Functional Conservation and Preservation of Waterlogged Archaeological Wood

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Waterlogged archaeological wood of shipwrecks has been preserved under seawater for centuries, such that microbial erosion has caused severe bacterial degradation and acidification. These wooden cultural relics are of great significance for understanding the shipbuilding technology, trade activities, and environmental ecology of centuries ago. From the perspective of structure and composition, these waterlogged archeological woods have the characteristics of high water content and a large loss of lignin and cellulose, which makes the hull prone to collapse during preservation. Therefore, it is urgent to apply conservation and preservation treatments for deacidification and consolidation. Due to the fragility of wood and the complexity of repair work, the current development of conservation and preservation technology has multiple aims, such as antibacterial, deacidification, and reinforcement effects. In this editorial, the current challenges and conservation treatments with antimicrobial or deacidification utilities will be introduced.

DOI: 10.15376/biores.19.1.10-12

Keywords: Cellulose; Waterlogged Archeological Wood; Antimicrobial; Nanhai No. 1

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Polymeric Consolidation of Waterlogged Archaeological Wood

For the past few decades, the salvage activities of sunken ships have gradually attracted the attention of scientists because of their archaeological value. The development of polymer science, nanotechnology, and innovative technologies have gradually demonstrated their advantages in the conservation and restoration of cultural heritages. Waterlogged archaeological wood, salvaged from historical sites, is water-saturated wood with evidence of having been worked by humans centuries ago. Although these waterlogged archaeological woods have maintained their original size and shape for hundreds of years due to slow degradation in an anoxic environment, the severe acidification and salt deposition on the surface is an important challenge for protecting the cultural heritage. Temperature, salinity, fungi, and bacteria are the cause of the severe cell wall decay and shrinkage of waterlogged archaeological wood, resulting in chemical and biological decomposition along with acidification of the wood. Taking the Vasa as an example, the sulfate contained in waterlogged archeological wood is produced by the metabolism of bacteria, which will gradually oxidize to become acidic, putting the wood in a severely corrosive environment (Sandström *et al*. 2002). If no protective treatment is given, the restored waterlogged wood becomes soft and fragile when dried directly without any treatment, which is due to the microscale defects and collapse of cell walls.

Most conservation technologies aim at enhancing the mechanical properties of waterlogged archaeological wood. Typically, polymer adhesives have been used as consolidants to fill the pores inside the waterlogged archeological wood *via* a moderate diffusion process. Polyethylene glycol (PEG) was one of the most used consolidants in the early years. Generally, PEG solution is filled into the pores of the waterlogged archeological wood successively according to the molecular weight from small to large, then dried by freeze drying or solvent exchange to avoid volume shrinkage. This preservation approach, especially the PEG diffusion part, is highly dependent on the molecular weight of the consolidant polymers, and the process needs to be conducted *via* long timescale treatments under mild conditions to avoid irreversible damage to the objects. Small molecular compounds and polymers with binding performances have also been used as consolidants to restore saturated wood, including trehalose, lactitol, and mannitol (Broda and Hill 2021). Subsequent research has shown that the restoration of waterlogged archeological wood is highly dependent on the age, wood species, state of decay, and preservation environments of the shipwrecks. Therefore, designing a conservation process based on the wood compositions and mechanical properties is essential for all shipwrecks.

Antimicrobial and Deacidification

The current conservation technologies of waterlogged archaeological wood mainly aim at the enhancement of mechanical properties, while multifunctional consolidants can contribute to wood restoration in terms of antibacterial, deacidification, and desalination at the same time. In addition to the consolidation utility, research on the development of functional consolidant has been conducted for antimicrobial and deacidification purposes (Giorgi *et al*. 2005; Dong *et al*. 2010). Among the deacidification treatments, inorganic micro- or nanoparticles have been proven to be efficient fillers for the consolidation and preservation of paper artifacts and archaeological woods. Alkaline nanoparticles, especially metal oxide or hydroxide nanoparticles, were extensively studied for the purpose of neutralizing the sulfuric acid in the waterlogged archeological wood (Schofield *et al*. 2011). Cavallaro *et al*. (2020) reported the use of halloysite nanotubes (HNTs) in consolidants and achieved excellent deacidification performance (Cavallaro *et al.* 2020). In addition to deacidification, the prevention of bacterial decomposition is also important, since the waterlogged wood raised and restored still confronts with the risk of bacterial degradation destroying the wooden structure and increase the concentration of sulfuric acid. Therefore, it is essential to ensure the mechanical strength of the restored wood and effectively inhibits bacterial growth on the surface. Magnesium hydroxide has been reported as to be an antimicrobial agent in liquid culture and in paper sheets (Dong *et al*. 2010). Silver nanoparticles (AgNPs) are a well-known antimicrobial agent that inhibits bacterial growth by modifying their cell membrane permeability.

Research on these restoration technologies has common features with 3D printing of biomass materials: doping with different components including biomass, polymers, and nanomaterials to introduce antibacterial and deacidification behaviors while maintaining excellent mechanical properties. Research has been carried out worldwide for decades, and with the vigorous development of shipwreck salvage in South-East Asia recently, an increase in scientific and archaeological opportunities are expected. An example is provided by the Nanhai No. 1, a Chinese merchant ship that sank during the Southern Song dynasty and was salvaged from the South China Sea. In 2007, the 800-year-old shipwreck was raised from the seabed and was moved to the Marine Silk Road Museum, where it was preserved. Early studies of the wood at the museum showed that the structural damage of the waterlogged archeological wood, composed of softwoods, was too severe to withstand long-term spray deacidification and moisture retention (Liu *et al*. 2018, 2023). The shipwreck was salvaged directly by building a large savage device undersea, and a nearby museum and research center was established for the conservation and preservation. The overall structure of the hull was preserved during the salvage process. The structure needs good mechanical reinforcement and antimicrobial and deacidification treatment. At present, as hull research enters the restoration stage, the development of related technologies is expected to promote the protection of wooden cultural heritage worldwide.

ACKNOWLEDGMENTS

This work was supported by GuangDong Basic and Applied Basic Research Foundation 022A1515110507.

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