Ultraviolet Light and Natural Weathering *vs.* the Compression Strength of Laminated Wood

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Effects of protective measures were evaluated relative to the compression strength in the direction parallel to the grain of laminated veneer wood (LVL). For this purpose, laminated panels were prepared from Scots pine, Oriental beech, *Castanea sativa*, and sessile oak wood veneer by gluing them with Desmodur vinyl trie ketonol acetate (D-VTKA), polyvinyl-acetate (PVAc) dispersion D4 adhesive, resorcinol formaldehyde (RF), and melamine formaldehyde (MF). The samples were impregnated with a mixture of wax, linseed oil, and coated with a synthetic-based translucent varnish. The control samples (without the treatment described above), impregnated samples, and varnished samples were kept in the external environment for 1 y and in an ultraviolet (UV) environment for 240 h. The samples were tested to determine the air-dried density, retention amount, and compression strength. The results indicated that, in terms of outdoor conditions, the varnished proceeding provided better protection compared to the impregnated proceeding. The best result for compression strength was obtained on the Oriental beech samples with RF and MF glues. The ratio of the UV environment to represent the external environment was 89%.

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INTRODUCTION

Despite the variable nature of natural materials and weather conditions, there is a general consensus on the causes of wood weathering. Continuous and repeated exposure to solar radiation, especially UV components, and intermittent washing by rain are seen to have a significant impact (Kropat *et al.* 2020). Wood is vulnerable to biodegradation and photodegradation, particularly when it is exposed to outdoor climatic conditions. This degrades the aesthetic and mechanical performance of wood (Brischke and Alfredsen 2020). Photodegradation of wood is usually triggered by environmental factors such as sunlight, humidity, oxygen, and temperature (Nzokou and Kamdem 2006). Various environmental factors degrade the structure of lignin, cellulose, and hemicellulose, which are the main chemical components of wood (Schmalzl and Evans 2003; Jebrane *et al.* 2009; Lesar *et al.* 2011). Wood weathering is mainly due to photodegradation of the lignin component. Free radicals are generated that react with oxygen to produce hydroperoxides, which in turn are decomposed to chromophoric groups, such as carbonyl and carboxyl groups (Feist and Hon 1984; Ayadi *et al*. 2003). Tannins, like lignin, absorb UV light and protect it for a certain period of time, but eventually break down (Tondi *et al.* 2013; Kropat *et al.* 2020). Driving rain creates mechanical abrasion, and degraded surfaces are washed off, revealing undamaged wood. It is also noteworthy that water may enhance degradation reactions by facilitating light penetration (Stark 2006). The degradation of wood's chemical structure leads to a deterioration in some of its physical, chemical, and biological properties (Temiz *et al*. 2005). Sunlight has the greatest impact on wood surface properties under outdoor conditions (Pandey 2005; Tolvaj *et al.* 2011). The photon energy in sunlight (ultraviolet (UV), visible, and infrared light) is extremely harmful and initiates a wide range of chemical degradations on wooden surfaces (Baysal *et al.* 2014). The moisture load causes dimensional changes and cracking, while the photodegradation from UV-radiation affects the lignin component that acts as an adhesive in the wood structure. Because of preferential lignin degradation, the surface is enriched with loosely bonded cellulose that washes off, resulting in a rough, uneven surface. A flaked and cracked coating allows moisture to penetrate and may lead to decay, and the eroded surface serves as a poor bonding base for finishing chemicals (Grüll *et al.* 2013; Strand and Hovde 1999; Rüther and Time 2015). Among all the components of wood, lignin can absorb 80% to 95% of the total UV radiation absorbed by wood (Nzokou and Kamdem 2006). The change in the moisture content of weathered wood during the cycles of wetting and drying often leads to cracking, warping, and mechanical failures on the surface (Varga *et al.* 2020).

There are various methods to prevent such physical and mechanical failures and to extend the outdoor lifespan of wood. Some methods to protect wooden surfaces against weathering and degradation include the surface treatment of wood with photostabilizers, protection with coatings, forming a thin film on wooden surfaces, treatment of wood with inorganic metal compounds and bio-based water repellents, chemical modification of wood, modification of wood and wood surfaces with thermosetting resins and furfuryl alcohol, and thermal modification of wood (Kutz 2005). The most common method of protecting wood against weathering and photodegradation is the use of coatings such as UV absorbers and/or antioxidants, varnishes, organic polishes, or water repellents (Kutz 2005). These methods are intended to cut off the contact of UV light and water with the surface of the wood. Therefore, different top surface products applied to wood materials in outdoor conditions have been introduced to the market in recent years, and there have been many studies on these products (Özgenç *et al*. 2012). Among these methods, clear coating is the easiest and most common method to protect the wood against natural weather conditions (Schwalm *et al*. 1997; Chang and Chou 2000). However, as the abrasion time increases in this practice, the coating thickness is reduced, and a tissue deformation occurs under the coating surface during abrasion (Saha *et al.* 2011). Impregnation with wood preservatives followed by the application of durable coatings or varnishes and paints makes the wood more resistant to photochemical degradation, dimensional changes, and biological organisms, and it can extend the lifespan of the treated wood (Yalinkiliç *et al*. 1999; Baysal 2008; Nejad and Cooper 2011; Baysal *et al*. 2014). Using both impregnation and subsequent surface treatment in this method can increase the costs. Therefore, the use of semi-transparent and colored varnishes and coatings that protect the color and texture of wood has been a method of choice in recent years to improve wood's resistance to UV rays and water.

Impregnation is another longstanding method for the protection of wood. Commonly used impregnation materials such as copper, chromium, arsenic, and their compound chromated copper arsenate (CCA) have provided long-term protection against weathering and erosion (Feist and Ross 1995; Jirous-Rajkovic *et al.* 2004). However, negative effects from these materials, such as increasing cancer cases and environmental pollution, have led people to use organic wood preservatives that will not adversely affect the environment and health, instead of inorganic toxic substances. One of these preservatives is linseed oil. Linseed oil, traditionally used as a surface coating, is a natural, organic chemical that can be used as a wood preservative. Linseed oil can penetrate the cell walls well enough during the impregnation process, reduce hygroscopic movements in the wood, and act as a stabilizer. Linseed oil is hydrophobic, so it is regarded as a unique chemical. Natural oils and resins have been shown to efficiently reduce the water intake of wood. Natural oils and resins can keep the moisture content of wood below 20%, which provides biological resistance. From this point of view, natural oils and resins are considered promising materials in the field of wood preservation (Koski 2008; Tomak and Yildiz 2012). At the same time, during impregnation, linseed oil prevents moisture ingress by filling the gaps such as tracheid lumens, rays, and cracks caused by the drying process (Olsson *et al.* 2001). Temiz *et al.* (2008) reported that wood treated with pyrolysis oil had a reduced level of water intake, similar to the effectiveness of other oils such as linseed oil, tall oil, and canola oil, and it prevented water from entering the wood by forming a mechanical barrier.

The weathering of wood material and having the knowledge of how the properties of aged wood change is very important for the preservation of wooden cultural heritage items such as historical wooden buildings, artistic structures, and objects. In addition, studies conducted on the weathering of wood enable the determination of the lifespan of the material. For this purpose, the material can be directly exposed to the degrading factors of natural outdoor conditions, and a simulation of outdoor degradation conditions can be performed artificially under laboratory conditions. Although exposure to natural outdoor conditions gives the most accurate and reliable results, artificial weathering, mostly carried out under laboratory conditions, is preferred due to high safety requirements and the many years that are required for natural weathering (Arpaci and Tokmak 2020). While several factors such as light, heat, and humidity affect the material in artificial weathering, there are various factors such as air pollution, air movements (wind, storms, *etc.*), and surface abrasives such as dust and sand carried by air movements according to the characteristics of the region in natural weathering. Kurt and Tomak (2020) stated that despite the widespread use of accelerated weathering tests, there is little information in the literature that would allow technologists to evaluate which conditions of accelerated aging are most likely to provide an accurate prediction of natural aging effects. Another fundamental uncertainty is that even if there were a set of conditions that best allowed predictions to be made about unprotected wood surfaces, there is no guarantee that the same accelerated weathering conditions would provide a fair estimate of the relative effects of different coatings, each of which may have different levels of vulnerability to the imposed conditions. Therefore, there are still unanswered questions about the relationship between accelerated weathering testing in the laboratory and outdoor exposure conditions. In particular, studies on the long-term performance of wood composites in outdoor practices are very limited. Although there are several publications on the degradability and photostability of the coating under accelerated weathering, studies on natural outdoor weathering of coatings are still limited. Therefore, there is a lack of information about the degradation and photostability behavior of synthetic resin-based coating and linseed oil under climatic conditions. In this study, the effect of impregnation with synthetic resin-based wood colorant and protective exterior varnish and linseed oil on the weather resistance during natural outdoor exposure, and weathering, which was accelerated with UV exposure and condensation, was monitored. To show the relationship between the accelerated weathering and the natural weathering, the data were compared with data from a natural test station for up to one year.

EXPERIMENTAL

Wood and Glue

In this study Scots pine (*Pinus sylvestris* L.), Oriental beech (*Fagus orientalis* Lipsky), *Castanea sativa* Mill., and sessile oak (*Quercus petraea* Liebl.) wood specimens, which are known to be resistant to outdoor conditions and used widely in the decoration and woodworking industry, were used. Ten layers of 2 mm thick laminated sheets were produced from the specimens and formed into 20 mm composites). Desmodur vinyl trie ketonol acetate (D-VTKA), PVAc dispersion D4 adhesive (PVAc-D4) (www.kleiberit.com), resorcinol formaldehyde (RF), and melamine formaldehyde (MF) (www.gentaskimya.com) glues, which are known for their durability to wet places and to environments exposed to external influences, were used to bond the layers. The glue solution was applied to only one surface of layers with 180 to 200 g/m^2, and they were pressed using a hydraulic hot press. For the hydraulic pressing, the MF, RF, and PVAc-D4 glues were at a temperature of 80 °C, and there was 12 kg/cm^2 of pressure for 20 min. The D-VTKA glue was at a temperature of 20 °C and held at 12 kg/cm^2 of pressure for 60 min. The laminated panels were sanded on each surface with emery 180 grit sandpaper, and the thicknesses of the panels were measured (Doruk 2009; Doruk *et al.* 2013). The draft samples were cut to the measurements specified in the TS 2595 (1975) standard for compression strength experiment samples. Then, the samples were kept in a conditioning cabinet with a temperature of 20 ± 2 °C and a relative humidity of 65 ± 5% until they reached a constant weight. The obtained test samples were subjected to the application of varnish and impregnation before the weathering process.

Protective Materials

A solution comprised of 3% linseed oil, 10% paraffin wax, and 87% white spirits (white sprite) water-repellent preservatives and synthetic-based varnish were applied to the test samples as a preservative against the weathering. The experimental samples were impregnated in accordance with the ASTM D1413-07 (2007) standard. The test samples were dried until they reached a moisture content of less than 20% for the synthetic based varnish. Two layers of varnish were applied to each sample, with 24 h of drying time between each application, as described by Temiz (2005).

Natural Weathering Method (Waiting in the External Environment)

The natural weathering test was carried out at Eskipazar, Karabuk (40.939182°N; 32.514087°E, elevation above sea level 838 m). The samples were exposed outdoors, at 45° inclination, facing south and placed approximately 1 m above the ground according to ASTM G7-05 (2005). Where temperatures normally range from -4 °C to 27 °C throughout the year, the rainiest month is October, with an average of 51 millimeters, the least rainy month being February with 22 millimeters (https://tr.weatherspark.com). The specimens were stabilized at 20±2 °C and 65% RH before the measurements.

Accelerated Weathering Method (UV Environment Waiting)

The control samples (process-free), varnished samples, and impregnated samples were subjected in a laboratory environment according to the ASTM G154-06 (2006) and G151-06 (2006) standards. The process was applied in the UV test device (Gazi Uni., Ankara, Turkiye) accelerated for 8 h UV 60 (± 3) °C, 4 h of condensation 50 (± 3) °C, and a 240 h cyclic program. The accelerated weathering test results were compared to the control samples.

Air-Dry Density and Retention Amount

The air-dry density was determined according to the TS 2472 (1976) standard using 20 mm × 20 mm × 30 mm samples. Air-dry density results are given in Table 1.

Table 1. The Average Air-Dry Density of the Control Group (Doruk 2009)

Tree Species	Glue Type	*δ*	S	Tree Species	Glue Type	*δ*	S
Q. petraea	PVAc-D4	0.72	0.0034	*C. sativa*	PVAc-D4	0.71	0.0031
	D-VTKA	0.67	0.0135		D-VTKA	0.65	0.0211
	RF	0.71	0.0212		RF	0.63	0.0154
	MF	0.66	0.0106		MF	0.68	0.0421
F. orientalis	PVAc-D4	0.75	0.0073	Scots pine	PVAc-D4	0.58	0.0136
	D-VTKA	0.76	0.0181		D-VTKA	0.58	0.0652
	RF	0.71	0.0102		RF	0.57	0.0328
	MF	0.72	0.0077		MF	0.58	0.0164
δ: air-dry density; s: standard deviation							

According to Table 1, in the laminated experiment samples, the density in the air-dry form was the highest in the *F. orientalis* D-VTKA glue (0.76 g/cm^3) and the lowest in the Scots pine (0.57 g/cm^3). It has been reported that the air-dry density of the Scots pine is 0.52 g/cm^3 (Bozkurt *et al.* 2000). The air-dry density values of laminated samples are higher than solid wood. This is because with the high-density glue layer between the wood layers and was pressed with high pressure during lamination. This is consistent with the research of Özçifçi *et al.* (2007) and Kurt and Tomak (2018).

RESULTS

The determination of the retention amount (R) (kg/m^3) impregnation process of the experimental samples was carried out according to the ASTM D1413-07 (2007) standard. The retention amounts can be seen in Table 2.

Accordingly, the highest retention amount (164 kg/m^3) was obtained from the impregnation process with a mixture of paraffin and linseed oil in the Scots pine laminated board glued with D-VTKA. This was attributed to the high viscosity of the glue laminated D-VTKA that was used, as it was unable to penetrate the surface and impregnate the wood. The viscosity of the other glue solutions was very low, so they penetrated deep into the structure of the wood and reduced the permeability of the wood.

Table 2. The Retention Amount According to the Wood Type of Impregnation Material (kg/m^3) (Doruk 2009)

Tree Species	Glue Type	X	S	Tree Species	Glue Type	X	S
Q. petraea	PVAc-D4	82.150	2.617	*C. sativa*	PVAc-D4	142.771	10.327
	D-VTKA	81.230	4.714		D-VTKA	83.848	12.061
	RF	41.060	8.781		RF	83.831	11.841
	MF	77.599	14.801		MF	116.696	7.803
F. orientalis	PVAc-D4	65.720	5.424	Scots pine	PVAc-D4	72.778	11.929
	D-VTKA	84.905	7.296		D-VTKA	163.906	54.248
	RF	76.200	22.348		RF	87.000	19.823
	MF	71.242	13.493		MF	93.873	11.309
X: average value; S: standard deviation							

Test Method

In accordance with TS 2595 (1975), the compression strength was measured with a gradual compression force parallel to the grain with a loading speed of 2 mm/min. The changes in the compression strength values of the samples were compared after they were subjected to external conditions and accelerated weathering. The multiple analyses of variance can be seen in Table 3. To determine the effect of the environment type, the tree species, the glue type, and the wood preservation type on the compression strength of the LVL samples, analysis of variance (ANOVA) testing was applied to the results. The Duncan test was applied to the mean values of results (using a 95% confidence interval) to determine which factors were statistically significant. The multivariate analysis results regarding the effect of the environment type, the glue type, the tree species, the wood preservation type, and the interactions with the test conditions are presented in Table 3.

Table 3. Tests of Between-Subjects Effects on the Dependent Variable

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Environment type (A)	8,635.307	1	8,635.307	1170.416	0.000*
Glue type (B)	11,107.310	3	3,702.437	501.823	0.000*
Tree species (C)	56,263.930	3	18,754.643	2,541.975	0.000*
Wood preservation type (D)	7,018.088	2	3,509.044	475.610	0.000*
A×B	506.736	3	168.912	22.894	0.000*
A×C	1,934.648	3	644.883	87.406	0.000*
A×D	117.859	2	58.929	7.987	0.000*
B×C	6,381.660	9	709.073	96.107	0.000*
B×D	552.308	6	92.051	12.476	0.000*
C×D	176.181	6	29.363	3.980	0.001*
A×B×C	5,841.168	9	649.019	87.967	0.000*
A×B×D	89.020	6	14.837	2.011	0.062
A×C×D	145.689	6	24.281	3.291	0.003*
B×C×D	2,633.541	18	146.308	19.830	0.000*
A×B×C×D	524.076	18	29.115	3.946	0.000*
Error	6,374.575	864	7.378		
Total	2,841,751.715	960			
*: Difference, significant reference to 0.05					

According to the ANOVA test results, all the other factors and interactions (except the A×B×D interaction) had a significant effect on compression strength ($P<0.05$). The Duncan test (HG) results of the compression strength of significant factors such as the environment, glue type, tree species, and wood preservation type are given in Fig. 1.

Discussion

According to the Duncan test results for the tree species, glue type, wood preservation type, and environment type factors for the compression strength, the highest compression strength was obtained for the Eastern beech tree species (66.1 N/mm^2), the UV environment type (56.4 N/mm^2), the RF glue type (57.3 N/mm^2), and the varnished sample wood preservation type (56.2 N/mm^2).

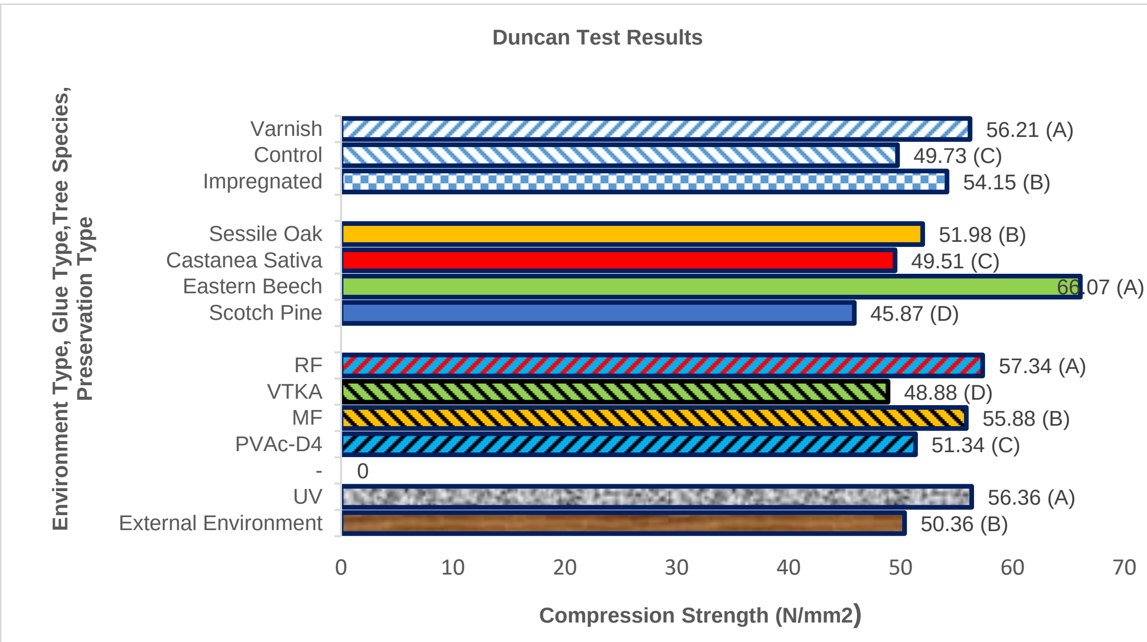

Fig. 1. The Duncan test results of the tree species, glue type, wood preservation type, and environment type for the compression strength

Among the environment types, the highest compression strength was obtained through the UV artificial weathering (56.4 N/mm^2), and it was determined that the external environment had a 10.6% greater degrading effect. With respect to abiotic degradation, environmental factors such as heat, humidity (rain, flooding, snow, and humidity), oxygen, pollution, the presence of chemicals, and sunlight can cause and accelerate wood degradation. Abiotic degradation, also called weathering, usually begins as oxidation when the wood is exposed to heat and UV radiation from sunlight. Wet events such as rain, wind-blown particles, temperature changes, and the effects of chemicals in the air can accelerate the degradation process (Shirmohammadi *et al.* 2021).

Among the tree species, the Eastern beech had the highest compression strength (66.1 N/mm^2), followed by the sessile oak, *C. sativa*, and Scots pine. This was likely because the densities of the Eastern beech and sessile oak species are higher than other wood species and the beech samples have a smoother adhesion surface. This result is in line with the research of Efe and Çağatay (2011). Density is an important parameter that affects the mechanical properties of wood material. When the density increases, the compression strength also increases significantly (Bozkurt and Erdin 1997).

Among the glue types, the highest compression strength was obtained in the RF (57.3 N/mm^2), followed by samples with the MF, PVAc-D4, and D-VTKA glues. Due to their low viscosity levels, the RF and MF glues may have performed the best because they penetrated deep into the tree structure and provided an irreversible and strong adhesion. These results are in line with other studies in the literature (Atar and Özçifçi 2005; Doruk 2009). In their study to determine the bending and compression properties parallel to the grains of Scots pine (*P. sylvestris* L.) and fir (*Abies bornmüelleriana* Mattf.) woods laminated using PVAc and polyurethane (PU) glues, Zor *et al.* (2016) obtained the highest compression strength in Scots pine woods laminated with PVAc glue (42.6 N/mm^2), and the lowest compression strength in Scots pine woods laminated with PU glue (40.1 N/mm^2).

Based on the treatment type, the highest compression strength was in the varnished samples (56.2 N/mm^2), followed by the impregnated samples, and lastly the control samples. This may have been because the impregnation and varnish applications protected the wood material against the environment's degrading effect. Regarding the treatment type, the impregnation treatment and varnish treatment had 9% and 13% better protection performance compared to the control samples. This may have been because the varnish treatment created a protective layer on the entire surface of the samples, which prevented the moisture in the environment from reaching the wood structure. The impregnated samples are thought to be less effective compared to the varnished ones due to the moisture entering the wood structure, albeit in a small amount, as a result of impregnating material being washed and dissolved in water for a long period of time in both settings. On the other hand, Tomak and Yildiz (2012) observed that high oil loading in wood decreased the mechanical resistance, while Olsson *et al.* (2001) found that the mechanical resistance decreased, and microstructural changes occurred at 75% and 105% weight gain values in impregnation with linseed oil. The presence of cracks in the tracheid cell wall was also observed at these loadings. The fact that the mechanical oil loading applied to the cell wall and the increase in the internal pressure in the cell wall cause microcracks in the cell wall layers has been reported to be the reason for this, and the microcracks in the S1 layer can decrease the resistance. A slight decrease in the compression strength parallel to the grains of wood impregnated with vegetable oils was also reported by Tomak (2011).

CONCLUSIONS

1. Although the lamination technique provides an important advantage on its own in wooden construction constructions to be used in outdoor environments, wood lamination must be strengthened with wood preservative components in order to increase its resistance against the negative effects of the external environment. This study found that when the wood preservative elements are not used, the compression strength decreases due to external conditions, so it must be reinforced with appropriate preservative elements.
2. The external environment had a degrading effect that was 10.6% greater than the UV environment. The ratio of the UV environment that represented the external

environment was determined to be 89%. The Eastern beech samples with both preservatives, the RF glue, and the MF glue exhibited the best performance against the degrading effects of the environments.

3. The varnish showed better protective properties than linseed oil in preventing the negative effects of air by covering all surfaces of the wood material. This is backed up by Grüll *et al.* 2013 by saying, “Coating systems are able to protect wood against moisture ingress, and they influence moisture release depending on their permeability for liquid water and water vapour.” The varnish showed better protective properties than linseed oil in preventing the negative effects of air by covering all surfaces of the wood material.

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