

EFFECT OF PINE WOOD MOISTURE CONTENT ON COATING ADHESION AND PROCESS STABILITY UNDER UV-LED AND UV MERCURY CURING

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Abstract. The adhesion performance and service durability of wood surface coatings are strongly influenced by the moisture content of wood and the characteristics of the applied curing technology. It plays a critical role in ensuring process reproducibility and product quality under industrial manufacturing conditions. Elevated wood moisture content adversely affects the interaction between the coating and the substrate, as well as the curing process itself, particularly in ultraviolet curing systems. The aim of this study is to investigate the influence of wood moisture content on coating adhesion properties by comparing conventional ultraviolet mercury lamp (UV-Hg) curing systems with modern ultraviolet light-emitting diode (UV-LED) lamp curing systems. Experimental investigations were carried out using profiled Scots pine (*Pinus sylvestris* L.) mouldings representing two macrostructural zones of wood – heartwood and sapwood – at different moisture content levels. Coating adhesion was evaluated using the cross-cut test method according to ISO 2409. The results demonstrated that the (UV-LED) curing system provides more stable and higher coating adhesion performance across a wider range of wood moisture content compared to the (UV-Hg) curing technology. It was concluded that the highest adhesion level was observed in the sapwood zone at $10 \pm 0.5\%$ wood moisture content, indicating a significant interaction between wood anatomical structure, moisture regime and the applied curing technology. The findings confirm the potential of (UV-LED) lamp curing systems to ensure high-quality and durable wood surface coatings under variable production conditions.

Keywords: pine, heartwood, sapwood, moisture content, cross-cut test.

Introduction

The moisture content of Scots pine wood is a key parameter influencing coating adhesion, mechanical performance, and long-term durability. Various curing technologies, including ultraviolet mercury (UV-Hg) and ultraviolet light-emitting diode (UV-LED) systems, have been widely investigated to improve coating efficiency and sustainability. However, the interaction between wood moisture content and different curing technologies is not yet fully understood, which may lead to variability in coating adhesion and limit the optimisation of industrial finishing processes [1-3]. By examining the effects of moisture content, heartwood, and sapwood on coating performance, this study aims to identify the most suitable curing method and the optimal wood moisture content that ensures the highest coating adhesion, as evaluated according to the ISO 2409 standard [4]. UV-LED technology represents an advanced and more environmentally friendly approach to coating curing in industrial wood processing. Unlike conventional ultraviolet mercury (UV-Hg) lamps, UV-LED systems do not contain toxic mercury, making them a safer and more sustainable alternative. This environmental concern is one of the key drivers encouraging the industry to transition towards less harmful curing technologies. UV-LED curing is based on a photopolymerization mechanism, in which UV radiation within the wavelength range of 365 nm to 405 nm activates photo initiators in the coating formulation, thereby initiating and promoting the polymerization reaction [1; 5].

Changes in wood properties and quality are strongly influenced by its hygroscopic nature and its ability to respond to variations in moisture content. This inherent heterogeneity, combined with hygroscopic behaviour, contributes to phenomena such as cracking, deformation, and structural degradation of wood. In freshly cut coniferous timber, the distribution of moisture across the stem cross-section is uneven, with sapwood typically containing two to four times higher moisture content than heartwood [6]. Wood, as a material, exhibits a range of distinct and highly specific properties that significantly influence coating application and the resulting surface quality. Due to the close interaction between the wood substrate and the coating layer, these characteristics play a crucial role in determining coating performance. Among the most important features are anisotropy and a capillary-porous structure. As a result of this structure, wood contains oriented cells with open lumens across all anatomical sections. In tangential and radial sections, the cell lumens form surface depressions,

commonly referred to as wood pores. During coating, these pores can lead to film irregularities and localized accumulation of material, which complicates surface levelling and finishing processes such as sanding and polishing [6; 7].

Strong adhesion between wood surfaces and applied coatings is essential to ensure high-quality performance and durability of the finish. According to the adsorption theory, adhesion between two materials is primarily governed by intermolecular forces. When a coating is applied in liquid form onto a wood surface, the polar groups of macromolecules approach each other, allowing attractive interactions to develop and promote bonding. In contrast, the electrostatic theory explains adhesion as a result of electrical forces acting between contacting surfaces, where oppositely charged regions on the materials generate electrostatic attraction [7]. The highest hardness values were observed at a moisture content of 8%, while no statistically significant differences were found between samples with 10% and 12% moisture content. Coating type had a substantial influence on adhesion performance, with a one-component water-based semi-matte coating demonstrating superior adhesion compared to a two-component water-based glossy coating. In contrast, the effects of wood species and moisture content on adhesion were minimal. Therefore, for applications requiring high surface adhesion, the one-component water-based coating appears to be more suitable option [8]. According to Abdullah Sonmez (2009), moisture content, wood type, and coating type have a significant influence on adhesion performance. For applications requiring high adhesion strength, the moisture content of the wood material should not exceed 8% [9].

De Meijer (2002) investigated that the highest adhesion strength was obtained at 8% moisture content, while 12% and 15% moisture contents gave lower adhesion strengths. It can be said that the increasing moisture decreases the chemical and specific adhesion strength. In this sense, varnish layer adhesion gets weaker with the saturating of OHs on cellulose polymer chain with the water molecules [10]. According to Landry et al. (2015), water-based coatings cured using UV-LED systems generally demonstrate lower surface hardness and abrasion resistance compared to those cured with conventional mercury UV lamps. This indicates that UV-LED technology still requires further development to reach comparable performance levels. In particular, the development of photo initiators specifically adapted to the emission spectrum of UV-LED sources is essential, especially those that ensure coating transparency after curing. Furthermore, increasing the irradiation intensity of UV-LED lamps is necessary to improve polymerization efficiency [11].

Wettability and liquid spreading are governed by a three-phase system involving solid, liquid, and gas, as well as the interactions between their surface free energies. Within the bulk of a liquid, molecular forces are balanced, whereas molecules at the surface are subjected to an unbalanced force field, resulting in the formation of surface free energy, which manifests as surface tension. This parameter determines the ability of a liquid to spread across a solid surface. The degree of wettability is commonly characterized by the contact angle, with 90° considered a critical threshold. When the contact angle is below this value, the liquid spreads readily across the surface, indicating good wettability. In contrast, a contact angle greater than 90° reflects poor wetting behaviour, which can adversely affect coating performance and interfacial bonding [7; 12]. Wood interacts with its surrounding environment primarily through its surface, and surface free energy describes the interactions between the wood substrate and external molecules, serving as a quantitative measure of wettability. Lower viscosity enhances fluidity and promotes deeper penetration into the wood surface, allowing the coating to fill micro-scale irregularities and improve interfacial contact. This enhanced contact facilitates stronger mechanical interlocking between the coating and the substrate, thereby improving adhesion and overall coating durability. In addition, surface preparation plays an important role in wettability and adhesion [3; 13].

Despite extensive research on wood coating technologies and UV curing systems, significant knowledge gaps still exist regarding the interaction between wood anatomical structure and coating performance. Most existing studies focus on process efficiency, curing kinetics, and the environmental aspects of coating systems. In softwoods such as Scots pine (*Pinus sylvestris* L.), heartwood and sapwood exhibit different physical and chemical properties, including differences in permeability, extractive content, and moisture dynamics, which can significantly affect coating adhesion and surface quality. However, there is still a lack of direct comparative studies evaluating the effects of UV-LED and conventional UV curing on coating adhesion in heartwood and sapwood.

The aim of this study is to provide a detailed insight into adhesion in industrial coating processes applied to interior finishing profile elements made of *Pinus sylvestris* L. wood at different moisture content levels, using different coating curing systems. Based on previous studies, where wood moisture content typically ranges from 8% to 15%, this study was designed within a similar moisture range [7]. The study determines the most suitable coating curing system depending on wood moisture content and wood macrostructure. The hypothesis of this study is that the use of UV-LED curing systems for finishing Scots pine wood will result in higher coating quality, providing improved mechanical performance and visual quality under varying influencing factors, compared to UV-Hg curing systems. This study provides a detailed understanding of coating adhesion mechanisms on pine wood, which determine optimal coating quality and durability.

Materials and methods

Data collection in this study was carried out in a carefully structured and systematic manner, ensuring transparency, accuracy, and reproducibility of the results. The main focus was on determining the moisture content of wood, as this parameter directly affects coating adhesion quality. A total of 480 Scots pine (*Pinus sylvestris* L.) wood finishing samples were used, of which 240 were analysed using UV-Hg (mercury lamp) technology and 240 using UV-LED curing. The samples were divided into four moisture content groups: 10%, 12%, 14%, and 16%, with 60 samples in each group. Within each moisture content group, the samples were further divided into two subgroups: heartwood and sapwood. Each group consisting of 30 samples ($n = 30$), ensuring a balanced experimental design. To evaluate data variability and reliability, standard deviation was calculated for each subgroup. The standard deviation values describe the dispersion of individual measurements around the mean and are presented as error bars in the figures. The relatively large sample size contributes to the reliability of the results by reducing the influence of random variation. Adhesion performance was assessed according to the manufacturer defined criteria, with a threshold in red colour value of 2.2 indicated in the figures as the maximum acceptable limit. Prior to coating application, the samples were conditioned under controlled industrial indoor conditions to achieve the target moisture content. Conditioning was performed at a temperature of 20 ± 2 °C, while relative humidity was adjusted according to the desired moisture level: $53 \pm 5\%$ relative humidity for 10% wood moisture content, $65 \pm 5\%$ for 12%, $75 \pm 5\%$ for 14%, and $85 \pm 5\%$ for 16%. The samples were maintained under these conditions until their mass stabilized, indicating that equilibrium moisture content (EMC) had been reached, Table 1. From each moisture group, 10 samples were randomly selected to determine the average moisture content and to verify the homogeneity of the group.

Table 1

Conditioning parameters of wood samples at different target moisture contents

Average moisture content of pine samples, %	Temperature, °C	Relative humidity, %
10 ± 0.5	20 ± 2	53 ± 5
12 ± 0.5	20 ± 2	65 ± 5
14 ± 0.5	20 ± 2	75 ± 5
16 ± 0.5	20 ± 2	85 ± 5

A balanced distribution of samples between heartwood and sapwood was ensured. Wood moisture measurements were carried out using a professional electrical moisture meter based on microwave technology, which enables non-destructive determination of moisture content throughout the wood cross-section. Eight measurements were performed for each sample to obtain a representative moisture content value. Two UV curing technologies with different operating parameters were used for the drying process. In the UV-Hg system, a lamp with a linear power of 120 W/cm was applied, providing broad-spectrum radiation and higher heat emission. In the UV-LED system, a lamp with a surface irradiance of 8–12 W/cm² (395 nm) was used, delivering high radiation intensity within a narrow spectral range and reduced thermal impact on the wood. A constant conveyor speed of 30 m/min was selected for both technologies to ensure directly comparable processing conditions and to eliminate the influence of this parameter on the results. At the same time, technology-specific irradiation parameters were maintained to ensure objective comparability of the results.

Prior to coating application, the samples were mechanically processed to obtain a uniform profile with dimensions of $15 \times 58 \times 200$ mm. Processing was carried out using a four-sided planing machine, ensuring consistent surface quality. Sample dimensions were verified using a digital caliper (accuracy ± 0.01 mm) at three points both ends and the centre. Samples exceeding a tolerance of ± 0.5 mm were excluded from further analysis. The measurement data were recorded and later used for correlation with adhesion and curing results. The coating system consisted of two layers. First, a UV-curable primer was applied to enhance adhesion between the wood substrate and the final coating. This was followed by the application of a water-based coating using vacuum coating technology, ensuring uniform coating thickness and effective penetration into the wood structure.

After curing, the samples were conditioned for 72 hours at a temperature of 23 ± 2 °C and a relative humidity of $50 \pm 5\%$, in accordance with ISO 2409 requirements. This stage ensured complete stabilization of the coating and uniform initial conditions for subsequent mechanical testing [4]. The assessment is carried out according to the ISO 2409 standard classification scale from 0 to 5. A lower classification class (0, 1 or 2) indicates good adhesion of the coating to the base material, where detachment is minimal or practically not observed. A higher classification (3, 4 or 5), on the other hand, suggests weak adhesion, with significant separation of the coating from the substrate.

Results and discussion

By combining technological testing with quantitative data analysis, a comprehensive assessment of the influence of each curing method on wood coating quality was obtained. This approach allowed not only the evaluation of adhesion-related mechanical properties but also provided insight into the suitability of each technology for industrial applications. The results indicate a general trend in which UV-LED technology achieves higher performance compared to UV-Hg. Initial experimental observations showed that at 10% moisture content, both curing systems achieved the best adhesion performance according to production quality criteria. Adhesion performance in Scots pine (*Pinus sylvestris* L.) heartwood was evaluated by comparing different curing systems.

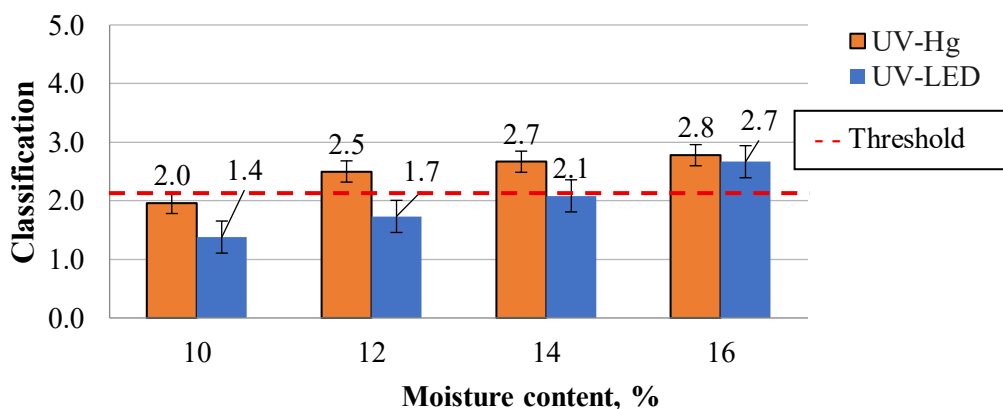


Fig. 1. Histogram of heartwood adhesion quality classification as a function of moisture content using UV-Hg and UV-LED curing systems

Based on the adhesion test results, the UV-LED system demonstrated the best performance, achieving an average classification value of 1.4 at 10% moisture content, without exceeding the specified quality limit indicated by the dashed red line in Fig. 1. The dashed red line represents the threshold for production quality requirements. However, when the moisture content exceeded 14%, heartwood samples in both curing systems failed to meet the required quality threshold, as the adhesion classification exceeded the acceptable limit of class 2, as shown.

Adhesion testing was also performed on Scots pine sapwood samples. Based on the average values, the adhesion classification was determined for each corresponding moisture content level. The histogram shows that the lowest performance, with a classification value of 2.4, was observed at 16% moisture content for both curing systems. In contrast, the UV-LED system maintained acceptable quality

levels up to 14% moisture content, whereas the UV-Hg system met the quality criteria only up to 12% moisture content, reaching a classification value of 2.1, as illustrated in Fig. 2.

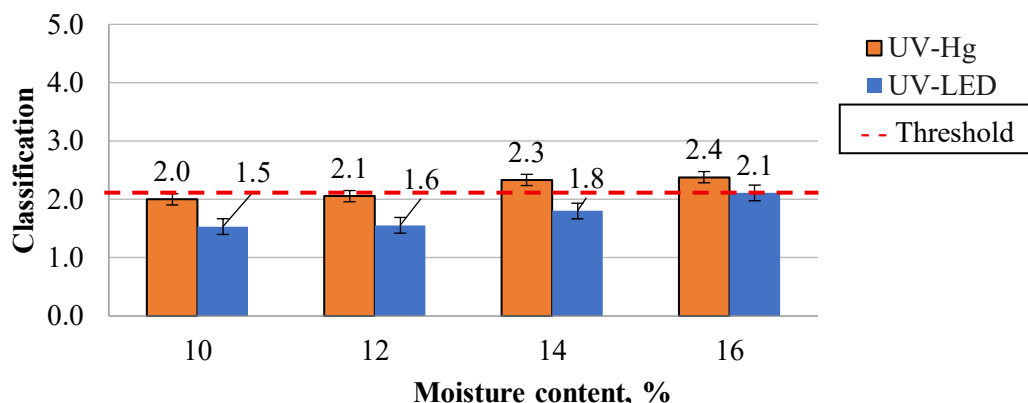


Fig. 2. Histogram of sapwood adhesion quality classification as a function of moisture content using UV-Hg and UV-LED curing systems

To provide a clearer comparison of the relative performance of each curing system across different moisture levels, two histograms were developed for both heartwood and sapwood. Based on all tested samples evaluated according to the ISO 2409 standard, it was observed that UV-LED curing consistently achieved better adhesion performance than UV-Hg across all moisture content levels. As shown in Fig. 3, the largest difference in adhesion performance reached 16%, where the UV-LED system demonstrated superior quality at 12% wood moisture content. In contrast, the smallest difference between the curing systems was observed at 16% moisture content in Scots pine (*Pinus sylvestris* L.), where the performance difference was approximately 2%.

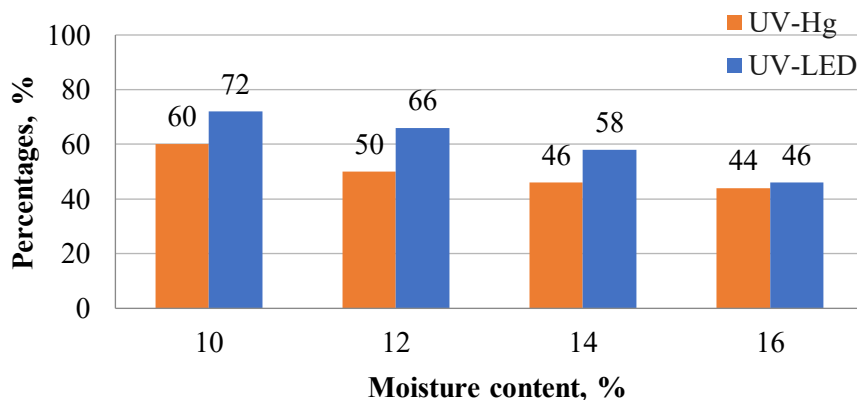


Fig. 3. Percentage improvement in adhesion classification of UV-LED compared to UV-Hg in heartwood

The histogram illustrating the percentage comparison of Scots pine (*Pinus sylvestris* L.) between the two UV curing systems, shown in Fig. 4, reveals the largest differences at moisture content levels of 10, 12% and 14%. At these levels, the UV-LED curing system demonstrates approximately 10% higher adhesion performance compared to UV-Hg. The smallest difference is observed at 16% moisture content, where the performance gap is about 6%, with UV-Hg showing lower adhesion than UV-LED.

Compared with previously published studies the observed trends are consistent with the findings, indicating that increasing wood moisture content leads to a decrease in coating adhesion performance regardless of the testing methodology. In both studies, the highest adhesion achieved at lower moisture contents is approximately 8 -10%, while higher moisture levels (≥ 12 -15%) result in reduced adhesion. This effect is mainly attributed to moisture-induced occupation of hydroxyl groups and dimensional changes in wood, which hinder effective bonding and promote adhesion defect [8; 9].

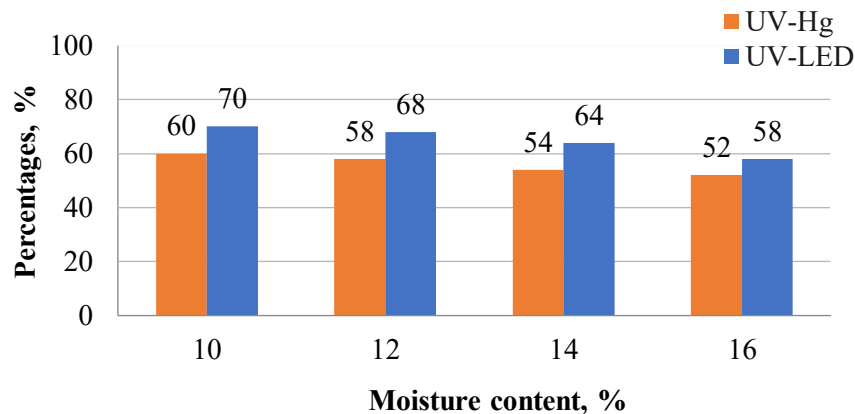


Fig. 4. Percentage improvement in adhesion classification of UV-LED compared to UV-Hg in sapwood

Conclusions

1. To meet the quality requirements established in production, the UV-LED classification not exceeding 2.1 units allows the use of Scots pine (*Pinus sylvestris* L.) wood in both heartwood and sapwood with a moisture content not higher than 14%. In contrast, when using a UV-Hg lamp system, it is recommended to use Scots pine wood in both structures with a moisture content not higher than 10%.
2. Based on the obtained results, it is concluded that increasing moisture content in Scots pine (*Pinus sylvestris* L.) wood leads to a decrease in coating adhesion classification. Although UV-LED lamps can provide better adhesion quality than UV-Hg, it is not recommended to exceed 14% moisture content in wood to maintain high adhesion performance under any curing method.
3. The results demonstrate that the use of UV-LED curing leads to higher adhesion quality across all wood moisture levels, outperforming the UV-Hg system. Considering all moisture content groups, the average adhesion performance in heartwood is 10.5% higher for the UV-LED system compared to UV-Hg. Similarly, in Scots pine (*Pinus sylvestris* L.) sapwood, the average difference between the curing systems is 9%, with UV-LED consistently providing superior results.
4. The findings of this study could be significantly enhanced by incorporating not only qualitative indicators but also quantitative analyses, which were not addressed in the present work. The inclusion of pull-off strength tests in accordance with ISO 4624 would provide more accurate, objective, and clearly interpretable results regarding coating adhesion performance.

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Author contributions

Conceptualization, A.D, A.U and V.J.; methodology, A.D. and V.J.; validation, V.J.; formal analysis, A.D.; investigation A.D, A.U and V.J.; data curation, A.D., V.J. and U.S.; writing – original draft preparation, A.D.; writing – review and editing, V.J. and U.S.; visualization, A.D.; project administration, A.U.; All authors have read and agreed to the published version of the manuscript.

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