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Analysis and prediction of selected mechanical/dynamic properties of wood after short and long-term waterlogging

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HIGHLIGHTS

- We analyse pine and oak samples in differing waterlogging conditions.
- We perform dynamic analysis of samples (free-vibration and ultrasound velocity).
- We use PLS models from FT-NIR spectra to predict dynamic/physical parameters.
- Analysed properties decrease in pine sapwood already after short-term waterlogging.
- Prediction models are proved to be reliable for conditioned samples.

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ABSTRACT

Wood is one of the oldest building materials and, thanks to its favorable mechanical and technological properties, one of the most versatile. Due to its biological nature, wooden artefacts can undergo some alteration during their service life that can be caused by mechanical, environmental or biological agents.

Waterlogged and buried wood elements, present in wetlands and aquatic environments, are subject to modifications at the chemical and anatomical level, which also affect physical and related mechanical properties of the material.

The possibility to predict long-term performance and the rate of modification of mechanical/physical properties of the wood material in specific environmental conditions is crucial for proper design and optimal maintenance of submerged load-bearing timber structures. Therefore, prediction models to estimate selected material properties were developed within this study. For this purpose Fourier Transform near-infrared (FT-NIR) spectroscopy and multivariate analysis based on partial least-squares (PLS) were used. The models proved to be effective to predict selected dynamic and physical parameters of waterlogged samples. However, in order to include the effect of water saturation in the material on site further research is indispensable.

The possible detrimental effect on wood mechanical properties of waterlogging in differing environmental conditions is also discussed in this paper. Dynamic tests were performed on samples of two species, *Quercus robur* L. and *Pinus sylvestris* L., after 8 years of deposition in two differing sites. Additionally, the results obtained from fresh and archaeological samples were compared.

No significant effects have been observed due to the depositional environment after short-term waterlogging. A more remarkable difference in the rate of the modification of dynamic and physical (density) properties can be attributed to differing natural features of the tested wooden species. It may be concluded that, in order to ensure a longer service-life of waterlogged timber structures, original wooden material should be properly selected, with regard to species, growth conditions, and log characteristics.

1. Introduction

Researches devoted to understanding the behavior of wooden material in time and in specific environments is justified by the increasing interest in the use of CO_2 neutral, renewable, local

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resources for new constructions, and by the necessity of preserving timber architectural heritage. Structural members affected by waterlogged conditions are timbers such as pilings, retaining walls, posts, and parts of cooling towers. These frequently reside in subaerobic or anaerobic environments, when they penetrate the groundwater table, enter into zones of waterlogged sediments, support structures above bodies of fresh or marine water, or are in permanent contact with circulating water. Wooden piles have been used for centuries all over the world to support buildings in areas with unstable soils, and it is estimated that millions of wooden foundation piles are still in service. Moreover, the use of wooden piles is not restricted to giving stability to buildings but also to the soil. The importance and vulnerability of this kind of constructions have been highlighted in some publications [1,2].

Waterlogged and buried wood elements are subject to modifications at the chemical and anatomical level, which also affect physical and related mechanical properties of the material. These modifications result from a complex interaction between wooden material and the environment (i.e. temperature, pH, presence of water and oxygen). Modification of wood components, as a consequence of long-term submersion or underground embedding, comprehends different kinds of degradation and conversion. The main degradation mechanism in waterlogged wood is bacterial erosion, whose severity mainly depends on the specific burial conditions and wood species [3]. Permeability of the wood and groundwater flux are believed to be the key parameters to determine the velocity of bacterial decay [1]. In many studies it has been shown that the depth of burial also affects the amount of deterioration in submerged wood [4].

Once the wooden species is identified, two main aspects should be analyzed for the characterization of the material in waterlogged load-bearing timber structures:

- The rate of decay (current extent and, if possible, estimation of the velocity of the decay process), in order to evaluate the actual and perspective residual effective cross-section.
- Mechanical properties of interest.

This information should be coupled with the data on selected environmental parameters (e.g. changes in the ground water level, pH and water conductivity, redox potential and soil temperature) in order to predict future degradation and quantify residual service life. In the case of on-site analysis of waterlogged wood, specific issues should be addressed, such as the accessibility of the elements, limitation in the use of some measurement devices, the influence of water on the measurements. An effect of wood moisture on the mechanical and physical properties of the material should also be considered.

Mechanical characteristics of waterlogged wood can be altered because of losses and changes of structural chemicals as well as loss of cell and tissue integrity. Physical parameters can be also altered by the deposition of minerals in the early stage of silification. Various approaches are used for diagnostic investigations of waterlogged wooden findings by determining micro-morphological, physical, chemical and biological parameters. These approaches allow characterization of the structural and chemical modifications as well as the extent and nature of biodegradation.

Many researches have been devoted to reliably estimating material mechanical properties in timber structures [i.e. 5–8]. Most published efforts for the non-destructive (or semi-destructive) characterization of archaeological waterlogged samples have been mainly focused on hardness measurements (i.e. nanoindentation) [e.g. 9,10]. Bader et al. combined hardness tests with ultrasonic tests for the micromechanical characterization of waterlogged oak samples [11]. Dynamic test methods, based on measurement of either stress wave time-of-flight or resonance frequency, are a simple and efficient way of characterising elastic properties of materials. These analytical techniques are nowadays used to a great extent in both wood industry and research. Brancheriau and Bailleres [12] review the most common theoretical models and define their validity range, application conditions, and accuracy levels with respect to measured values.

There are several researches exploring the relationship between dynamic-mechanical properties and structural features of wood at the various length scales [e.g. 10]. The changes in the dynamic properties of wood due to waterlogging may reflect changes in both structure and volume fractions of cell wall constituents. Wood can be schematically described at a macromolecular level (1–100 nm) as a complex composite of cellulosic chains, which form thread-like units called microfibrils embedded in lignin matrix. The microfibril angle and the cellulose content exert the predominant influence on cell wall stiffness [10]. Microfibrils are almost parallel to the longitudinal direction in the S2 layer of a wood cell wall. The S2 cellulose content is also higher than in the other layers. The influence of mass density on dynamic properties of wood at the macroscopic scale has been extensively investigated since the second half of the nineteenth century [e.g. 13–17]; conclusions of various studies differ considerably. However, it seems that the density and dynamic properties of wood are not totally independent from each other. It is due to the fact that with increasing wood density the proportion of the S2 layer within the cell wall increases too. Therefore, such increase of matter (highly organized cellulose microfibrils in S2) elevates the overall mechanical resistance of wood [16]. In the case of waterlogged wood, however, a pronounced decrease of dynamic properties (ultrasound velocity) in archaeological oak samples of density comparable of that of contemporary wood has been reported [11]. The reasonable conclusion of these results is that dynamic properties are not only affected by the amount of wood substance, but also by its integrity in terms of bonds between polymers in the cell wall. It is clear therefore, that analysis of waterlogged wood at the molecular level may help understand degradation mechanisms at the macroscopic scale.

Recent developments in the fields of optics and electronics opened new possibilities for nondestructive measurements of various physical and chemical properties of materials.

FT-NIR spectroscopy, for example, is widely used for estimation of the chemical composition, prediction of physical and mechanical properties, evaluation of decay and weathering of wood among others [18]. Even if this technique gives only local estimates, global parameters can be inferred through adequate measurement protocols [19].

In the research reported in this paper stress wave-based techniques and FT-NIR spectroscopy have been used for the characterization of waterlogged wood.

The researched materials included archaeological objects (long-term waterlogged) and contemporary wooden samples buried in the ground or submerged in water for 8 years (short-term waterlogging). The deposition site was located in an archaeological area of the settlement of the Lusatian culture (the eighth century BC) in Biskupin, Poland. A dedicated research project was initiated in Biskupin in 2003, with the aim of monitoring site parameters of waterlogged archaeological wood [20]. Later on, an experimental campaign was initiated to investigate changes to the contemporary wood buried in the environment of decomposition of archaeological artefacts [21]. The set of unique experimental samples has become available for investigation after recent excavation of the wood as a supplement to the collection of ancient samples.

The goal of the research was to investigate the long-term performance of the wood material exposed to specific environmental conditions. Such information may be essential for proper use and maintenance of submerged load-bearing timber structures, but