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Evaluation of Mechanical Properties and Surface Quality of Wood from Bosnia and Herzegovina Exposed to Outdoor Conditions

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ABSTRACT

This study investigated the mechanical properties of beech (*Fagus sylvatica* L.) and fir (*Abies alba*) wood from Bosnia and Herzegovina under outdoor exposure. Samples were exposed for 3-month exposure to assess bending strength, color changes, and surface quality. Results showed outdoor exposure negatively affected mechanical properties, particularly in samples with extended finger joints, causing significant surface cracks in uncoated samples. Beech wood exhibited notable color changes under exposure, with approximately 50% darkening without coating compared to 25% under covered conditions. Coated samples displayed minimal color changes, affirming the efficacy of surface treatment. Fir wood exhibited a roughness of 8.264 μm , while beechwood average roughness increased from 6.767 to 13.916 μm after exposure, with micro-pore development affecting water performance. Microscopic analysis identified prevalent fungal colonies, including *Penicillium*, *Aureobasidium*, *Sclerophoma*, and *Chaetomium*, underscoring their role in organic matter decomposition. This study highlights the importance of wood exposure and treatment selection for various applications.

KEYWORDS

Mechanical properties; outdoor conditions; cracks; wood species

1 Introduction

Wood, a timeless and renewable material used by humans for centuries, exhibits exceptional adaptability across various applications, from furniture to construction. Despite this, its susceptibility to organisms that degrade wood, such as fungi and insects, has traditionally limited the outdoor applicability of wood with insufficient durability [1]. The integration of wood composites is indispensable in modern construction and building methods, presenting a sustainable alternative to traditional materials like steel and concrete in various construction applications [2].

Adhesive bonding, a technique employed for centuries, underwent significant advancement in the 20th century, becoming pivotal in nearly all branches of production [3]. The bonding process, involving surface



preparation and adhesive application, facilitates the creation of strong joints between different materials [4]. Furthermore, research into novel ways of utilizing waste and recovered wood and optimizing resources is crucial for sustainable construction, with innovations like glued laminated timber gaining popularity in structural applications [5–9]. Numerous authors have investigated various aspects of finger joint strength through experimental research, mathematical modeling, and numerical simulation to enhance process efficiency and predictability. The strength of finger joint bonding depends on critical parameters, including height, length of the tooth, tip depth, and slope, as elucidated in research works [10].

Researchers discovered that 10 mm-long teeth and class D3 PVAc adhesives showed the highest strength when assessing bonding effects on resistance classes D1, D2, and D3 according to standard EN 204:2001 [11–14]. Engineered wood products (EWPs) have gained prominence over traditional timber due to their superior span capabilities and performance consistency. The finger joint method, a crucial step in EWP production, enhances structural integrity by interlocking timber boards. Flexural tests determine the load-bearing capacity of finger joints, ensuring quality in EWP manufacturing [15–18]. Investigations into the impact of ambient climates on beech glued laminated timber (glulam) revealed variations in moisture content and finger-joint delamination. Additionally, research explored cyclic temperature effects on the bending properties of glued laminated timber from different wood species. Studies also evaluated methanol's influence on the stability and adhesion performance of PRF resin adhesives [19–23]. Other studies analyzed fingertip surface impact on bending strength and finger parameters on tensile strength [24–27], examined various wooden joints for mechanical, physical, or chemical properties, and compared experimental findings with ANSYS software outcomes [28]. Further research investigated lap joint strength in oriental beech samples bonded with different adhesives [29] and utilized laminated pine wood elements to assess strength under specific conditions. In research [30], laminated elements of pine wood with an average density of 575 kg/m^3 and a moisture content of 8.9% were used, and the results showed that samples with reinforced edge inserts had improved bending strength of 90.3 N/mm^2 .

An investigation [31] into the influence of geometric parameters of the toothed joint profile on the tensile strength of individual bonded wooden panels demonstrated that the group of samples with the shortest teeth had the highest tensile strength. In contrast, the group with the longest teeth resulted in the lowest tensile strength. The study [32] of angular joints with beech wedge teeth in chair products showed that teeth measuring 7.5 mm exhibited greater durability under dynamic loads and greater stiffness at certain moments compared to 10 mm teeth. Research [33] on the strength of bonded toothed joints on fir wood samples demonstrated compliance with quality standards.

This research aims to present the results of experimental testing conducted on solid wood and wood joined by finger joints manufactured from various species, including fir and common beech. Special emphasis is placed on the mechanical properties of polyvinyl acetate (D4) adhesive joints, commonly used for connections exposed to outdoor conditions susceptible to the influence of biological and abiotic degradation factors, particularly fungi, color alteration, and surface roughness.

2 Materials and Methods

This research involves experimentally examining the bending strength of wooden samples, color, surface change, and fungi colonies after exploitation. These samples were prepared by cutting them in the longitudinal direction to enable a detailed study of their mechanical properties. The experimental segment encompasses several steps, including sample preparation, conducting the tests, analyzing the results, and drawing conclusions. Twenty samples without visible defects, a full cross-section and white finger joints, and free from knots and resin pockets were prepared for each test. The primary aim of this research lies in investigating the mechanical behavior of solid wood and wood joined by a finger joint under conditions of external exposure, partial external (covered) exposure, and laboratory conditions. Such an

analysis allows for a detailed understanding of the behavior of these materials under various conditions, providing valuable insights into their stability and durability in different environments.

2.1 Materials

In this study, Rectangular defect-free samples of dimensions (length, width, height) $380 \times 20 \times 20$ (mm³) as Fig. 1, made according to the BAS EN 408 + A1 standard [34] for bending strength testing in four-point bending were used. For bonding along the length of the samples, a finger joint with a mini finger length of 9 mm was used, with an average moisture content ranging from 7%–8%. Bostik polyvinyl acetate (PVAC) glue of D4 category, certified for water resistance as D4 BS-EN-204-D4 [35], with a bonding time of 7 min, was used as the adhesive. For the bonding of finger-jointed wooden specimens, a press manufactured by WEINIG, model ProfiPress L II, was used at standard room conditions (temperature of 20°C–25°C and relative humidity of 40%–60%), a pressure of 0.7 MPa, and a pressing time of 20 min to achieve optimal bond strength.

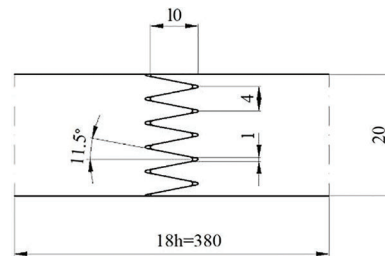


Figure 1: Wooden samples joined by a 9 mm-long mini-finger joint

The wooden samples used in the experiment were prepared by the company Malak Janj from Donji Vakuf, a specialized company in manufacturing solid panels made from segments connected by a longitudinal and transverse finger joints.

2.2 The PVAC D4 Adhesive

The adhesive utilized was Bostik Polyvinyl Acetate (PVAC) D4 grade, certified for water resistance according to BS-EN-204-D4 [35] standards. Polyvinyl Acetate (PVAC) cold wood glue of D4 grade is a dispersion adhesive based on polyvinyl acetate, designed for bonding various types of wood. Applying PVAC D4 wood adhesive was performed bilaterally and mechanically using standard tools within an optimal processing temperature range of 18°C to 20°C and an ideal wood moisture content for bonding of 7% to 8%. The adhesive was evenly applied to contact surfaces at a rate of 150–200 g/m². Joined samples were then subjected to pressure in a parts bonding press for a duration of 7 min. Typical application areas for Bostik PVAC D4 adhesive include kitchen, bathroom, and garden furniture, windows, doors, fences, fiberboards, plywood, and similar products.

2.3 Varnish with Wax Finish

In our research, we utilized the “Jubin” varnish with wax formulated on the basis of water dispersion to protect wooden samples in outdoor conditions. This coating was chosen for its exceptional effectiveness and durability, proving to be a reliable option for safeguarding wood from adverse weather conditions. The application quantity amounted to 145 g/m² of the wooden sample’s surface area.

2.4 Sample Exposure

Our investigation entailed a three-month exposure of wood specimens in Cazin, Bosnia and Herzegovina (44.966°N 15.942°E, altitude ranging from 200 to 400 m), commencing on 01 March, 2023.

Samples were tested under laboratory conditions (exposure factor-F1) and outdoor conditions (exposure factors F2 and F3), where a portion of the samples underwent treatment for outdoor use and were exposed to outdoor influences (exposure factor 2, samples exposed outdoors but sheltered-F2, and exposure factor F3, samples exposed outdoors without shelter and above ground level-F3). Samples exposed to outdoor conditions F2 and F3 were placed on a metal structure 0.5 m above the ground, as defined by EN 335 (CEN, 2013) [36]. The primary objective of employing these exposed specimens was to conduct a comprehensive evaluation of the mechanical properties of wood subsequent to a three-month exposure to outdoor conditions. This encompassed the identification of surface irregularities (e.g., cracks, discoloration) and fungal infestation attributable to atmospheric influences.

2.5 Determining Wood Density

The density of wood samples was determined by precisely measuring their mass and volume following the EN 384 [37] standard. Samples, sized consistently at $50 \times 20 \times 20$ millimeters, were prepared and weighed using a digital scale with a minimum accuracy of 0.1 grams. Volume was determined using a micrometer to measure sample dimensions. Density was calculated by dividing mass by volume, yielding results in grams per cubic centimeter (g/cm^3), providing quantitative insight into this vital wood parameter. This method ensures a comprehensive analysis of wood density, crucial for understanding its structural properties and diverse applications. The volume of the samples is determined by measuring their dimensions using a micrometer and applying the following equation:

$$\rho = \frac{m}{V} [\text{g/cm}^3] \quad (1)$$

where:

m = Sample mass in grams (g)

V = The sample volume in cubic centimeters (g/cm^3)

2.6 Method for Determining the Moisture Content in Wood Samples

The wood samples, measuring $50 \times 20 \times 20 \text{ mm}^3$, were meticulously prepared and weighed on a digital scale with an accuracy of 0.1 grams, recording the precise mass of each sample. Following this initial measurement, the samples were subjected to drying at a temperature of $103^\circ\text{C} \pm 2^\circ\text{C}$ following ASTM D2016 [38] standards for a period of 24 h. Upon completion of the drying process, the samples were re-weighed to record their final mass. To calculate the moisture content in the wood, the difference between the initial and final mass of the wood sample was used, applying the following Eq. (2):

$$MC = \left[\frac{W1 - W2}{W2} \right] \times 100\% \quad (2)$$

where:

MC = Moisture Content (%)

W1 = Initial sample mass (g)

W2 = Final sample mass (g)

2.7 Bending Tests

To assess the mechanical properties of the samples pre and post-exposure, bending strength was determined in accordance with BAS EN 408 + A1 (CEN 2010) [34]. Prior to testing, the samples were conditioned under standard laboratory climate conditions: temperature (T) of 20°C and relative humidity

of 65%. The samples, with a minimum length of approximately 19 times the cross-sectional thickness, were subjected to simple support and symmetric loading through 2-point bending, spanning about 18 times the thickness. Four-point bending samples measured $380 \times 20 \times 20 \text{ mm}^3$ in dimension. Mechanical testing was conducted using a SHIMADZU (Kyoto, Japan) shredder type SIL-50KNAG apparatus at the Faculty of Technical Engineering in Bihać. Each material underwent twenty replicate tests. The samples were subjected to incremental bending under a pressure rate of 2 mm/min until the point of fracture.

2.8 Colour Analysis

The test samples underwent scanning and processing utilizing Corel Photo-Paint 8 software. Corel Photo-Paint was employed for color analysis, chosen for its ability to provide color data for the entire surface rather than isolated spots, thereby ensuring more comprehensive measurements. This method has demonstrated reliability, as corroborated by comparative analysis [39].

Color measurements were conducted on samples exposed to external weather conditions over a three-month period using the CIE Lab system, developed by the International Commission on Illumination (CIE) for colorimetry [40]. This system comprises three parameters: L^* , a^* , and b^* . The L^* axis signifies lightness, ranging from zero (black) to one hundred (white), serving as the achromatic axis for gray tones, while a^* and b^* denote the chromaticity coordinates.

The color difference (ΔE) from a reference color (L_0, a_0, b_0) to a target color (L_1, a_1, b_1) in CIE Lab space is determined by calculating the Euclidean distance between the two colors. This computation is expressed by the following equation (Eq. (3)):

$$\Delta E = \sqrt{(\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2} \quad (3)$$

By summing ($\Sigma \Delta E$) the obtained results of the analysed points (Eq. (4)), the course of the colour changes can be determined:

$$\sum_{i=1,1}^n \Delta E_{i,n} = \Delta E_{0,1} + \Delta E_{1,2} + \dots + \Delta E_{n-1,n} \quad (4)$$

2.9 Advanced Surface Morphology Analysis of Wood Samples Utilizing Laser Scanning Confocal Microscopy

The surface morphology of the samples under investigation was meticulously characterized by utilizing an Olympus LEXT OLS5000 laser scanning confocal micro-scope, which is headquartered in Tokyo, Japan. The microscope offered precise insights into surface features by capturing 3D images of the longitudinal surfaces at a magnification of $50\times$ over an area measuring $0.26 \times 0.26 \text{ mm}^2$ [41]. Measurement locations were systematically chosen at random to ensure comprehensive coverage. For each material combination, five measurements were recorded across two randomly selected samples, ensuring robustness in data collection.

Subsequent analysis of surface roughness was facilitated through the sophisticated microscope software included in the LEXT OLS5000 package. While several parameters were computed, particular emphasis was placed on S_a , acknowledged as the most representative and widely utilized metric for assessing surface roughness. S_a quantifies the deviation in point height from the arithmetic mean of the surface, providing a concise representation of surface texture.

Statistical scrutiny of the gathered data was conducted using industry-standard software suites, including Microsoft Excel (Microsoft, 2019, Redmond, Washington, USA) and GraphPad Prism (GraphPad Software, 9.0, San Diego, CA, USA), ensuring rigorous analysis and interpretation of results.

3 Results and Discussion

3.1 Mechanical Properties Analysis

As previously mentioned, the research conducted in this study provides detailed insights into the changes in the mechanical properties of wood under various meteorological conditions. The results clearly indicate that the resistance of different wood species to external factors depends on their material resistance to fungal degradation and their ability to absorb moisture. Over the course of several months of exposure, wood samples subjected to bending tests exhibited maximum force and fracture point. This study analysed the impact of wood joined with dovetail joints compared to solid fir and beech wood. These samples were exposed to the influence of three factors (F1, F2, and F3). The results of these investigations for exposure factor F1 are systematically presented in Table 1. This analysis meticulously documents the test results at four key points for exposure factors F1–F3, providing a basis for a deeper understanding of the influence of external factors on the mechanical properties of the tested wood species.

Table 1: Results of the bending force tests non-weathered and weathered samples three months of exposure

Materials	Expos-ure factor	Moisture (%)	Maximum force F_{max} (N)	Stan dev	Displacement (mm)	Bending time (s)	Modulus of elasticity–E (N/mm^2)
Without finger joints							
Beech (B)	F1	7.60	3124.48	9.75	17.84	305.99	14580.70
	F2	17.05	2251.42	10.88	14.78	151.72	16139.81
	F3	19.92	2164.86	9.17	162.91	177.76	14003.90
Fir (J)	F1	7.72	1804.14	9.55	13.67	234.43	10822.03
	F2	17.46	659.38	8.32	7.65	77.72	7484.64
	F3	20.21	1089.06	11.53	923	145.61	10226.93
Beech impregnated with wax (B-W)	–	–	–	7.11	–	–	–
	F2	16.19	2275.46	9.74	22.58	243.20	12361.05
	F3	20.89	2144.48	10.28	18.49	201.79	12489.48
Fir impregnated with wax (J-W)	–	–	–	–	–	–	–
	F2	17.19	1292.88	11.44	11.83	129.22	11292.88
	F3	21.23	1048.20	10.89	13.53	61.12	8074.20
With finger joints							
Beech (B-FJ)	F1	10.63	1063.33	9.23	5.20	81.24	1790.56
	F2	16.29	452.21	8.73	2.61	40.36	1165.23
	F3	20.78	500.66	8.58	3.20	37.05	1261.94
Fir (J-FJ)	F1	9.23	892.04	8.06	5.81	99.77	1789.34
	F2	19.05	481.04	11.77	4.05	43.32	481.34
	F3	21.25	547.19	8.23	4.57	199.58	545.19

(Continued)

Table 1 (continued)							
Materials	Exposure factor	Moisture (%)	Maximum force F_{max} (N)	Stan dev	Displacement (mm)	Bending time (s)	Modulus of elasticity–E (N/mm ²)
Beech	–	–	–	–	–	–	–
impregnated with wax (BFJ-W)	F2	18.99	427.15	6.21	2.27	36.52	1192.31
	F3	22.04	414.59	6.05	3.86	42.45	1015.80
Fir	–	–	–	–	–	–	–
impregnated with wax (JFJ-W)	F2	19.69	413.98	6.41	3.17	39.49	931.02
	F3	16.83	448.59	5.69	4.50	103.52	728.99

Analyzing the data for firewood, the mean maximum force was notably higher in the sample group (F1) exposed to outdoor conditions, as anticipated, registering at 1783.39 N. Conversely, the mean maximum force values in sample groups (F2) at 1043.56 N and (F3) at 1054.27 N showed more consistency but lower values than group (F1), [Fig. 2](#). These findings imply that external factors diminish the maximum force values in groups (F2 and F3) compared to group (F1), despite only a 3-month exposure period. As expected, the highest mean values of the maximum force were recorded in samples of solid beech (B), with a mean value of 2479.36 N. The mean value for beech samples with surface protection (B-W) is slightly lower, at 2258.50 N.

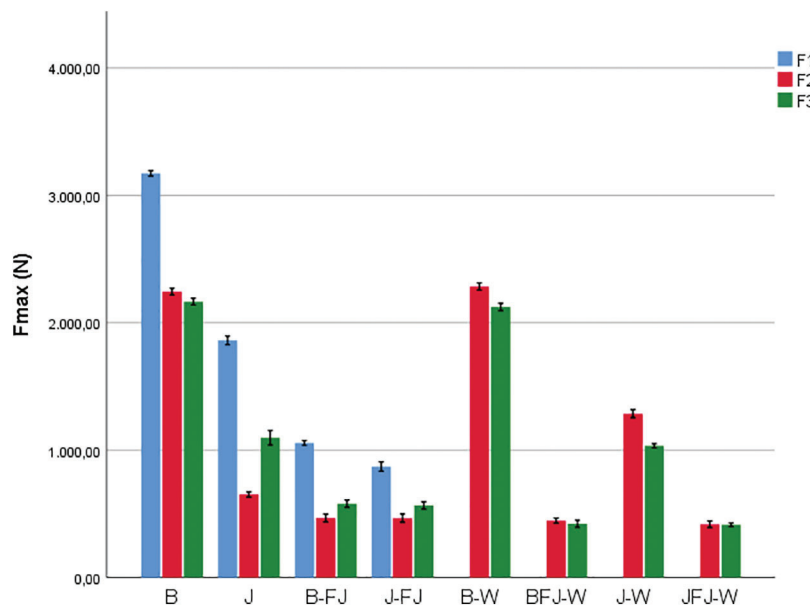


Figure 2: The results of maximum bending force under various exposure factors

Fir wood (J) achieved slightly lower values of maximum force, with an average of 1186.82 N, while samples of fir with surface protection (J-W) yielded better results with an average of 1156.95 N. This is noteworthy because samples (J-W) were exposed to external conditions (F2 and F3).

The samples of beech with extended toothed joints (B-FJ) exhibited an average maximum force of 670.19 N. In comparison, samples with surface protection (BFJ-W) had a slightly lower average maximum force of 420.87 N. Fir samples with extended toothed joints achieved a mean maximum force of 655.84 N. In contrast, fir samples with surface protection achieved an average of 453.19 N.

The highest mean values of the maximum force were observed in samples of solid beech (B) and beech with surface protection (B-W) under all exposure conditions (F1, F2, and F3), attributed to the undamaged wood structure (fibers), resulting in lower mean maximum force values for samples (B-FJ and BFJ-W). Improvements in the finger joint could lead to better results.

Comparing fir (J) samples with beech (B) samples, lower values of maximum force were recorded, which can be attributed to the lower density of fir wood. Solid fir samples (J) showed similar results to fir samples with surface protection (J-W), with minor differences, especially under exposure conditions (F2 and F3). Fir samples with extended finger joints (J-FJ) and samples with surface protection (JFJ-W) had lower maximum force values attributed to the interrupted wood structure.

Solid wood samples (B, J, BW, and JW) demonstrate superior performance compared to finger joint samples under various external exposure conditions (F1, F2, and F3). Solid wood samples exhibited higher modulus of elasticity values, indicating better resistance to environmental changes, particularly moisture content variations (1,2). In contrast, finger joint samples consistently showed lower modulus of elasticity values across all exposure conditions. The elongation caused by finger joints significantly diminishes their resistance, leading to reduced displacement and weaker stability under load (1). These findings align with previous studies that have investigated the impact of moisture content on the mechanical properties of wood. Wood density, which is directly related to the modulus of elasticity, is known to decrease with increasing moisture content (2). The presence of finger joints in wooden structures can exacerbate this effect, as the joints are more susceptible to moisture-induced changes (3). Solid wood structures, like beech and fir, exhibit more consistent resistance to environmental changes compared to extended finger joints (4).

3.2 Colour Changes of the Weathered Samples

The conducted color measurements on larger-sized samples that were exposed to external influences. It is well-known that wood color changes due to various factors. Wood exposed to light and ultraviolet rays darkens or yellows, which is particularly noticeable in light-colored wood species. Weather conditions such as rain and snow also have a significant impact. Over time, wooden structures, fences, facades, playgrounds, and other outdoor wooden products acquire a characteristic grey color. Knowing that wood changes color outdoors, some samples were previously coated with a coating in the test. The question is how the added pigments affect color changes due to weather influences. By employing the CIE Lab* method, the color change (ΔE) was determined after a specific time interval of exposure.

In [Table 2](#), it is noted that the average (ΔE) value decreased during the measurements. The most significant color changes are observed in beech wood, where the beech samples were exposed without coating to external conditions F2 and F3. Additionally, noticeable changes in values can be observed in the samples of fir and beech wood treated with wood stain. Samples treated with the coating exhibit the least color changes. Thus, the desired effect of the prior surface treatment with coating has been achieved. Fir wood samples record minimal differences in ΔE values according to [Table 2](#). Although both control samples and those treated with coating achieved the lowest average values for ΔE , significant differences among the coating-treated samples were not observed. [Table 2](#) shows that samples untreated with the coating but exposed to above-ground external conditions (F3) showed darkening by approximately 50% after 3 months of exposure compared to samples not exposed. Conversely, significant changes were not noticed in samples exposed to external conditions but under covered circumstances (F2), where the

changes amounted to approximately 25%. Our results are in line with previous studies that investigated the color change of wood. Hrčková et al. [42] examined the functionality of the wood color measurement method, where assessments were conducted in the CIE Lab* color space. The measured values confirmed a decrease in the lightness of the wood.

Table 2: Influence of weathering on wood color, expressed in the CIE lab system

Wood species	Weathering		Color change due to exposure to weather conditions			
	Exposure factor	Coating	L*	a*	b*	ΔE
Beech	F1	No	82.9	6.5	8.2	83.55
	F1	Yes	28.0	12.1	10.8	32.50
	F2	No	51.9	5.3	6.8	52.61
	F2	Yes	38.9	9.9	11.4	41.72
	F3	No	44.0	3.9	2.2	44.22
	F3	Yes	42.4	11.0	11.2	44.83
Fir	F1	No	88.8	3.5	9.2	89.34
	F1	Yes	21.7	13.8	18.1	31.44
	F2	No	62.9	11.4	12.3	65.09
	F2	Yes	28.5	13.0	18.1	36.17
	F3	No	57.5	9.9	11.4	59.43
	F3	Yes	33.2	14.8	15.4	39.47

3.3 Characteristics of Wood Surface Roughness

Roughness denotes the presence of fine irregularities on surfaces treated by machinery. These irregularities, arising from wood processing and anatomical structural features, can be quantified by measuring the height, width, and shape of peaks and valleys. Nonetheless, since all samples were processed using identical technical equipment, disparities observed in these tests are likely attributable to the inherent characteristics of the wood. Comparison of roughness across various control surfaces (Table 3) reveals a value of 6.767 μm for beech. In contrast, a higher roughness of 8.264 μm was noted for fir wood, indicative of the anatomical distinctions between the two wood species. Beech, characterized by a highly anatomically homogeneous structure, belongs to the category of diffuse-porous hardwoods, while fir represents a typical coniferous species [43].

Table 3: Influence of outdoor weathering on surface roughness Sa

Wood species	Weathering		Change in roughness due to exposure to weather conditions
	Exposure factor	Coating	Roughness Sa (μm)
Beech	F1	No	6.76
	F1	Yes	5.86
	F2	No	13.91

(Continued)

Table 3 (continued)			
Wood species	Weathering		Change in roughness due to exposure to weather conditions
	Exposure factor	Coating	Roughness Sa (μm)
Fir	F3	Yes	14.66
	F2	No	7.02
	F3	Yes	12.34
	F1	No	8.26
	F1	Yes	7.62
	F2	No	10.11
	F3	Yes	10.15
	F2	No	9.17
	F3	Yes	6.78

The parameter Sa is influenced by cell size, highlighting the complexities of wood anatomy in contributing to surface roughness. Notably, the roughness of beechwood samples surged from 6.767 to 13.916 μm after three months of exposure in the second exposure factor (F2) without protective wood stain. Similarly, Sa in beech samples subjected to exposure factor (F3) escalated to 14.666 μm . These observations align with prior findings documented in the study [44]. Importantly, naturally exposed samples encountered a spectrum of biotic and abiotic factors, fostering the development of micropores that impact roughness and water performance [44,45].

The coating, characterized by its formation of a thin protective layer on material surfaces, offers resistance against abrasion, UV radiation, moisture, and other external influences. Typically formulated with transparent pigments and binders, the coating penetrates the wood, preserving its natural appearance while safeguarding it from environmental stressors. Given its protective attributes, wood stain serves to impede moisture infiltration, thus mitigating roughness fluctuations induced by climatic variability. Moreover, wood stain contributes to surface preservation, shielding against damage inflicted by sunlight, UV radiation, and other external factors. Consequently, the presence and properties of wood stain play a pivotal role in shielding surfaces from external influences, thereby maintaining relatively stable roughness levels during exposure to environmental conditions. The darkening of wood color results from two processes. Firstly, weather conditions cause the degradation of lignin and the subsequent leaching of degradation products from the wood, resulting in a silvery hue. Secondly, darker coloration is also associated with melanin pigments (as seen in CLSM Roughness images) secreted by blue stain and sapstain fungi. However, less noticeable changes were observed in wood protected by wood stain.

The main reason for this is that coated wood is already darker, so the blue staining does not cause as significant a change in the L* component as noted for unmodified species. After twelve months of exposure, one of the main changes observed is the degradation of lignin on the surface and the leaching of quinones after UV radiation. Visual changes, such as color alteration and cracking, of samples before and after weathering can be seen in Fig. 3.

The results indicate that exposure to sunlight and precipitation leads to relatively rapid color change towards silverygray. It has also been stated that color change is a function of two processes: lignin degradation and associated leaching of degradation products from wood, as well as melanin pigments secreted by blue stain and sapstain fungi. Additionally, colonies of blue stain fungi or weathering

conditions, which contribute to increased roughness due to the appearance of loose fibers, also play a role. However, as the wood was analyzed at higher magnifications, larger cracks did not affect roughness parameters.

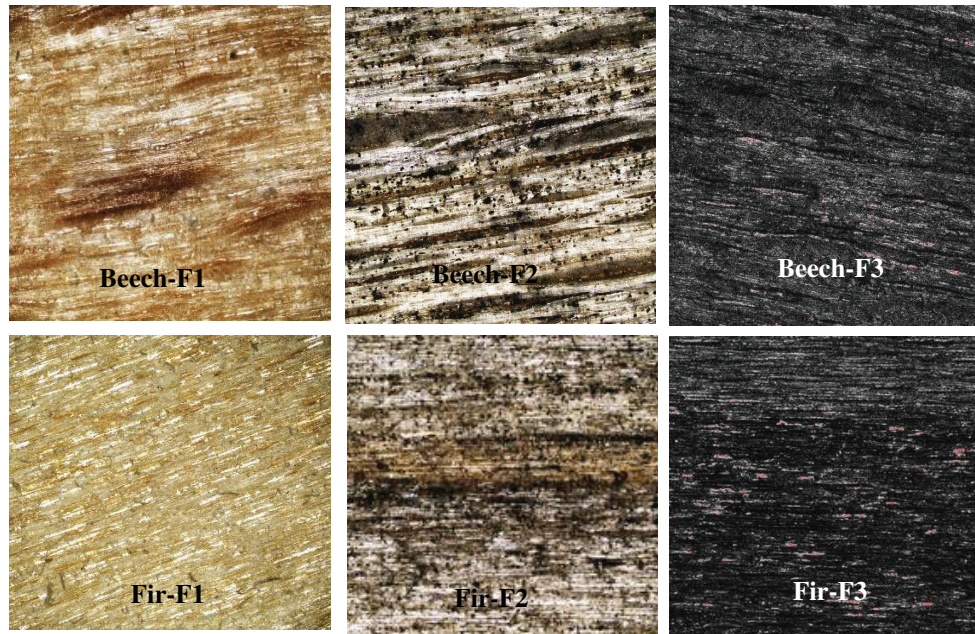







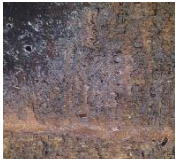


Figure 3: Surfaces of samples, dimensions (2000 μm × 2000 μm) generated by LEXT 3D measurement laser microscope OLS5000 before exposure and after 3 months of exposure outdoors

3.4 Fungal Colonization

Based on microscopic analysis (Table 4), the predominant fungal colonies identified on the wood samples belong to the genus *Penicillium*, *Aureobasidium*, *Sclerophoma* and *Chaetomium*. This genus, comprising ascomycetous fungi, holds widespread distribution in natural habitats and plays a pivotal role in organic matter decomposition. Typically thriving in environments characterized by elevated relative humidity, these fungi indicate moisture-rich conditions conducive to their proliferation.

Table 4: Influence of outdoor weathering

Wood species	Laboratory	Weathering		
	F1	F2	F3	Coating after 3 months
Beech				
Fir				

The wood in the analyzed samples retained its structure, as confirmed by detailed microscopic and mechanical analysis. Despite exposure to external conditions over three months, degradation primarily manifested only on the surface layer of the wood, evident through color changes on the exterior of samples exposed to atmospheric conditions. Lignin, responsible for the darker color of wood, degrades under the influence of UV radiation, while cellulose fibers remain on the surface, imparting a silvergray hue to the wood [46]. Analysis of samples that were coated did not show the presence of blue coloration, implying that the presence of the coating prevents the growth of blue spots caused by fungi on the wood surface. Coatings, acting as protective layers, provide resistance to moisture, UV radiation, and other atmospheric factors that could lead to wood deterioration [47].

4 Conclusions

The study emphasizes the critical importance of joint quality through evaluations of the bending strength of beech and fir wood, with and without finger joints, under various exposure factors. Compliance with BAS EN 408 standards facilitated the assessment of crucial physical and mechanical properties for joint quality determination. Key conclusions from the findings include the variation in bending strength and modulus of elasticity observed in samples of beech and fir wood, both with and without finger joints. Laboratory conditions (F1) positively impacted bending strength, while the modulus of elasticity experienced a reduction compared to exploitation conditions due to moisture content alterations. External conditions (F2 and F3) can influence the durability of adhesive joints and the structural stability of solid wood. It is crucial to emphasize the importance of using protective coatings to preserve the color and surface quality of wooden samples, recommending their application as a preventive measure against adverse external influences. Furthermore, careful selection of wood species according to intended use can be pivotal, while regular maintenance and inspection are essential for prolonging the lifespan of wooden materials and preventing more serious damage. Detailed analysis reveals the intricate interactions between external factors and material characteristics, highlighting the need for further research to achieve a comprehensive understanding. Continuous testing beyond adhesive certificates is necessary for accurately evaluating solid wood bonding strength. Coatings applied to wood surfaces form surface films, affecting liquid absorption without diminishing wood hygroscopicity. Color changes observed in untreated samples suggest inherent wood sensitivity to environmental factors such as UV radiation. Future research endeavors should prioritize expanding treatment analysis and exploring different adhesive types for finger joint bonding.

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