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ADHERENCE OF CERAMIC AND POLYMERIC COATINGS ON THE SURFACE OF WOOD AFTER VERSATILE WEATHERING RESISTANCE

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Abstract:

Wood is known as a sustainable material with several advantageous for various applications. One restrictive factor for wider use is the sensitivity of wood to weathering factors. The effects of coatings on Scots pine wood, after treatment and accelerated weathering and freeze - thaw cycles, were examined in this study. The studied coating materials were made from combinations of hydrated magnesium compounds with hydrated minerals and a combination of polymineral fire retardant with sulfonated graphene. The adhesion properties were measured by the tape method, and the results were calculated with the Python Programming Language. We found that each coating had an individual adhesion feature on wood and differing resistance to the stresses of weathering and freeze - thaw cycles. Weathering stress could be eliminated to a certain degree, but the influence of freeze - thaw cycles on the coating's adhesion was high, indicating the large effect of moisture on the coating.

Key words: *coating; freeze-thaw cycling; scots pine; weathering; wood.*

INTRODUCTION

Wood is a widely accepted natural material for many applications, due to its sustainable characteristics, which can help to meet the requirements raised by environmental concerns. Wood characteristics, such as, renewability, biodegradability and carbon sequestration are generally accepted as good for the environment (Risbrudt 2013). In addition to the sustainable advantages, its characteristics contribute to its use as a structural material. Its properties include, also, good insulation, high ratio of strength to weight, low heat and electrical conductivity, a high level of sound absorption, and ease of processing. Despite several advantageous features, wood also has some inherent properties that restrict its use in construction. For example, wood is stressed in outdoor applications by environmental degradation, which leads to undesired outcomes such as discoloration and other surface damage, especially in yard constructions, which is reflected as a grey, cracked, and rough surface (Evans 2013). Also, under a specific temperature and moisture conditions, biological organisms may attack wood and degrade its quality (Ibach 2013). Wood is also susceptible to fire, but solid wood also chars evenly at a speed of about 0.8 mm/min per minute in standard fire exposure (Fonseca and Barreira 2011), which ensures the structural integrity of wood material.

Wood can be blended into various products, such as engineered wood products (plywood, orientated strandboard (OSB), glulam, cross-laminated timber (CLT), and laminated veneer lumber (LVL)), which can be used in construction, as well as in furniture and artworks (Brandner *et al.* 2016, Jakes *et al.* 2016). Due to the various applications and the development of wood products, the market outlook is positive. Wood competes with other materials, such as metals, ceramics, and polymers to meet the needs of modern society. Selecting the correct material, for example, for construction, can be challenging and the economic perspective can be the deciding factor. Other factors for the selection of construction materials include, in addition, the type of building, design, and ecological impact. Different mathematical models help to enable a rational selection of the most appropriate material. Wood is often called an "environmentally friendly material" because it, as a durable material, can reduce carbon emissions during the manufacturing process, and the energy loss is considerably lower compared to metal and concrete (Kuzman and Grošelj 2012, Nässén *et al.*

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2012). The arguments in support of slogan for environmentally friendly characteristics are presented in Table 1, and we can see the advantages of wood on water and air quality, for instance. In addition, energy usage is less for wood production; concrete consumed twice as much energy as metal during the construction process.

Table 1

The environmental impacts of metal and concrete (Nässén et al. 2012)

	Embodied energy	**Climate impact**	**Negative impact on air quality**	**Negative impact on water**	**Resources consumed by weight**	**Waste produced**
Metal	+53%	+23%	+74%	+247%	+14%	-21%
Concrete	+120%	+50%	+115%	+114%	+93%	+37%

As stated, the application of wood in building construction can decrease the carbon footprint, but factors that restrict wood use are, e.g., its ignitability and weathering vulnerability. The solutions to fire sensitivity are classification for materials and standards. For example, construction materials can be classified into five categories. The first and second categories are fire-resistant construction (Type I) and noncombustible construction (Type II), respectively, with a limit for usage of combustible materials as in construction. The selection of wood for building purposes can be permitted only by the Type III (ordinary), Type IV (heavy timber), and Type V (light-frame), and fire-retardant-treated (FRT) wood is allowed in Type III assemblies when a rating of the fire resistance level is two hours or less (White and Dietenberger 2010). These standards also help to meet the demand for wood as a construction material. For example, “Fire Safety in Timber Buildings – Technical Guidelines for Europe” presents standards that should be followed by European countries (Östman *et al.* 2017).

Even though fire resistance has been standardized, the weathering vulnerability is a more open feature that does not have a universal solution. Weathering is defined as the outdoor and above ground degradation of materials, which depends on many environmental factors such as moisture, temperature, oxygen, and air pollutants; however, the main factor for it is solar radiation, and especially UV-light (Hon 2001). One certain solution to improve resistance against weathering stress is to use a coating, including chemicals, such as anhydrides, isocyanates, silicon dioxide, aldehydes, and epoxides, which are the most common for coating (Gérardin 2016). Another option is ceramic and polymeric coating, which can prevent detrimental environmental effects on wood.

OBJECTIVE

The main aim of this work is to discern the most suitable and effective types of wood coating, contributing wood use. The performance of wood coating was evaluated by measuring the adherence of the coated samples, including changes in its adhesion characteristics caused by moisture, UV irradiation, and other weather conditions.

METHOD

Three coatings were studied in this work. Scots pine wood (*Pinus sylvestris*) was coated by two ceramic coatings and one polymeric coating, consisting of the combinations of hydrated magnesium compounds with hydrated minerals (ceramic coatings) and the combination of polymineral fire-retardant with an aqueous solution of sulfonated graphene (polymeric coating). Samples originated from same Scots pine panel and the coated materials were treated by brushing. Samples were cut from the coated materials and the noncoated cross-ends of the samples were treated with epoxy, in order to avoid disturbance from moisture. After epoxy treatment, the samples were dried for three days and conditioned at 23°C and 50% relative humidity for over 48 h. There were 36 wood samples, 12 samples for each type of coating and six samples each were used for weathering and cycling.

Weathering performance was simulated by an accelerated weathering test in a test chamber (Q-Sun Xe-3 Xenon Test Chamber) for 500 hours. The simulation procedure consisted of intervals of UV-light and water spray, according to the standard of EN ISO 4892-2.

The cycling test determines the effect of freeze - thaw cycles where samples are exposed to a water bath, a freezing cabinet (Electrolux, EC4230A0W2/BNI425), and a drying cabinet (Gallenkamp, Hotbox Oven with fan, Size 2), based on the standard of EN 15534-1:2017 + A1:2017. The test samples were conditioned to a constant mass under established conditions (20°C and RH 65%) before the test. First, the samples were exposed to water immersion for 28 days, followed by 24 hours freezing, and then, 72 hours drying in the cabinet at 70°C. After drying, the samples were cooled at 20°C for four hours and the next (second and third) cycles were performed. The second and third cycles were identical to the first one, but the duration of water immersion was 72h. The positions of samples were identical in the first and third test during each cycle, but in the second cycle, the samples were set on their opposite edge, ensuring the varied exposure of the sample material.

The adherence of the coatings was determined based on the tape method that included three main steps with commercial flexible transparent adhesive tapes of 40 mm: 1) the adhesive tape was placed on the upper surface of the sample; 2) firm pressure was applied (the whole area of connection was pressed down); 3) the tape was removed perpendicularly. The evaluation of the coatings' adhesive strength was performed by examining the tape on at selected background, based on the contrast with coating residues. At black background was used for the ceramic coatings, while the polymeric coating was evaluated on a white background. The evaluation of coating residue was determined according to the ISO 4628-1. The tape method was performed twice, before and after the adherence/stress tests. The results of the coating residues were determined by calculation with Python Programming Language, where the black/white images of tapes were used as a code input, and the code assigned a fraction for each pixel of the picture. The threshold for determining the spots of coatings was also established and varied from 0.8 to 0.85 depending on the obtained image.

RESULTS&DISCUSSION

The results for the adherence of the ceramic and polymeric coatings are presented below in Tables 2 and 3. The control samples were not subjected to cycling and weathering tests, indicating the adherence of coatings before various weathering stresses and after accelerated weathering and freeze - thaw cycles. The results of the tape method showed "flaking", the coating separation from the substrate. The flaking results are presented in Table 2, indicating the percentage of coating on the tape.

Table 2

Remained coatings (%) on the tape of control and weather-stressed samples as an average value from six samples, with standard deviations (±)

	Control, flaking before weathering stress	**Flaking after accelerated weathering**	**Flaking after freeze-thaw cycles**
Ceramic-1	8.17 / ±8.89	36.2 / ±12.7	49.7 / ±7.84
Ceramic-2	0.83 / ±1.17	6.50 / ±5.24	49.8 / ±19.3
Polymeric	1.00 / ±0.63	25.2 / ±7.73	6.83 / ±2.14

The average result of coating residue (flaking) with control samples on tape were 8.17%, 0.83%, and 1.00% for the ceramic coatings 1 and 2, and polymeric coating, respectively. The results showed that the ceramic-2 and polymeric coatings remained quite well on the material samples, while the adhesive property of the ceramic-1 coating was lower, and its deviation was also high. Ceramic-2 had the best resistance to the weathering stress, 6.50% flaking residue on tape, while the corresponding values of ceramic-1 and polymeric coatings were 36.2% and 25.2%, respectively, after weathering stress. Despite good resistance of ceramic-2 against accelerated weathering, its colour change was visible, indicating that UV-light exposure influenced the chemical features of the ceramic coating. After freeze - thaw cycles, the adhesive properties of both ceramic coatings were weakened significantly, flaking results on the tapes were almost half, 49.7% and 49.8%. The non-adherence was not so remarkable visibly with the coating of ceramic-2, but its nature was the most heterogenous, which was shown by a high standard deviation. However, the ceramic-2 coating was strongly affected during freeze–thaw cyclic stress, as the coating residue increased from 0.83% to 49.83%, while the corresponding change with ceramic-1 was from 8.17% to 49.67%. The polymeric coating was quite stable, in spite of the stresses caused by freezing and thawing, only 6.83% of coating was flaked onto the tape, indicating a minor flaking increase of 5.66%.

Successful coating depends on the diffusion between material and coating, along with other factors. For example, Kanokwijitsilp *et al.* (2016) stated that adhesion between the coating and the wood surface originated from both physical and chemical interactions. In general, there are two main mechanisms for adhesion to a substrate: mechanical adhesion and chemical interaction. The latter includes the formation of chemical bonds and electrostatic interactions between the material substrate and the coating, while mechanical adhesion is a result off the penetration into and hardening of the coating on the substrate. Mechanical adhesion plays an important role in wood, because this material is porous (Yona *et al.* 2021). The tape test can also be influenced by the sample's surface, and its smoothness level. Poor adhesion was primarily determined on the top layer of the coating, and if the surface roughness were large, the tape test could not fully attach to the coating, just to the top layer of roughness in coating. This was a challenge for the polymeric coating, which had an irregular surface on the samples. On the other hand, the surface irregularities were subjected to more significant UV irradiation due to the smaller distance between the UV source and the coating. A better UV resistance of the coating could be improved by nanoparticles. For example, Auclair *et al.* (2011) found that zinc oxide (ZnO) nanoparticles as an additive restricted the discoloration of clear-coated wood on outdoors application. Dispersion of ZnO nanoparticles also restricted color changes and photodegradation of wood polymers, as well as enhanced photostability (Salla *et al.* 2012).

The ceramic coatings had a low adhesion property with the wooden substrate, especially under the influence of moisture. The methods to improve the adhesion of wood and coating are various, including a primer layer, modifications in viscosity, or some pre-treatments. For example, premineralization, which is the saturation of material with mineral particles (Doubek *et al.* 2018), was used to improve adhesion (Yona *et al.* 2021). However, the intensity of mineralization must be carefully studied because salt impregnation can reduce the strength by more than 10% (Karaman *et al.* 2019). The study of Peng and Zhang (2018) showed that plasma treatment can improve the wettability of wood and primer, further improving adhesion between coating and substrate. In the case of viscosity, it has been found that a low viscosity improved the adhesion strength, especially with Scots pine (Ozdemir *et al.* 2013). Another study by Ozdemir *et al.* (2015) stated that wood species and the chemical composition of modification agent influence the adhesion strength and surface roughness, for example, waterborne agents increased the surface roughness of wood while organic-based agents decreased it.

Data on the influence of the weathering and freeze - thaw cycles on the weight are presented in Table 3. A higher weight increase was observed after the stress of the freeze - thaw cycles compared to the influence of accelerated weathering. The weight increased just below one gram after accelerated weathering, demonstrating a 3.16% increase as a maximum for ceramic-1. The weight increase of the ceramic-2 coating was only 0.88% after accelerated weathering. The weight of the polymeric coating samples increased 2.26% during weathering, and correspondingly during the freeze - thaw cycles, the weight increase was 3.95%. The weight increase after freeze–thaw cycles was more dramatic for ceramic coatings, whose weight increased 14.1% and 16.1%.

Table 3

Weight increase (g) during the accelerated weathering and freeze–thaw cycles tests, with standard deviations (±). Italicized values in parentheses indicate the corresponding percentage increase

	Weight increase during accelerated weathering	**Weight increase during the freeze-thawing cycles**
Ceramic-1	0.80 / ±0.19 (*3.16*)	3.34 / ±0.32 (*16.1*)
Ceramic-2	0.22 / ±0.15 (*0.88*)	3.58 / ±1.09 (*14.1*)
Polymeric	0.34 / ±0.25 (*2.26*)	0.60 / ±0.17 (*3.95*)

One explanation for weakened adhesion is moisture, shown in Table 3 by calculating the samples' weight increase after the test. After cyclic stress, the water absorption of the ceramic coatings was much higher than the polymeric coating. Comparing the remained coating with the water absorption, it can be argued that poor water-repellent properties correlate with weak adhesion. The methods to improve moisture resistance properties include, like, a rough superficial layer. The study of Li and Cao (2018) utilized coatings with silica particles that formed nonregular roughness in the film, simultaneously increasing hydrophobicity by mimicking the surface structure of a lotus leaf. The correct particle size also correlates positively with the hydrophobicity of various cellulose-based substrates (Zhang *et al.* 2019), and in particular, a higher particle size reduces water absorption, for instance (Temiz *et al.* 2006). The role of moisture is clear but difficult to remove since according to Wang *et al.* (2013), the water and moisture absorption of wood can be inhibited or retarded, but a complete prevention is not possible.

The cyclic stress caused clear changes for materials with ceramic coatings (ceramic-1 and ceramic-2), such as non-adherence and formed cracks, which might weaken the usability of the material because of an increase in water uptake, which contributes to rapid degradation between the coating and the substrate. The polymeric coating was less affected compared to the others. Visible changes were noted, and its surface was found to be glue-like. Fig. 1 illustrates the cyclic stressed coatings after tape test. A rough surface structure of polymeric coating was remained during the test, which might give a faulty visual observation in Fig. 1, but all samples were coated into longitudinal direction, not cross section.

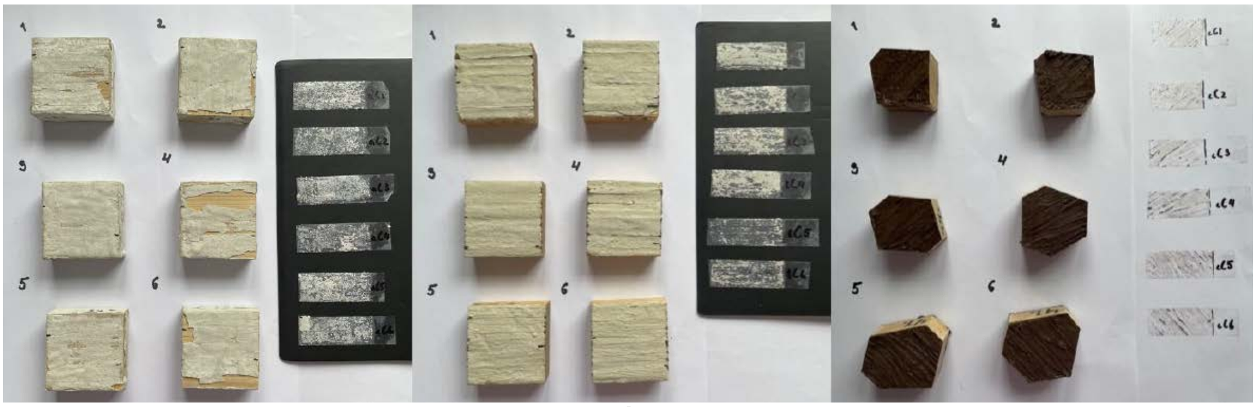

Fig. 1.
Ceramic-1 coating (left), ceramic-2 coating (middle), and polymeric coating (on right) after cyclic stress and tape test.

Despite the results of the study, the coating of wood is still a potential mechanism for improving its properties, because the hydrophobization of wood in deeper layers might be too complex, costly and time-consuming (Wang *et al.* 2013).

CONCLUSIONS

The adhesion properties of various coatings on wood were studied, including an analysis of accelerated weathering and freeze - thaw cycles on the materials. The adhesion property varied between coatings, despite the combination of similar compounds and additives. The results showed a good resistance of coatings against the weathering effect, but the freeze - thaw cycles had a large influence on the sustainable adhesion between the coating and Scots pine wood. In conclusion, based on the performed adhesion feature tests, the presence of moisture caused significant degradation of the coatings. However, the coating could be improved through different pretreatments or additives, such as a correct ratio of nanoparticles in dispersion, achieving nano science advantages such as the lotus effect, which could prevent or reduce the influence of moisture on the material.

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