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Influence of Coating Formulation on Its Mechanical Properties and Cracking Resistance

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Abstract: The mechanical properties of coatings strongly influence wood coatings' performance, as coatings may be stressed by dimensional variations of wood when exposed outdoors. Within the European project SERVOWOOD (2014–2016), the influence of coating formulation on mechanical properties and cracking resistance has been studied. Several acrylic and alkyd formulations with different pigment volume concentrations (PVCs), with and without UV protection have been applied on pine samples and exposed to artificial weathering (EN 927-6) for 12 weeks. Persoz hardness of coatings applied on wood was assessed before and after weathering. Tensile tests on free films have been carried out at −10 °C, 20 °C, and 45 °C. For each formulation, elastic modulus, tensile strength, and strain at break have been determined for the three test temperatures. For each test temperature, there was no correlation between the elastic modulus and strain at break, nor between tensile strength and strain at break. The results showed a relation between Persoz hardness and elastic modulus. The best performing formulation had a mean elastic modulus at room temperature lower than 400 MPa and a mean strain at break higher than 30%.

Keywords: wood; coating; tensile test; elastic modulus; hardness; cracking; weathering

1. Introduction

Improving the durability of exterior coatings is essential for the use and development of wood as a building material. The approach of trying to improve the performance of coatings by optimizing different elements of the coating system that contribute to coating longevity has been recently published for clear coatings [1], taking into account the dimensional stability of wood, photostability of the wood surface, moisture ingress via end-grain, coating flexibility and photostability, and finally, coating thickness.

Mechanical properties of coatings strongly influence wood coatings' performance when exposed outdoors, as coatings may be stressed by dimensional variations of wood [2,3]. Despite their significant influence on performance, a prior control of the tensile properties of coating formulations has not yet been systematically assessed. As a result, the European Standard EN 927-2 [4] regarding performance specification for exterior wood coating does not include any mechanical properties in the performance criteria. However, a first draft of a Technical Specification on the tensile properties of wood coatings has recently been produced by the European Committee for Standardization in charge of exterior wood coatings (CEN/TC 139/WG2) [5], showing the growing interest of this Committee in the mechanical properties of exterior wood coatings.

The objective of the SERVOWOOD project (2014–2016) was to develop and establish European Standards that will facilitate the prediction of service life for exterior wood coatings. The work content of this European project and some preliminary results have been recently presented [6]. Within this project, the influence of coating formulation on mechanical performance and resistance to cracking has been studied and is presented in this paper. The mechanical properties of 24 coatings produced by Teknos Drywood (Enschede, The Netherlands) and based on four binders were assessed at FCBA (Forêt Cellulose Bois Ameublement Technological Institute, Bordeaux, France). Tensile tests on free films have been carried out at −10 °C, 20 °C, and 45 °C. Elastic modulus, tensile strength, and strain at break have been determined and analyzed in terms of cracking resistance after exposure to artificial weathering according to the standard EN 927-6 [7].

2. Materials and Methods

2.1. Coatings

Four resins (two acrylics and two alkyds) described in Table 1 were used. Each resin was used to produce six formulations mixed on a high-speed dissolver with or without UV protection and three pigment volume concentrations (PVCs) as follows: clear PVC (0%), low PVC (17%), and high PVC (48%) using TiO_2 and other fillers (calcium carbonate and talc). In total, 24 formulations were produced by Teknos Drywood and are described in Table 2. The UV protection was achieved using two additives as described in Table 3. Details about pigment and fillers loading are shown in Table 4.

Table 1. Description of the four resins used.

Resin	Information/Recommendations on Formulation and Use (from Data Sheets)
Acrylic 1	Dispersion; Good elasticity, especially at low temperature; For highly durable wood coatings
Acrylic 2	High-gloss paints interior/exterior/wood stains
Alkyd 1	Long oil alkyd emulsion; Interior/exterior primers and topcoat; Outdoor durability
Alkyd 2	Alkyd dispersion; Interior/exterior stains and trim paints for wood and metals

Table 2. Description of the 24 coatings. PVC: pigment volume concentration.

Resin	UV Protection	PVC	Coating Reference
Acrylic 1	No	Clear	05
		Low	06
		High	07
	Yes	Clear	11
		Low	12
		High	13
Acrylic 2	No	Clear	17
		Low	18
		High	19
	Yes	Clear	23
		Low	24
		High	25
Alkyd 1	No	Clear	29
		Low	30
		High	31
	Yes	Clear	35
		Low	36
		High	37
Alkyd 2	No	Clear	41
		Low	42
		High	43
	Yes	Clear	47
		Low	48
		High	49

Table 3. UV protection of the formulations.

Additive	wt %
2-Hydroxyphenyl-s-triazine	3.0
Amino-ether hindered amine light stabilizer	1.5

Table 4. Pigment and fillers loading for the different PVCs.

PVC	Pigment and Fillers (wt %)		
	TiO_2	Calcium Carbonate	Talc
Clear	n/a	n/a	n/a
Low	18	1.5	0.75
High	18	15	7.5

2.2. Hardness

Hardness was assessed for coatings applied on wood directly in order to achieve a realistic film formation. Coatings were applied on Scots pine selected to fulfil the requirements of EN 927-6: it was free from knots, cracks, and resinous streaks, and the inclination of the growth rings to the test face was 5° to 45°. Three coats of 50 g/m^2 (wet) with a mean total dry film thickness of 40.6 μm were applied on three samples. Their dimensions were 150 mm (*L*) × 75 mm (*R*) × 20 mm (*T*). After 1 month of drying at 20 ± 2 °C and 65% ± 5% relative humidity, hardness was measured using the Persoz pendulum (N3, Touzart & Matignon, Paris, France) at FCBA. The time for damping from 12° to 4° displacement was recorded, and represented the hardness of the surface tested—the longer the damping time, the harder the coating. The pendulum was calibrated using a glass plate (without any coating) and checking that the damping time was 430 ± 15 s. For each coating, nine measurements were made and the mean hardness was calculated.

2.3. Tensile Test

Each coating was applied on silicone foils using a four-side film applicator (VF2167, TQC B.V., Capelle aan den IJssel, The Netherlands). Coatings were air-dried for two weeks in a controlled environment at 20 ± 2 °C and 65% ± 5% relative humidity. Then, films were carefully detached by hand and cut to size (70 mm × 20 mm) using a scalpel. Specimens were oriented longitudinally relative to the direction of film preparation. The mean dry film thickness was 317 μm. The specimens were conditioned at 20 ± 2 °C and 65% ± 5% relative humidity for a further two weeks prior to testing.

Tensile tests were carried out at FCBA using a hydraulic actuator (MTS, 25 tons, MTS Systems Corporation, Eden Prairie, MN, USA) equipped with a 100 N load cell. The film specimens were held by mandrel type holders to avoid damage by cutting the films near the grips. The gauge length used was the distance of the free film between the clamps and was set to 50 mm. The actuator speed was set to 10 mm/min. The elastic modulus was determined as the slope of a linear portion of the strength–strain curve as detailed by FCBA in the document CEN/TC 139/WG2 N872. Five replicates were used for each coating and for each test temperature: –10 °C, 20 °C, and 45 °C. Mean values were calculated for elastic modulus, strain at break, and tensile strength at the maximal load.

2.4. Artificial Weathering

Each coating was applied on four Scots pine samples fulfilling the requirements of EN 927-6. They were free from knots, cracks, and resinous streaks, and the inclination of the growth rings to the test face was 5° to 45°. Their dimensions were 150 mm (*L*) × 75 mm (*R*) × 20 mm (*T*). After two weeks of drying at 20 ± 2 °C and 65% ± 5% relative humidity, three samples were exposed to fluorescent UV lamps (UVA-340 nm, Q-Lab, Westlake, OH, USA) and water in an artificial weathering device (QUV/Spray/RP, Q-Lab) at EMPA (Dübendorf, Switzerland). They were exposed to 24 h of condensation at 45 ± 3 °C followed by 48 cycles alternating 2.5 h of UV and 0.5 h of water spray for a total of 2016 h according to EN 927-6. One sample was kept as a control. At the end of exposure, the cracking density was assessed by EMPA on a scale from 0 (no cracking) to 5 (severe cracking) using ISO 4628-4 [8].

3. Results and Discussion

3.1. Hardness before Weathering

Figure 1 shows the influence of the coating formulation on the mean Persoz hardness for each resin.

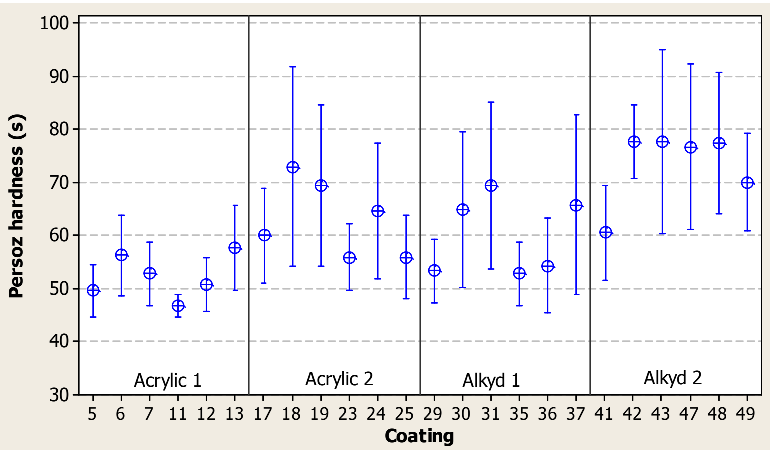

Figure 1. Mean Persoz hardness and confidence interval at 95% for the mean for the 24 coatings.

An interaction plot established using MINITAB statistical software (Version 16) is included in Figure 2. It shows that the hardness was mainly influenced by the resin type and the PVC. The Acrylic 1 clearly led to the lowest hardnesses (48.2 s for clear coatings), whereas coatings made with Alkyd 2 displayed the highest values (68.6 s for clear coatings). The increase due to pigments was especially significant for Acrylic 2 and Alkyd 2 (low PVC). One could expect a higher increase in hardness with the highest PVC. However, for these two coatings a slight decrease in hardness was observed. The highest PVCs were obtained by using pigments and fillers. The apparent decrease in hardness for the highest PVC may be due to a difference in the pendulum hardness of pigments and fillers. The UV protection had almost no influence on hardness, except maybe for Acrylic 2 where a slight decrease in hardness was observed.

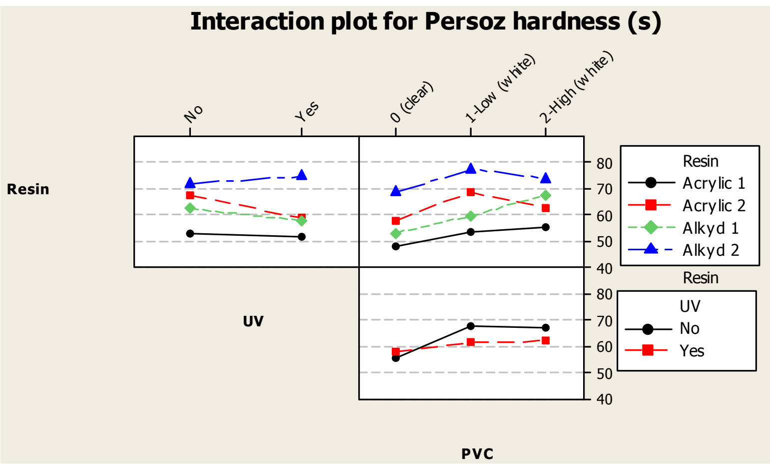

Figure 2. Interaction plot for the mean Persoz hardness.

3.2. Tensile Tests

Figure 3 compares the tensile properties of the acrylic and alkyd coatings for the three test temperatures. It shows that the shape of the strength (MPa)–strain (%) curves were different between the acrylic and the alkyd coatings.

From the shape of the curves, the ductile or brittle behavior can be summarized as shown in Table 5.

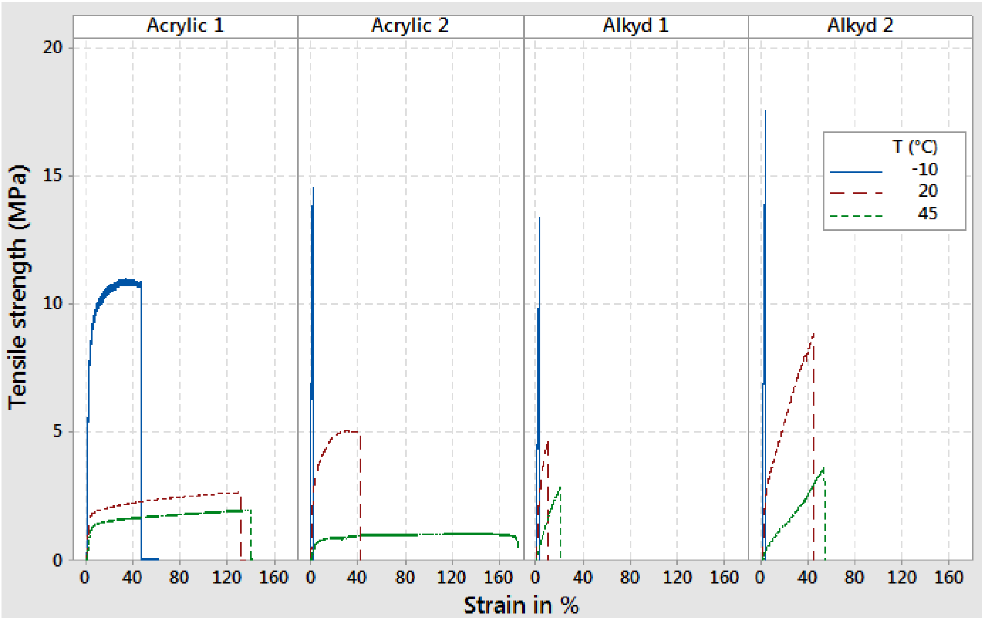

Figure 3. Comparison of the tensile strength–strain curves of the different coatings (examples with coatings 06, 18, 30, and 42 made with low PVC).

Table 5. Ductile or brittle behavior of the coatings (examples for clear and low PVC coatings).

Resin	Temperature		
	−10 °C	**20 °C**	**45 °C**
Acrylic 1	Ductile	Ductile	Ductile
Acrylic 2	Brittle	Ductile	Ductile
Alkyd 1	Brittle	Ductile	Ductile
Alkyd 2	Brittle	Ductile	Ductile

The two acrylic resins were more ductile than the two alkyds, as they were capable of undergoing larger strains (room temperature and 45 °C) before failure. Acrylic 1 was especially interesting, as it was ductile even at low temperature, which confirms the qualitative information provided in its data sheet.

At room temperature, Alkyd 2 was more ductile than Alkyd 1. Both alkyds were brittle at −10 °C. Only Acrylic 1 was used above its glass transition temperature (T_g), as it was ductile for the three test temperatures. It can be estimated that T_g of the three other coatings was between −10 °C and 20 °C.

The mean elastic modulus is presented in Figure 4 for each coating and each test temperature (–10 °C, 20 °C, and 45 °C). Figure 4 shows a broad range of elastic modulus from 130 to 1900 MPa at −10 °C, from 5 to 1615 MPa at room temperature, and from 2 to 738 MPa at 45 °C. The lower the test temperature, the higher the elastic modulus. For all coatings, the higher the PVC the higher the elastic modulus. The elastic modulus of Alkyd 2 was the least influenced by the recipe changes.

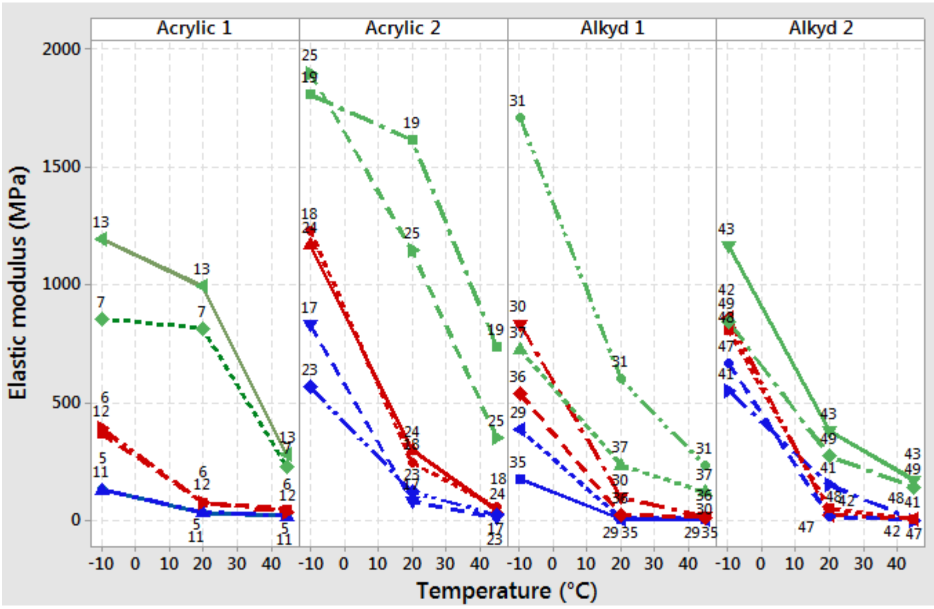

Figure 4. Influence of coating formulation on elastic modulus for the three test temperatures (in blue: clear PVC; in red: low PVC; in green: high PVC).

The strain at break for each coating and each test temperature is included in Figure 5. It varied from 1% to 106% at −10 °C, from 1% to 259% at room temperature, and from 2% to 322% at 45 °C. The acrylic coatings clearly displayed higher strain at break than the alkyds. Increasing the PVC clearly decreased the strain at break for all coatings. For example, increasing the amount of pigments from clear to low PVC decreased the strain at break of 74% for Acrylic 2 and Alkyd 1, 49% for Acrylic 1, and 20% for Alkyd 2. With higher amounts of pigments and fillers (high PVC), the strain at break was dramatically reduced to less than 15% for all coatings and for all test temperatures. For clear and low PVC coatings, cold temperature clearly decreased the strain at break.

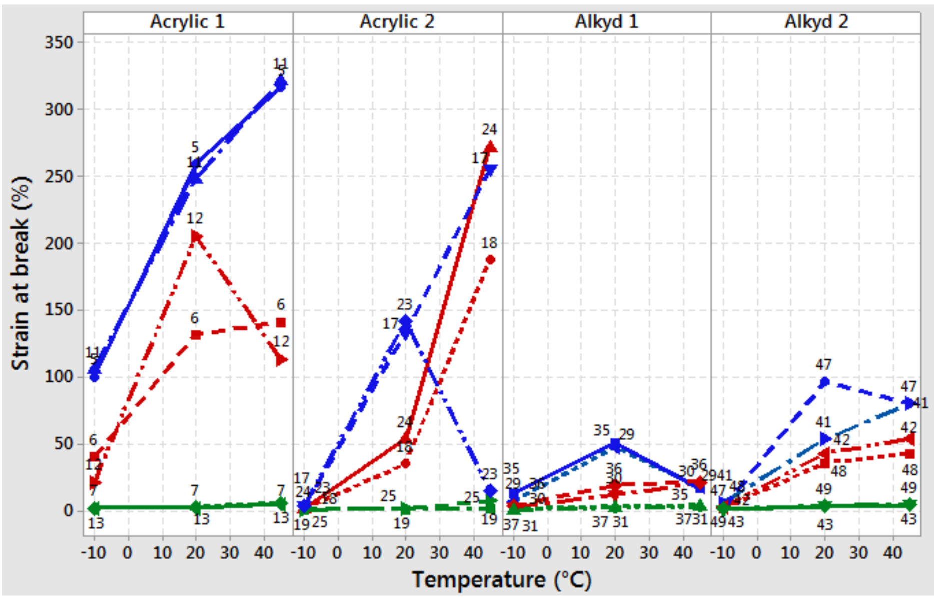

Figure 5. Influence of coating formulation on strain at break for the three test temperatures (in blue: clear PVC; in red: low PVC; in green: high PVC).

The tensile strength for each coating and each test temperature is shown in Figure 6. It varied from 5.3 to 15.8 MPa at −10 °C, from 2.2 to 11.7 MPa at room temperature, and from 0.5 to 5.1 MPa at 45 °C. The lower the test temperature, the higher the tensile strength. A significant increase in tensile strength was observed at −10 °C compared with room temperature. The effect of high PVC was different according to the type of binder. For the acrylic coatings there was a general trend towards an increase in the tensile strength with high PVC compared with clear and low PVC for the three test temperatures. This increase was in good agreement with the increase in the elastic modulus due to high PVC (Figure 4). For the alkyd coatings, this trend was not observed and the opposite effect was even shown at −10 °C with a decrease in tensile strength with high PVC formulations. This trend should be confirmed with the study of a larger range of coatings.

For each test temperature, there was no correlation between the elastic modulus and strain at break, nor between tensile strength and strain at break.

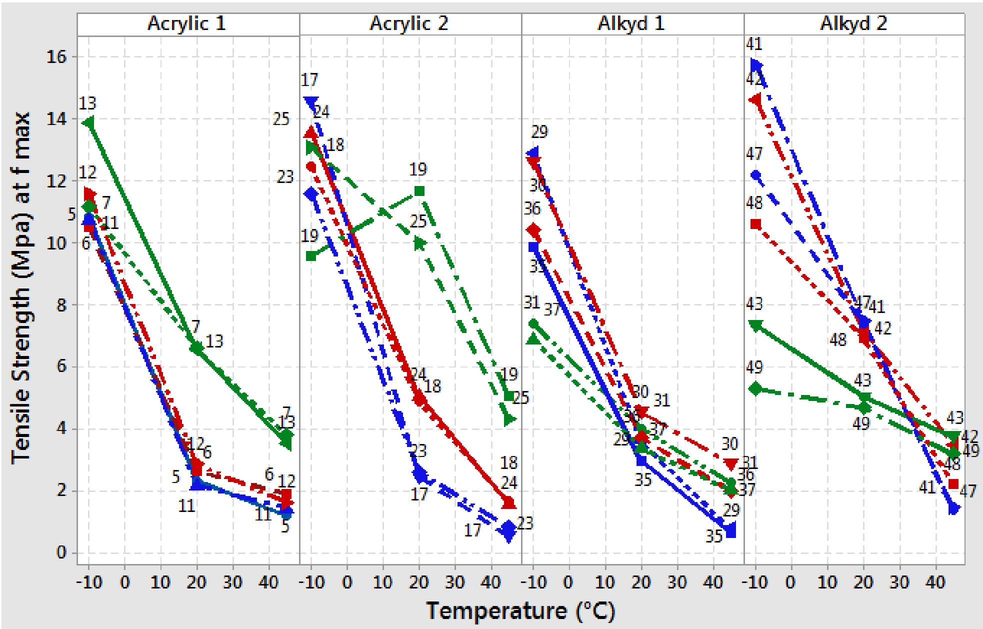

Figure 6. Influence of coating formulation on tensile strength for the three test temperatures (in blue: clear PVC; in red: low PVC; in green: high PVC).

3.3. Cracking and Weathering Resistance

Figure 7 shows the main effects plot for mean cracking produced by the statistical software MINITAB. In such a plot, the steeper the slope of the line, the greater the magnitude of the main effect. This figure shows that all parameters (coating, number of coats, UV protection, PVC) had an influence on cracking. The lowest cracking scores were obtained with coatings made with Acrylic 1 and Alkyd 2. Increasing the number of coats from two to three clearly reduced the cracking density, as did including UV protection in the recipe. The PVC had a large influence on cracking, and higher degradation was obtained for coatings with high PVC.

The influence of the different parameters on the mean elastic modulus and the mean strain at break are summarized using main effects plots shown in Figures 8 and 9, respectively. Figure 8 shows that the main influence on the mean elastic modulus comes from the PVC and the type of binder. The highest moduli were obtained with coatings with high PVC. The influence of the UV protection on the mean elastic modulus was minor. However, it may influence the mechanical properties after weathering.

Figure 9 shows that the main influence on the mean strain at break comes from the PVC and the type of binder. The lowest strain at break was obtained for coatings with high PVC and coatings made with Alkyd 1. The influence of the UV protection on the mean strain at break was minor.

From Figures 7–9 it can be observed that coatings made with Acrylic 2 had a mean elastic modulus of 584 MPa and a mean strain at break of 61%, which led to a mean cracking score of almost 4. Coatings based on Alkyd 1 also had the same mean cracking score, a mean elastic modulus of 161 MPa, and a mean strain at break of 22%.

It can be observed that the best performing coatings were those made with Acrylic 1 and Alkyd 2. Their elastic modulus at room temperature was lower than 400 MPa and their strain at break was higher than 30%. Acrylic 2 displayed interesting properties regarding strain at break (60% as shown in Figure 9), but displayed high cracking (see Figure 7) because its elastic modulus was the highest (almost 600 MPa). In other words, selecting coating based on just strain at break may lead to incorrect selection. These results show that the elastic modulus must also be taken into account when designing coatings for wood which is exposed outdoors.

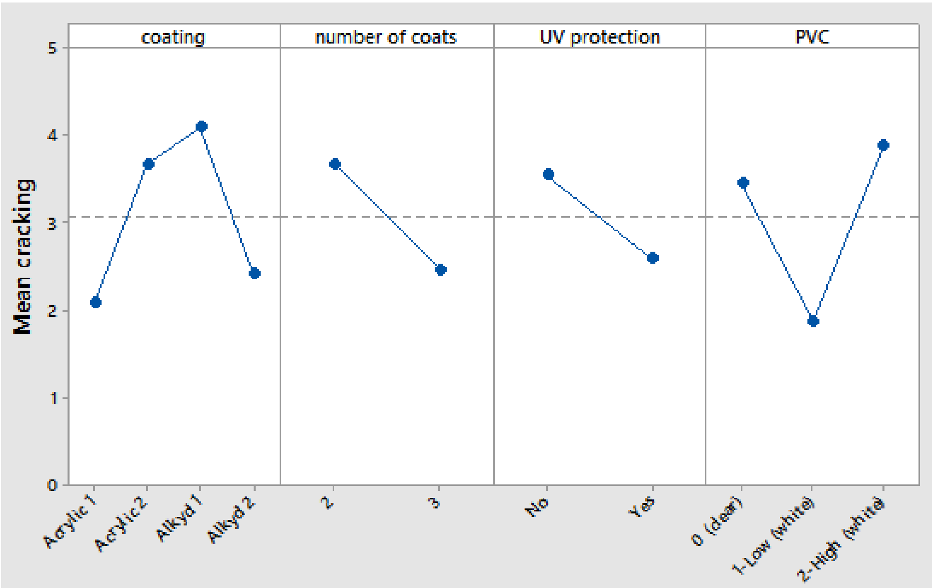

Figure 7. Main effects plot for the mean cracking.

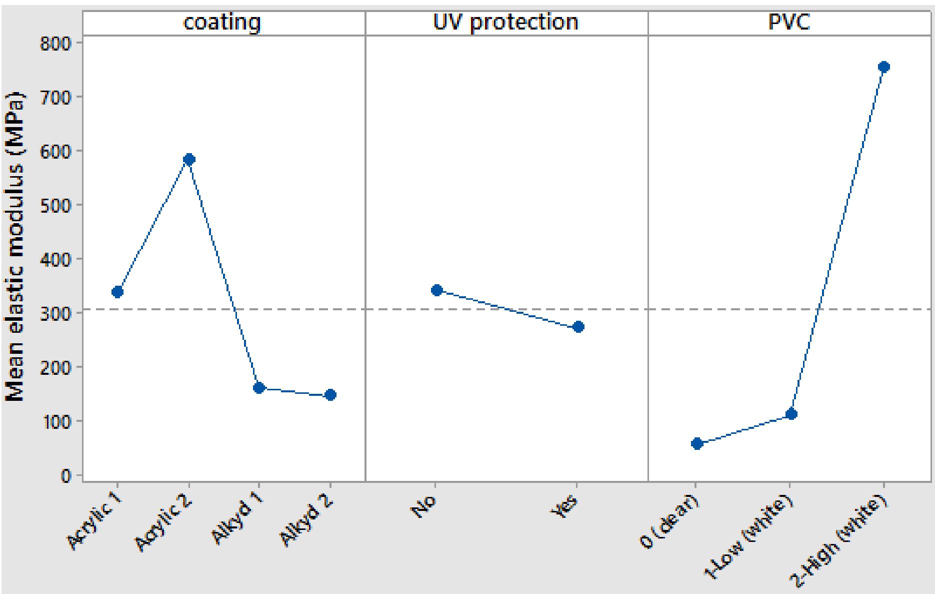

Figure 8. Main effects plot for the mean elastic modulus (room temperature).

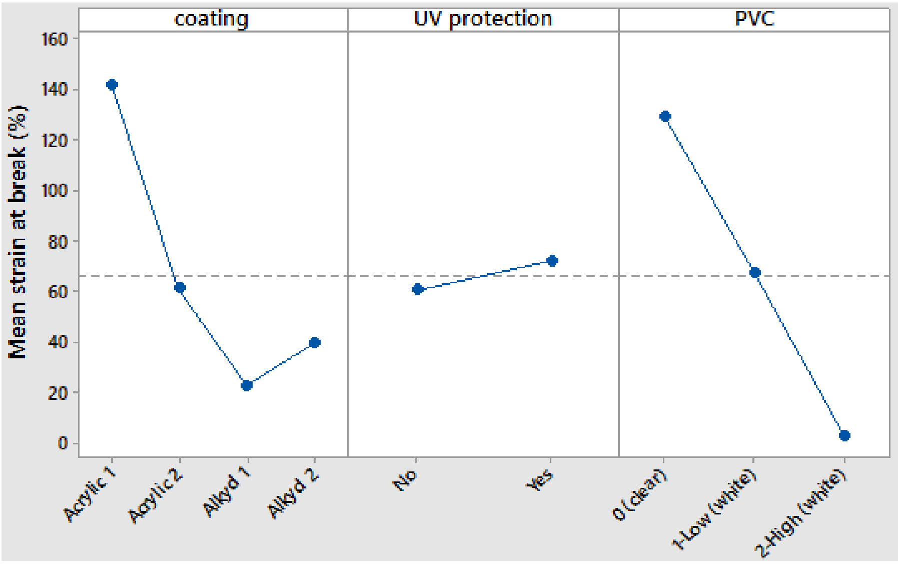

Figure 9. Main effects plot for the mean strain at break (room temperature).

It was recently shown that there was a relation between the elastic modulus and the Persoz hardness of exterior wood coatings based on acrylic resins [9]. Furthermore, previous results within the SERVOWOOD project have shown that the exposure to weathering led to an increase in coatings' hardness [10]. It can therefore be anticipated that the exposure to weathering certainly leads to an increase in the elastic modulus in relation with cracking development.

Results have shown that the tensile strength seems not to influence the weathering performance in the QUV. However, it will probably have an influence on impact resistance (hail damage).

3.4. Relation between Elastic Modulus and Persoz Hardness

Figure 10 shows the Persoz hardness versus the elastic modulus of the 24 coatings. It can be seen there was a relation between the elastic modulus and the Persoz hardness for elastic moduli lower than 400 MPa: the higher the Persoz hardness, the higher the elastic modulus. For high PVC coatings, Persoz hardness was probably more influenced by the hardness of the pigment and/or fillers than by the binder hardness.

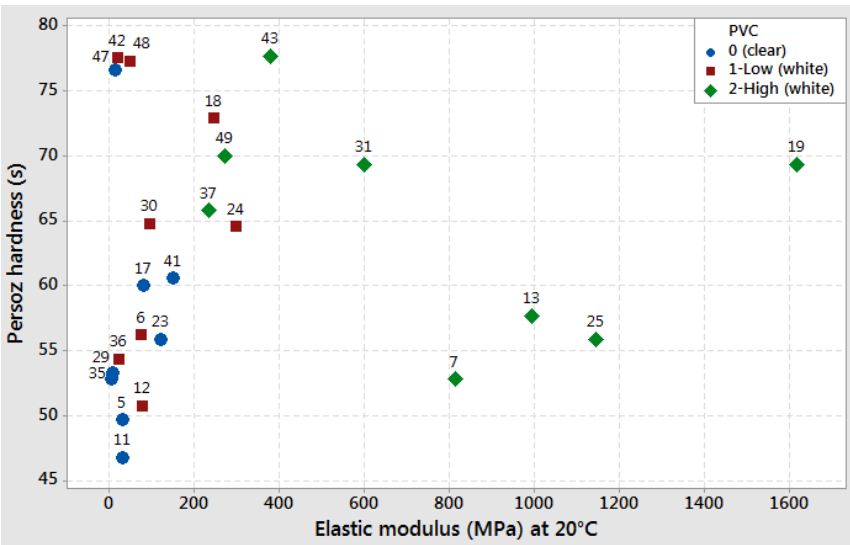

Figure 10. Relation between Persoz hardness and elastic modulus at room temperature.

Based on the results with the clear and low PVC coatings, it can be seen that the relation between elastic modulus and hardness seems to be influenced by the nature of the binder (acrylic versus alkyd), and therefore should be restricted to coatings with similar viscoelasticity as recommended by Sato [11]. The study of coatings made from a broader range of alkyd resins for exterior wood coatings would be useful to refine this analysis, as the relation found between Persoz hardness and elastic modulus of acrylic coatings was already shown [9].

These results should encourage the use of the Persoz pendulum to assess the mechanical properties of coatings. However making tensile tests gives additional and useful information, especially through the shape of the strength–strain curves and its change due to test temperatures (negative and positive).

4. Conclusions

The influence of coating formulation on mechanical properties and weathering performance has been studied using several acrylic and alkyd formulations with different PVCs, with and without UV protection.

The study has shown that making tensile tests both at negative and positive temperatures was useful to understand the mechanical behavior of the different formulations and the resistance to cracking. It allows the ductile properties to be checked over a range of temperatures encountered by coatings during their service life. Selecting coatings on just strain at break may lead to the incorrect selection, as the elastic modulus must be considered. The best performing coatings (made with Acrylic 1 and Alkyd 2) had a mean elastic modulus at room temperature lower than 400 MPa and a mean strain at break higher than 30%. The relation between Persoz hardness and elastic modulus observed in previous work was confirmed, and coatings with low Persoz hardness had better performances.

These results are an input for the standard standardization committee CEN/TC139/WG2 (exterior wood coatings) when drafting the Technical Specification on tensile properties for wood coatings. They should contribute to help the coating producers to design good performing coatings and should encourage resin manufacturers to include elastic modulus and strain at break in their data sheets.

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Author Contributions: Mari de Meijer designed the 24 formulations. Jean-Denis Lanvin supervised the mechanical tests and provided the MINITAB graphs. Laurence Podgorski analyzed the data and co-wrote the paper with Jean-Denis Lanvin with approval by Mari de Meijer.

Conflicts of Interest: The authors declare no conflict of interest.

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