calibration, allowing for the maximal top veneer thickness exposed to fire, thereby expecting to observe the highest level of fire protection. All samples were conditioned according to EN 13238:2010 until the constant mass criteria were reached. The reaction to fire performance of the material was determined by conducting tests according to EN 13823:2020. Each test specimen consisted of two pieces jointed together, forming a corner 1500 mm high with a short edge of 500 mm for both wings. For experimental purposes, the long wing was also reduced to 500 mm, as fire retardant wood products typically do not cause lateral flame spread beyond 500 mm. The mounting method directly onto a standard gypsum plasterboard substrate was applied to all samples.

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 the potential compliance with B class requirements according to EN 13501:2018.

Descriptive statistics analysis and histograms were utilized to evaluate the distribution of fire retardants in the veneers, and comparisons with normal distribution curves were made. Reaction to fire test data were obtained for only one single specimen per variable; therefore, comparative analysis and predictions of potential reaction to fire classes according to EN 13501-1:2018 were conducted.

Table 1

Plywood variable identification and description

Identification	Concentration, % /duration, h	Wood species	Impregnated plywood veneers	Average moisture content of veneers, %	Retention level, %
FR1-1	40%/24 h	birch	top 2 of 9	10	17
FR1-2	40%/24 h	birch	top 3 of 9	10	17
FR1-3	40%/24 h	birch	9 of 9	10	17
FR1-4	20%/24 h	birch	top 2 of 9	10	9.7
FR1-5	20%/24 h	birch	top 3 of 9	10	9.7
FR1-6	20%/24 h	birch	9 of 9	10	9.7
FR1-7	20% + additive/24 h	birch	top 2 of 9	10	9.8
FR1-8	20% + additive/24 h	birch	top 3 of 9	10	9.8
FR1-9	20% + additive/24 h	birch	9 of 9	10	9.8
FR1-10	40%/24 h	birch + black alder	top 3 of 9	10	14
FR1-11	40%/24 h	birch + white alder	top 3 of 9	10	16
FR1-12	40%/24 h	birch	top 2 of 9	80	8.8
FR1-13	40%/24 h	birch	top 3 of 9	80	8.8
FR1-14	40%/24 h	birch	9 of 9	80	8.8
FR2-1	50%/4 h	birch	9 of 9	10	18.2
FR2-2	20%/4 h	birch	9 of 9	10	7.2
FR2-3	50%/24 h	birch	9 of 9	80	11.3

Results and discussion

The results of veneer impregnation were evaluated by analyzing the individual veneer weight data for dry veneers. Average values are shown in Table 1. This paper presents only two histograms depicting the retention level frequencies for sample groups (FR1-1 to FR1-3) with a fire-retardant liquid concentration level of 40% and sample groups (FR1-4 to FR1-6) with a fire-retardant liquid concentration level of 20%, representing the upper and lower concentration limits for fire retardant FR1.The highest concentration level, 40%, resulted in a larger fire retardant load. However, a side effect was observed: the variance of retention level between each veneer was more than five times larger than when soaking at a 20% concentration level solution. Histograms of retention level frequencies are shown in Figures 1 and 2.

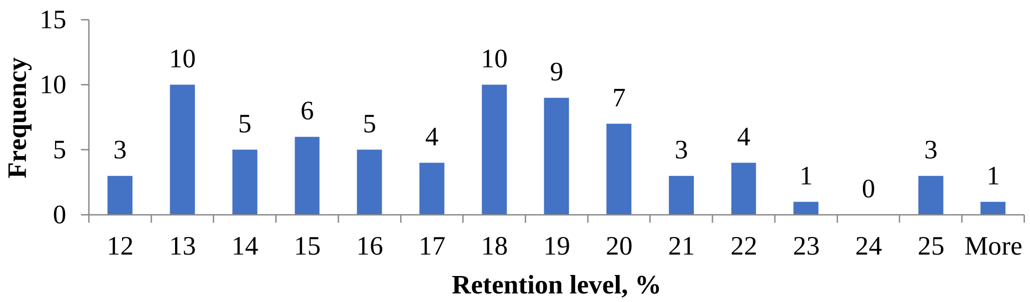

Fig. 1. **Histogram of fire retardant retention level in birch veneers soaked at 40% concentration liquid**

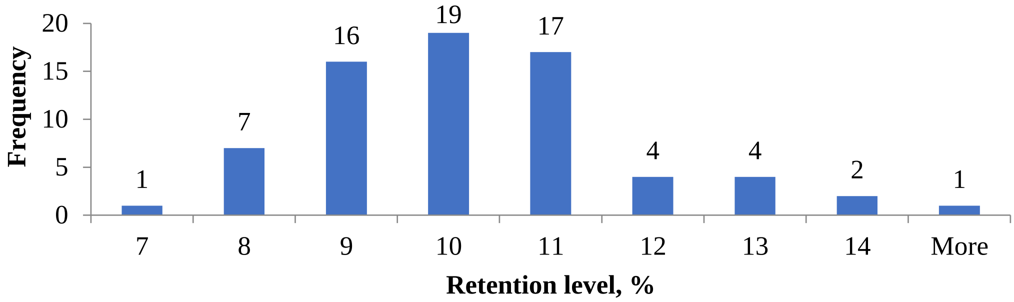

Fig. 2. **Histogram of fire retardant retention level in birch veneers soaked at 20% concentration liquid**

A mean retention level of 17% was reached when veneers were soaked at a 40% concentration solution, with the following statistical results calculated: standard deviation – 3.57; median – 17.22; mode – 18.58; sample variance – 12.76; minimum – 11.81; maximum – 27.83. A mean retention level of 9.73% was reached when veneers were soaked at a 20% concentration solution, with the following statistical results calculated: standard deviation – 1.57; median – 9.75; mode – 9.75; sample variance – 2.5; minimum – 5.96; maximum – 14.38.

None of the researchers mentioned in the literature review has used a higher fire retardant concentration level than 20%, and no data was available for the fire retardant uptake level for higher concentration solutions. The target 15% retention level was not reached for soaking at a 20% concentration liquid; therefore, uptake must be increased. Surface activation additives were used for sample groups (FR1-7 to FR1-9) to improve the capillary uptake of fire retardant, but unfortunately, the improvement was not significant, only 0.01%. Statistical normal distribution of retention level was not reached by any sample group, and improved soaking technology is needed to reduce variance between individual veneer load by fire retardants.

Gluing results and mechanical properties of fire retardant plywood were not within the scope of this article, but it is important to note that good adhesion was achieved with standard phenolic phenol-formaldehyde resin glue, which gives a good chance to introduce this technology in the production line.

After meeting the conditioning criteria, birch plywood samples were tested using the EN 13823:2020 test method, which provides a direct prediction of the potential reaction to fire class of the plywood product. Bekhta (2016) and Olesia (2016) conducted interesting work on birch soaking with fire retardants, but the GOST 16363-98 test method does not allow for the prediction of potential reaction to fire class according to EN 13501-1:2018. Test results are shown in Figures 3 and 4, and sample identification can be found in Table 1. C and B reaction to fire class threshold values are displayed in the chart diagram as red lines to better evaluate the potential reaction to the fire class of each variable. All bars in orange colour indicate B class non-compliant results, and both factors – FIGRA0.2 and THR600s – should be evaluated simultaneously to achieve compliance within B-s1,d0 class according to EN 13501-1:2018.

All birch veneer samples soaked at a 20% fire retardant concentration showed a lack of protection level to fulfil B class requirements, which may be explained by the reduced fire retardant retention level in the veneers. A very good reaction to fire performance level was achieved by the combined plywood layout, consisting of birch veneers in the core and three top layers of black or grey alder wood veneers.

Wet veneers loaded with fire retardants using the diffusion method showed a smaller retention level of 8.8%, but all results in fire tests showed B-s1,d0 compliance. This phenomenon can be explained by the more deep and even distribution of fire retardant chemicals within the cross-section of the veneers, as also concluded by Bekhta (2016) and Olesia (2016). The diffusive impregnation technology also has the benefit of lower energy consumption, as the veneers are dried only once compared to two times in the dry veneer soaking method. The alternative fire retardant FR2 also showed similar results and conclusions.

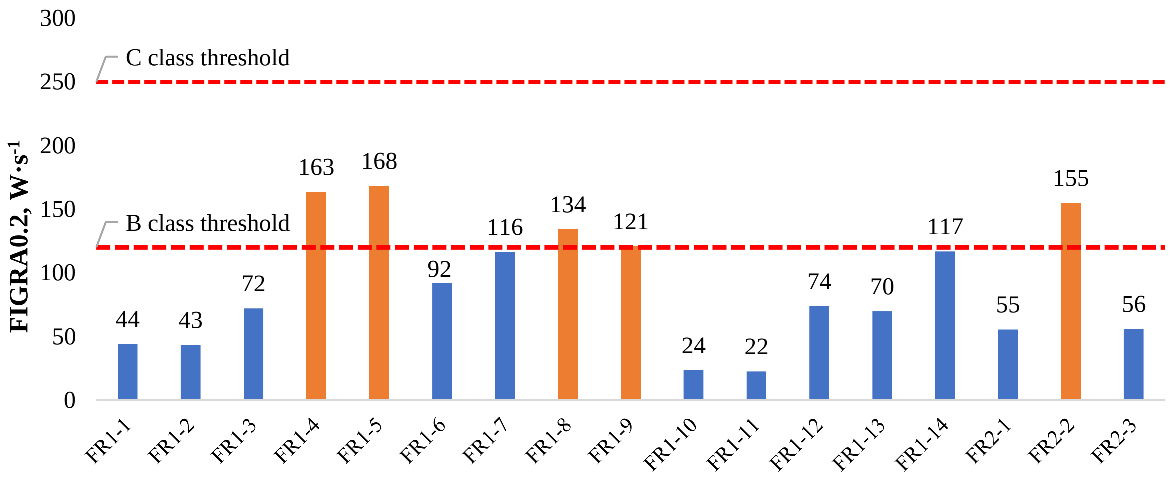

Fig. 3. **Fire growth rate index for 17 variables of fire retardant treated plywood**

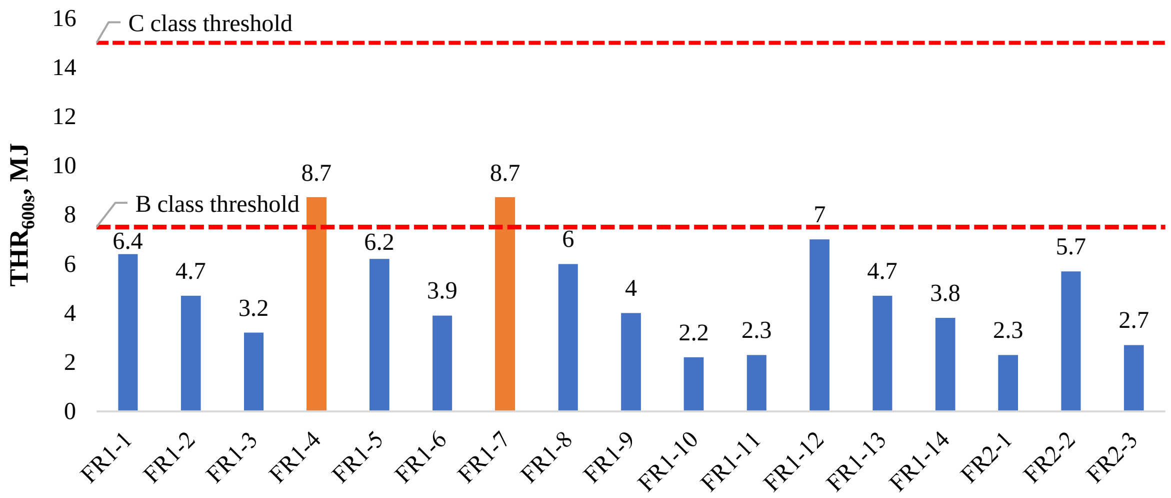

Fig. 4. **Total heat release in 600 s for 17 variables of fire retardant treated plywood**

It may be concluded that several salt-based fire retardants may be viable options, but significant obstacles may arise from adhesion problems during the plywood gluing process caused by changes in the surface energy of veneers. This issue has been highlighted by several researchers in the literature review. An interesting outcome of this research is the potential for other wood species to create high fire protection level plywood composite materials. Alder wood, for example, exhibits FIGRA0.2 and THR_{600s} values more than two times lower than those of birch plywood. Using a single fire retardant top veneer has proven to be an insufficient solution for fire retardant plywood production, as it may only achieve a C class performance level. Plywood produced from all veneer layers impregnated by fire retardant will deliver the highest possible fire protection level for birch plywood. This fully impregnated plywood option is in high demand from acoustic panel manufacturers, who require the highest possible protection level due to the better combustion rate of wood ribbon elements inherent in their construction.

Conclusions

1. Both fire retardants used at a liquid concentration level of 20% were confirmed as insufficient to achieve the appropriate fire protection level required for B-s1,d0 class birch plywood.
2. The capillary soaking method with a fire retardant load of retention level more than 15% showed good potential for fire protection of dry veneers.
3. Wet veneers soaked using the diffusive impregnation method demonstrated the same level of reaction performance with only half the fire retardant retention level.
4. The diffusive impregnation technology for wet veneers presents several challenges that need to be addressed before its introduction into birch plywood manufacturing production lines.

5. It should be noted that the results were obtained using non-calibrated plywood samples, and the sanding process after gluing may reduce the reaction to the fire performance level. Further investigation will be conducted in subsequent work.
6. Further research will focus on determining soaking parameters such as temperature, soaking time, and liquid concentration level, and their influence on the fire retardant load and fire performance of birch plywood as well gluing quality investigations.

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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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