Hydrophobic Effect of Self-Cleaning Hydrophobic Nanocoating on Wooden Materials

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Abstract

A major limitation of wooden building materials is their high susceptibility to water absorption and, as a result, rot from mold and mildew growth. Self-Cleaning Hydrophobic Nanocoating (SCHN) offers a long-term solution through its use of a sol gel solution to apply the formation of a hydrophobic matrix onto the surface of wood. A sol-gel solution is a liquid mixture of chemical precursors that undergo hydrolysis and condensation reactions to form a solid network (gel). Wooden materials coated with SCHN display a significant resistance to the absorption of water, and, as a result, mold infestation. SCHN also contains metallic nanoparticles with high solar reflectance that impart a dye onto the wood to offer enhanced protection against damage accumulated from prolonged light exposure, as is expected in outdoor environments.

This paper aims to develop a simplified approach towards improving water repellency and reducing the water adsorption capacity of wood treated with Self-Cleaning Hydrophobic Nanocoating (SCHN) in sol-gel solution. The findings indicate that the CaraPro™ sol-gel provides the most significant protection, with a 68.5% reduction in water uptake compared to the control. In biological resistance trials, the coating demonstrated a consistent ability to inhibit the growth

of *Aureobasidium pullulans*, *Aspergillus niger*, and *Penicillium*, by successfully maintaining the wood below the minimum level of moisture required for fungi to colonize the surface. These results suggest that the application of SCHN provides a functional mechanism for controlling the supply of water and moisture, thus mitigating the primary factors behind structural instability and decay.

Introduction

Moisture absorption is a major drawback of the utilization of wood as a building material. Wood is inherently hygroscopic, meaning it readily absorbs and releases water depending on the surrounding environment. This occurs due to the presence of hydroxyl groups in its structural components, particularly cellulose and hemicellulose, which attract and bind water molecules. As moisture content fluctuates, wood undergoes repeated shrinkage and swelling, leading to structural instability which can cause cracking, warping, and joint failure in architectural applications. In addition, elevated moisture levels create acclamatory conditions for biological degradation, including mold, fungal growth, and decay. Prolonged moisture exposure can further accelerate chemical breakdown processes within wood, further reducing its strength over time.

The economic burden of wood degradation in the United States is substantial, as moisture-induced rot and termite damage cost property owners an estimated $5 billion annually in direct repairs [27]. For residential structures, individual repair costs for advanced dry rot vary significantly depending on whether major framing must be replaced, with costs often exceeding several thousand dollars per instance [28]. This financial strain is further intensified by the ongoing volatility in lumber markets, where framing lumber costs have reached record highs in recent years [29]. Beyond the immediate cost of materials, structural decay significantly impacts property appraisals and overall infrastructure longevity [2,17]. By establishing a robust moisture barrier that extends the service life of timber, the SCHN system effectively mitigates the costly tax-dollar and time-consequence repercussions typically associated with conventional maintenance and frequent structural replacement [25,30].

In this study, three different wood samples are treated with sol-gel. To ensure the study's results are scientifically rigorous and comparable to established industrial benchmarks, moisture absorption was evaluated following protocols set by ASTM International, formerly known as the American Society for Testing and Materials. This organization provides the consensus-based technical standards used globally to ensure the repeatability and reliability of experimental data across different laboratories. In the ASTM nomenclature, the prefix "D" designates the category of "Miscellaneous Materials," which encompasses wood-based products, paints, and coatings. Specifically, ASTM D1037 (Standard Test Methods for Evaluating Properties of Wood-Base Fiber and Particle Panel Materials) was employed to standardize the physical submersion and drainage parameters of the wood specimens. Additionally, ASTM D5401 (Standard Test Method for Evaluating Clear Water Repellents on Wood) was utilized to provide a verified framework for calculating the Water Repellent Efficiency (WRE) of the coatings. By adhering to these internationally recognized standards, the study ensures that the performance of the experimental sol-gel treatments can be accurately measured against existing commercial products that are credible to both the scientific community and the timber industry.

The presence of hydrophilic hydroxyl groups in the three major polymeric components of wood (cellulose, hemicellulose, and lignin) is the main factor responsible for many of the unfavorable attributes of wood as a building material. The hydroxyl group of wood attracts water molecules from the surrounding environment through hydrogen bonding, leading to high water absorption, which results in rapid deterioration by rotting, mold, or mildew [17]. A solution that reduces the moisture adsorption of wooden surfaces could potentially mitigate these unfavorable attributes, indicating that water repellency is a key factor in protecting wooden materials.

Developments in the field of wood modification have accelerated considerably in the past few decades. This acceleration is due to a few circumstances, mainly the increasing price of wooden materials, sparking a broad range of modification techniques to increase the life of wooden building materials. The use of resins to fill up the lumen of wood slows down the process of water intake, but resins do not modulate adsorption over a longer period of time [17]. Bulking treatments fill the cavities in the cell wall and lumen, leading to a reduction in the swelling or shrinkage of wood. The most effective treatments are those that chemically modify the structure of the cell wall components–cellulose, hemicellulose, and lignin–and enhance overall stability.

Modification techniques are broadly divided into heat treatments without additives and treatments involving the use of chemicals [2]. Thermal treatments involve the controlled pyrolysis of wood, being heated to over 180°C in the absence of oxygen, inducing chemical changes which cause the wood polymers to break down and form new, hydrophobic (water-insoluble) polymers.

In the Thermwood process, wood is heated in the presence of steam at temperatures of 150-240°C [2]. The steam serves multiple roles: it limits oxidative degradation by displacing oxygen, enables heat transfer, and helps control cracking during treatment. These combined chemical and thermal changes result in wood with improved resistance to reduced swelling and shrinkage, biological degradation, and increased durability, although some loss in mechanical strength may occur due to polymer breakdown. The chemical modification of wood has great potential in improving dimensional stability against moisture and bio-deterioration, increasing functional service life, and extending applicability. For example, treated wood can be used in outdoor environments such as decking or building facades, whereas untreated wood would rot or degrade quickly due to constant exposure to moisture. Numerous reviews can be found on chemical modification of wood with a variety of chemicals. Most of them, however, are focused on acetylation or esterification. Acetylation is a chemical process where small acetyl (carbonyl-methyl) groups are added to a material, such as wood, to make it absorb less water and become more durable in esterification, esters are formed by the reaction of wood with carboxylic acids or acid anhydrides. Ester bonds can be liable to acid or base attack, which leads to hydrolysis. During the esterification of wood, an acid is produced as a by-product if an alkylic anhydride is used; however, a new hydroxyl group is formed when esterification is performed with the use of a cyclic anhydride. This new hydroxyl group can cross link with another hydroxyl group of cell wall polymers in a possible acetylation reaction. A post treatment process removes the residual acetic acid [17]. The two processes are illustrated in Figure 1.

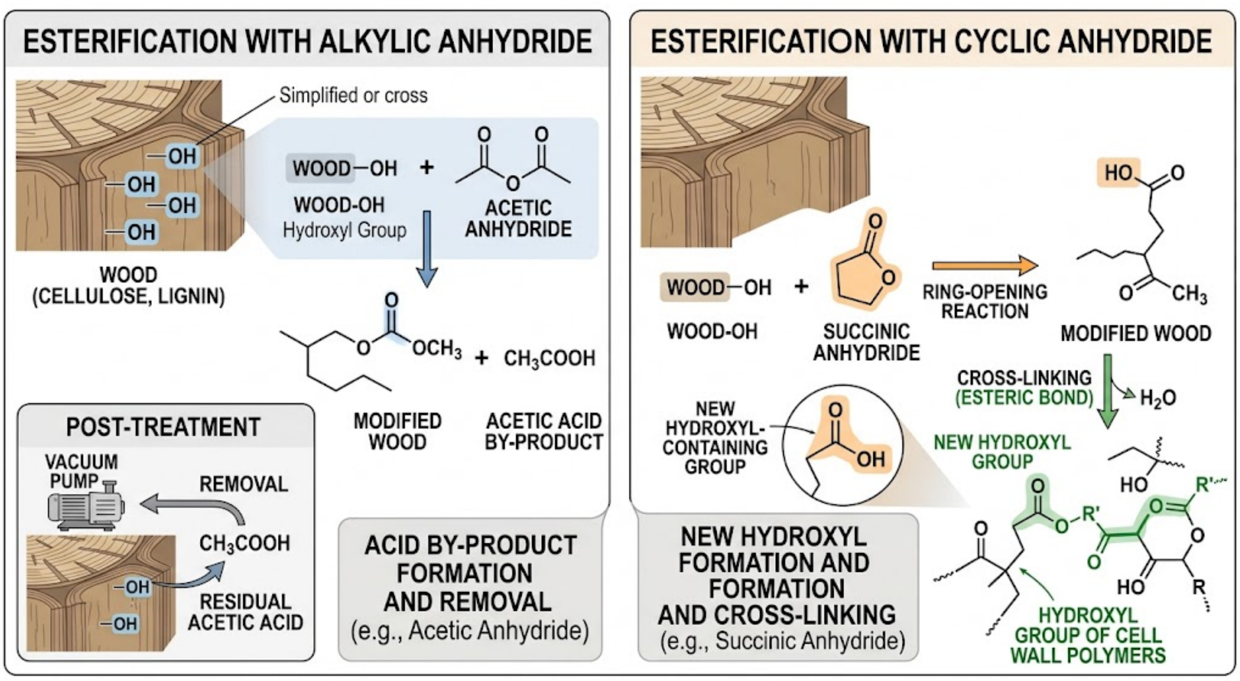

Fig. 1. *Side-by-side comparison of the esterification process with an alkylic anhydride to the esterification process with a cyclic anhydride. Google. (2026, April 5). [AI-generated technical diagram of wood esterification comparing alkylic and cyclic anhydrides]. Gemini 3 Flash. https://gemini.google.com/*

The use of isocyanates and isothiocyanates for chemical modification of wood is also prevalent. The hydroxyl groups react with isocyanate to form urethane [17]. The modification of wood with furfuryl alcohol resin (furfurylation) results in a highly branched and cross-linked furan polymer grafted to the polymers of the cell wall [1]. It is an extremely efficient method to obtain wood products with high dimensional stability, high durability, and resistance towards alkalis and acids [17].

Hydrophobation treatments, which are designed to reduce a substrate's affinity to water, include techniques which change the nature of the cell wall from hydrophilic to hydrophobic. Linseed and hemp oil have been used as water repellent agents, as well as melamine resins, which form a stiff solid network on the surface [2]. Some of the most common groups of chemicals used for hydrophobation are organic silicon compounds, such as Tetraethoxysilane (TEOS) and Hexamethyldisiloxane (HMDSO) [16,23,24].

There are several approaches to improving water-repellency and the dimensional stability of wood, including immersion-diffusion, vacuum-impregnation, heating, painting, and surface coating. One emerging technique is chemical modification, where chemicals such as anhydrides, isocyanates, or alkyl chlorides react with hydroxyl groups, generally the most reactive groups of cell wall polymers [2,17]. For economic and logistic reasons, surface coating has long been preferred to modifications by chemical immersion [3]. It is worth noting that a one-step approach that significantly improves water and oil repellency and long-term stability, which would simplify application and make large-scale use more practical, is rarely discussed in literature. This highlights a gap in current research and the need for more efficient, scalable solutions.

Fluorine-containing coatings are frequently used to lower the surface tension of various substrates (e.g., glass or silicon wafer), leading to super water repellency on the surfaces, with a contact angle of greater than 150° [15]. This enhancement of water repellency is attributed to extremely low surface tensions which are ordered in terms of surface energy as follows:

$$\mathbf{R{-}CF_3 < R{-}CF_2 < R{-}CH_3 < R{-}CH_2}$$

The above identifies the descending order of surface energy for specific functional groups. In surface science, lowering surface energy is the primary mechanism for increasing the contact angle and reducing the work of adhesion for water. For instance, a CF_3-terminated flat surface exhibits high water repellency with a contact angle of 110-120° due to its low surface energy (~6 mN/m) [6,7,8].

Chemical modification of wood aims at modulating the various properties of wood such as durability, moisture sorption, dimensional stability, strength, and hardness [2,17]. Accordingly, this study aims to develop a simple approach towards improving water repellency and reducing the water adsorption capacity of treated wooden substrates using self-cleaning hydrophobic nanocoating (SCHN) in a sol-gel solution.

Modern wood preservation is increasingly defined by the need for environmental compliance, specifically in the mitigation of per-/polyfluoroalkyl substances (PFAS), frequently referred to as "forever chemicals" [31]. Historically, the industry has relied on persistent fluoropolymers to achieve stain and water resistance; however, the bioaccumulative nature and environmental toxicity of these long-chain compounds have led to global regulatory restrictions [32]. The SCHN platform serves as a high-performance, green-chemistry alternative by utilizing a silane-based sol-gel matrix to achieve hydrophobicity [17,25]. Unlike legacy treatments like creosote that pose acute toxicological risks, the SCHN formulation leverages silane-bonded anatase titanium dioxide to immobilize protective functional groups through molecular encapsulation [25]. This organosiloxane-based approach allows for superior water repellent efficiency (WRE) while ensuring the construction remains below the threshold of environmental susceptibility associated with persistent fluorinated chemistry [2,17].

The Self Cleaning Hydrophobic NanoCoating Range

The SCHN nanocoating is designed to prevent or minimize water from interacting with surfaces by creating a hydrophobic barrier. This concept is inspired by the natural properties of water beading on a lotus leaf, where water does not absorb or spread, but rather forms droplets that roll off the surface of the leaf. It is important to note, however, that not all leaves display this behavior. Leaf surfaces vary widely in structure and composition; some are absorbent or smooth, while others, such as the lotus leaf, contain microscopic surface roughness and waxy coatings which promote water repellency. By mimicking these features, the coating can be applied to a variety of materials, including glass, fabrics, and for this case, wood. This nanocoating allows the materials to resist water regardless of the volume of exposure.

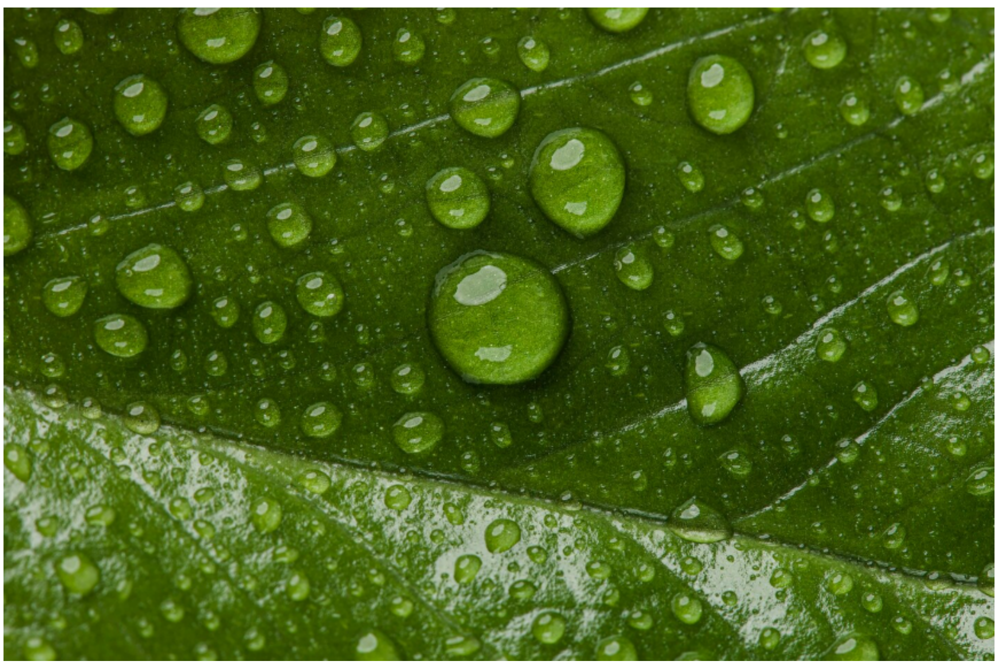

Fig. 2. Water beading on a leaf – a classic example of hydrophobic coating which has proven challenging to mimic. *(freepik.com)*

Hydrophobic materials are those that repel water rather than absorb it, meaning water droplets bead up and roll off instead of spreading across the surface. This behavior depends on both the chemical composition of the material (typically involving nonpolar groups) and its surface structure. In natural systems, such as plant leaves, hydrophobicity is achieved through a combination of waxy coatings and textured surfaces that minimize water adhesion. When applied to wood, however, achieving this effect is more complex because wood is naturally hydrophilic due to its abundance of hydroxyl groups, meaning it tends to absorb moisture rather than repel it.

Although similar hydrophobic innovations have been developed, achieving both cost-effectiveness and durability remains a challenge. Spray-based coatings are relatively easy to apply but tend to be short-lived because they cohere physically rather than forming strong chemical bonds with the surface. More durable methods involve chemically binding particles to the material; however, these processes often require high-vacuum conditions, making them less economical, and consequently, less feasible. Furthermore, while inspiration is drawn from surfaces of a plant, materials such as wood differ notably in structure from leaves. Leaves are thin, flexible, and specific for photosynthesis, whereas wood consists of dense, rigid tissue, primarily responsible for water transport and support. As a result, replicating the water-repellent aspects of certain leaves onto wood and other structurally different materials further contributes to the complexity of developing an effective and practical coating.

Hydrophobic coatings on wood are typically evaluated using water contact angle measurements, which indicate how a droplet interacts with the treated surface [6]. A contact angle greater than 90° suggests hydrophobic behavior, while values above 150° indicate superhydrophobicity. For wood specifically, these measurements are especially important because untreated wood readily absorbs water, so an increase in contact angle directly reflects improved surface performance. Additional assessments, such as sliding angle tests, evaluate how easily water droplets roll off the wood surface, while durability tests examine how well the coating withstands weathering, abrasion, and prolonged moisture exposure. Together, these methods help determine whether a hydrophobic treatment is not only effective initially but also capable of maintaining its performance on wood over time.

Synthesis of Sol-Gel Formulation

Sol-gel allows for the preparation of transparent, solid, and porous inorganic matrices at low temperature, and the incorporation of organic molecules in its porosity [18,19]. The method of its use involves hydrolysis and condensation reactions with silicon alkoxides to produce a three-dimensional, amorphous, porous and stable silica network. Organically modified alkoxide precursors are an excellent modulator of the structural properties of the porous surface of the matrix, as they allow for the controlling of polarity and size of the pores according to the nature and amount of the non-hydrolysable organic group used [20,21]. In addition, these matrices allow for the introduction of large amounts of organic molecules, especially those with large organic modifiers [22].

The sealant was prepared utilizing a sol-gel synthesis to immobilize functionalized anatase TiO_2 particles within an organosiloxane matrix. This specific formulation leverages the high refractive index of anatase to scatter UV radiation, while the silane-based matrix provides a hydrophobic barrier by capping the free hydroxyl groups of the wood substrate [25].

One option to increase surface hydrophobicity is silanization, the reaction of hydroxylic materials with alkyltrichloro/alkyltrialkoxysilanes. The most extensively studied agent is octadecyltrichlorosilane (OTS) [9].

Contact Angles and Sliding Angles

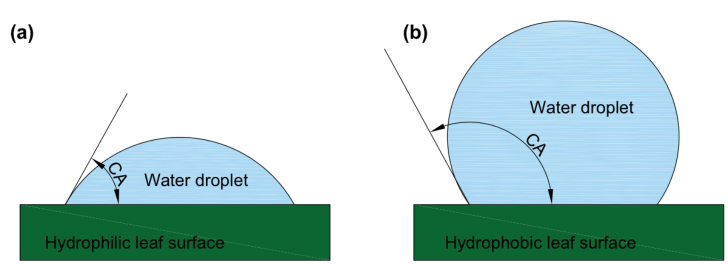

Fig. 3. *Schematic representation of water droplet contact angles (CA) on solid surfaces. (a) A hydrophilic surface results in a low contact angle and increased spreading of the droplet, while (b) a hydrophobic surface results in a high contact angle and reduced spreading [26].*

An optical contact angle meter was adopted to measure the contact angle of droplets on the prepared surfaces. The equation applied for this measurement is Young's equation.

$$\gamma_{SV} = \gamma_{SL} + \gamma_{LV} \cos\theta$$

Water contact angle measurements were taken using the sessile drop method on wood blocks (30 91095 mm). The static contact angle was recorded with a camera immediately after the drop was deposited (10-15 seconds), while the ImageJ software processed the images by approximating the drop to an ellipse. ImageJ is an open-source image analysis software used to quantify features such as contact angle measurements from surface images. The measurements were performed along the wood's grain and the volume of the water drop was 3 μl. Although sessile contact angle is not the most accurate measurement, it provides the most accurate representation because it corresponds to the greatest possible contact angle when the surface is heterogeneous or rough, as in the present case.

It is important to note that contact angle measurement on wood suffers several difficulties, which has caused a wide variation in the literature data. Wood is porous and, therefore, capillary penetration occurs. Capillary penetration is when a liquid gets pulled into small pores or spaces (like in wood) on its own, without needing pressure. Surface roughness is not negligible, either. Consequently, liquid spreading is more pronounced parallel than perpendicular to the orientation of the wood grains [7,10]. An additional factor is the chemical heterogeneity of the wood surface. Wood is composed of cellulose (37–51%), hemicellulose (20–30%), lignin (20–30%), and extractives (1–5.5%) [7]. Although the extractives' content of wood is relatively low compared to other components, they affect the hydrophobicity of the wood surface significantly, because these compounds are not evenly distributed within the cell walls.[10] Moreover, the structure and morphology of tropical wood species differ from those of European wood types (see, e.g. Ref. 7, 10). The knowledge of both structure and morphology is important since they influence the industrial applicability of wood as a structural material [2,17].

Contact and sliding angle measurements were utilized to quantify the capacity of the SCHN in regulating the supply of moisture to the substrate. Given the inherent porosity and chemical heterogeneity of wood, these tests were necessary to determine if the treatment could override surface irregularities and grain-dependent liquid spreading. This analysis provides critical insight into the degree of surface energy reduction achieved. While the static contact angle quantifies immediate resistance to water ingress, the sliding angle offers new knowledge regarding the dynamic water-shedding and self-cleaning efficiency.

Ultimately, these results confirm that the coating successfully maintains the construction below the moisture threshold required for fungal colonization. By demonstrating that the treatment remains effective despite the varied morphology of the wood, these tests validate the SCHN as a functional barrier against the primary drivers of structural decay.

Water Absorption (D1037/D5401)

Water absorption characteristics of wooden panels were tested according to the procedure detailed in *ASTM D1037, Section 22: Standard Test Methods for Evaluating Properties of Wood-Base Fiber and Particle Panel Materials*. The panels were conditioned and weighed before undergoing horizontal submersion in one inch of water maintained at a temperature of 20°C. After two hours of submersion, the panels were retrieved and drained for ten minutes. Once visible drops of water were removed from the surface, the sample was weighed and the panels were submerged again for an additional period of 22 hours before the procedure was repeated.

The amount of water absorbed by the specimen during the submersion was calculated from the increase in weight and expressed as the percent by weight. To evaluate the effectiveness of the coatings, two sorts of testing were used. For the first test, 5 ponderosa pine specimens were treated with sol-gel (CaraPro™) and allowed to dry. Five more were covered in a standard paint (Behr), while another five were used as controls (Pristine). The treated and untreated specimens were allowed to float in water for 30 minutes. The results are shown as labeled in Figure 3.

For the second test, Cedar wood samples were treated with CaraPro™ Wood Sealer + CaraPro™ Transparent Water Repellent for Wood performed similarly to otherwise identical samples of Cedar wood treated with Rust-Oleum NeverWet®. CaraPro™ Wood Sealer exhibited an 8.21% increase WRE as compared to BEHR PREMIUM® Transparent Waterproofing Wood Finish (Natural, No. 400), a 164% increase in WRE as compared to BEHR PREMIUM® Transparent Weatherproofing Wood Finish (Natural, No. 500), and identically to Thompson's® WaterSeal® Wood Protector. The results are shown in Figure 4.

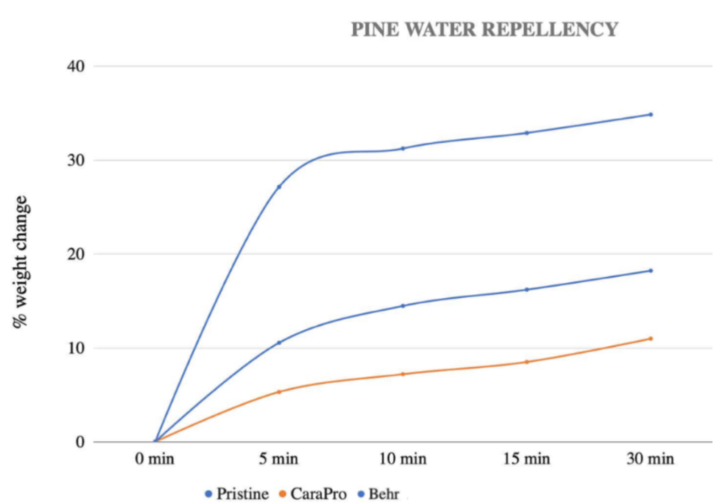

Fig. 3. *Evaluation of moisture absorption in Ponderosa Pine over a 30-minute floating interval. The graph illustrates the efficacy of the coating in regulating the supply of moisture to the wood, with the CaraPro™ sol-gel maintaining the weight change at 11% compared to the 35% uptake in pristine specimens, and 18% with a regular paint application (BEHR).*

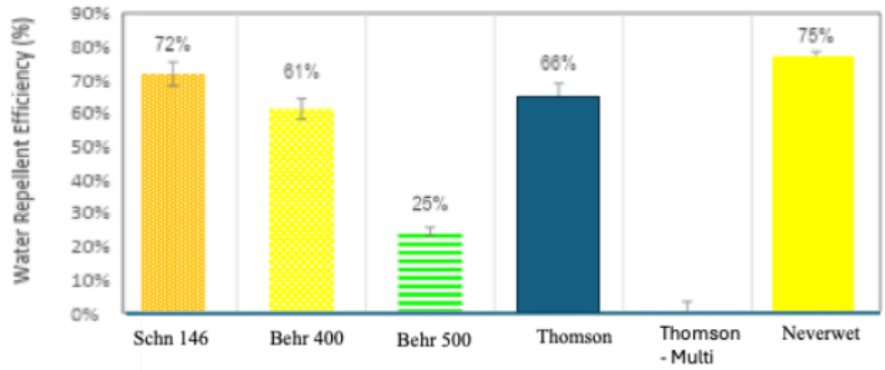

Fig. 4. *Water Repellent Efficiency (WRE) of various surface treatments. SCHN 146 demonstrated a 72% efficiency, effectively regulating the moisture supply to the substrate below the level where the risk for decay by fungi occurs.*

Table

Sample Type	% Weight Change (30 min)	Effectiveness vs. Control
Pristine	~35%	0% (Baseline)
Behr	~18%	~48.5% Reduction
CaraPro	~11%	~68.5% Reduction

The 30-minute floating test measured the effectiveness of surface treatments in regulating a wood sample's absorption of moisture. Untreated pine samples demonstrated a 35% weight change, illustrating a high susceptibility to water ingress, the damaging intrusion of water into buildings. The role of the Behr coating is to mitigate this moisture supply, resulting in a reduced intake level of 18%. The CaraPro™ sol-gel provides the most significant protection, maintaining the moisture content at 11% over the same interval. By restricting the weight change to this level, the treatment serves as a functional barrier that limits the overall moisture retention of the wooden construction.

Fungal Resistance

The following describes the procedure for fungal growth test of treated samples and the result. Sample 1, 2 and 3 were subjected to a Standard Test Method for Resistance to Mold on the Surface of Interior Coatings in an Environmental Chamber (ASTM D3273, where ASTM stands for American Society for Testing and Materials). This test method describes a small environmental chamber and the conditions of operation to evaluate reproducibly in a 4-week period the relative resistance of paint films to surface mold fungi, mildew growth in a severe interior environment. The ASTM D3273 test chamber contains soil that was seeded with fungal spores of *Aspergillus niger* ATCC# 6275, *Penicillium citrinum* ATCC# 9849, and *Aureobasidium pullulans* ATCC# 9348 and allowed to grow. The D3273 chamber was maintained at 32.5 ± 1°C with a relative humidity between 95 ± 3%. The test samples were hung in the D3273 chamber with three pieces of untreated generic wallboard to confirm validity of the fungal inoculum coming from the soil. Samples were examined and rated for fungal growth and defacement weekly on a 0 to 10 rating scale by estimating the percentage of surface defacement with 10 being no defacement and 0 being completely defaced. As shown at the table below, all treated samples have the highest rating, 10, corresponding to no defacement, demonstrating resistance to fungal growth.

Table

Sample Description	**Week 1**	**Week 2**	**Week 3**	**Week 4**

	(Front/Back)	(Front/Back)	(Front/Back)	(Front/Back)
Untreated wallboard	9/10	5/5	0/0	0/0
Sample 1	10/10	10/10	10/10	10/10
Sample 2	10/10	10/10	10/10	10/10
Sample 3	10/10	10/10	10/10	10/10

In an exterior wooden construction, the only factor that can be controlled is the susceptibility of the wood to moisture. Therefore, an important role of coating is to protect the construction from moisture. Moisture content in construction must be kept below a level where the risk for decay by fungi can occur. This level can be described as a probability function, with gradual increasing risk of decay by fungi with increasing moisture content [2].

SCHN 146 treated samples were subjected to *ASTM D3273: Standard Test Method for Resistance to Growth of Mold on the Surface*. This test method can be used to evaluate resistance coating to accelerated mildew growth.

Test samples: SCHN 146 (unmodified silica sol-gel matrix), SCHN 146 Premium C1-F (involving a single fluorinated carbon), SCHN Premium C6-F (involving a chain of 6 fluorinated carbons).

The samples were tested against fungal species, verified by the American Type Culture Collection (ATCC): *Aureobasidium pullulans (ATCC 9348), Aspergillus niger (ATCC 6275), Penicillium (ATCC 9849).*

Samples were examined weekly for fungal growth and defacement and rated according to visual defacement of fungal growth, with a rating of 10 indicating no defacement, a rating of 9 indicating 1-10% defacement, a rating of 8 indicating 11-20% defacement, and so on until a rating of 0, indicating 91-100% defacement.

Samples were tested independently by MicroStar Lab Limited. After 4 weeks, only 1 out of 6 surfaces exhibited small areas of mold growth (shown by red boxes), corresponding to a rating of 9 = -10% defacement. More than 80% of the surfaces rated only 0-10% defacement. Even in an environment controlled to severe conditions that suit accelerated mold growth, SCHN 146 coatings offer excellent mold resistance.

Pigment Color Absorption

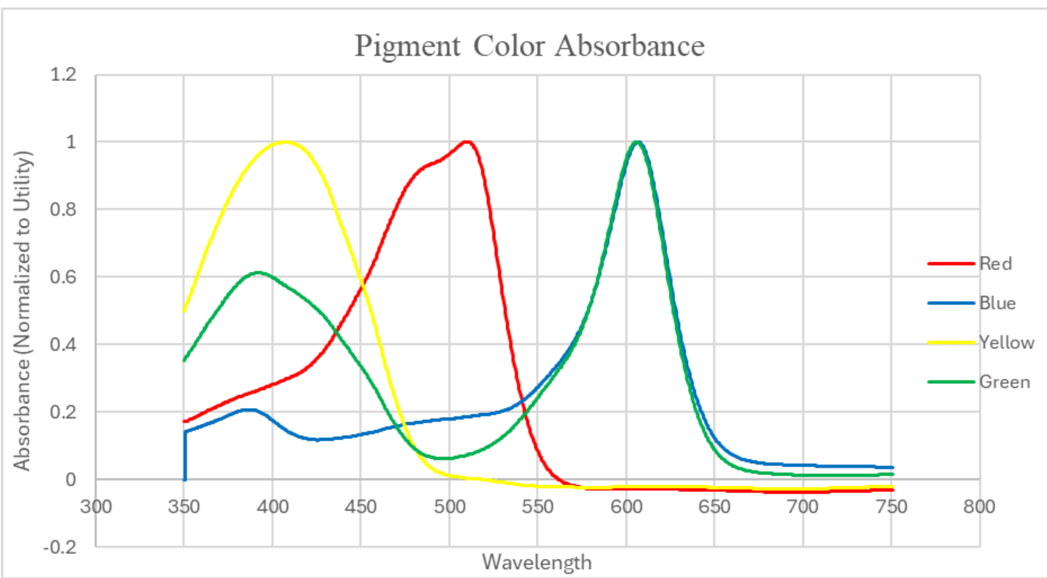

Fig. 5. *Normalized absorbance spectra of integrated pigments within the sol-gel matrix. These additives effectively regulate the supply of radiation to the substrate, providing a functional barrier against UV-induced photo-oxidation. This protection is critical for preventing the degradation of lignin and ensuring the construction remains below the threshold of light-induced structural decay.*

Two fundamental facets comprise the cornerstone of this technology, which holistically differentiates us from other existing technologies: 1.) The mechanism by which our technology protects a given host material; 2.) The ability of our technology to function as a penetrating delivery system for an assortment of additional functional additives (e.g., IR-reflectants, biocides, flame-retardants, UV stabilizers, etc.). In contrast to the vast majority of polymeric coatings, this molecular system percolates through porous materials while intimately interacting with the molecular structure of a suitable host/substrate material to form a three-dimensional protective barricade against the elements. This is functionally and dynamically different from conventional sealers, lacquers, varnishes, enamels, or glosses that merely form an easily erodible surface coating. As a result of the robust encapsulation mechanism underlying our this core platform technology operates system, our system is it is also proficient at extending the useful life of various elements/additives construction/building materials while concurrently reducing the frequency of coating reapplication, mitigating the costly tax- dollar and time- consequence repercussions typically associated with conventional alternatives.

An estimated 90% of residential structures in the United States are currently outfitted with some form of air conditioning [18,22]. With increasing urbanization coupled with ongoing global warming trends, average temperatures of population hubs across the United States are expected to continue rising accordingly. Studies have shown that at temperatures exceeding 20ºC, peak electricity demand in urban areas rises between 2–4% for each 1ºC - increase in maximum daily temperature [19,23]. In the United States, electricity continues to be predominantly generated through the combustion of fossil fuels. Such an increase in electricity demand establishes a direct correlation between increased demand for air-conditioning and increased carbon dioxide emissions. This problem is further exacerbated by the fact that demand for electricity is steadily increasing at a greater rate than environmentally preferred renewable energy systems are being added [20,24]. Consequently, viable solutions aimed at reducing electricity demand from air conditioning units in urban areas focus on innovative methods by which to reduce the accumulation of heat within enclosed structures. The unwanted heating of urban structures is largely attributed to incident infrared (IR) radiation from the sun, which comprises 53% of terrestrial solar radiation [21,25]. IR radiation incident upon urban structures is either directly absorbed at external surfaces or transmitted through and absorbed by objects within the structure and subsequently converted to heat. An economically pragmatic method for mitigating heat buildup is by increasing the total solar reflectance (TSR) of the exterior surfaces of enclosed structures through the use of functional coatings. TSR is defined as the amount of radiative energy reflected by an object upon irradiation. A number of IR-reflective coatings based on scattering granular pigments, micron-scaled metal flake pigments, and tandem systems combining chromatic pigments with micron-scaled metal flakes have been proposed [22,26].

However, these systems are known to suffer from low reflectivity, dimensional restrictions, and color constraints. A comparatively new class of inorganic transition metal-based pigments belonging to a broader group of colorants referred to as complex inorganic color pigments (CICPs) exhibit exceptionally high IR-reflectivity while affording a sizable range of colors. Additionally, CICPs generally exhibit outstanding color fastness, temperature stability, and chemical resistance [23,27]. which collectively contribute towards a more robust coating. In effect, select CICPs can be incorporated into our coating system through chemical functionalization to provide substantial heat management properties without compromising in chromatic combinations or vibrancy.

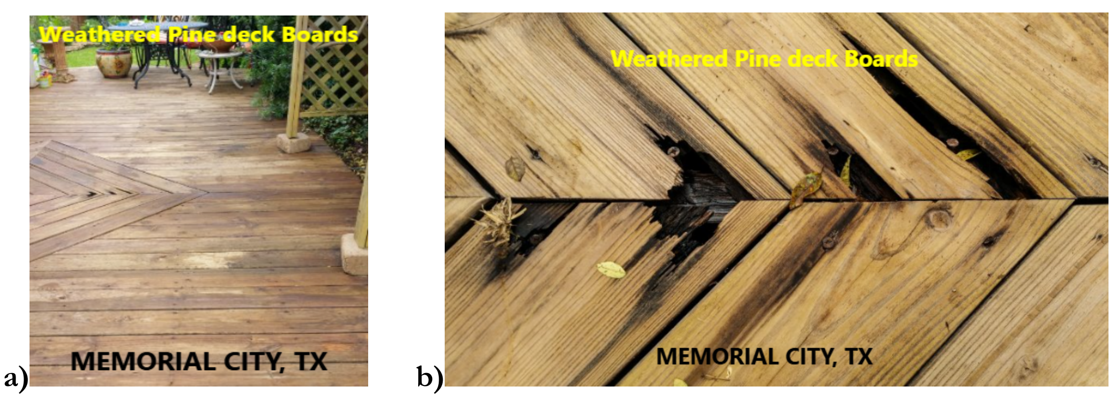

Fig. 6. *Advanced biological decay of untreated pine in Memorial City, TX. These samples demonstrate the high probability of structural failure when moisture levels are not maintained below the threshold for fungal colonization by a functional coating.*

Sample Description		Week 1 (6/11/14)	Week 2 (6/18/14)	Week 3 (6/25/14)	Week 4 (7/2/14)
		Front/Back	Front/Back	Front/Back	Front/Back
SCHN 146	1A	10/10	10/10	10/10	10/10
	1B	10/10	10/10	10/10	10/10
	1C	10/10	10/10	9/10	9/10
SCHN 146 Premium A	2A	10/10	10/10	10/10	9/10
	2B	10/10	10/10	10/10	10/10
	2C	10/10	10/10	10/10	10/10
SCHN 146 Premium B	3A	10/10	10/10	10/10	10/10
	3B	10/10	10/10	10/10	10/10
	3C	10/10	10/10	10/10	10/10
Controls and Conditions					
MSL-1 ½” Untreated wallboard		9/10	5/4	1/0	0/0
MSL-2 ½” Untreated wallboard		9/10	5/5	0/0	0/0
MSL-3 ½” Untreated wallboard		9/10	0/0	0/0	0/0
Temperature ˚C (32.5 ± 1°C)		31.7	31.8	31.8	31.6
Relative Humidity (95 ±3%)		94.9	94.8	95.7	96.7

Fig. 7. *Evaluation of biological resistance in SCHN-treated specimens and untreated controls. Testing was conducted under accelerated conditions (32.5 ± 1°C; 95 ± 3% RH) to increase the probability of fungal colonization. While the untreated wallboard controls exhibited rapid degradation to 0/0 scores by the final week, the SCHN 146 and Premium formulations maintained high protective efficacy. These results indicate that the sol-gel treatment successfully regulates the surface environment, keeping the substrate below the threshold of biological susceptibility even under extreme environmental stressors.*

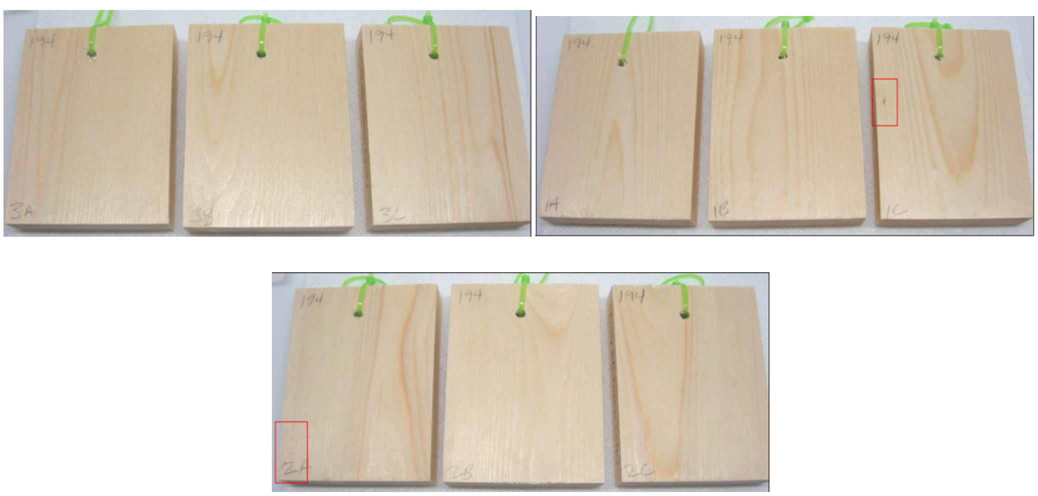

Fig. 8. *Side-by-side comparison of SCHN 146, SCHN 146 Premium A, and SCHN Premium B treated samples.*

The biological resistance test was conducted under conditions of high temperature (~32°C) and extreme relative humidity (~95°C), parameters that significantly increase the mathematical probability of fungal colonization. The untreated wallboard specimens serve as a clear baseline for this risk, exhibiting rapid failure as scores dropped from 9/10 to total degradation (0/0) within the four-week observation period. The role of the SCHN coatings is to regulate the surface environment to inhibit such biological growth. SCHN 146 and Premium A both demonstrated high protective efficacy, with only localized instances of colonization (9/10) observed by the final week, as indicated by the visual markers in the specimens. Premium B provided the most robust protection, maintaining a consistent rating of 10/10 across all replicates throughout the duration of the study. These results indicate that the sol-gel formulations successfully maintain the wooden substrate below the threshold of biological susceptibility, effectively mitigating the risk of decay even under extreme environmental stressors.

Self-Cleaning Hydrophobic Nanocoating (SCHN) on Outdoor Structures

(a)
(b)


Fig. 9. *Before and after comparison of Single-Coat-Stain-Wood Sealer (SCHN) application on outdoor wooden structures. (a) Public footbridge prior to treatment (left) and after SCHN application (right). (b) Park bench before (left) and after SCHN application (right).*

a) 

b) 

Fig. 10. *SCHN application on wooden substrates. (a) Lab samples demonstrating aesthetic and functional pigmented sol-gel options. (b) Field application on an exterior spruce fence. The treatment regulates the supply of moisture and UV radiation, maintaining the construction below the threshold for biological colonization and structural decay.*

Several exterior wooden structures within the Rock Creek Community were selected to observe the performance of the SCHN sealant under real-world environmental exposure. The surfaces underwent high-pressure aqueous cleaning (power washing) to ensure optimal adherence and penetration of the treatment. This step was critical not only for removing accumulated debris and biological oils, but also for physically abrading the photo-oxidized surface layer to create a porous and uneven surface. However, as shown in Fig. 5, power washing alone results in a significant visual downgrading of the wood, producing a gray and uneven appearance in both the foot bridge and bench samples. Once applied, the sealant transformed the weathered wood into a vibrant, rich brown with deep, warm tones. Beyond aesthetic restoration, the treatment established a robust moisture barrier by filling the surface pores and capping the cell-wall hydroxyl groups to significantly reduce the wood's moisture retention capacity. A reduction in the equilibrium moisture content keeps the wood below the threshold required for fungal colonization, effectively protecting the structures against mold, mildew, and long-term structural decay.

The active ingredient in the Self-Cleaning Hydrophobic Nanocoating is anatase titanium dioxide, a crystal with a high solar reflectance and poor solubility with organic materials. When chemically bound to a silane molecule, the crystal surface becomes hydrophobic, making it able to mix with the organosiloxane matrix. The finished product, silane-bonded anatase titanium dioxide in an organosiloxane matrix, has both the hydrophobicity and low surface energy required to induce the lotus effect, a phenomenon where water beads up and rolls off instead of spreading and sinking into surfaces. As the organosiloxane fills surface pores in the stripped wood, there is a significant decrease in the refractive index difference. Differences between wood, air, and the human eye are much larger than between wood, organosiloxane, and the eye, and the subsequent reduction of light scattering enhances grain visibility to leave a richer and warmer color [25].

Interpretation of Results

Wooden materials coated with Self-Cleaning Hydrophobic Nanocoating (SCHN) in sol-gel displayed a significantly increased capability to withstand moisture retention and moisture-related degradation, with little to no visible degradation under severe conditions. On the other hand, untreated wood displayed significant defacement under the same conditions, with each sample reaching 91–100% defacement by the end of the four weeks of testing.

The hydrophobic effect of CaraPro™ (SCHN) is evident in the soaking test, as well. Wood treated with SCHN resisted the uptake of water 65% more than untreated wood, and nearly 50% more than a standard paint totally submerged under water. At first, the efficacy of the different coats seemed to follow the pattern of lowest to highest: SCHN 146, followed by SCHN 146 Premium A, then SCHN 146 Premium B. Premium B showed no visible defacement throughout the four weeks of testing, whereas the others showed minor surface damage. In particular, one side of one surface displayed slight visible defacement (1–10% of surface) during the testing, with SCHN 146 showing defacement one week prior to SCHN 146 Premium A.

Most of the treated wood, however, showed no visible signs of defacement, and the minor defacement present on one surface of each (SCHN 146 standard and Premium A) appeared to have been arrested, or inhibited. More testing may be required to see any significant difference in the efficacy of the different coatings before any conclusion may be reached regarding the differences in different SCHN 146 coatings.

The application of SCHN 146 coating to wooden materials displays much greater hydrophobicity, and thereby a greater resistance to the colonization and subsequent degradation of the material at the hands of mold or mildew, compared to wooden materials untreated by SCHN 146.

Conclusion

Wood is a building material used in most forms of construction. Moisture and moisture-related degradation due to fungi, mildew, or other related factors remain a large hurdle in the strength and longevity of such building materials.

Self-Cleaning Hydrophobic Nanocoating (SCHN) in sol-gel presents itself as a reliable and novel approach to prolonging the robust nature of these building materials. This nanocoating has shown a significant improvement in the resistance of the wooden materials in regard to the adsorption and uptake of moisture, showing little to no signs of mold growth within 4 weeks of severe conditions ideal for the growth of mold. This hydrophobicity is further emphasized by a resistance to the uptake of water displayed by wooden materials treated with SCHN, absorbing significantly less water compared to untreated wood.

SCHN provides a simple, one-step approach to the protection of wooden materials. Having the option of a dyed coating, the capability of a greater resistance to light damage remains well within the domain of SCHN.

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