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DIFFUSION ANALYSIS OF PROTECTIVE PIGMENT OIL COATINGS

Jakub Dömény[1], Richard Slávik[2], Jan Baar[3]

ABSTRACT: The conservation of historic wooden structures is challenging due to their susceptibility to environmental degradation. This study investigates diffusion properties of nine commercially available protective pigment oil coatings using a dynamic vapor sorption (DVS) analyzer. By analyzing the water vapor transmission rate (WVTR), vapor permeability (δ_m), and equivalent vapor diffusion thickness (Sd), we aim to enhance the performance of these coatings and extend the lifespan of treated wood. The findings reveal substantial variability in moisture transport properties among the coatings, highlighting the importance of selecting appropriate products based on specific environmental conditions. This research contributes to the development of effective conservation strategies for wooden cultural heritage, promoting the use of ecological and non-toxic ingredients to align with broader sustainability goals. The results underscore the need for comprehensive experimental studies to evaluate coating performance and inform conservation practices.

KEYWORDS: Diffusion Analysis, Oil Paints, Cultural Heritage, Wood Protection

1 – INTRODUCTION

The use of wood as a building material dates back centuries, with its application ranging from structural components to decorative elements. Natural wood is inherently susceptible to weathering deterioration, leading to the degradation of its surface layers. Additionally, it frequently faces attacks from biotic agents such as wood-rotting fungi and wood-boring insects [1]. This necessitates the application of protective coatings to increase its service life during exterior use [2]. Moreover, coatings not only enhance protection against environmental factors, including moisture, radiation, biological decay, and potential damage from mechanical or chemical sources, but also contribute to the visual appeal of wooden products through features like color and gloss [3].

2 – BACKGROUND

Currently, there is significant emphasis on investigating ecological coatings for wood protection, considering environmental concerns and issues associated with synthetic wood coatings [4]. These issues may arise from factors such as their origin, toxicity, or challenges in end-of-life disposal [3].

2.1 HISTORICAL USE OF NATURAL BINDERS

Historically, wood surface protection involved the use of coatings based on natural binders like animal skin or bone glue, casein or plant oils. Linseed oil was a commonly used, either in the form of covering pigment coatings or transparent oils itself acting as a hydrophobizing agent [5]. Growing environmental consciousness has sparked a revival of oil paints as a traditional wood surface treatment spanning centuries. This trend has led to the increased popularity of oil coatings in the market. Traditional oil paints not only offer environmental benefits, but also provide a connection to historical preservation practices.

2.2 FUNCTION AND IMPORTANCE OF COATINGS

The primary function of a coating is to serve as a barrier, protecting wood from the adverse effects of weathering and regulating moisture movement within the material. A crucial aspect of this protection is the prevention of

[1] Jakub Dömény, Department of Wood Science and Technology, Faculty of Forestry and Wood Technology, Mendel University in Brno, Czech Republic, jakub.domeny@mendelu.cz

[2] Richard Slávik, Department of Wood Science and Technology, Faculty of Forestry and Wood Technology, Mendel University in Brno, Czech Republic, richard.slavik@mendelu.cz

[3] Jan Baar, Department of Wood Science and Technology, Faculty of Forestry and Wood Technology, Mendel University in Brno, Czech Republic, jan.baar@mendelu.cz

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excess moisture absorption, which can lead to dimensional changes such as cupping and result in wood cracking [6]. As wood is naturally hygroscopic, it interacts with the relative humidity (RH) of the environment, creating a moisture flux between the coating and the wood. This flux is driven by the adsorption of water molecules into molecular sites and the diffusion of water molecules through free spaces or along particle interfaces [7]. Vapor permeability in some coating types may be larger toward the wood than back out through the coating, leading to increased moisture content of the wood beneath the coating [8]. The permeability of water vapor therefore significantly impacts the effectiveness of wood coatings.

2.3 CHALLENGES WITH CURRENT OIL-BASED COATINGS

Oil-based paints rate high on the permeability and vapor-diffusion spectra. This characteristic decreases opportunities for wood decay, as well as for paint failure like blistering and peeling resulting from vapor drive [9]. However, current coatings available on the market, labelled as a “oil-based”, are often very far from the original recipes in their compositon. It is also essential to note that there is a scarcity of comprehensive and comparable experimental data documenting the moisture behavior of oil coatings. This information gap has given rise to various myths surrounding oil coatings and their properties. One of the key challenges in the performance of commercially available oil-based coatings is the variability in their composition, including the non-volatile matter (NVM) content. While many products are labeled as "oil-based," their formulations can differ significantly, impacting their ability to regulate moisture, drying time, and overall performance. The composition, which includes pigments, binders, and other additives, contributes to the coating's durability, gloss, and protective qualities. Therefore, it is essential to conduct comprehensive and comparable experimental studies to evaluate the performance of different coatings and understand the diffusion properties and NVM content for effective wood conservation.

2.4 STUDY OBJECTIVE

To address this need, this study was set up to investigate the diffusion properties of oil-based coatings from different manufacturers on the market in the Czech Republic. A significant factor influencing the durability and effectiveness of coatings is their moisture permeability. Excessive moisture accumulation can lead to deterioration, microbial growth, and dimensional instability in wood. Consequently, the ability of a coating to regulate vapor diffusion is crucial for ensuring long-term protection [8]. The equivalent vapor diffusion thickness (Sd) is a widely used parameter to evaluate the resistance of coatings to moisture transport. It provides insights into how coatings balance moisture protection and breathability, ensuring the longevity of wooden structures.

2.5 IMPLICATIONS AND FOCUS

The findings of this study have important implications for conservation strategies for wooden cultural heritage. By understanding the diffusion properties of different coatings, conservators can make informed decisions about which products to use in specific contexts. This knowledge can help extend the lifespan of treated wood, preserve aesthetic qualities, and enhance overall conservation efforts. Furthermore, the emphasis on ecological coatings aligns with broader sustainability goals. By promoting the use of natural and non-toxic ingredients, this research supports the development of environmentally friendly conservation practices. These practices not only benefit the preservation of cultural heritage but also contribute to the overall health of the environment. This study focuses on the assessment of nine commercially available oil-based coatings, analyzing their NVM content and investigating their diffusion properties using a Dynamic Vapor Sorption (DVS) analyzer. Specifically, the study evaluates the water vapor transmission rate (WVTR), vapor permeability (δ_m), and equivalent vapor diffusion thickness (Sd) values of these coatings.

3 – PROJECT DESCRIPTION

This paper was created at the Research Center Josef Ressel in Brno-Útěchov, Mendel University in Brno with financial supports from project “Wooden structures prevention and maintenance for heritage conservation purposes” NAKI III, reg. No. DH23P03OVV005, provided by the Ministry of Culture of the Czech Republic.

4 – EXPERIMENTAL SETUP

To assess the moisture behavior of oil-based coatings, diffusion experiments were conducted on nine commercially available protective pigment oil coatings:

Table 1: List of protective pigment oil coatings

Brand	Product Name	Code
Biofa	Vernilux aqua	AW
Gnature	Paint for rural houses and cottages	BW
Leinos	Covering varnish	CW
Kreidezeit	Stand oil paint	DW
Osmo	Rustic paint	EW
Ottosson	Linseed oil paint	FW
PNZ	Wood deck paint – covering natural oil	GW
Saicos	House and garden paint	HW
Sokrates	Rustic paint	IW

Samples were prepared by casting a single layer of white pigment oil-based coating onto a PTFE block using a film applicator with a thickness of 120 µm. The coatings were dried at room temperature for a two weeks and then peeled off the substrate. Since oil drying can be influenced by additives such as driers, extenders, and pigments, the percentage of NVM content was determined by measuring the mass change of the paint film after curing and drying, using the formula:

$$NVM = \frac{m_{dp}}{m_{wp}} \cdot 100 \qquad (1)$$

where NVM is the percentage of non-volatile matter [%], m_{dp} is the mass of dry paint [g], and m_{wp} is the mass of wet paint [g].

The final film thickness was measured using a digital thickness gauge (Mitutoyo 547-500S, Mitutoyo Corp., Kawasaki, Japan). Sample films were subsequently cut into 6 mm diameter test specimens before diffusion analysis. Conditioning followed standard EN ISO 7783 2018 to ensure comparability.

The diffusion analysis was measured with a dynamic vapor sorption (DVS) instrument (DVS Intrinsic, Surface Measurement Systems Ltd, London, UK). The device uses very sensitive scales with a high resolution, up to the microgram level. The sample is weighed continuously to track the real response of the material in real time and not just particular discrete points that are identified throughout several hours or days by conventional methods, using the desiccator method and air-conditioning chambers. The humidity of the environment is maintained by mixing dry and saturated humid air from a gas cylinder in the desired ratio. The air in the sample space has a large volume flow, which even allows the measurement of highly sorption-active materials.

A "Payne-type diffusion cell" was used in this test, specifically designed to measure the permeability and moisture transmission rate of thin films. The design of this cell is shown in Figure 1.

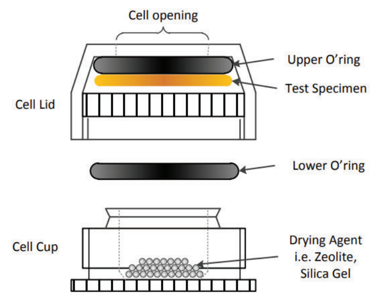

Figure 1. Experimental set-up for diffusion analysis using "Payne-type diffusion cell" [9].

The Payne cell has two main components: a cell lid with two O-rings that create a hermetic seal around the test sample and a cell cup with a small reservoir containing a drying agent, silica gel (SiO_2), to maintain nearly 0% RH. The cell opening provided an active area of 15.54 mm^2 for moisture transport. The Payne cell, loaded with the drying agent and sample film, was placed on the sample holder in the DVS microbalance and exposed to humidity steps of 0–50% RH and 0–95% RH. Measurements were conducted at a constant temperature of 25°C and a nitrogen flow rate of 200 sccm. The total mass of the Payne cell was continuously recorded at one-minute intervals using the DVS ultra-high precision balance. The mass of vapor flowing into the cell was deduced from the increase in weight of the Payne cell over time. The test were performed in duplicate measurements and average recordings were reported.

To conduct a comprehensive diffusion analysis of protective pigment oil coatings, three key parameters were evaluated: WVTR, δ_m and Sd.

The WVTR was calculated by dividing the slope of the linear portion of the weight change of the Payne cell, i.e., the weight gain curve over time, by the tested surface area of the sample, using the following equation:

$$WVTR = \frac{\Delta m}{\Delta t \cdot A} \qquad (2)$$

where WVTR is the water vapor transmission rate [g/m^2 h], Δm is the mass difference between weighings with the linear portion of the weight change [g], Δt is the

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time difference between weighings with the linear portion of the weight change [h], and A is the effective surface area of the sample film [m^2].

The vapor permeability was then derived using Fick's laws of diffusion, which describe the rate at which vapor molecules permeate through the coating material. The δ_m was calculated using the following formula:

$$\delta_m = \frac{WVTR \cdot d}{\Delta P} \quad (3)$$

where δ_m is the vapor permeability [g/Pa h m], d is the sample film thickness [m], and ΔP is the water vapor pressure difference across the sample film [Pa].

The equivalent vapor diffusion thickness, which represents the diffusion resistance of the coating compared to an equivalent thickness of stagnant air, was calculated as:

$$s_d = \mu \cdot d \quad (4)$$

where μ is the water vapour resistance factor of a product material, and d is the sample film thickness [m].

The water vapour resistance factor of a material is defined as the ratio between the vapour permeability of stagnant air δ_a [g/(Pa h m)] and the vapour permeability of the material δ_m [g/(Pa h m)] under consistent temperature and pressure identical thermodynamic conditions, see equation (5).

$$\mu = \frac{\delta_a}{\delta_m} \quad (5)$$

The data were processed in STATISTICA 10 software (StatSoft Inc., USA) and evaluated using a one-factor analysis of variance (ANOVA), completed with Fisher's least significant difference test (LSD test). Statistically significant differences were considered at $p \leq 0.05$. Additionally, correlation analysis was performed to explore the relationship between equivalent vapor diffusion thickness and NVM content.

5 – RESULTS AND DISCUSSION

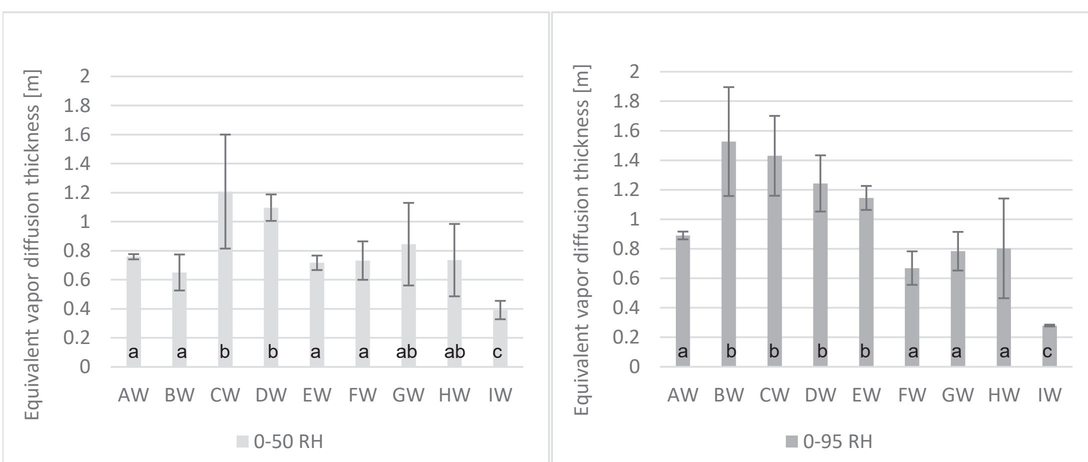
The WVTR measures the ability of coatings to allow moisture to pass through, which is critical for maintaining wood stability and preventing moisture buildup. Table 2 presents WVTR values for different coatings under relative humidity (RH) conditions of 0–50% and 0–95%. The highest WVTR under 0–50% RH was recorded for coating IW (2.759 g/(hr·m²)), whereas coating AW exhibited the lowest value (0.758 g/(hr·m²)). Under 0–95% RH, the WVTR values increased for all samples, with IW again showing the highest transmission (7.245 g/(hr*m²)). The increased WVTR at higher RH indicates greater moisture permeability under humid conditions. This trend aligns with findings by [7], who reported that coatings with high WVTR tend to offer better breathability but may provide less moisture protection in extreme humidity fluctuations. Coatings with moderate WVTR, such as FW (3.071 g/(hr·m²)) and HW (2.769 g/(hr·m²)), balance moisture exchange without excessive permeability, which can help prevent moisture entrapment under the film. These results are consistent with studies by [10], which emphasize the importance of balancing WVTR to reduce paint failures like blistering and peeling. Additionally, findings from [11] show that linseed oil paint has a WVTR between 54.8–124.5 g/m²/day, up to 2.5 times higher than alkyd paint (50.3 g/m²/day). This supports our results, as the oil-based coatings in our study also exhibited relatively high moisture transmission, reinforcing their suitability for breathable protective finishes.

Vapor permeability describes the ease with which moisture diffuses through a material. To ensure accurate results, the thickness of each film was taken into account during the measurement process, allowing for a more precise assessment of permeability characteristics across different coatings. Under 0–50% RH, the highest δ_m was found in DW (10.996×10^{-8} g/Pa·h·m), followed by BW (10.540×10^{-8} g/Pa·h·m). Conversely, GW exhibited the lowest permeability (3.060×10^{-8} g/Pa·h·m), suggesting a higher resistance to moisture transfer. Under 0–95% RH conditions, the permeability increased for most coatings, with IW displaying the highest value (10.480×10^{-8} g/Pa·h·m). This is in agreement with previous findings by [6], who highlighted that coatings with higher δ_m allow greater moisture movement and can help in preventing wood decay. Furthermore, [11] reported that the water vapor permeation coefficient δ_m of linseed oil paint ranges from $0.0058–0.0104 \times 10^{-12}$ kg/(Pa·s·m), a range comparable to some of the values observed in our study. This reinforces the notion that oil-based coatings offer significant moisture regulation benefits. The variation in permeability values suggests that different coatings will perform better under specific environmental conditions. For instance, highly permeable coatings (e.g., IW and DW) may be suitable for applications where rapid moisture dissipation is desired, while lower permeability coatings (e.g., GW and AW) may be more effective for environments requiring moisture protection.

Table 2: Results of water vapor transmission rate (WVTR), vapor permeability (δm) and equivalent vapor diffusion thickness (Sd).

Material code	Thickness [mm]	WVTR [g/(hr·m²)]	δ_m [g/Pa·h·m] × 10^{-8}	s_d [m]
Relative humidity step 0–50%				
AW	0.040 (0.013)	0.758 (0.017)	3.492 (1.109)	0.759 (0.018)
BW	0.106 (0.099)	1.670 (0.318)	10.540 (3.033)	0.650 (0.124)
CW	0.088 (0.007)	0.932 (0.303)	5.248 (2.100)	1.207 (0.392)
DW	0.179 (0.013)	0.976 (0.081)	10.996 (0.132)	1.096 (0.091)
EW	0.085 (0.013)	1.491 (0.104)	7.910 (0.711)	0.717 (0.049)
FW	0.097 (0.007)	1.480 (0.267)	9.006 (0.976)	0.732 (0.132)
GW	0.039 (0.013)	1.337 (0.449)	3.060 (0.041)	0.845 (0.284)
HW	0.069 (0.018)	1.538 (0.521)	6.400 (0.484)	0.735 (0.249)
IW	0.044 (0.002)	2.759 (0.446)	7.548 (0.856)	0.392 (0.063)
Relative humidity step 0–95%				
AW	0.040 (0.013)	2.277 (0.067)	2.974 (0.928)	0.890 (0.026)
BW	0.106 (0.099)	1.367 (0.330)	4.442 (0.637)	1.527 (0.369)
CW	0.088 (0.007)	1.442 (0.273)	4.186 (0.459)	1.430 (0.271)
DW	0.179 (0.013)	1.649 (0.253)	9.756 (0.807)	1.243 (0.191)
EW	0.085 (0.013)	1.774 (0.126)	4.955 (0.438)	1.145 (0.081)
FW	0.097 (0.007)	3.071 (0.521)	9.964 (2.403)	0.669 (0.113)
GW	0.039 (0.013)	2.622 (0.438)	3.257 (0.610)	0.783 (0.131)
HW	0.069 (0.018)	2.769 (1.166)	5.993 (0.981)	0.803 (0.338)
IW	0.044 (0.002)	7.245 (0.155)	10.480 (0.734)	0.280 (0.006)

Standard deviations in parentheses.



The same letters within the testing group indicate that the difference between the means is not significant at the 0.05 level.

Figure 2. Results of equivalent vapor diffusion thickness (Sd).

Equivalent vapor diffusion thickness (Sd) represents the resistance of a coating to water vapor diffusion. Higher values indicate stronger resistance, while lower values suggest better vapor exchange. Figure 2 presents Sd

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values for different coatings under relative humidity (RH) conditions of 0–50% and 0–95%. At 0–50% RH, CW exhibited the highest value (1.207 m), followed by DW (1.096 m), indicating greater resistance to vapor diffusion. Conversely, IW (0.392 m) demonstrated the lowest resistance, implying that this coating allows significant moisture passage. The same trend was observed at 0–95% RH, where CW and BW had the highest values (1.430 m and 1.527 m, respectively), and IW retained the lowest (0.280 m). These findings correlate with results from [8], who reported that high values can reduce the risk of excessive moisture penetration but may also increase susceptibility to coating failures if moisture becomes trapped underneath. Balancing is therefore crucial to optimizing the protective function of coatings. Additionally, [12] recommends an exterior paint Sd ≤ 0.5 m for optimal vapor permeability in Ottawa's climate. Our results indicate that IW (0.280 m) and FW (0.669 m) align well with this guideline, whereas CW (1.430 m) and BW (1.527 m) exceed it, suggesting lower breathability. [12] further discusses how high Sd values can trap moisture, leading to blistering and peeling, reinforcing the importance of selecting coatings based on environmental conditions.

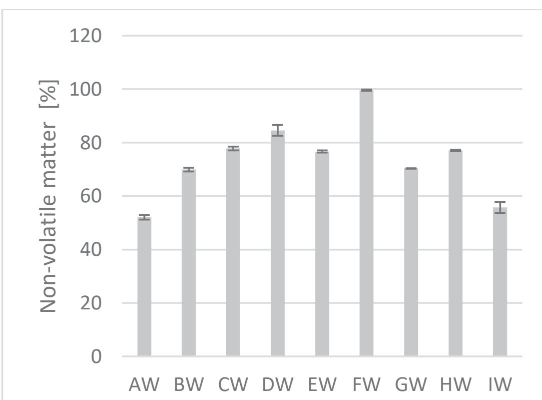

Figure 3. Results of non-volatile matter (NVM)

Figure 3 presents results of NVM. The NVM content is a key parameter influencing final film thickness, durability, and other coating properties. A correlation analysis between final film thickness and NVM content revealed a moderate relationship, with an R value of 0.593. Additionally, a correlation analysis between Sd and NVM content revealed a relatively weak relationship, with an R value of 0.349. This suggests that while NVM content may influence Sd, it is not the sole determining factor. Other variables, such as coating composition, application thickness, and drying behavior, likely play significant roles in defining the diffusion resistance of the coatings. Although coatings with higher NVM content (e.g., FW: 99.62%, DW: 84.58%) generally form thicker and more durable films, this does not always directly translate into reduced permeability. Likewise, coatings with lower NVM content (e.g., AW: 52.03%, IW: 55.74%) may exhibit greater vapor transmission, but their overall diffusion resistance is influenced by additional factors beyond film thickness. The weak correlation suggests that the relationship between NVM and is complex, requiring consideration of coating formulation, the interaction of binding agents, and curing conditions to fully understand how these parameters interact.

The results demonstrate significant variability in moisture transport properties across different protective pigment oil coatings. The high WVTR and δ_m values of IW and FW suggest that these coatings may perform well in environments requiring rapid moisture release. However, their low values may make them more prone to allowing excessive moisture penetration in humid conditions. Conversely, coatings like CW and BW, which exhibited high values and moderate permeability, align with studies by [4], which emphasized the importance of coatings that maintain moisture balance while offering sufficient resistance to vapor diffusion. Such coatings may be more suitable for exterior applications where gradual moisture release is necessary to prevent cracking and surface degradation. The study by [11] further supports these findings, noting that natural linseed oil paint has a medium classification for water vapor permeability according to EVS-EN ISO 7783-2:2001 standards, meaning that while it allows moisture movement, it still provides a level of vapor resistance that helps regulate diffusion. This highlights the importance of balancing permeability and resistance based on the specific needs of wood conservation applications.

6 – CONCLUSION

This study provides a comprehensive analysis of the moisture diffusion properties of nine commercially available protective pigment oil coatings, with a particular focus on the equivalent vapor diffusion thickness (Sd) as a key parameter. The findings reveal significant variability in moisture transport properties among the coatings, emphasizing the need for careful selection based on specific environmental conditions to optimize wood protection. The study also highlights the influence of NVM content on the final film thickness, durability, and diffusion properties of the coatings. Although a weak correlation was found between NVM content and Sd, it is clear that other factors, such as coating composition, application thickness, and drying behavior, play critical roles in defining the diffusion

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resistance of the coatings. By understanding the diffusion properties of different coatings, conservators can make informed decisions about which products to use in specific contexts, thereby extending the lifespan of treated wood and preserving aesthetic qualities. The emphasis on ecological coatings aligns with broader sustainability goals, promoting the use of natural and non-toxic ingredients to support environmentally friendly conservation practices.

Future research should focus on investigating the long-term performance of these coatings under real-world weathering conditions to validate their effectiveness. Additionally, further studies should explore the interaction of binding agents and curing conditions to fully understand how these parameters influence the diffusion properties of protective pigment oil coatings.

Overall, this research contributes to the development of effective conservation strategies for wooden cultural heritage, enhancing the durability and performance of protective coatings while supporting sustainability and environmental health.

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