

Article

UV-LED Curing Efficiency of Wood Coatings

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Abstract: Ultraviolet light emitting diodes (UV-LEDs) have attracted great interest in recent years. They can be used to polymerize coatings, such as those used for prefinished wood flooring. In this project, two lamps were compared for their suitability to be used on a wood flooring finishing line: a UV-microwave and a UV-LED lamp. Low heat emission was found for the UV-LED lamp compared to the UV-microwave one. This study also reveals that the 4 W/cm² UV-LED lamp used is not powerful enough to cure UV high solids acrylate coatings while satisfactory results can be obtained for UV water-based formulations. In fact, conversion percentages were found to be low for the high solids coatings, leaving the coatings tacky. Higher conversion percentages were obtained for the UV water-based formulations. As a result, mass loss, hardness, and scratch resistance found for the samples cured by UV-LED were closed to the ones found for the samples cured using the UV microwave lamp.

Keywords: UV-LED; UV-curable coatings; wood flooring; acrylates; photoinitiators; mechanical resistance; conversion percentages

1. Introduction

UV-curable technology is one of the fastest growing markets in the paint and coating industry. In 2008, a market analysis for the UV coating technology anticipated a world growth between 8% and 13% on average over the next five to seven years [1]. In 2011, UV/EB-formulated product usage in North America was 120,000 metric tons. For wood finishes only, UV/EB product usage went from 14,900 metric tons in 2001 to 23,200 metric tons in 2011 [2]. In 2013, according to the Radtech biennial market survey [3], the percentage of UV/EB formulated product usage by volume was 19% for wood, which represents an annual growth rate of 6.3% for wood stains/sealers and 5.8% for flooring.

The reasons for the rapid and steady growth of UV-curable coatings are numerous. The most commonly cited are the following: low VOC emissions, excellent mechanical and chemical resistance, and fast curing/drying. Currently, most UV systems for flat line wood coating operations are Hg arc lamps and are operated at either 200 or 300 W/inch [4]. However, lamp requirements are closely related to the formulation to be cured and its reactivity. The latter depends on two main factors: the type of acrylate used and their functionality. Cure speed is higher for epoxy acrylate followed by polyester acrylate, urethane acrylate, and finally unsaturated polyester acrylate [5]. A high concentration of monofunctional monomer used as thinner strongly reduces the coating cure speed. At the opposite, highly functionalized monomers increase coating cure speed and increase cured film resistance to abrasion. Recent work has led to advances in improved outdoor weathering, adhesion increase, faster cure speeds, and the use of UV-Light emitting diodes (UV-LEDs) [3]. Replacement of conventional mercury or gallium arc lamps by UV-LEDs has intensified. According to Radtech, the main motivations for users to switch for UV-LED technology are their suitability for heat-sensitive substrates, their energy efficiency, LED lifetime, and their instant on/off capability. UV-LEDs also present significant environmental benefits (ozone free, workplace safety, UV-A wavelength range) as well as advanced capabilities (through cure, compact equipment, controlled curing intensity) [6]. All this put together makes it an environmentally friendly technology which has the potential to significantly reduce the carbon footprint of the UV-curing technology. UV-LEDs have been commercially available for over 10 years but with recent developments, *i.e.*, increased energy output and lower initial cost, they have become commercially viable for several industries, including the wood coating one.

Light-emitting diodes (LEDs) are semiconductor light sources. When the excited electrons relax, they emit energy in the form of photons. The wavelength of the emitted photons depends on the material used for the construction of the diode. The output of the LEDs is one very narrow band (± 10 nm) where 96% of the energy is emitted. At the opposite, conventional arc lamps present several peaks distributed throughout the UV spectrum (UVA, UVB, UVC, UVV). This explains why UV-LEDs are 60%–80% more efficient than conventional mercury lamps at a given wavelength [7]. Moreover, UV-LEDs do not emit infrared energy (700 nm to 1 mm), which is the contributor to the heat buildup, since the energy of the UV-LED is concentrated in a narrow region. As stated previously, changing to UV-LEDs also reduces environmental impact. Indeed, each UV-LED lamp consumes on average 50% less energy than an equivalent arc lamp which could be explained in part by an instant on/off (no warm-up time) and no unnecessary wavelength [8]. In addition, UV-LEDs do not contain harmful compounds such as mercury and do not produce ozone or any other harmful gases. Their consumption power is much lower than the one of UV-mercury lamps and neons and their service life is significantly longer; UV LED lamps last

over 20,000–50,000 h of run time as compared to a mercury lamp running ~2000 h total [6]. This technology also offers energy and cost saving due to the performance of the lamp and the system; lower surface temperature, smaller lamp, and less maintenance and downtime which lead to a higher productivity rate. According to the literature, with the integration of this technology in a coating line, it is possible to achieve energy savings on the order of 30% and even more when a UV-LED can replace several conventional UV arc lamps [9].

All this said, UV-LED technology still presents some major drawbacks. Still according to Radtech [3], the main factors that may be limiting the use of UV-LED are, (1) the lack of suitable curable materials; (2) high investment costs; (3) technical limitations of existing equipment (output, cooling, size, wavelength). Suitable curable materials should be more easily available in the next few years as photoinitiators adapted to UV LED technology [10,11] are currently under development. Purchase price of UV LEDs is still higher than the one of conventional lamps although the development of the technology and the increased market shares are both reversing this trend. As for the technical limitations, UV-LEDs are sensitive to heat and the use of high power diodes often requires the addition of a cooling circuit. Their power is still low compared with conventional lamps and as a result UV-LEDs' coating polymerization is slower than with traditional UV lamps. Lamp manufacturers are working on the development of more powerful lamps with should improve curing shortly.

UV-curing has always been a technology of choice for wood flooring products [4]. However, traditional UV lamps still emit little heat which can be problematic for products that are packaged immediately after the coating operations, such as wood flooring, as wood is a heat sensitive material and is prone to cracking/splitting. Since UV-LEDs emit no infrared energy, recent studies showed that they provide significant advantages compared to conventional UV-curing method for wood coating applications [8]. The purpose of our work was to compare the mechanical properties of UV-curable high solids and UV-curable water-based coatings formulated for wood flooring after UV-LED curing and UV mercury curing (mercury lamps microwave). A technological evaluation was also carried out on the heat emissions for the two technologies.

2. Experimental Section

2.1. Materials

The UV-LED lamp used is the RX Starfire MAX (Phoseon Technologies, Hillsboro, OR, USA). The lamp has a width of 150 mm. It emits in the UV-A spectrum (380 to 420 nm) at an irradiance of 4W/cm². For comparison purposes, a UV-microwave mercury lamp UV-MAC10 (Nordson Corporation, Wetlake, OH, USA) was used. This lamp uses a microwave technology. The UV microwave lamp contains a mercury bulb of 25 cm in width whose illumination (power per unit area) can vary from 80 to 235 W/cm². In this work, two coating formulations were prepared; an UV high-solids acrylate and an UV water-based polyurethane acrylate. The photoinitiators used in the various formulations are presented in Table 1.

Table 1. Chemical identity and trade name of the photoinitiators used.

Trade Name	Photoinitiators (Chemical Identity)
Genocure DMHA	Aromatic ketone
Omnirad CureAll700	Proprietary blend of photoinitiators
Esacure KTO46	Mixture of trimethylbenzoyldiphenylphosphine oxide, α -hydroxyketones and benzophenone derivatives
CQ	camphorquinone/amine
TPO	Diphenyl(2,4,6-trimethylbenzoyl)phosphine oxide
Darocure 1173	2-Hydroxy-2-methyl-1-phenyl-propan-1-one
Varnifm Photoinitiator 907	2-Methyl-4'-(methylthio)-2-morpholinopropiophenone
Shoufu-6699	2-Benzyl-2-(dimethylamino)-4'-morpholinobutyrophenone
Photoinitiator 184	1-Hydroxy-Cyclohexyl-Phenyl-Ketone
Irgacure 2100	Phosphine oxide
Chivacure 2-ITX	2-Isopropylthioxanthone
SpeedCure-EDB	Ethyl-4-(dimethylamino)benzoate
Irgacure 819	Bis(2,4,6-trimethylbenzoyl)-phenylphosphineoxide
Esacure DP250	2,4,6-trimethylbenzoyldiphenylphosphine oxide, α -hydroxyketones and benzophenone derivatives

The UV high-solids acrylate formulation selected is composed of five main reactives: two acrylate monomers, two acrylate oligomers, and a photoinitiator or a mix of photoinitiators. The two acrylate monomers selected are the 1,6 hexanediol diacrylate (HDODA) and the tripropylene glycol diacrylate (TRPGDA). The oligomers used are an aliphatic polyester-based urethane hexaacrylate oligomer (CN 968) and a difunctional bisphenol A based epoxy acrylate blended with TRPGDA (CN 104A80). All acrylate products were provided by Sartomer. The UV high-solids formulations were prepared as followed: 711 g of each acrylate oligomers were mixed together with a high speed mixer (Ragogna Custom Machinery Ltd., Brampton, Canada). Defoaming agent (BYK 170, BYK Chemie) was added if necessary and mixing was pursued for 5 min. 289 g of each monomer were added and mixed again for 5 min. Photoinitiators were always added at the end to prevent evaporation. Table 2 presents the photoinitiator concentration used for each formulation and the curing method. Concentrations vary from one formulation to another, photoinitiators suppliers' recommendations were followed.

The resin used for the UV-curable water-based formulations is a polyurethane-acrylate resin, Bayhydrol 2282, from Bayer Material Science. Its solid content is 39% w/w. The water-based formulations were prepared by incorporating the photoinitiator to the polyurethane-acrylate resin and then mixed mechanically for 10 min with a high speed mixer (Ragogna Custom Machinery Ltd., Brampton, Canada). Table 3 presents the formulation identification, the photoinitiators concentration and the lamp used.

The main criterion for the selection of the photoinitiators was the absorption peak which has to be around the UV-LED emission wavelength (395 nm). Darocure 1173 was used as a comparative photoinitiator (no absorption peak at 395 nm).

Table 2. Photoinitiators concentrations (in wt.%) for each formulation and the curing method used.

Formulation	Photoinitiators Concentrations (wt.%)	Curing Method
A	10% mix of DMHA + TPO + CQ	UV-LED
B	7% CureAll700	UV-LED
C	4% Esacure KTO46	UV-LED
D	8% Esacure KTO46	UV-LED
E1	4% Darocure 1173	UV-mercury
E2	4% Darocure 1173	UV-LED
F	3% 907+ 2% Chivacure ITX	UV-LED
G	3% 6699 + 2% ITX + 3% EDB	UV-LED
H	2% 6699 + 2% 184	UV-LED
I	2% Irgacure 2100 + 2% ITX	UV-LED
J	3% Irgacure 2100 + 3% ITX	UV-LED
K	2% 907 + 0.5% ITX	UV-LED
L	2% 907 + 1% ITX	UV-LED
M	3% TPO + 2% EDB	UV-LED
N	4% 6699 + 1% ITX	UV-LED
O	3% Irgacure 819	UV-LED

Table 3. Photoinitiator concentrations (in wt.%) for each water-based formulation and the curing method used.

Formulation	Photoinitiator Concentrations (wt.%)	Photoinitiator Name	Curing Method
1	5%	Genocure DMHA	UV-LED
2	7.5%	Genocure DMHA	UV-LED
3	1%	Irgacure 2100	UV-LED
4	2%	Irgacure 2100	UV-LED
5	1%	Esacure DP250	UV-LED
6	2%	Esacure DP250	UV-LED
7	1%	Darocure 1173	UV-LED
8	2%	Darocure 1173	UV-LED
9	1%	Irgacure 819	UV-LED
10	2%	Irgacure 819	UV-LED
7a	1%	Darocure 1173	UV-mercury
8a	2%	Darocure 1173	UV-mercury
9a	1%	Irgacure 819	UV-mercury
10a	2%	Irgacure 819	UV-mercury

2.2. Methods

2.2.1. Evaluation of the Irradiation and Surface Temperature

To measure the irradiation of the two lamps used, a radiometer UV Power Puck II (EIT Inc., Sterling, VA, USA) was employed. Radiation measurements were taken at different speeds and at different lamp heights. Due to the lamp specifications, the irradiation was not measured at the same heights for the two lamps. For optimal curing, the UV-LED lamp had to be placed as close as possible from the substrate and the UV-mercury lamp must be at the focus. The surface temperature of the floorboards was measured

with an infrared thermometer model Raynger ST (Raytek, Wilmington, NC, USA). For the flooring strips cured with the UV-LED lamp, the temperature at the surface was taken at a lamp height of 1.25 cm at four conveyor speeds (0.8, 4.6, 6.7, and 12.5 m/min). For the ones cured with the UV-mercury lamp, the temperature was registered at a lamp height of 5 cm and at conveyor speeds of 3.7, 7.4, and 11 m/min.

2.2.2. Sample Preparation

Preliminary tests were performed in order to determine the most promising formulations, that is to say, the ones with the best mechanical properties. For the preliminary tests, each formulation was applied on standardized glass plates. The UV high-solids formulations were applied with a four-side applicator (BYK). The water-based formulations were applied on glass plates with a foam brush. Three coats were applied to reach a dry film thickness of 100 microns. After the preliminary test, the best formulations obtained with UV-LED lamp and the UV-mercury lamp were applied with a paint gun on glass plates and sugar maple (*Acer saccharum* March) samples. The thickness of all the coatings was 100 microns (4 mil) wet. Wet film thickness was measured using a wet film gauge.

The UV water-based formulation were first dried in the oven at 60 °C for 15 min to remove water before being polymerized under the UV-LED or the UV-mercury lamp. The UV-LED formulations were cured at an irradiation of 467 mJ/cm² and a conveyor speed of 0.8 m/min. UV-mercury formulations were cured at an irradiation of 456 mJ/cm² and the conveyor speed was 11 m/min.

2.2.3. Measurement of the Curing Percentage

Conversion percentage of each formulation was calculated by following the decrease of the peaks at 1408 cm⁻¹ for the water-based formulations and 1635 cm⁻¹ for the UV high-solids formulations both C=C bond absorption bands. These bands were selected based on information from previous studies [12,13]. The apparatus used is a Tensor 37 Fourier-transform infrared spectrophotometer equipped with a Platinum ATR (diamond crystal) from Bruker Corporation, (Billerica, MA, USA) using a resolution of 4 cm⁻¹. The conversion degree was calculated using the equation 1 where A_0 is the absorbance (area of the band) before irradiation and A_t is the absorbance at time t .

$$\text{Percentage of conversion} = [(A_0 - A_t)/A_0] \times 100 \quad (1)$$

Three measurements on three different samples were performed.

2.2.4. Color Measurements

The color of the different cured formulations was measured with a portable sphere spectrophotometer from X-rite model SP62 (X-rite, Grand Rapids, MI, USA). The CIE $L^*a^*b^*$ color scale was used for color measurements. It describes all the colors visible to the human eye. Three basic coordinates (L^* , a^* and b^*) were determined for each sample. The color axes (a^* and b^*) are based on the fact that a color cannot be both red and green, or both blue and yellow, because these are opposite colors. On each axis, the values run from positive to negative. On the a - a' axis, positive values indicate amounts of red while negative values indicate amounts of green. On the b - b' axis, yellow is positive and blue is negative.

For both axes, zero is neutral gray. The central vertical axis represents lightness (signified as L^*) whose values run from 0 (black) to 100 (white).

From the L^* , a^* , and b^* values, delta values (ΔL^* , Δa^* , and Δb^*) were calculated for each coordinate. The total color change, ΔE , was measured according to the following equation:

$$\Delta E = \sqrt{(L_1 - L_2)^2 + (a_1 - a_2)^2 + (b_1 - b_2)^2} \quad (2)$$

2.2.5. Scratch Resistance Tests

The scratch resistance tests were carried out using an apparatus that performs back and forth cycles of a Scotch-Brite™ (3M-07445 light duty white) on the surface of sugar maple samples. To increase the weight applied on the surface of the flooring strips, a 1000 g weight was placed on the Scotch-Brite™. The results obtained are function of the gloss retention of the samples after a number of given cycles in comparison with the initial gloss. The gloss was measured initially, after 100 and 200 cycles at an angle of 60° with the micro-TRI-gloss (BYK-Gardner, Columbia, MD, USA) glossmeter.

2.2.6. Abrasion Resistance Tests

The abrasion resistance test is in the spirit of the ASTM D 4060-14 test method “*Standard Test Method for Abrasion Resistance of Organic Coatings by the Taber Abraser*” using a Taber Abraser 5130 Digital (Taber Industries, North Tonawanda, NY, USA). The samples were placed under abrasive wheels (CS-17 Abrasive Wheels) and were subjected to a number of rotations. A weight of 1000 g was placed on each abrasive wheel to ensure constant pressure on the sample throughout the test. The weight of the sample is taken initially and after each cycle of 100 rotations up to 500 rotations. The total weight loss is obtained by subtracting the weight after 500 rotations to the initial weight. Another way to indicate rate of wear is with the wear index. It is calculated by measuring the loss in weight per thousand cycles of abrasion. The weight loss per thousand cycles of abrasion is calculated as followed:

$$I = \frac{(A - B) \times 1000}{C} \quad (3)$$

A is the initial mass, B is the mass after abrasion, and C is the number of cycles. The lower the wear index, the better the abrasion resistance. Before each test, the abrasive wheels are resurfaced with an abrasive disk (S-11) and dusted.

2.2.7. Hardness Tests

The König pendulum hardness test was performed using a pendulum hardness tester (BYK-Gardner, Columbia, MD, USA) in the spirit of the ASTM D4366-14 test method. The hardness of the sample is given by the number of oscillations or the oscillation time. The amplitude of the pendulum’s oscillation decreases more quickly when supported on a softer surface. The sample is first put on the pendulum table, then the pendulum is tilted at a 6° angle and fixed in that position. Once the counter is reset, the pendulum is released. The timer is stopped when the pendulum’s amplitude is not high enough to reach the photovoltaic cell which is at a 3° angle.

3. Results and Discussion

3.1. Characterization of the Lamps Use for UV Curing

3.1.1. Lamp Irradiation

The irradiation of the UV-LED and UV-mercury lamps was measured at different heights and different conveyor speeds. Figure 1 presents the irradiation curves (mJ/cm^2) obtained with the two lamps at different heights and speeds of the conveyor. No measurement was made with the UV-mercury lamp at a speed of 0.8 m/min since the heat at the surface was too high.

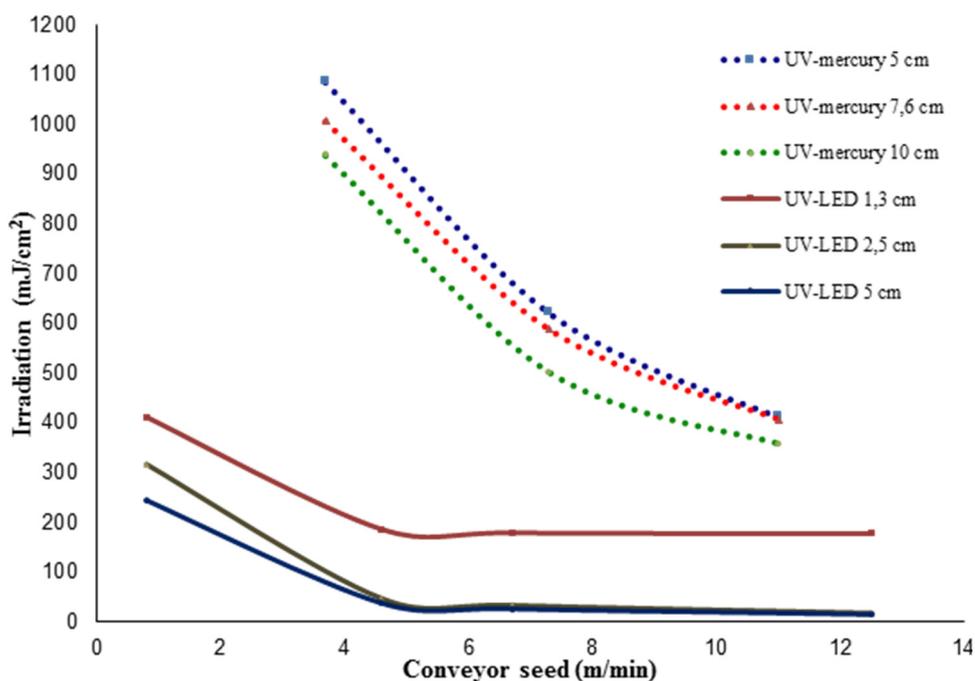


Figure 1. Irradiation of the UV-LED and UV-mercury in function of height and conveyor speeds.

As presented in Figure 1, there is an important difference of irradiation between the two types of lamps. There is also a major difference for the UV-LED lamp between a height of 1.3 cm, 2.5 cm, and 5 cm. At a height of 1.3 cm, the irradiation is 5 to 12 times higher compared to a height of 2.5 cm and 5 cm, respectively. At speed higher than 4.6 m/min the irradiation remains constant no matter the lamp position. The maximal irradiation obtained with the UV-LED lamps is $412 \text{ mJ}/\text{cm}^2$ at a height of 1.3 cm and a conveyor speed of 0.8 m/min. For the UV-mercury lamp, the irradiation does not differ significantly in function of the position. The factor that influences the irradiation of a UV-mercury lamp most is the conveyor speed. The highest irradiation registered is $1085 \text{ mJ}/\text{cm}^2$ at 5 cm height with a conveyor speed of 3.7 m/min. In sum, to reach the irradiation maximum of the UV-LED lamp ($412 \text{ mJ}/\text{cm}^2$), the UV-mercury lamp has to be placed 7.6 cm high and at a conveyor speed of 11 m/min.

As per mill visit, flooring finishing lines operate at a speed of 9 m/min to cure high solid content coatings. To keep that speed with UV-LED, the polymerization of the system must be achieved with an irradiation level of $175 \text{ mJ}/\text{cm}^2$.

3.1.2. Surface Temperature

The surface temperature of the flooring strips was measured right after the pre cure in the oven. Figure 2 presents the curve of the surface temperature of the flooring strips in function of the conveyor speed.

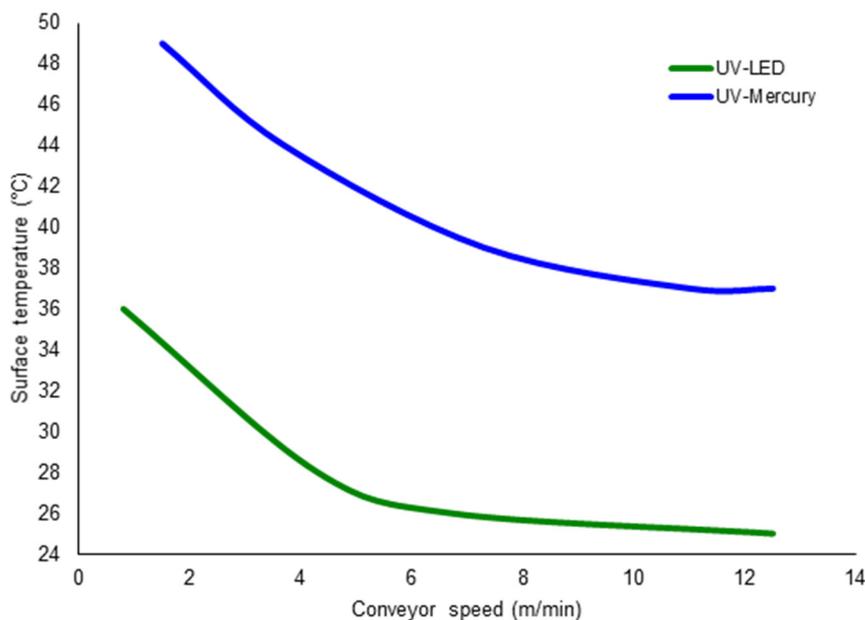


Figure 2. Surface temperature obtained with the two lamps in function of the conveyor speed.

The surface temperature of the flooring strips varies greatly depending on the type of lamp and the conveyor speed. There is a mean difference of 12 °C between the two lamps. At a speed of 9 m/min which is the standard speed on a finishing line, the temperature at the surface reached 25 °C with the UV-LED lamp compared to 38 °C with the UV-mercury lamp. The initial temperature of the flooring strips was 24 °C. Thus, there is a real benefit to using an UV-LED lamp to reduce the surface temperature of the flooring strips. This could prevent the development of micro checks at the surface of the strips.

3.2. Coating Characterization

3.2.1. Conversion Percentages

The conversion percentages (calculated using the equation 1) for the UV high-solids formulations are presented in Table 4.

As shown in Table 4, all the conversion percentages are quite low, under 70% except for the formulations E2, G, and J. Those low conversion percentages shows that the polymerization is not sufficient. In addition, the surfaces were tacky, also proving that polymerization is low. This also means that the photoinitiators used have adequate absorption for the chosen UV-LED. However, the power of the lamps does not seem sufficient to cure the UV high-solids formulations. The formulations that present the highest conversion percentages used the following photoinitiators; Darocure 1173 (absorption peaks: 245, 280 nm) (E2), a mixture of 6699 + Chivacure 2-ITX (absorption peak: 260 nm) + Speedcure-EDB (absorption peak: 261 nm) (G), and a mixture of Irgacure 2100 (absorption peaks: 275, 370 nm) + Chivacure 2-ITX (absorption peak: 260 nm) (J).

Table 4. Conversion percentages obtained for the UV high-solids formulations.

Formulations	Conversion Percentages (%)
A	37 ± 7
B	38 ± 6
C	21 ± 7
D	23 ± 6
E1	15 ± 8
E2	78 ± 4
F	67 ± 3
G	78 ± 4
H	21 ± 6
I	54 ± 8
J	71 ± 3
K	26 ± 5
L	48 ± 6
M	41 ± 4
N	65 ± 3
O	28 ± 7

As the UV high-solids formulations were still tacky, no other tests were performed. The rest of the study presents results obtained for the UV water-based formulations. Table 4 presents the conversion percentages of the acrylate groups of the UV-water-based formulations.

The conversion percentages presented in Table 5 are, for most of the UV water-based formulations, higher than the conversion percentages obtained with the high-solids formulations. This means that the UV-LED lamp selected is more suitable for curing UV water-based formulations. The formulation that presents the highest conversion percentage is the formulation 6 that used Esacure DP250 as a photoinitiator.

Table 5. Conversion percentages obtained for the UV water-based formulations.

Formulations	Conversion Percentages (%)
1	44 ± 5
2	43 ± 5
3	84 ± 4
4	92 ± 3
5	66 ± 3
6	93 ± 2
7	29 ± 6
8	43 ± 4
7a	91 ± 5
8a	92 ± 4
9a	87 ± 3
10a	73 ± 4

3.2.2. Mechanical Properties

The following section presents the mechanical properties of the most promising formulation for UV-LED curing and UV-mercury curing synthesized in this study; formulation 6 for UV-LED curing and formulation 7a for UV-mercury curing.

Scratch Resistance Tests

The scratch resistance of the coating cured with UV-LED and UV-mercury lamp was evaluated on sugar maple samples coated with the formulations 6 and 7a. Initially, the gloss at 60° is higher for the UV-mercury cured (gloss of 74) compare to the UV-LED cured (gloss of 60). Figure 3 presents the gloss loss of the cured samples after 100 and 200 cycles of the Scotch-Brite™ (3M-07445 light duty white) on the surface of the samples.

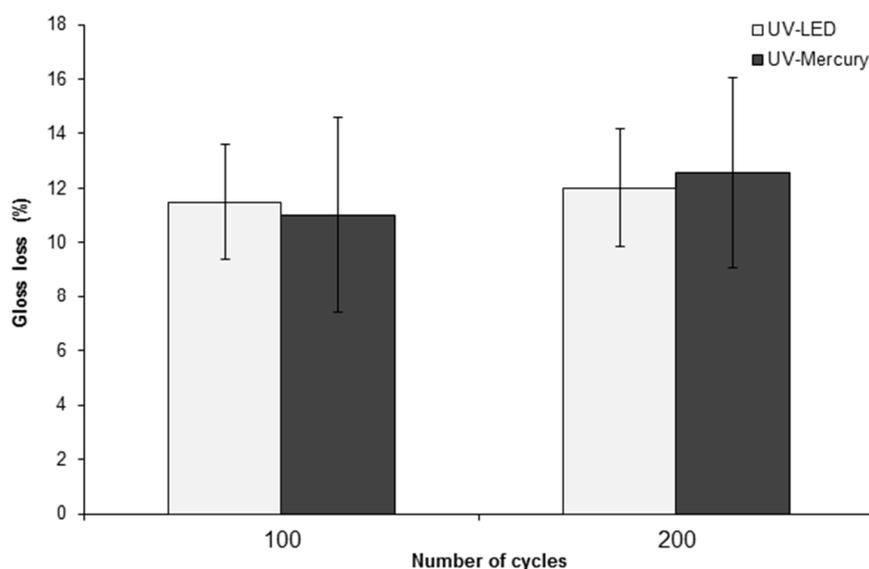


Figure 3. Gloss loss of the cured samples with UV-LED and UV-mercury lamp in function of the number of cycles.

Due to the high variability between measurements, no significant difference of gloss loss between the two curing methods could be observed. The average gloss loss after 200 cycles is 12.0% and 12.6% for the UV-LED and the UV-mercury lamps respectively, which demonstrates that the two curing method give similar results with the scratch resistance tests. Note that the values obtained are relatively small considering that no additive was added to the varnish to increase its mechanical properties.

Abrasion Resistance Tests

The abrasion resistance of the varnishes 6 and 7a cured with UV-LED and UV-mercury lamps was measured on sugar maple samples, inspired from the ASTM D-4060 standard. Figure 4 presents the cumulative mass loss of the samples in function of the number of rotations.

As shown in Figure 4, the resulting mass loss increase as the number of rotations increase, independently of the curing method. However, the mass loss for the samples cured with the UV-LED

lamp is 1.5 times greater than for the one cured with the UV-mercury lamp. Figure 5 presents the wear index of the formulations cured by UV-LED and UV-mercury lamps.

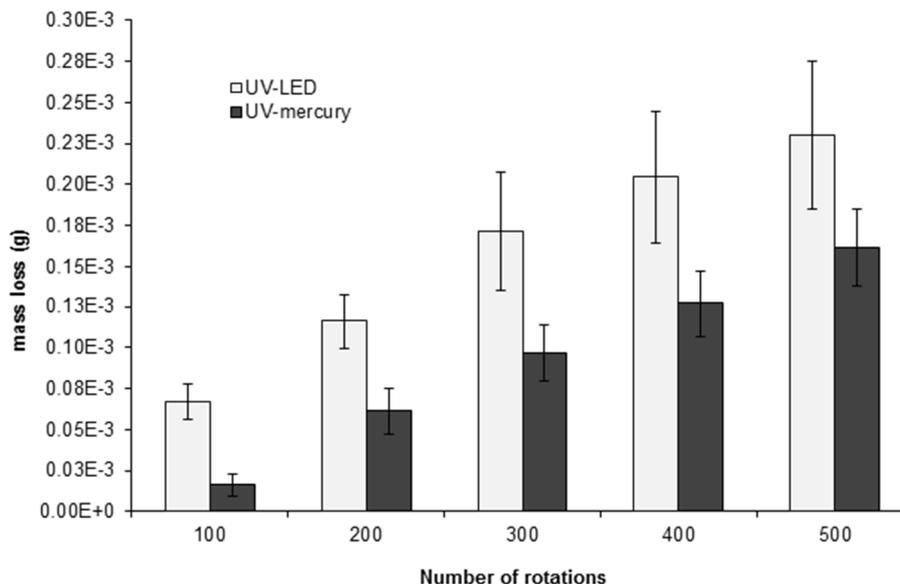


Figure 4. Graph of the mass loss in function of the number of rotations.

By reporting on a comparative basis of 1000 rotations (wear index) the mass loss obtained for every 100 rotations, it becomes clear that the mass loss rate differs between the two types of curing methods. The mass loss of the formulation 6 (UV-LED) is high for the first 100 rotations and then tends to decrease. The mass loss goes from 0.067 g/1000 rotations to 0.046 g/1000 rotations. The mass loss for the formulation cured with the UV-mercury lamp is only 0.019 g/1000 rotations after the first 100 rotations and the mass loss seems to stabilize at 0.032 g/1000 rotations. In both cases, for the same curing method, the differences observed between 100 and 500 rotations are not statistically significant. Nevertheless, the Figure 5 shows the tendency of mass loss for the two curing methods. This could mean that UV-LED lamps allow a better deeper curing [3] of the coating while the UV-mercury lamps allow better surface curing. Note that a high power UV-LED lamp is not necessary to fully cure a formulation. With the results present in this section, the formulation cured with the UV-mercury lamp present a better abrasion resistance.

Hardness Tests

The hardness of the formulation cured with the UV-LED and UV-mercury lamp were measured on glass plates as the hardness of the substrate use can influence the results. Thus, a substrate that presents a homogeneous hardness is required for this type of test. Figure 6 shows the hardness of the varnishes in function of the curing method used.

The hardness of the formulation cured with UV-LED is of 180 s compared to a hardness of 201 s for the formulation cured with UV-mercury. The difference between the two values is significant. Thus, the formulation cured with the UV-mercury lamp presents a greater hardness. This could be due to an incomplete polymerization of the UV-LED formulation.

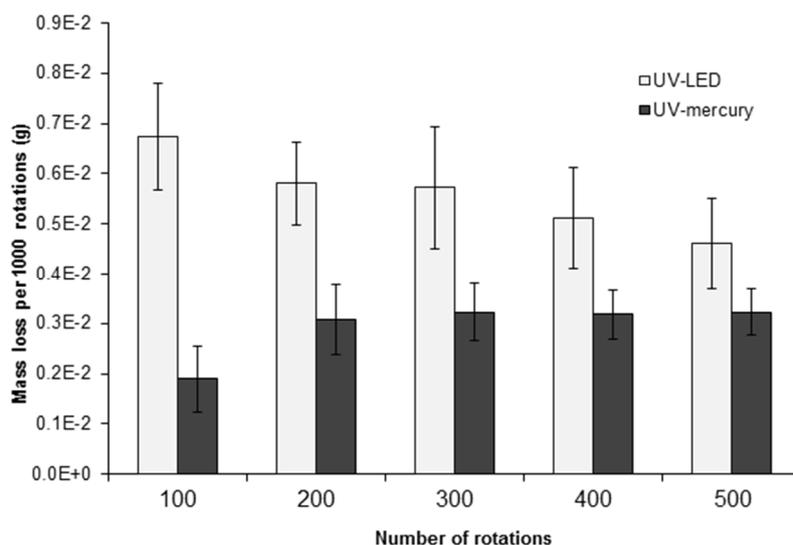


Figure 5. Graph of the mass loss per 1000 rotations in function of block of 100 rotations and reported on a comparative basis of a 1000 cycle (wear index).

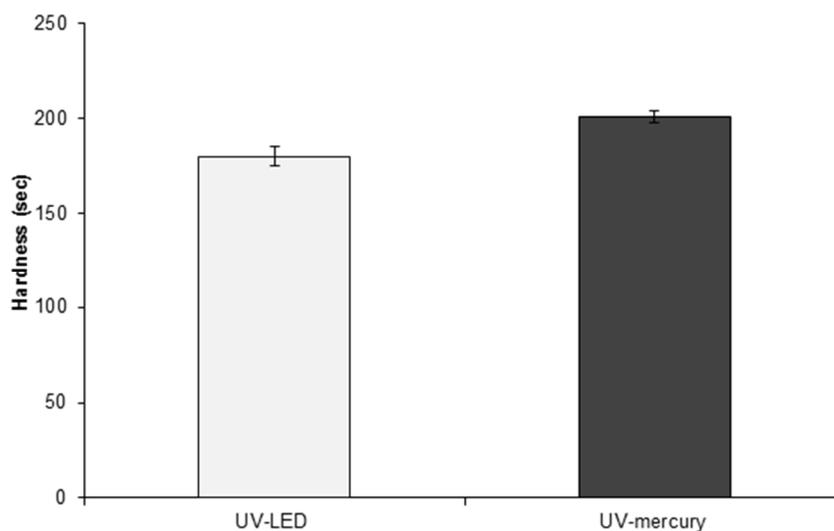


Figure 6. König hardness of the UV-water-based formulations.

4. Conclusions

In this study, the UV-LED curing efficiency and mechanical properties of UV water-based formulations were evaluated. For comparison, some formulations were cured with a UV-mercury lamp. The irradiation of the UV-mercury lamp can be 5 to 12 times higher than the one of UV-LED lamp depending on the position of the lamp and the conveyor speed. Thereby, the surface temperature of the flooring strips obtained with UV-LED lamp is an average of 12 °C lower than when a UV-mercury lamp is used.

Preliminary tests showed that the intensity of the UV-LED lamp is not high enough to cure UV high-solids coatings at a conveyor speed of 1.5 m/min, which is a conveyor speed significantly lower than for a standard UV-curing flooring line. Uncured monomer residues increase the VOC emissions. However, the UV-LED lamp possesses sufficient intensity to cure clear UV water-based coatings. The main reason is that UV high-solids are in liquid form before curing compare to the UV water-based

which, once the water is evaporated, there is coalescence resulting in fewer chemical links to be created. Water-based coatings cured under UV-LED lamps have a coating hardness and an abrasion resistance lower than the coating cured under the UV-Mercury lamps. There is still some work to do in order to bring the UV-LED technology to the same level of UV-mercury curing such as developing photoinitiators that are best suited for this type of technology, *i.e.*, clear after curing. The development of UV-LED lamps with higher irradiation is also necessary.

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Author Contributions

Experimental measurements, analysis, and interpretation of the results as well as conclusions have been conducted by all the co-authors. The manuscript has been written by Gabrielle Boivin, Véronic Landry, and Jean-François Bouffard. Artworks have been prepared by Gabrielle Boivin, Véronic Landry, and Jean-François Bouffard. The whole paper has been revised by Véronic Landry and Pierre Blanchet with approval by the other co-authors.

Conflicts of Interest

The authors declare no conflict of interest.

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