Theory and Practice of Science and Technology
2025, VOL. 6, NO. 2, 157-162
DOI: 10.47297/taposatWSP2633-456930.20250602

Reviewing Conservation Treatments of Waterlogged Wood

Ruxiao Jiang, Fengjiao Wang, Meng Ding

Sichuan Provincial Institute of Cultural Relics and Archaeology, Chengdu, Sichuan, 610041

ABSTRACT

Waterlogged wood forms after long periods in wet soil, marine sites, and other humid environments. In anaerobic conditions, complete burial can preserve wood for extended periods, even with some decay, making it a rare but significant archaeological resource. This article explores the components of wood and its decay, highlighting the physical and chemical changes in wood exposed to water. It reviews various conservation treatments for waterlogged wood, examining each method's mechanism, procedure, advantages, and limitations. By assessing these treatments, the essay identifies which techniques might be preferred in the future, tailored to different situations and considerations.

KEYWORDS

Waterlogged Wood; Conservation treatment; Polyethylene glycol

Understanding Wood Structure

Understanding the changes in wood requires knowledge of its structure at various levels. Microscopically, wood is structured from the inside out as pith, heartwood, sapwood, cambium, and bark[1]. At the molecular level, the wood cell wall consists of a primary wall and three layers (S1, S2, S3) of the secondary wall, with the S2 layer providing mechanical support[2]. The cell wall primarily contains cellulose, lignin, and hemicellulose, along with water, sugars, extractives, and inorganic compounds.

Cellulose ($C_6H_{10}O_5$): provides strength for the wood.

Hemicellulose: a matrix or binder.

Lignin: a matrix or binder, providing some protection from biodeterioration.

Sugars and inorganic compounds: nutrients for wood growth.

Extractive: organic impurities for the wood ' s colour, smell and other physical or chemical features.

Decay of waterlogged wood

Whether found underwater or buried in soil, waterlogged wood is typically saturated with excess water. While it may appear stable in its waterlogged state, once it is removed from this environment, the degraded wood is highly susceptible to drying stress and its own weight. Common damages include surface cracking, splitting, collapse, and shrinkage in various directions[3]. The degradation of waterlogged wood results from various sources. Table. 1 shows three major deterioration agents to the waterlogged wood.

Table 1 Three deterioration agents on waterlogged wood

Deterioration Agents	Description	Impacts
Physical forces	mechanical stress, temperature variations, water movements	weaken structure
Chemical effects	acids, salts, and other chemical compounds in the environment	loss of strength, decomposition, discoloration
Biological attack	bacteria, fungi, and insects	weaken structure, discoloration, loss of strength, decomposition

Understanding these agents and their impacts is crucial for developing effective conservation strategies for waterlogged wood.

Conservation challenges

Conservation challenges appears during treatments, including cleaning, drying, consolidation and display. The drying treatment is especially important because it is which damages, for example shrinkage and collapse, mostly occur.

Particular challenges are:

Prevent dimensional changes: Due to its anisotropic nature, distortions occur in various directions. Typically, most swelling and shrinkage happen longitudinally, cracks appear radially, and collapse occurs tangentially.

Increase in the hygroscopicity: As cellulose degrades, wood becomes more porous, absorbing moisture from the environment and risking waterlogging.

Display the original appearance: Waterlogged wood affected by soft rot fungi changes to light brown or black, depending on decay severity. Conservators must choose coatings to either reveal the original colour, protect against future degradation, or both.

Prevent further damages: The storage environment is crucial, as conserved wood is sensitive to RH fluctuations.

Conservation treatments

The priority for conservators is to prevent the shrinkage and deformation of the waterlogged wood and then to reveal the artefacts to the public in an appropriate way. Here are four methods[4] to treat waterlogged wood shown in Table.2, however, conservators have discovered that it is quite impossible for one technique to be adequate solving all problems. Combination treatments become more and more widely used in recent years.

Table 2 Various treatments for waterlogged wood conservation

Methods	Mechanism	Treatments
Impregnation or Bulking	Impregnation: solution to fill the lumen, cell wall capilliaries, and microcapillaries. Bulking: solution to fill the cell wall.	Polyethylene glycol (PEG) with various molecular weight Sugars Alum (potassium aluminum sulphate)
Replacement of water with a non-aqueous solvent	Immerse wood or wooden artefacts in solution baths. Some may require sealed containers.	Acetone-carried materials Alcohol-carried materials Silicone oil
Freeze drying	Use of freezer, freeze-drying chamber and vacuum. Sometimes need pre-treatment of PEGs. Freezing water vapors onto the condenser coils.	Vacuum freeze drying Non-vacuum freeze drying
Air drying	RH control Remove water by natural drying	Use of plastic tent Controlled air drying

1 Polyethylene glycol (PEG) treatment

Polyethylene glycol (PEG), a synthetic material with the formula $H_2OCH(CH_2OH_2)CH_2OH$, is widely used as a bulk impregnation agent for waterlogged wood conservation due to its water solubility and non-toxicity. Studies show low molecular weight PEG suits slightly degraded wood, while higher molecular weight PEG is better for more degraded wood[5].

In the 1970s, conservators often used a single PEG type. For instance, Ferriby boat III's oak timbers were treated with PEG 4000, starting at 30°C and increasing by 10°C per stage. This caused some timbers to distort by nearly 20% and lose 25% weight[6]. Similarly, a 2006 experiment with PEG 600 showed limited effectiveness, reducing radial compressive strength by 50% and having little impact on longitudinal tensile strength[7].

Combining various PEGs is now preferred for comprehensive treatment. A notable example is the Vasa conservation in Stockholm, where PEG spraying took years to complete[4]:

1962-1965: 3% solution of sodium pentachlorophenol in 20% PEG 800, 25% PEG 1500, and 15% PEG 4000

1965-1971: 10%PEG 1500

1971-1978: additional 25-35% PEG 600 and PEG 4000

1979: 45% PEG 4000

1980-1982: 45% PEG 600

According to Vasa records, tangential drying cracks were inevitable, but their impact is minor compared to the overall success.

The whole structure has remained stable for years, demonstrating PEG's effectiveness for large wooden artefacts.

Further Studies on the Vasa indicate that PEG degradation poses issues, such as weakening wood through reactions and offering minimal mechanical strength[8]. Degraded PEG products accelerate wood cell wall decay, and low molecular weight PEG can liquefy, seeping out of timbers.

Additionally, low molecular weight PEG is more hygroscopic than higher ones[11][9], therefore, the moisture contents in timbers would be different and the risk of deteriorations from RH fluctuations increases.

2 Sugar treatment

Sugar, especially sucrose was once a popular anti-shrinkage agent for waterlogged wood conservation for the following reasons:

High solubility: can penetrate further into the cell walls.

No need of heating: more economic and environment friendly.

Release water vapors unless the RH is greater than 83.5%: requires an easily achieved storage condition thus guarantees little dimensional changes[10].

Sucrose treatment was replaced by PEG due to its superior anti-shrinkage properties. However, research on sugar treatments continues. An experiment[11] (Table. 3) testing sugars' effects on waterlogged wood's mechanical strength found that sucrose, trehalose, and sucralose significantly increased the modulus of elasticity and resistance to deformation. Sugars form a crystalline lattice within the wood, providing strong mechanical support, though cracking sounds were observed during testing.

Table 3 Modulus of elasticity and stress at failure for each set of samples.

	Modulus of elasticity/GPa	Stress at failure/MPa
Fresh tongue depressors	11.50 ± 1.28	135.5 ± 6.1
Degraded untreated	3.34 ± 1.36	75.4 ± 3.9
Treated with 60% sucrose	19.10 ± 1.26	196.9 ± 7.8
Treated with 60% trehalose	36.90 ± 2.18	260.6 ± 20.5
Treated with 60% sucralose	29.00 ± 2.27	232.8 ± 29.7

Other previous studies also prove that sugars sometimes show better improvements over PEG technique. However, risks exist as well[14]:

Results are erratic.

Possibility of microorganism growth until high concentration of sugar is reached.

Possibility of attacking by insects or vermin after treatments.

3 Alum treatment

The use of alum for conservation began in Denmark in 1861. Pre-heated artefacts were placed in an alum solution, followed by applying linseed oil, and a final glycerol coating to prevent shrinkage and cracks[12]. However, by the 1950s, notable disadvantages were identified:

Artefacts became very heavy but lacked strength.

Shallow penetration of the alum solution.

Only the surface was stabilized.

Alum was replaced by PEGs in the 1960s and is no longer recommended. Due to its widespread use from the 1860s to the 1950s, many alum-conserved woods now require re-conservation. It is essential for conservators to understand this technique to choose suitable alternatives.

4 Acetone-carried materials treatment

Non-aqueous solvents or consolidants for replacing water could be dissolved in acetone. The acetone-rosin treatment is designed to preserve hardwoods that the high molecular weight PEGs cannot penetrate. This treatment serves as an alternative to PEG, with other rosins and mixtures also applicable. In 2010, five natural and synthetic rosin consolidants were tested for their effects on waterlogged wood, focusing on equilibrium moisture content (EMC) and dimensional stability[13]. Their hydrophobic nature prevents wood from absorbing moisture, resulting in limited EMC variations (within 11%) and reduced fungal attack risks. Treated samples showed stable dimensional changes with minimal shrinkage, aided by low moisture absorption[17]. However, the acetone-based treatment poses flammability risks, as the infusion solution needs to be heated in final stages[14]. The high cost also limits the application for large wooden artefacts.

5 Alcohol-carried materials treatment

This treatment begins with immersing the wood in baths of alcohol until all free water is replaced by alcohol. Once this outcome is achieved, the wood is immersed in baths of ether (or dimethyl ether) and dried by placing it in a vacuum. The alcohol-ether treatment was proved to be successful by maintaining the stable structure of the wood and producing a natural-looking of the wood.

6 Silicone oil treatment

Silicone oil, a liquid siloxane (Si-O-Si) polymer, was initially used as a wood coating additive. Recently, methyltrimethoxysilane (MTMOS) has been tested to stabilise waterlogged wood by replacing water and air with silicone polymers. There are two methods: soaking method and pressure impregnation[15]. Soaking: Dehydrate the wood sample with 96% ethanol, then immerse it in a 50% MTMOS and 96% ethanol solution before drying. Pressure impregnation: Follow the same steps as soaking but under vacuum conditions. A 2017 study on MTMS as a stabilising agent found it a potential option for waterlogged wood[16]. This study showed that compared to PEG, while PEG significantly improved wood stability overall, MTMOS also showed notable effectiveness (Figure 1). The study revealed MTMOS's stabilising effect depends on wood degradation: it works better on less degraded wood.

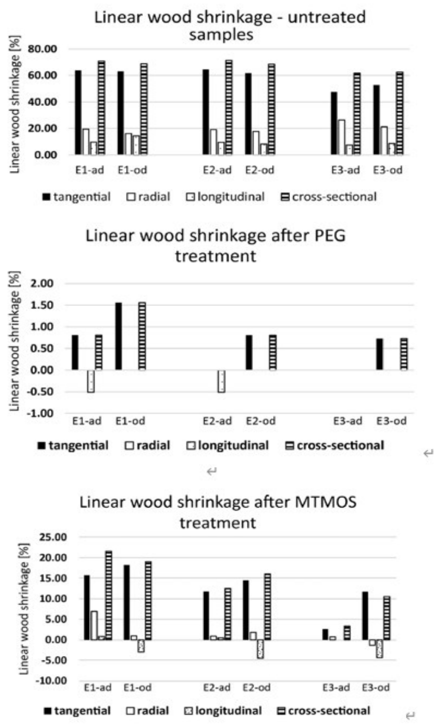

Figure 1 Mean values of linear and cross-sectional wood shrinkage before treatment and after treatment with PEG and MTMOS

Silicon oil treatment preserves wood's natural colour and, due to its hydrophobic nature, prevents fungal attacks. Studies show MTMOS is more effective than PEG in protecting wood from biodegradation[17], making it suitable for waterlogged wood conservation. However, as a recently developed method, conservators emphasise the need for further research to assess its long-term durability.

7 Freeze drying

Many accounts show that frozen waterlogged wood, without pre-treatment, causes significant damage. PEG impregnation combined with vacuum freeze-drying is the preferred method for highly degraded wood.Usually a vacuum freeze dryer is used and it is noteworthy that this type of dryer is expensive. Studies on this combined treatment also highlight risks: despite no visible cracking, the internal structure can collapse[18]. Balancing low sublimation temperatures and rapid freeze-drying is challenging, increasing handling risks[19].

8 Controlled air drying

Air-drying, applicable both in situ and in laboratories, is effective for drying waterlogged wood if water is removed slowly. A successful example is the 1981 conservation of large Roman timbers from Geneva, where timbers were dried under a plastic tent with controlled RH. After two years, water content dropped from 200-500% to 10%, with minimal deformation[20]. However, risks include unexpected rapid water loss at early stages[24] and the challenge of maintaining RH across seasons due to the lengthy process. Other previous studies show air-dried samples often sustain little damage, though the treatment itself can sometimes cause harm[8].

9 Combination treatments

One of the most popular combination treatments is PEG with freeze-drying, though it has limitations. As an alternative, PEG with controlled air-drying is more accessible. Currently, most combination treatments are PEG-based, as PEG delivers the most effective results in waterlogged wood conservation in general. Table 4 shows the antishrink efficiency values (ASE) of various treatments, including PEG dissolved in different solvents. ASE measures treatment effectiveness: 0% indicates no benefit, while 100% means no dimensional change[21].

Table 4 Antishrink efficiency values of various treatments

Treatment Method	ASE(%)
Air Drying - no PEG	0
Freeze Drying - no PEG	19
Freeze Drying, rapid pre-cool - no PEG	46
Freeze Drying, 25% PEG 400	105
Acetone Rosin	76
PEG 4000 (3350) in water	58
PEG 4000 (3350) in tertiary butanol	83
PEG 4000 (3350) in methanol	45

The results indicate that PEG combined with solvents other than water, like tertiary butanol, may yield better outcomes. Although PEG remains the most popular material for preserving waterlogged wood, conservators are aware of its issues and ongoing research is exploring alternatives. New materials mentioned in the literature include chitosan, crystalline cellulose, biomimetic cellulose, guar gum, and 2-hydroxy-ethyl cellulose[22-23].

Comparison of various treatments

A comparative table (Table 5) summarizes the discussions on different waterlogged wood treatments. The choice of treatment depends on various factors: scale of the wood; desired appearance; reversibility, flexibility, or rigidity of the treated wood; sensitivity to RH or temperature variations; financial constraints of the laboratory; storage conditions and other project-specific factors. For large artefacts like Vasa, the decision involves not only conservators but also curators, sponsors, and other project staff.

Table 5 Comparison of various waterlogged wood treatments

	Control on dimensional change	Biological attack protection	Weight & Colour change	Reversibility	Cost (time and money)	For large or small objects	Other risks
PEG	Excellent with freeze drying and various types of PEG	Good with coating	Lighter; lighter	Reversible	Months or years; can be high cost	Both	Corrosive to all metals; PEG decay; risk of heating
Sucrose	Good (excellent if well controlled)	Poor	Heavier; dull colour	Reversible	Weeks; lowest cost	Both	Erratic; Small cracks on surface
Alum	Poor	Good with coating		Reversible		Both	Sensitive to RH fluctuation; Alum degradation
Acetone-rosin	Excellent	Excellent	Lighter; Natural colour	Reversible	Various duration; high cost	Small	Flammability
Alcohol-ether	Excellent	Excellent	Lighter; lighter	Reversible	Various duration; high cost	Small	Flammability
Silicone oil (MTMOS)	Good (excellent with less degraded wood)	Excellent	Natural colour	Irreversible	Various duration; low cost	Both	Need further studies
Freeze drying	Good	Good		Reversible	Months or weeks; high cost	Small	Pre-treatment of PEG; sensitive to RH
Air drying	Good	Good		Reversible	Years; low cost	Small	Intensive monitoring; Sensitive to environmental changes

Conclusion

After evaluating various treatments, PEG-based methods are expected to remain the most widely used over the next 20 years due to their reliability and relatively low cost. However, conservators are increasingly aware of PEG's degradation issues. Conservation advancements must be driven by new generations to find alternatives, with MTMOS being considered a potential replacement. In the coming decades, modifying existing PEG treatments and exploring alternatives will be key tasks for waterlogged wood conservators.

References

[1] T. Nilsson, R. Rowell, Historical wood – structure and properties, ScienceDirect, 13(3S), 2012.

[2] Plomion, C, Leprovost, G and Stokes, A, Wood Formation in Trees, Plant Physiology, 12(4), 2001.

[3] McConnachie, G, Conservation of waterlogged archaeological wood. In Mark Jones ed, For Future Generations: Conservation of a Tudor Maritime Collection. Portsmouth: Oxbow Books. 2003.

[4] Grattan, D. W. and Clarke, R. W, Conservation of waterlogged wood. In Conservation of marine archaeological objects. Butterworths.; Texas A&M University. Wood Conservation. 1987.

[5] Hoffmann, P. On the stabilization of waterlogged oakwood with PEG. II. Designing a two-step treatment for multi-quality timbers. Studies in Conservation 31, 1986.

[6] Suthers, T, The treatment of waterlogged oak timber from Ferriby Boat III using polyethylene glycol. In W. A. Oddy ed, Problems of the Conservation of Waterlogged Wood. London: National Maritime Museum.1975.

[7] Mortensen, M.N, Egsaard, H, Hvilsted, S, Shashoua, Y and Glastrup, J, Characterisation of the polyethylene glycol impregnation of the Swedish warship Vasa and one of the Danish Skuldelev Viking ships. Journal of Archaeologucal Science, 34(8),2007.

[8] Lechner, T, Bjurhager, I, Kilger, R, Strategy for developing a future support system for the Vasa warship and evaluating its mechanical properties. Heritage Science, 1(1), 2013.

[9] Bjurhager, I, Ljungdahl, J, Wallstrom, L, Gamstedt, E. K, Berglund, L. A, Towards improved understanding of PEG-imprgnated waterlogged archaeological wood: A model study on recent oak. Holzforschung, 64(2), 2010.

[10] Grattan, D. W. and Clarke, R. W, Conservation of waterlogged wood. In C. Pearson ed, Conservation of marine archaeological objects. Butterworth-Heinemann, 1987.

[11] Tahira, A, Howard, W, Pennington, E. R., Kennedy, A, Mechanical strength studies on degraded waterlogged wood treated with sugars.Studies in Conservation, 62(4), 2016.

[12] Haggstrom, C and Sandstrom, T, ed. Alum-treated archaeological wood: Characterization and re-conservation. Swedish National Heritage Board, 2013.

[13] Giachi, G, Capretti, C, Donato, I. D., Macchioni, N, Pizzo, B, 2011. New trials in the consolidation of waterlogged archaeological wood with different acetone-carried products. Journal of Archaeologucal Science, 38(11), 2011.

[14] Kaye, B, Conservation of Waterlogged Archaeological wood. Chemical Society Reviews, 24(1), 1995.

[15] Borda, M, Mazela, B and Radka, K, 2019. Methltrimethoxysilane as a stabilising agent for archaeological waterlogged wood differing in the degree of degradation. Journal of Cultural Heritage, 35(1), 2019.

[16] Borda, M and Mazela, B, 2017. Application of methyltrimethoxysilane to increase dimensional stability of waterlogged wood. Journal of Cultural Heritage, 25(7), 2017.

[17] Borda, M, 2018. Biological effectiveness of archaeological oak wood treated with methyltrimethoxysilane and PEG against Brown-rot fungi and moulds. International Biodeterioration & Biodegradation, 134, 2018.

[18] Waston, J, Research into Aspects of freeze-drying Hardwoods between 1982 and 1984. In Waterlogged wood, study and conservation: proceedings of the 2nd ICOM Waterlogged Wood Working Group Conderence, 1985. Grenoble: Centre d'etude et de traitement des bois gorges d'eau.

[19] Jensen, P and Jensen, J. B, 2006. Dynamic model for vacuum freeze-drying of waterlogged archaeological wooden artefacts. Journal of Cultural Heritage, 7(3), 2006.

[20] Schweizer, F, Houriet, C and Mas, M, Controlled Air Drying of Large Roman Timber from Geneva. In Waterlogged wood, study and conservation: proceedings of the 2nd ICOM Waterlogged Wood Working Group Conderence, 1985. Grenoble: Centre d'etude et de traitement des bois gorges d'eau.

[21] Grattan, D, Malcolm, B, Grant T and Logan, J, Outcome Dtermines Treatment – An approach to the treatment of Waterlogged wood. Journal of Wetland Archaeology, 6(1), 2006.

[22] Christensen, M, Kutzke, H, Hansen, F. K, New materials used for the consolidation of archaeological wood-past attempts, present struggles, and future requirements. Journal of Cultural Heritage, 13(3S), 2012.

[23] Walsh, Z, Janecek, E-R, Jones, M, Scherman, O. A., 2017. Natural polymers as alternative consolidants for the preservation of waterlogged archaeological wood. Studies in Conservation, 62(3), 2017.