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RESEARCH ARTICLES

WATER PERMEABILITY OF EXTERIOR WOOD COATINGS: WATERBORNE ACRYLATE DISPERSIONS FOR WINDOWS

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ABSTRACT

Permeability of coatings for water and water vapor is an important factor in their wood protective function. In this study, the permeability of coatings in terms of liquid water and water vapor absorption and desorption was measured based on different parts of the standard EN 927. This study evaluated the permeability of commercial coating systems and ascertained effects of coating layering on the coating permeability. For this measurement, six different waterborne acrylate dispersions were used as paint on spruce test samples. The results clearly revealed that liquid water and water vapor uptake were affected by coating film thickness, number of coats, and coating composition (producer). It was ascertained that the type of coating pigmentation affected water absorption of coatings and that with a constant coating film thickness, the number of coats affected water vapor absorption and desorption, but not water absorption. Furthermore, it was observed that the number of coats affected the correlation between the coating film thickness and water vapor absorption and desorption. The values for water vapor absorption were much higher than for liquid water absorption and, unlike the water vapor absorption rate, the water vapor desorption rate was approximately 50% lower.

KEYWORDS

wood, waterborne acrylates, exterior coatings, permeability, non-destructive coating, thickness measurement

INTRODUCTION

Recent studies have shown the need to look for renewable and sustainable resources to avoid doing harm to the environment and affecting climate change. As a renewable resource, wood is less harmful to the environment than most of its alternatives. In addition, its ease of repair

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contributes to its environmentally friendly image and long service life (Windt et al. 2014). Therefore, wood is widely used in outdoor constructions, such as for structural timber, windows, and doors, and can be exposed to high moisture, direct contact with rainwater, and UV damage. Despite all the advantages over other alternatives, some undesirable properties of wood could be considered disadvantages. Wood is an anisotropic material that is unstable when it encounters moisture and changes dimensions (Graystone 2001). Moisture uptake in wood can be explained by three different mechanisms: liquid water absorption into the wood, water vapor absorption into the wood, and water vapor desorption out of the wood (Ekstedt and Ostberg 2001). Wood can be protected against moisture in different ways. Wood can also be modified to provide dimensional stabilization by reducing moisture absorption (Ahola 1991; Hill 2006). For this purpose, numerous methods have been developed such as exterior wood coatings. These coatings have two functions: to give an aesthetically acceptable surface appearance and color, and to provide sustainable protection for the wood with no cracking, blistering, flaking, adhesion failure, or degradation via microbiological attack (Dawson et al. 2005). Protection against high levels and rapid fluctuation of wood moisture content is one of the main functions of exterior wood coatings, especially in humid areas (de Meijer 2002; Ekstedt 2003; Evans et al. 2015). In recent years, waterborne coating systems have become a major area of research and development due to their environmental friendliness, good processability, and mechanical properties (de Meijer et al. 2001; Wang et al. 2013).

Liquid water and water vapor permeability, two of the most important properties that affect coating performance, are influenced by coating film thickness (Feist et al. 1985). The coating film thickness is as important as the ingredients of the coating system. According to EN ISO 2808 (2007), the coating film thickness should be above 60 µm. For the determination of coating film thickness, several non-destructive methods have been developed, including permanent magnet (Korolev and Melai 2012), magnetic induction (Shukevich et al. 2000), eddy current (Zhang et al. 2015), X-ray fluorescence (Manhas et al. 2009), and ultrasonic (Lavrentyev and Rokhlin 2001) methods. Wood is a diamagnetic material on which it is difficult to determine the coating film thickness correctly using ultrasonic methods. However, developments in technology provide new techniques for measuring wood coating film thickness through the ultrasonic method. In this study, the thickness of coating films was determined by the ultrasonic method using the new method of signal processing, which has been previously used (Hora and Betz 1998; Beamish 2004).

Up to the present, different tests have been developed to quantify the efficiency of a coating at protecting wood from water (EN ISO 12572 (2001); EN ISO 7783 (2011). Moisture permeability has become a part of the performance specifications of EN 927, the general European standard related to exterior wood coatings. The specification EN 927-2 (2014) classifies performance criteria, in relation to the expected dimensional movement of the wood, into stable (maximum water absorption 175 g/m^2), semi-stable (250 g/m^2), and non-stable (250+ g/m^2) end-use categories. Furthermore, some researchers have derived their own methodology by using classified standards combined with the neutron imaging method (NMR) and magnetic resonance imaging (MRI) (Pourmand et al. 2011; Johansson et al. 2013; Sonderegger et al. 2015).

The purpose of this study is to evaluate water and water vapor permeability of exterior wood coatings (waterborne acrylate dispersions for windows) at the initial phase after coating application. These characteristics partly predict the performance and durability of wood coatings.

EXPERIMENTAL METHODS AND MATERIALS

For the tests, Norway spruce (*Picea abies*) with a density of 496 kg/m^3 (at an equilibrium moisture content of 12%) was used (Window Holding a.s., Prague, Czech Republic). The samples were prepared in the dimensions 140 mm ± 2 mm × 70 mm ± 2 mm × 20 mm ± 2 mm (longitudinal, tangential, and radial directions, respectively). For accurate results, specimens were selected without any defects, such as knots, cracks, resin spots, etc., with four to eight annual rings per 10 mm. Inclination of the growth rings to the test face was 45° ± 10°. The specimens were conditioned before the coating applications according to standards (20 °C ± 2 °C and 65% ± 5% RH). Two types of coated samples, namely 3-layered samples and 4-layered samples, were prepared from six different producers. The paints were applied by both spraying and dipping, using waterborne acrylate dispersions. The technology of the paint application is presented in Table 1. The composition of the coating systems of producers 1 through 6 is stated in Table 2. All coatings were opaque. The coating application, including coating weight, was performed according to technical data sheets supplied by the producers, which resulted in different thicknesses of coating film from different producers (80 µm to 130 µm). For each combination of coating system and producer, 5 specimens were examined.

After the application of the coatings, all remaining sides were sealed with silicon-acrylate paints. Paints were applied in three steps and stored for 72 h between each step. Before the measurement started, the film thickness of the coating on all specimens was measured using the non-destructive ultrasonic method. The determination of the coating film thickness using ultrasound is a quick method, useful for practical application, which has been employed in several scientific papers (Hora and Betz 1998; Moya et al. 2017). Although the pitfall of this method is the uncertainty as to whether it yields sufficiently accurate results. The verification of the accuracy of this method was already completed in the authors' previous work (Hýsek et al. 2017). Certainly, there are other methods to determine and characterize coating film thickness (Masaryková et al. 2010; Grüll et al. 2014; Moya et al. 2017), but this study used a fast and reliable method that could be used in the industry as well. For this purpose, a Sursonic Squirrel measuring device was employed (Testima, Prague, Czech Republic). The signal processing

TABLE 1. Technology of paint application for different coating systems.

Coating system	No. of coats	Colour	Impregnation	Basis coat	Middle coat	Surface coat	Pigmentation
1	3	brown	dipping	dipping	none	spraying	iron oxide, wolfram acid
2	4	brown	dipping	dipping	dipping	spraying	iron oxide, wolfram acid
3	3	white	dipping	dipping	none	spraying	titanium dioxide
4	4	white	dipping	dipping	dipping	spraying	titanium dioxide

Note: For all coating systems, the pigment volume concentration was below the critical pigment volume concentration.

TABLE 2. Composition of coating systems of different producers.

Producer	Impregnation	Basis coat	Middle coat	Surface coat
1	fungicides and insecticides (propiconazole, permethrin, iodopropynyl butylcarbamate (IPBC))	acrylate basis	acrylate basis	acrylate basis, UV-stabilizers (benzotriazol)
2	IPBC and propiconazole as fungicides	acrylate basis	acrylate basis, zinc oxide	acrylate basis, zinc oxide, phenyl-phosphates
3	IPBC and permethrin as biocides	alkyd-acrylate hybrid basis	acrylate basis	alkyd-acrylate hybrid basis with zinc oxide, siloxanes, fungicides, and UV-stabilizers (benzotriazol)
4	propiconazole and permethrin as biocides	acrylate basis	acrylate basis	acrylate basis, UV-stabilizers (benzotriazol), silicon dioxide and methylsiloxane
5	IPBC and permethrin as biocides	acrylate basis	acrylate basis, UV-stabilizers (benzotriazol), silicon dioxide and methylsiloxane	acrylate basis, UV-stabilizers (benzotriazol), silicon dioxide and methylsiloxane
6	propiconazole and IPBC as fungicides	acrylate basis	acrylate basis modified by fatty acids and tall oil containing UV-stabilizers (benzotriazol).	acrylate basis modified by fatty acids and tall oil, also containing UV-stabilizers (benzotriazol).

Note: Exact composition of paints is not known because of secreting from the side of producers; technical and safety data sheets include only the partial, above-mentioned information

technique in Sursonic is based on a convolution of the reference echo to obtain a similar signal as the measured echo. This signal processing allows for the measurement of films that are thinner than the wavelength of the ultrasound. Because the water permeability of some coatings can change markedly during a relatively short exposure to water, the following pre-conditioning procedures were completed twice for each specimen: 24 h floating in deionized water, 3 h drying at 20 °C and 65% RH, 3 h drying at 50°C and 18 h drying at 20 °C and 65% RH. After pre-conditioning, the weight of the specimens was measured with a 0.001 g accuracy. The samples were floated in deionized water for 72 h at 20 °C, then weighed, and the values were recorded for the calculation of liquid water permeability. For the measurement of water vapor permeability, the specimens were put in a climate chamber that was conditioned at 20 °C and 98% RH. Specimens were exposed to 98% RH for 14 days for the absorption cycle, weighed, then put in 20 °C and 65% RH for 14 days for the desorption cycle and reweighed. In-between the processes, samples were kept outside less than 5 min. Liquid water permeability and water vapor permeability were determined by the weight differences between water absorption and water desorption as stated by EN 927-4 (2000), which is now invalid, thus EN 927-5 (2006) was used.

The statistical data analysis was conducted using Statistica12 software (StatSoft, Tulsa, OK, USA). An analysis of variance, as well as Spearman's correlation and linear regression analysis were employed. A significance level of $\alpha = 0.05$ was selected.

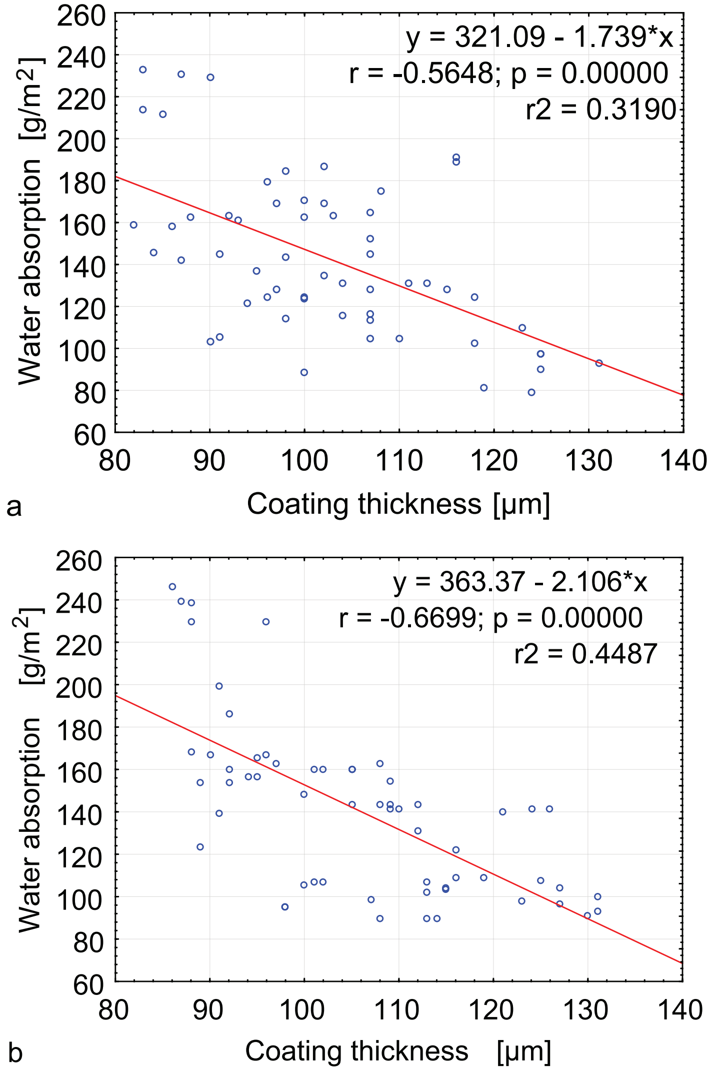
RESULTS AND DISCUSSION

The water absorption data for both 3- and 4-layered samples are shown in Figure 1. The coefficients of determination were low; however, the regression models were statistically significant and the following statements can be concluded. Water absorption values for lower film thicknesses were higher than 200 g/m^2; however, water absorption values rapidly decreased for the higher film thickness values. Water absorption values for uncoated samples (552 g/m^2) were nearly three times higher than for the coated samples. At around 130 µm film thickness, water absorption rates were under 100 g/m^2. When the water absorption rate of coatings obtained in this study was compared with earlier findings, the absorption rate was higher than that reported by other researchers (de Meijer 2002). This could be explained by different coating systems. Otherwise, it was comparable to the observations by Ekstedt (2003). In contrast, for uncoated samples, water absorption rates were lower than in earlier findings. According to EN 927-2 (2014), where coatings are classified in 3 end-use categories according to water absorption values, it can be stated that the tested coating systems were not sufficient to use in stable (maximum water absorption 175 g/m^2) constructions in lower film thickness rates. However, the higher coating film thickness values that were provided required water repellency. This corresponded with the producers' requirements for coating film thickness, which was at least 100 µm for all of the coating systems.

Water vapor absorption and desorption data for both 3- and 4-layered samples are shown in Figures 2 and 3. The water vapor absorption average values for both 3- and 4-layered samples (222.9 g/m^2 and 205.9 g/m^2, respectively) were much higher than the values for liquid water absorption. This was explained by the longer sorption time as well as the different physical process of permeation. Unlike the water vapor absorption rate, the water vapor desorption rate (102 g/m^2 for 3-layered samples and 98 g/m^2 for 4-layered samples) was approximately 50% lower, which means that less water could have been released than taken up into the wood in the same period. It can be surmised that wood hysteresis was the cause of the lower desorption rate. In addition, the coating might have affected the desorption rate because its chemical composition is different than wood. This phenomenon is explained later. The water vapor absorption rate for uncoated wood (401 g/m^2) was nearly two times higher than for coated samples; the water vapor desorption (226 g/m^2) was relatively similar.

The results of the correlation analysis led to the results predicted by Fick's law and proved that the water vapor absorption and desorption and water absorption of all coatings were negatively correlated to coating film thickness. The correlation between coating film thickness and water absorption can be classified as medium for both 3-layered and 4-layered coating systems

FIGURE 1. Water absorption values, 3-layered samples **(a)**, 4-layered samples **(b)**.



(it was stronger for 4-layered); the coefficients of correlation were in both cases lower than –0.55. However, the correlation between coating film thickness and water vapor absorption/desorption differed in 3-layered and 4-layered coating systems. While no statistically significant influence between coating film thickness and water vapor absorption and desorption was found for 3-layered coatings, a strong correlation (correlation coefficients were lower than –0.65) was found in the samples coated with 4-layered coating systems. While in the case of 4-layered coating systems, changes in water vapor absorption and desorption were explained by changes in coating film thickness by 43%, for 3-layered coating systems these influences were negligible. Furthermore, it was also observed that the coating system color affected the water absorption of coatings ($p < 0.01$); white coatings reached higher water absorption. This may have been caused by pigmentation, because it is well known that titanium dioxide decreases the stability of coatings (Figure 4) (Liu et al. 2008; Zhang et al. 2010). Nevertheless, at the same coating film thickness level, the number of coats in the coating system did not affect water absorption,

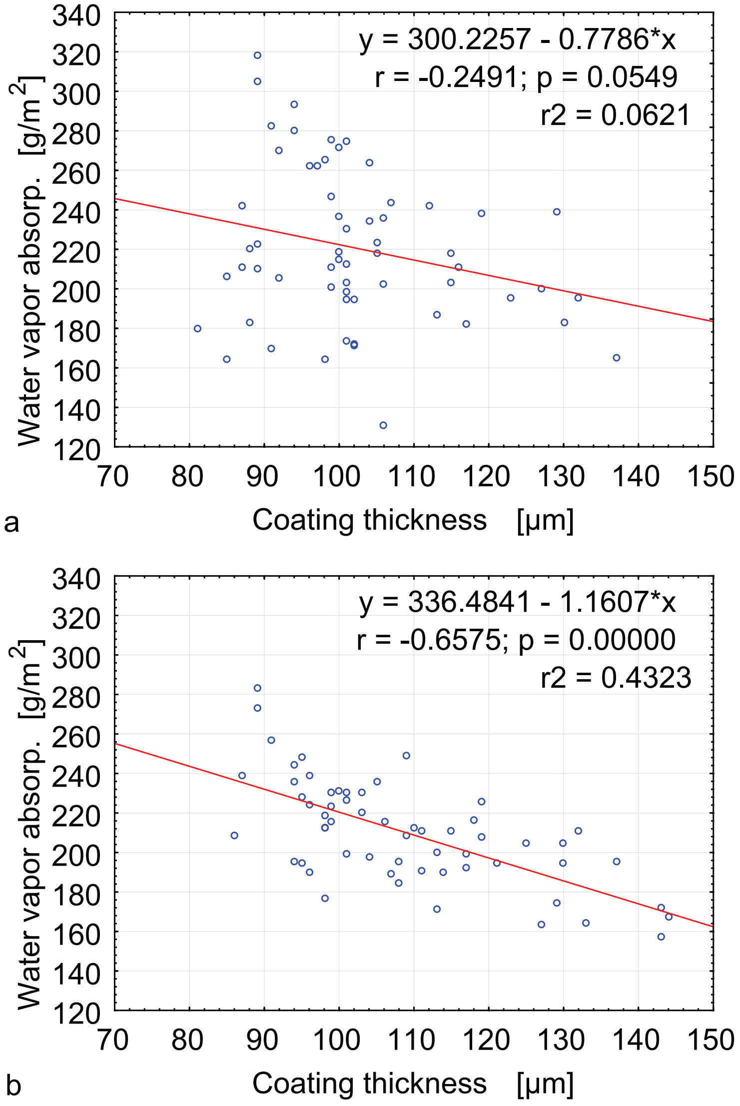
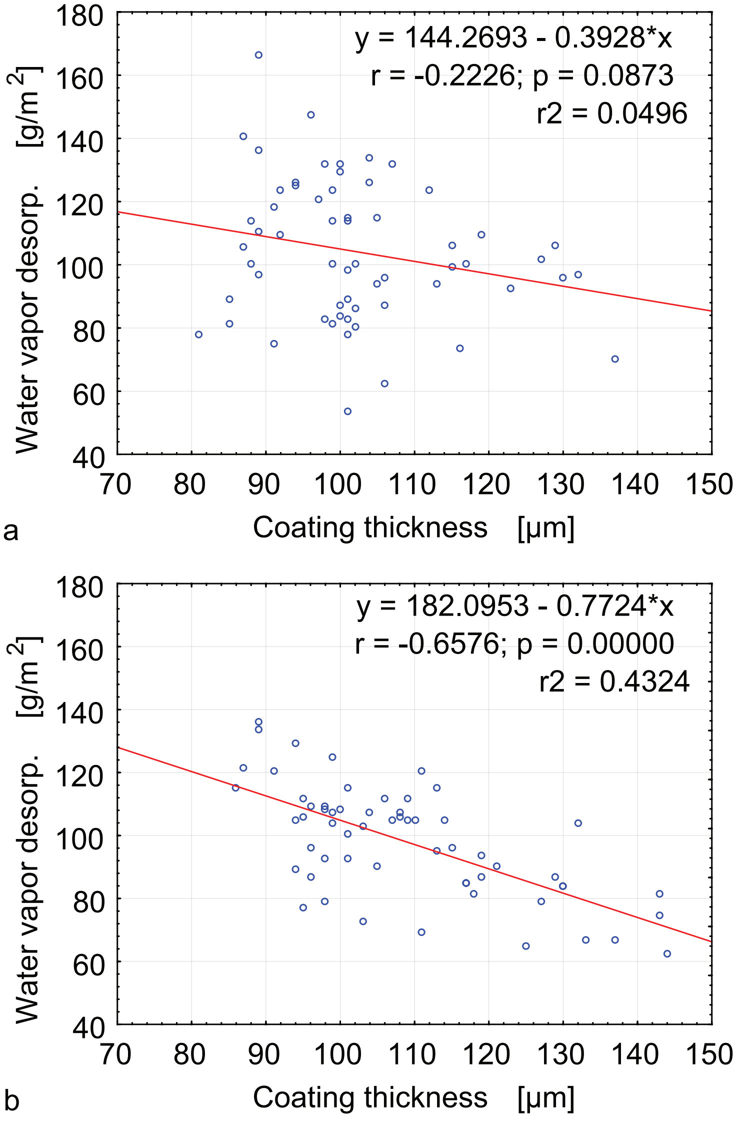


FIGURE 2. Water vapor absorption values, 3-layered samples **(a)**, 4-layered samples **(b)**.

as shown in Figure 4. However, at the same coating film thickness level, the number of coats in the coating system led to statistically significant ($p < 0.01$) differences in water vapor absorption and desorption. This different effect of the number of coats on water absorption and water vapor absorption/desorption was also noticeable from the coefficients of determination of linear regression curves.

When the regression curves were investigated, the regression lines for water absorption had a greater slope than the regression lines for water vapor absorption; with a decrease in coating film thickness, water absorption increased more than water vapor absorption. This has an important practical impact, because insufficient coating film thickness does not provide sufficient protection against liquid water in comparison with protection against water vapor. The slope of regression lines for water vapor absorption was greater than the slope of those for water vapor desorption, and this corresponded with higher water vapor absorption than water

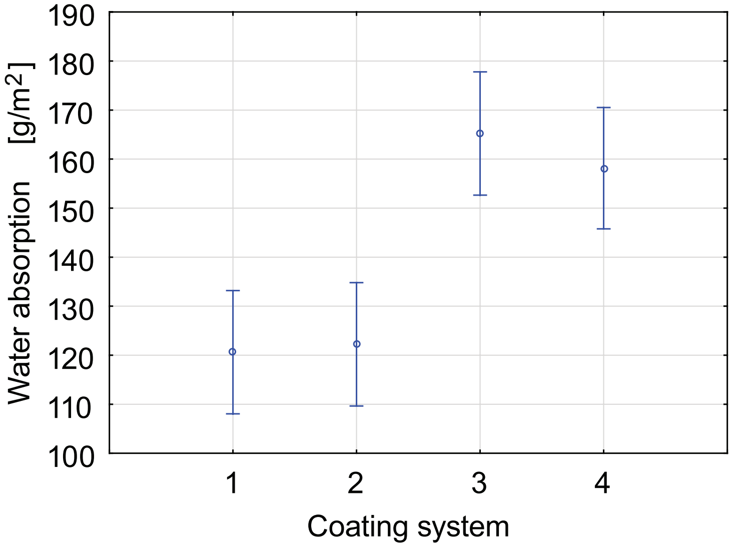
FIGURE 3. Water vapor desorption values, 3-layered samples **(a)**, 4-layered samples **(b)**.



vapor desorption values. This phenomenon was largely explained by wood sorption hysteresis. On uncoated reference samples, water vapor desorption reached 56% of the value of water vapor absorption. The water vapor desorption of experimental samples reached 47% of their water vapor absorption. This 9% difference is explained by differences in wettability between the wood and coatings (Landry and Blanchett 2012).

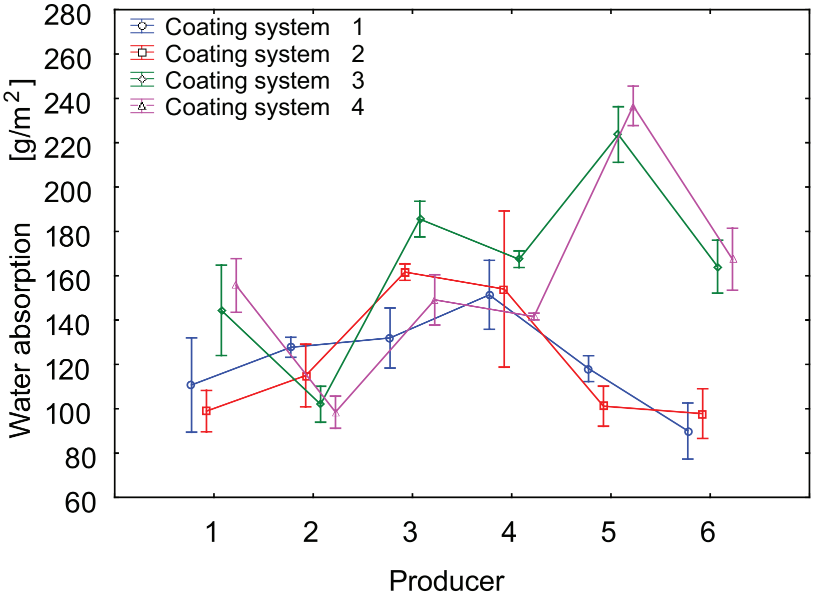
Detailed graphs of liquid water absorption values are given in Figure 5. When the graphs were investigated, the number of coats did not affect absorption rates. In addition, coating system 4 had a smaller range of absorption rates, which can be defined by the variability of absorption rates. Water absorption values were also influenced by the producer (Figure 5). The best results for water absorption were observed for producer 6 and the brown-colored coating, where tung oil and fatty acid treatment of the acrylate polymer system most likely increased its

FIGURE 4. Analysis of variance (ANOVA)—Water absorption values for different coating. systems (Explanation of coating systems can be found in Table 1)



hydrophobicity. Although, for the white-pigmented system, the results were much worse. This is important knowledge: one coating system from the same producer can give various practical results due to different pigmentation, as was also seen in this work for producer 5 (Figure 5). It is a well-known fact that adding only a small amount of different additives or pigments to the polymeric base of a coating system can cause an expressive change in its properties (Grüll et al.

FIGURE 5. ANOVA—water absorption values for each producer.



2014; Windt et al. 2014; Evans et al. 2015; Pánek and Reinprecht 2016). In this case, it could be caused by titanium oxide in the white systems in contrast to iron oxide and wolfram acid in the brown-pigmented systems. These results were in opposition to the results of other research (Ekstedt 2003), where it was mentioned that white-colored coatings produced the lowest water absorption rates in comparison with other colors. However, these differences could be explained by the totally different coating types used in these two research projects, because the coating type has a greater effect on coating properties (Gobakken and Lebow 2010; Robinson et al. 2013). The coating systems of producers 3 and 4 showed similar water absorption values. The partly different polymer base (alkyd-acrylate hybrid) in the two coats (producer 3), unlike having acrylate in all coats (producer 4), did not have an important effect on the researched properties in this work. A greater effect was observed for a combination of additives- oils in producer 6, siloxanes and silica dioxide in producer 5. Coating systems containing zinc oxide as an additive, from producer 2, had the most homogenous and relatively consistent results, without a large influence from layering and type of pigmentation, which confirmed this additive's positive effect on coating stabilization in former research (Schaller et al. 2012; Forsthuber et al. 2013).

Detailed graphics of water vapor absorption values are given in Figure 6. For the water vapor absorption rates, producers 3 and 4 had the expected results for absorption rates and number of coats; however, for the other producers only brown-colored coating systems had the expected results for number of coats. Producer 6 had better results on average for this measurement than the other producers. For this experiment, for liquid water absorption, white-colored coating systems were more permeable than brown-colored coating systems.

Detailed graphics for water vapor desorption values are given in Figure 7. Water vapor desorption values were much lower when compared with the absorption values. In coating system 1 and coating system 2, the desorption rates decreased when the number of coats

FIGURE 6. ANOVA—water vapor absorption values for each producer.

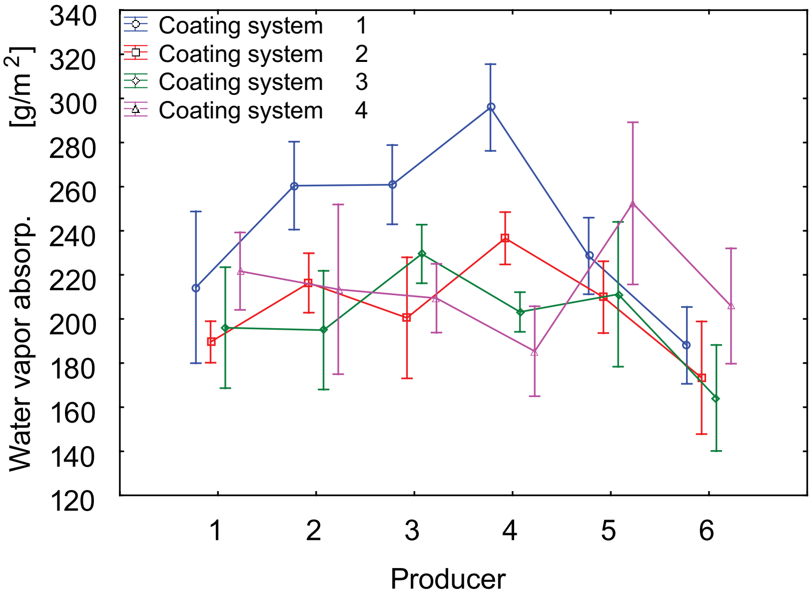
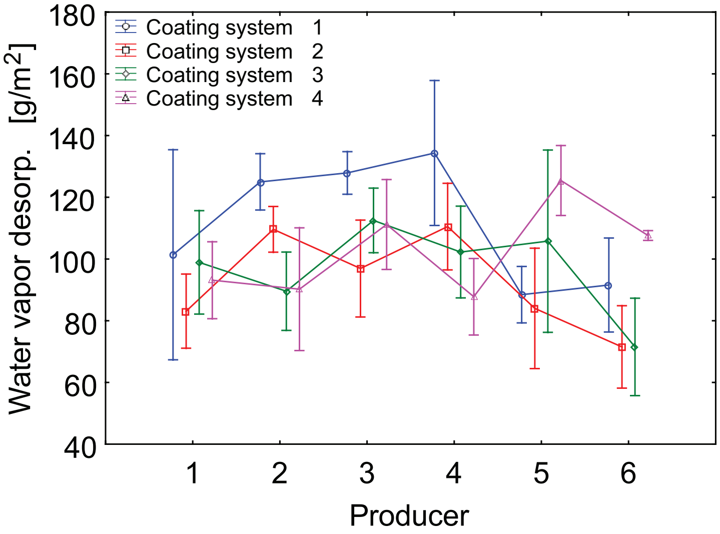


FIGURE 7. ANOVA—water vapor desorption for each producer by ANOVA.



increased, whereas the desorption rates of coating system 3 and coating system 4 increased for producers 5 and 6. For this measurement, producer 6 had the best results. For the 3-layered, brown-colored system, a good ratio between low water vapor absorption and relatively higher desorption was also observed in comparison with other producers (the water vapor desorption/absorption ratio was at a level of 0.49; see Figures 6 and 7). This could be an important factor in practice through the faster drying of wetted wood under the coating system. It was probably caused by the oil additives, creating a more porous coating structure (see Experimental Methods and Materials). However, this effect was minimal for the 4-layered system, and desorption copied absorption with some level of hysteresis (the water vapor desorption/absorption ratio at a level of 0.41).

It is possible to say that 4-layered systems provided more stable coatings in terms of scattering values of water vapor absorption and desorption, as well as water absorption. In addition, correlations between coating thickness and water permeability were stronger for 4-layered systems than for 3-layered systems.

Finally, it is necessary to point out that in this study coating systems were compared only on the basis of water and water vapor permeability at the initial phase after coating application. The permeability should not be the only aspect of coatings as a protective layer for wood, and other aspects should be considered as well, e.g. resistance to weathering and biodegradation. The water and water vapor permeability can change during altering the exterior because of the decrease of coating film thickness and creation of microcracks. The extent of this degradation of the polymer structure is different for different coating systems (Van den Bulcke et al. 2006; Grüll et al. 2014; Valverde and Moya 2014; Evans et al. 2015; Moya et al. 2017).

CONCLUSION

This study measured the water and water vapor absorption and desorption characteristics of six commercial waterborne acrylate dispersions that resulted in wide variations of these properties:

1. The investigated waterborne acrylate coating systems were not sufficient to use in stable constructions in lower film thickness rates. However, higher coating film thickness values, above 110 µm, could provide the required water repellency.
2. The water and water vapor absorption and desorption were dependent upon the producers of the coatings. These differences can be explained by the different content and composition of additives, pigments, UV-stabilizers, or by the modification of acrylate basis in different coats of tested coating systems.
3. The permeability of the coating system from a producer was significantly influenced by the pigmentation (the white coatings were more permeable than the brown coatings).
4. Layering affected the permeability, where 4-layered coatings were less permeable than 3-layerd coatings of the same coating film thickness.
5. The brown acrylate dispersion modified by oils showed that using 4 coats worsened the water vapor desorption/absorption ratio, which was the best for this 3-layer system. This can result in the prolongation of wood drying during exposition in exterior coatings.

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REFERENCES

Ahola, P. (1991). “Moisture transport in wood coated with joinery paints.” *Holz als Roh- und Werkstoff.*, 49(11), 428–432.

Beamish, D. (2004). “Using ultrasonic coating thickness gauges.” *Materials Performance*, 43(9), 30–33.

CEN (European Committee for standardization). (2014). “Paints and varnishes. Coating materials and coating systems for exterior wood. Part 2: Performance specification” *EN 927-2*, Brussels.

CEN (European Committee for standardization). (2000). “Paints and varnishes. Coating materials and coating systems for exterior wood. Part 4: Assessment of the water-vapour permeability” *EN 927-4*, Brussels.

CEN (European Committee for standardization). (2006). “Paints and varnishes. Coating materials and coating systems for exterior wood. Part 5: Assessment of the liquid water permeability” *EN 927-5*, Brussels.

Dawson, B.S.W., Göttgems, A., and Hora, G. (2005). “Natural weathering performance of exterior wood coatings on Pinus sylvestris and Pinus radiata in Germany and New Zealand.” *Journal of Coatings Technology*, 2(7), 539–546.

de Meijer, M. (2003). “Comparison between laboratory water permeability tests and wood moisture content of full-scale window frames.” *Surface Coatings International Part B: Coatings Transactions*, 85(2), 79–168.

de Meijer, M., Creemers, J., and Cobben, W. (2001). “Relationship between the performance of low-VOC wood coatings and the dimensional changes of the wooden substrate.” *Surface Coatings International Part B: Coatings Transactions*, 84(1), 77–85.

Ekstedt, J., and Ostberg, G. (2001). “Liquid water permeability of exterior wood coatings-testing according to a proposed european standard method.” *Journal of Coatings Technology*, 73(914), 53–59.

Ekstedt, J. (2003). “Influence of coating system composition on moisture, dynamic performance of coated wood.” *Journal of Coatings Technology*, 75(938), 27–37.

Evans, P.D., Haase, J.G., Shakri, A., Seman, B.M., and Kiguchi, M. (2015). “The search for durable exterior clear coatings for wood.” *Coatings*, 5(4), 830–864.

Feist, W.C., Little, J.K., and Wennesheimer, J.M. (1985). *The moisture-excluding effectiveness of finishes on wood surfaces*. U.S. Dept. of Agriculture, Forest Service, Forest Products Laboratory, Madison.

Forsthuber, B., Schaller, C., and Grüll, G. (2013). “Evaluation of the photo stabilizing efficiency of clear coatings comprising organic UV absorbers and mineral UV screeners on wood surfaces.” *Wood Science and Technology*, 47(2), 281–297.

Gobakken, L.R., and Lebow, P.K. (2010). “Modelling mould growth on coated modified and unmodified wood substrates exposed outdoors.” *Wood Science and Technology*, 44(2), 315–333.

Graystone, J.A. (2001). “Moisture transport through wood coatings: The unanswered questions.” *Surface Coatings International Part B: Coatings Transactions*, 84(3), 169–242.

Grüll, G., Tscherne, F., Spitaler, I., and Forsthuber, B. (2014). “Comparison of wood coating durability in natural weathering and artificial weathering using florescent UV-lamps and water.” *European Journal of Wood and Wood Products*, 72(3), 367–376.

Hill, C.A.S. (2006). *Wood modification—chemical, thermal and other processes*, Wiley, Chichester, U.K.

Hora, G., and Betz, A. (1998). “Measuring commercial layer-thickness on wood with an ultrasonic unit.” *Paint & Coatings Industry*, 14(11), 62–69.

Hýsek, Š., Trgala. K., Fidan, H., Pánek, M., Lexa, M., Böhm, M., and Veverka, J. (2018). “Ultrasound measurement of exterior wood coating thickness.” *Maderas: Ciencia y Tecnología, article in press*.

ISO (International Organization for Standardization). (2001). “Hygrothermal performance of building materials and products—determination of water vapour transmission properties.” *EN ISO 12572*, Brussels.

ISO (International Organization for Standardization). (2007). “Paint and varnishes—determination of film thickness.” *EN ISO 2808*, Brussels.

ISO (International Organization for Standardization). (2011). “Paints and varnishes. Determination of water-vapour transmission properties. Cup method” *EN ISO 7783*, Brussels.

Johansson, J., Blom, A., and Dvinskikh, S. (2013). “NMR-measurement for determination of local moisture content of wood.” *Journal of Coatings Technology*, 10(5), 601–697.

Korolev, K.V., and Melai, A.M. (2012). “Measuring the thickness of nonmagnetic coatings.”
Russian Engineering Research, 32(7-8), 587–589.

Landry, V., and Blanchett, P. (2012). “Weathering resistance of opaque PVDF-acrylic coatings applied on wood substrates.” *Progress in Organic Coatings*, 75(4), 494–501.

Lavrentyev, A.I., and Rokhlin, S.I. (2001). “An ultrasonic method for determination of elastic moduli, density, attenuation and thickness of a polymer coating on a stiff plate.” *Ultrasonics*, 39(3), 211–221.

Liu, Y.M., Ge, C., Ren, M., Yin, H.B., Wang, A.L., Zhang, D.Z., Liu, C.Y., Chen, J., Feng, H., Yao, H.P., and Jiang, T.S. (2008). “Effects of coating parameters on the morphology of SiO_2-coated TiO_2 and the pigmentary properties.” *Applied Surface Science*, 254(9), 2809–2819.

Manhas, F., Pereira, V., and Bueno, M.I.M.S. (2009). “Evaluation of varnish and paint films using digital imaging processing, energy dispersive x-ray fluorescence spectrometry, and chemometric tools.” *Journal of Coatings Technology*, 6(4), 445–455.

Masaryková, M., Pánek, M., and Reinprecht, L. (2010). “Micro-structural analysis of coatings with nanoscale particles after ageing in Xenotest.” *Wood Structure and Properties*. Technical University in Zvolen—Slovakia, 209–216.

Moya, R., Rodríguez-Zúñiga, A., Vega-Baudrit, J., and Puente-Urbina, A. (2017). “Effects of adding TiO2 nanoparticles to a water-based varnish for wood applied to nine tropical woods of Costa Rica exposed to natural and accelerated weathering.” *Journal of Coatings Technology*, 14(1), 141–152.

Pánek, M., and Reinprecht, L. (2016). “Effect of the number of UV-protective coats on the color stability and surface defects of painted black locust and Norway spruce woods subjected to natural weathering.” *BioResources*, 11(2), 4663–4676.

Pourmand, P., Wang, L., and Dvinskikh, S.V. (2011). “Assessment of moisture protective properties of wood coatings by a portable NMR sensor.” *Journal of Coatings Technology*, 8(5), 649–654.

Robinson, S.C., Tudor, D., Mansourian, Y., and Cooper, P.A. (2013). “The effects of several commercial wood coatings on the deterioration of biological pigments in wood exposed to UV light.” *Wood Science and Technology*, 47(3), 457–466.

Schaller, C., Rogez, D., and Braig, A. (2012). “Organic vs inorganic light stabilizers for waterborne clear coats: A fair comparison.” *Journal of Coatings Technology*, 9(4), 433–441

Shukevich, A.K., Lukhvich, A.A., and Sharando, V.I. (2000). “Magnetic measurements of component thickness in structures composed of nonmagnetic coating and ferromagnetic base.” *Russian Journal of Nondestructive Testing*, 36(1), 22–26.

Sonderegger, W., Glaunsinger, M., Mannes, D., Volkmer, T., and Niemz, P. (2015). “Investigations into the influence of two different wood coatings on water diffusion determined by means of neutron imaging.” *European Journal of Wood and Wood Products*, 73(6), 793–799.

Van den Bulcke, J., Rijckaert, V., Van Acker, J. and Stevens, M. (2006). “Adhesion and weathering performance of waterborne coatings applied to different temperate and tropical wood species.” *Journal of Coatings Technology*, 3(3), 185–191.

Valverde, J.C. and Moya, R. (2014). “Correlation and modeling between color variation and quality of the surface between accelerated and natural tropical weathering in Acacia mangium, Cedrela odorata and Tectona grandis wood with two coating.” *Color Research & Application*, 39(5), 519–529.

Wanga, Y., Qiua, F., Xub, B., Xub, J., Jiangb, Y.,Yanga, D., and Li, P. (2013). “Preparation, mechanical properties and surface morphologies of waterborne fluorinated polyurethane-acrylate.” *Progress in Organic Coatings*, 76(5), 876–883.

Windt, I.D., den Bulcke, J.V., Wuijtens, I., Coppens, H., and Ackererkstoff, J.V. (2014). “Outdoor weathering performance parameters of exterior wood coating systems on tropical hardwood substrates.” *European Journal of Wood and Wood Products*, 72(2), 261–272.

Zhang, J., Yuan, M., Song, S., and Kim, H. (2015). “Precision measurement of coating thickness on ferromagnetic tube using pulsed eddy current technique.” *International Journal of Precision Engineering and Manufacturing*, 16(8), 1723–1728.

Zhang, Y.S., Yin, H.B., Wang, A.L., Ren, M., Gu, Z.M., Liu, Y.M., Shen, Y.T., Yu, L.B., and Jiang, T.S. (2010). “Deposition and characterization of binary Al_2O_3/SiO_2 coating layers on the surfaces of rutile TiO_2 and the pigmentary properties.” *Applied Surface Science*, 257(4), 1351–1360.