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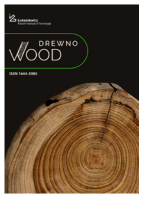

Effect of Sodium Borate on Adhesion Resistance of Varnished Surfaces

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This study aims to evaluate the adhesion resistance of water-based single-component varnish layers on wood surfaces when sodium borate is incorporated in varying proportions. The research was conducted on specimens obtained from the wood of Scots pine (*Pinus sylvestris* L.), Turkish fir (*Abies bornmülleriana* Mattf.), sessile oak (*Quercus petraea* L.), and Oriental beech (*Fagus orientalis* L.). These specimens were impregnated with sodium borate solution at concentrations of 1.5% and 2.5%. After the impregnation process, water-based varnish formulations also containing different proportions of sodium borate (1.5% and 2.5%) were prepared. Once the varnish layers were fully dry, an adhesion test was conducted according to the ASTM D-4541-02 standard. As a general conclusion, it was found that the modified varnish and impregnation processes were most effective with beech and oak wood, while the impact of the sodium borate was more limited on Scots pine and fir wood.

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Introduction

Wood materials are preferred in many areas due to their aesthetic properties and durability. However, protecting these natural materials against environmental effects is of great importance. Water-based varnishes form both an aesthetic and protective layer by providing hardness to the wood surface. The surface hardness provided by these varnishes increases the wood's resistance to impact, abrasion, and other physical effects. Additionally, the surface adhesion resistance of water-based varnishes provides long-lasting protection after application. This helps increase the durability of wood surfaces while preserving their aesthetic appearance. Impregnation additives such as sodium borate further enhance the effectiveness of varnishes, strengthening the wood's resistance to moisture and pests (Kılıç and Söğütlü, 2020; Kılıç, 2009; Kurt and Özçifçi, 2023).

Sodium borate is a compound used in various industrial and chemical processes, such as the wood impregnation industry. It is generally obtained from boron minerals and is used in many applications, especially in glass, detergents, and agricultural products. The effect of sodium borate on surface adhesion resistance and surface hardness is quite important from a materials science standpoint and for applications. This compound can increase the durability of coatings and can be used in various surface treatments on wood structures. Kassab et al. (2015) found that sodium borate increased the adhesion resistance of varnishes on metal surfaces. Their study revealed that sodium borate extended the service life of varnishes and improved adhesion resistance by preventing

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oxidation on the surface. Petrov et al. (2018) found that sodium borate weakened the adhesion capability of varnishes in studies on organic polymers. Sung et al. (2020) demonstrated that coatings containing sodium borate altered the adhesion resistance of varnishes depending on the chemical structure of the surface. They concluded that borate ions formed stronger bonds with some polymers by increasing the polarity on the surface, but formed weak bonds in some organic materials. Liu and Chen (2023) found that combining materials such as nano-alumina and nano-silica with sodium borate improved the surface hardness of the samples by 35% and the adhesion resistance by 40%. This study also showed that the water repellency of the material increased. Kurt and Özçifçi (2023), in studies examining the fire retardant properties of boron-based varnishes, found that these materials reduced the burning rate of wood by up to 40% and reduced smoke emissions. Tomak and Hughes (2021) reported that boron-based varnishes increased the surface hardness of wood samples by 15% to 20% and had positive effects against decay.

Surface adhesion resistance is a property that indicates how well a material or coating adheres to a surface. High adhesion resistance increases the longevity and durability of various types of varnishes, paints, and coatings against external factors. Because wood materials are sensitive to physical and mechanical effects, various synthetic and natural-based varnishes and resins are applied to their surfaces to increase durability and improve their aesthetics (Kılıç, 2009). The structure of varnishes and the heterogeneous properties of wood are important factors affecting the adhesion strength of varnish layers, and various studies have been conducted on this subject (Vitosyte et al., 2012; Marra, 1992; Sönmez et al., 2004). The type of varnish emerges as a critical factor determining surface adhesion resistance (Kılıç and Söğütlü, 2020; Söğütlü et al., 2016).

Although there are many studies on the adhesion strength of varnishes in the literature, research on impregnant-modified varnishes is quite limited. In a study conducted by Pelit and Korkmaz (2019), nano-graphene (NG) was added to water-based varnish at 0.25%, 0.50%, and 1% by weight, and the changes in some physical properties of beech wood samples and the surface adhesion resistance of the varnish were examined. The study found that increasing the amount of NG added resulted in a significant increase of up to 25% in the surface adhesion resistance of the varnish. In the same study, similar results were found for Oriental beech and sessile oak wood (Pelit and Korkmaz, 2019).

Studies on the adhesion resistance of modified varnishes on surfaces are quite limited. However, researchers such as Vitosytė et al. (2012), Kılıç and Söğütlü (2020), Vitosytė et al. (2012), Söğütlü et al. (2016), Kaygın and Akgün (2008), Ayata et al. (2016), Wang et al. (2019), Herrera et al. (2018), and Barański et al. (2017) have conducted important studies in this area regarding the effects of various additives on adhesion resistance.

Boron compounds are effectively used as fire retardant impregnation agents and yield positive results. Thus, varnishes containing such compounds, applied to wood materials for both protective and aesthetic purposes, can also retard combustion. Consequently, the use of varnishes modified with boron compounds is becoming increasingly significant. The aim of this study was to determine how a water-based varnish enriched with boron compounds affects surface adhesion resistance and surface hardness when applied to wood surfaces.

Materials and methods

1. Wood

Test specimens were prepared from Scots pine (*Pinus sylvestris* L.), Turkish fir (*Abies bornmülleriana* Mattf.), sessile oak (*Quercus petraea* L.), and Oriental beech (*Fagus orientalis* L.). which are widely used in the wood and furniture industries in Turkey. Samples were randomly selected from first-class timber, with straight grain, free from knots and cracks, showing no difference in color and density, and with annual rings perpendicular to the surfaces.

The specimens, air-dried and cut into 110×110×12 mm rectangular pieces, were conditioned in a climate chamber at 23±2 °C and 50±5% relative humidity for 16 hours prior to testing, in accordance with the ASTM D-3924 standard. After the samples were brought to net dimensions of 100×100×10 mm, they were sanded with 80 and 100 grit sandpaper following initial wetting; after the final wetting, they were polished with 120 grit sandpaper. The sanded surfaces were made dust-free using a soft brush and vacuum.

In the study, a total of 140 test samples were prepared by applying impregnation and varnish modifications containing 1.5% and 2.5% sodium borate. The samples were produced using four different wood species. For each wood species, two different impregnation modifications (1.5% and 2.5% sodium borate), one control group (no impregnation but with varnish modification), and two different varnish modifications (1.5% and 2.5% sodium borate) were applied. Five samples were prepared for each of these combinations, resulting in a total of 120 modified samples (4 wood species × 3 impregnation groups × 2 varnish modifications × 5 samples). In addition, 20 control samples—five from each wood species—were prepared and tested without any impregnation or varnish application, remaining in their completely natural form. Thus, a total of 140 test samples were used in the study.

2. Impregnation of test samples

Sodium borate produced by the Turkish National Boron Research Institute was used as the impregnating agent in the experiments. Sodium borate is a chemical compound with a high boron content and has a solubility capacity of 16% at 20 °C. This compound, produced in powder form, has a bulk density of 700 kg/m³ and a neutral pH value. When necessary, the pH value can be adjusted to a range of 7–8. Its molecular weight is 590 g/mol (Boren, 2024).

The test samples were impregnated with mixtures prepared by adding sodium borate at 1.5% and 2.5% weight of the water used for impregnation. For the impregnation process, the pressure of the vessel was set to 80 kPa and the temperature to 60 °C. The samples were kept under these conditions for 30 minutes, followed by the application of 300 kPa atmospheric pressure for 5 minutes. After impregnation, the fully wet samples were kept in a conditioning cabinet at 20±2 °C and 50±5% relative humidity until they reached equilibrium moisture content.

3. Varnish modification and application

In the experiments, single-component primer water-based varnish was used as filler and top coat. The ASTM D-3023 standard was followed in varnishing the samples. In preparing the varnish application processes, mixing ratios were determined in accordance with manufacturer's recommendations and in a way that would not negatively affect layer performance (Polisan, 2024). The amount of varnish was determined with an analytical balance with ±0.01 g precision.

In the first stage, distilled water was prepared for the solution at the rate recommended by the manufacturer. Considering the solid content of the varnish, 1.5% to 2.5% sodium borate was mixed with water and this mixture was added to the varnish. The mixture was carefully stirred until it became homogeneous. The varnish was applied with a medium-hardness homogeneous brush (~20 °C). Three layers of varnish were applied to the samples at 24-hour intervals without sanding. Table 1 details the physical properties and application parameters of the varnish used in the experiment.

4. Surface adhesion resistance test

The test samples were conditioned for 24 hours at a temperature of 23±2 °C and at 50±5% relative humidity in accordance with the ASTM D-4541-02 standard. Test cylinders of Ø 20 mm were adhered to the conditioned surfaces at normal room temperature (20 °C). In the experiments, an adhesive with no solvent effect on dual-component epoxy resin protective coatings was used at a rate of 150±10 g/m² according to ASTM D-4541-02. Surface adhesion resistance was measured using an adhesion testing device in compliance with the principles laid down in ASTM D-4541-02. Figure 1 shows the test sample preparation process and the adhesion testing device.

5. Statistical analysis

In the statistical evaluation, the effect of sodium borate impregnation and surface coating with water-based varnish on the adhesion strength of the varnish was investigated using multifactorial analysis of variance (ANOVA). The data analysis was performed using SPSS statistical software. The factor effects were determined based on the type of wood material, varnish, and impregnation material. When significant effects were identified ($p < 0.05$), pairwise comparisons were performed using the Duncan test to examine the source of these effects in more detail.

Results and discussion

Values of the adhesion resistance of the varnish on the surface are presented in Table 2.

Table 1. Physical properties and application parameters of varnishes (Polisan, 2024; Boren, 2024)

Varnish	pH	Density (g/m³)	Viscosity (sn DIN Cup / 4mm)	Amount of varnish to be applied (g/m²)	Solid content % (by weight)
One-component water-based varnish	9	1.02	18	70	38
1.5% sodium borate	8.7	1.03	18	70	38.25
2.5% sodium borate	8.2	1.05	18	70	38.48

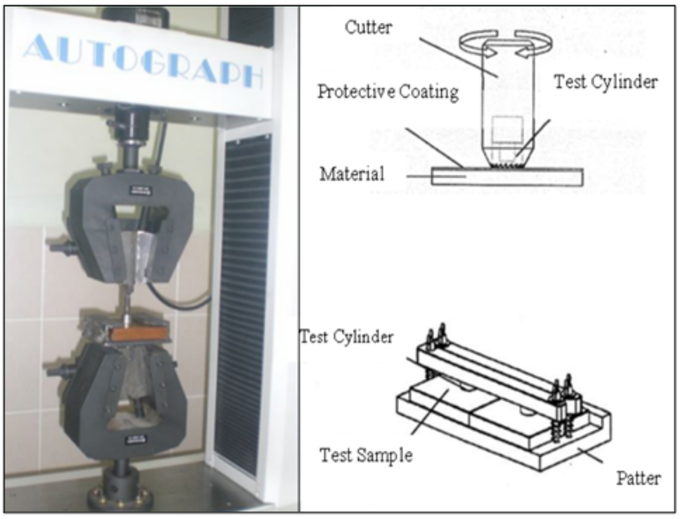

Fig. 1. Adhesion test device and test sample preparation process

As shown in the table, the surface adhesion resistance values display significant differences depending on the studied factors: wood species, impregnation material, and sodium borate modification of varnish. To determine the reasons for these differences in more detail, multifactorial analysis of variance (ANOVA) was conducted; the findings are presented in Table 3. These differences result from each factor's altering the physical and chemical properties of the wood surface. Characteristics such as the structure of the wood material, surface roughness, and lignin content are key factors affecting adhesion resistance. Impregnation materials can increase the wood's resistance to water, but by changing the surface structure, they may also affect adhesion capacity. Sodium borate modification can be assumed to enhance the wood's chemical components, thereby increasing adhesion resistance.

It was determined that the interactions of wood material, sodium borate modification of varnish, and impregnant concentration have a significant effect on the surface adhesion resistance of varnish layers ($p < 0.05$). Such interactions are directly related to the mechanical and chemical properties of the material, and this can be assumed to have a decisive impact on the durability and performance of the surface coatings.

Table 2. Average values for adhesion strength (N/mm²)

Wood materials	Impregnation treatment	Varnish without modification	Modified varnish (1.5% SB)	Modified varnish (2.5% SB)
Scots pine	1.5% sodium borate	64.60	65.60	64.61
	2.5% sodium borate	67.20	64.48	64.60
	Control	54.60	73.40	62.00
Turkish fir	1.5% sodium borate	56.40	70.20	62.22
	2.5% sodium borate	62.80	59.14	67.20
	Control	46.80	56.80	61.80
Sessile oak	1.5% sodium borate	71.60	70.60	74.31
	2.5% sodium borate	77.20	68.47	79.00
	Control	63.20	67.60	69.60
Oriental beech	1.5% sodium borate	82.00	86.20	84.20
	2.5% sodium borate	80.80	70.16	95.40
	Control	58.40	63.00	74.60

Table 3. Multiple analysis of variance results for surface adhesion resistance

Factor	Sum of squares	df	Mean square	F	Sig. (p<0.05)
Wood material (A)	6145.835	3	2048.612	62.786	0.000
Sodium borate modification (B)	1588.572	2	794.286	24.343	0.000
Interaction (AB)	1140.555	6	190.093	5.826	0.000
Impregnation (C)	4207.030	2	2103.515	64.468	0.000
Interaction (AC)	1822.130	6	303.688	9.307	0.000
Interaction (BC)	281.653	2	140.827	4.316	0.016
Interaction (ABC)	405.120	6	67.520	2.069	0.042
Error	3654.400	112	32.629		
Total	18180.886	139			

As shown by the comparison of results for wood species in Figure 2, the highest varnish adhesion resistance was observed on Oriental beech samples (77.2 N/mm²), and the lowest on Turkish fir samples (60.29 N/mm²). This result shows that the structure and properties of Oriental beech create a stronger bond with varnish in terms of interaction. Oriental beech is known for its dense and hard structure, which may have caused the varnish to adhere better to the wood surface. On the other hand, the softer structure of fir may be a factor that makes it more difficult for the varnish to adhere to the surface.

Similar findings have been reported in previous studies. For example, in a study on the varnish adhesion resistance of different wood species, Pelit and Korkmaz (2019) reported that beech wood has high adhesion resistance. Additionally, it has been reported that lighter and softer species, such as fir, exhibit lower resistance to surface treatments (Aykaç and Sofuoğlu, 2022).

A comparison of surface adhesion resistance values depending on varnish modification is presented in Figure 3.

The findings presented in Table 2 and Figure 3 clearly demonstrate that the modification with sodium borate has a significant effect on the surface adhesion resistance of the varnish layer. Specifically, it is observed that as the sodium borate content decreases, the varnish adhesion resistance also decreases. The reduction in sodium borate content can be assumed to lead to insufficient interaction with the wood surface, resulting in a weakening of the adhesion strength of the varnish layer.

A comparison of surface adhesion resistance values depending on the impregnant concentration is presented in Figure 4.

These results clearly demonstrate the effects of sodium borate on surface adhesion resistance. The 2.5% sodium borate impregnation produced the highest surface adhesion resistance when compared with other concentrations. This suggests that sodium borate enhances adhesion resistance by forming a strong bond on the material surface. Furthermore, the observation that surface adhesion resistance decreases as the sodium borate concentration decreases indicates that the effect of this compound is directly proportional to its concentration. Several studies in the literature have also reported findings indicating that impregnation agents containing boron compounds increase surface adhesion resistance. Atar and Peker (2010) reported that boron compound-based impregnations applied to different wood species increased the adhesion resistance of varnishes. In that study, it was concluded that as the concentration of the impregnant solution increased, the adhesion resistance also increased. Another study by Sönmez et al. (2004) highlighted that sodium borate impregnation produced higher adhesion resistance values compared with control samples.

A comparison of surface adhesion resistance values depending on the binary interaction of wood species and impregnant concentration is presented in Figure 5.

As Figure 5 shows, the highest adhesion strength value was obtained for Oriental beech wood samples impregnated with 2.5% sodium borate. This result indicates that sodium borate is an effective substance in enhancing the adhesion strength of beech wood. Sodium borate can interact with the chemical structure of wood cells, improving the wood's resistance to water and its mechanical properties. It is believed that beech wood, due to its high density and hardness, is more sensitive to such chemical treatments. Turkish fir, due to its natural structure and low density, may be less affected by impregnation treatments with chemicals like sodium borate.

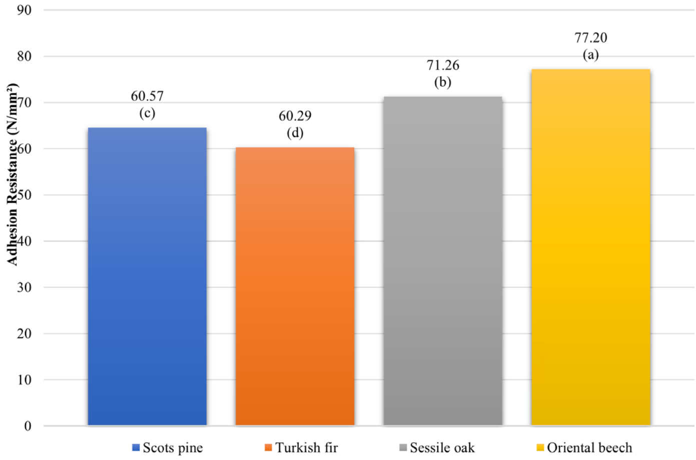

Fig. 2. Wood adhesion resistance results for different wood species

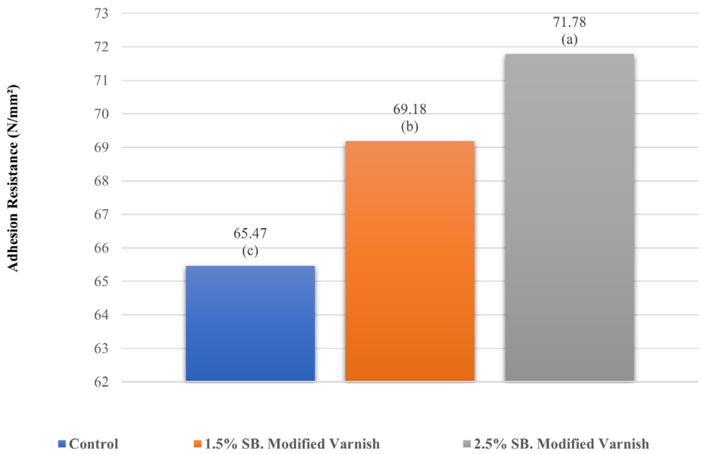

Fig. 3. Comparison of surface adhesion resistance across different varnish types

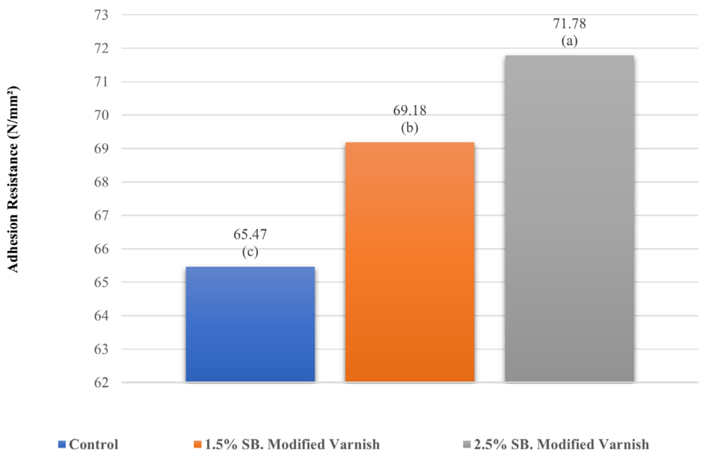

Fig. 4. Comparison of results depending on impregnant concentration

A comparison of surface adhesion resistance values depending on the binary interaction of wood species and varnish modification is presented in Figure 6.

As shown in Figure 6, the results for combinations of wood type and varnish type show that the highest adhesion resistance value was obtained for beech wood samples with varnish modified with 2.5% sodium

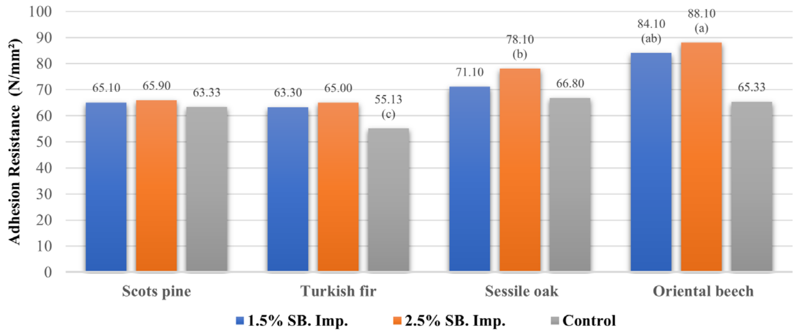

Fig. 5. Comparison of results depending on the interaction between wood species and impregnant concentration

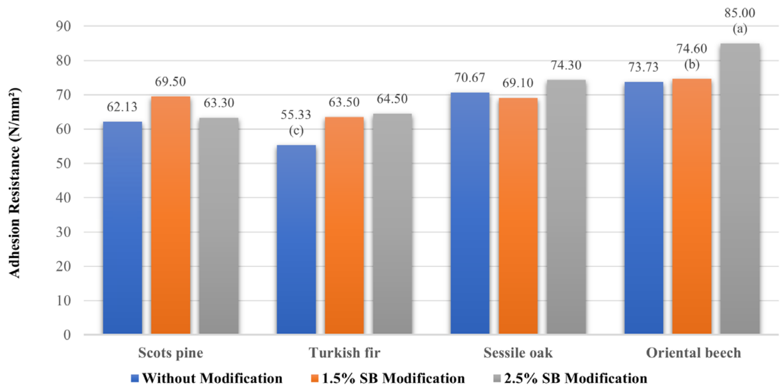

Fig. 6. Comparison of results depending on the interaction between wood species and varnish modification

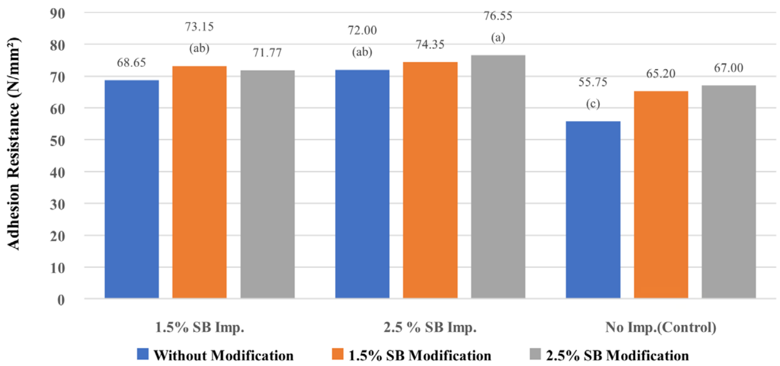

Fig. 7. Comparison of results depending on interaction between impregnant concentration and varnish modification

borate, and the lowest value was obtained for control samples of fir wood.

The results presented in Figure 6 demonstrate that both wood and varnish modification play a significant role in determining the adhesion resistance of wood surfaces. In particular, beech samples coated with varnish modified with 2.5% sodium borate attained the highest adhesion resistance. This result can be attributed to the chemical interaction between the cell wall structure of beech wood and the sodium borate modifier.

The results for surface adhesion resistance depending on the binary interaction of the impregnant concentration and varnish modification are presented in Figure 7.

According to the results for the interaction between impregnant concentration and varnish type, the samples with 2.5% sodium borate impregnation and 2.5% sodium borate modified varnish gave the highest surface adhesion resistance values, while unmodified control samples produced the lowest values. These results demonstrate the significant advantages of sodium borate in impregnation and modification processes. Sodium borate was found to contribute to obtaining a more robust and durable surface by increasing its adhesion capacity.

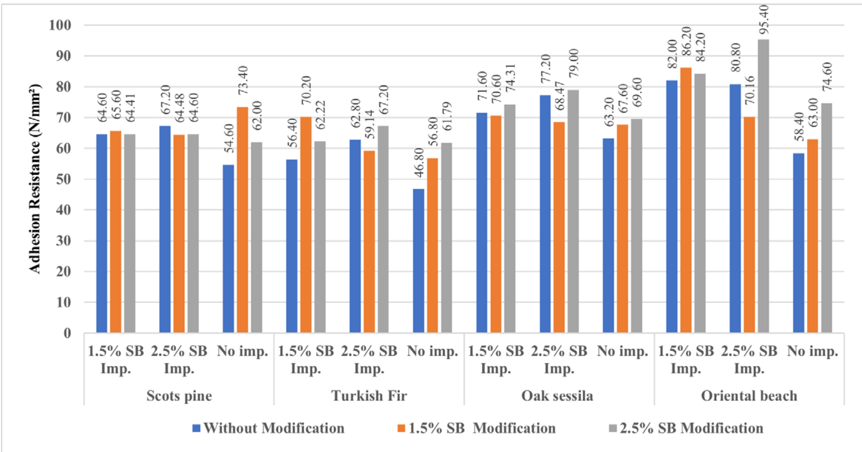

Fig. 8. Comparison of results depending on the interaction between wood species, impregnant concentration and varnish modification

The results for surface adhesion resistance depending on the three-way interaction of wood species, impregnant concentration and varnish modification are presented in Figure 8.

The presented graph illustrates the effects of sodium borate (SB) modifications on varnish adhesion resistance across four wood species: Scots pine, Turkish fir, oak (sessile oak), and oriental beech. Adhesion resistance was evaluated under three treatment conditions: unmodified control, 1.5% SB modification, and 2.5% SB modification. Additionally, for each species, samples were subjected to impregnation treatments at 1.5% and 2.5% SB concentrations, as well as non-impregnated controls, to assess the combined influence on varnish adhesion.

Results indicate that oriental beech samples treated with the 2.5% SB impregnation and modification regime exhibited the highest adhesion resistance, measuring 95.40 N/mm². Overall, samples subjected to 2.5% SB treatment (both impregnation and modification) demonstrated superior adhesion performance compared to other groups. Conversely, Turkish fir samples displayed relatively lower and less variable adhesion resistance values among the tested wood species.

Unmodified samples showed comparatively lower adhesion resistance, particularly in oak and oriental beech. In contrast, specimens treated with 1.5% and 2.5% SB modifications exhibited marked improvements in adhesion resistance. For Scots pine and oak, the 1.5% SB modification occasionally resulted in adhesion values comparable to or slightly lower than unmodified samples, while 2.5% SB treatment consistently enhanced varnish adhesion.

Conclusions

The results obtained in this study reveal that surface adhesion resistance values exhibit significant variation depending on factors such as wood material, impregnation agent, and sodium borate modification of varnish. Furthermore, it was determined that the interactions of wood materials, sodium borate modification, and impregnation agent also had a significant impact on the surface adhesion resistance of the varnish layer.

Comparisons among wood materials showed that the highest adhesion resistance was observed on beech, while the lowest values were found for fir samples. Additionally, it was noted that as the sodium borate content decreased, the varnish adhesion resistance also decreased. Analysis of impregnant concentration showed that samples impregnated with 2.5% sodium borate exhibited the highest surface adhesion resistance, and this value decreased as the sodium borate concentration decreased.

Results for the interaction between wood species and varnish content showed that beech wood samples impregnated with varnish containing 2.5% sodium borate had the highest adhesion resistance, while the lowest values were observed for the unmodified control samples of fir. Furthermore, the results for combinations of impregnant concentration and varnish type revealed that samples impregnated and modified with 2.5% sodium borate attained the highest adhesion resistance, whereas unmodified and unimpregnated fir samples gave the lowest values.

In general, the results of this study indicate that wood impregnation and varnish modification using sodium borate play a significant role in increasing surface adhesion resistance, and the effects of wood species and modifications on this property are quite pronounced. These findings provide valuable information for the optimization of varnish and impregnation processes in wood material applications.

Different combinations may be tested to improve adhesion strength and impregnation values. It is recommended to examine the results achieved by using sodium borate and similar substances in different ratios in impregnation processes. In this way, results of greater benefit to the wood industry can be obtained.

Conflict of interest

The author(s) declare(s) that there is no conflict of interest concerning the publication of this article.

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