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Assessing the wood compressive strength in pile foundations in relation to diagnostic analysis: The example of the Church of Santa Maria Maggiore, Venice

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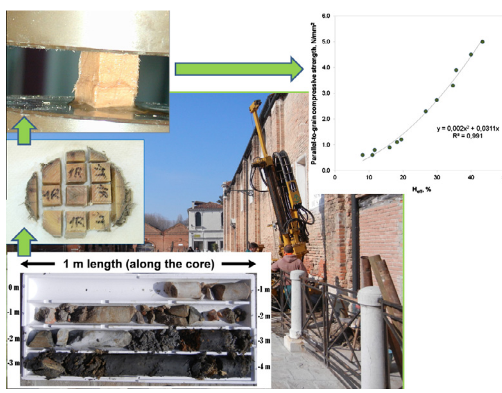
HIGHLIGHTS

- The foundation piles of the Church of Santa Maria Maggiore, Venice, were investigated.
- The elements are still in service, and their mechanical properties were assessed.
- Loss for residual strength was greater than for decay-related residual mass.
- Both holocellulose decrease and mass loss contribute to the compressive strength reduction.
- Basic density and holocellulose could be used as possible predictors of residual strength.

GRAPHICAL ABSTRACT



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ABSTRACT

Foundation piles are a noteworthy example of waterlogged wood still constituting load bearing structures. Micromorphological analysis, investigation of physical properties (water content, residual basic density), compressive tests in wet conditions and chemical analyses (lignin, holocellulose) were carried out on samples taken in Venice. Obtained results demonstrated that both mass and strength were lost due to decay, but the residual strength loss was greater than the residual mass. It is also shown that this occurrence was due to the holocellulose decrease. Present results point out that basic density and holocellulose amount could be used as possible predictors of woodpiles residual strength.

1. Introduction

Wood has been used in many towns throughout Europe in building foundations as a system for transferring loads to stronger layers of the underground. In European countries, historic buildings built after the 17th century have been often founded on wooden piles, and several examples exist in particular in northern, eastern and central parts of the continent. Among them, there are the Stockholm parliament building, Bryggen (a monumental UNESCO area in Bergen, Norway), the Hermitage in Saint Petersburg, the Reichstag in Berlin, the Docklands in London and also

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the Grand Palais of Paris and the Royal Palace of Amsterdam [21]. In contrast, except for some sites in the Alpine region dating back to the Neolithic period, like Fiavé [24], Venice is the only city in Italy with buildings founded on wooden piles.

The location of the city, promoted the establishment of a metropolis based on an urban structure unique in the world; the proximity of forests and the presence of waterways (in particular the Piave river) made available to the Venetians a large amount of wood useful for the soil reinforcement of the lagoon and hence the expansion of Venice, from the 14th to the 16th century [1].

During the 16th century, a construction system typical of the Venetian palaces became an established technique: piles, typically short (around 1.5–3 m long) were densely inserted into the soil (hammered, or by suitable machines) and a wood deck was placed above them. This deck was called *zatterone*, and it was made of two or three layers of timber planks [1,11]. The purpose of pile insertion was not reaching a stiff deep stratum, but reinforcing the soil through this dense insertion; however, this complex structure was adopted only below the bearing walls of selected Venetian buildings.

Foundation piles are a noteworthy example of wood in waterlogged conditions that still constitutes load bearing structures, differently from the majority of other examples of historical waterlogged wooden objects that, after retrieval, stopped to act as structures and became artworks to be displayed in museums. Therefore, it is very important the quantitative assessment of the residual mechanical properties of this kind of structural elements, and of course compressive strength is the most important characteristic to be evaluated in foundation piles.

Nowadays the need to study waterlogged wood in different ways is widely recognized, due to the fact that it is a complex material, substantially different from the sound one; for this reason only an integrated approach with well-established procedures allows the reliable and correct evaluation of the state of preservation of the material [10,14,26]. This means that wood has to be studied for its current chemical composition and physical properties, and the alterations on its morphology; thus, it is possible to determine to which extent waterlogged old wood is different from the sound one.

Biodeterioration induced by soft rot fungi and bacteria is often observed in waterlogged archaeological wood. The main effect of this decay on its chemical composition is the decrease of polysaccharides into the wooden structure [18,27,30]; as a consequence, an increase in the relative amount of lignin is observed. This latter substance is usually more resistant to bacteria and several fungi, and it can be chemically modified only because of oxidative processes of biological origin [2,12,13] [34]. All the above-mentioned phenomena make essential the quantitative evaluation of the chemical composition of waterlogged ancient wood. In particular, the H/L ratio (holocellulose/lignin) gives a direct measurement of the relative decrease of holocellulose compared to lignin; therefore, the decrease of H/L indicates an increasing level of decay [28].

Any characteristic of wood is influenced by its anatomical structure, and consequently observations of cells morphology through microscopy are pivotal in order to know the state of preservation of waterlogged wood and, if possible, to identify the agents of decay [6,7,8,14,24]. In particular soft rot fungi, and erosion and tunnelling bacteria, are able to cause profound deformations of their shape and even size. In case of soft rot decay, fungal hyphae are often visible, and conical ends cavities usually occur. Bacteria cause "groove-like erosion" [20] of cell wall and, in case of severe decay, they transform walls into a granular and amorphous material. Both these organisms are able to depolymerise cellulose in the cell walls. From the anatomical aspect a classification of decay may arise [7,20,24]; this grading process is useful for a direct comparison with the numeric results obtained after both the chemical and the physical characterizations described in present paper.

The increase in wood microporosity in decayed wood has a dual effect: on one hand, part of the mass is lost (and hence a decrease in basic density can be observed); on the other hand, the water content increases compared to sound material.

Only a few studies concerning the residual mechanical strength of historic wood in waterlogged conditions are available in the literature. Schniewind [33] reported on: (a) the maximum compression strength parallel to the grain and (b) static bending tests, to evaluate both strength and stiffness of buried archaeological wood. The mechanical properties were plotted vs. the sample residual density, and values of residual strength were lower than those of residual density (both expressed as percentage) in practically every case. The results from several species were reported, but no correlation with wood species was put in evidence. Also Klaassen [20] carried out compression tests parallel to grain during the activities of the Bacpoles project. In his report Klaassen found a relationship between strength and moisture content for samples of 2 different species, and this relationship was different between conifers and hardwoods. Similar results were also found by Bertolini et al. [5], whereas Bader et al. [3] adopted a different approach, carrying out nanoindentation tests on already dried material, in order to try an indirect estimation of residual mechanical characteristics on a larger scale. Moreover, Riggio et al. [32] compared the dynamic modulus of elasticity, measured by means of both resonance frequency in free transverse vibration and ultrasound velocity measurements, between archaeological and reference material for pine and oak, and found appreciable decrease in the modulus values of pine samples and practical equivalent results for the oak ones.

The CORILA,[1] a non-profit organization supervised by the MIUR (Italian Ministry of Education, University and Research) which associates several Public Bodies in Venice, promotes and coordinates researches on the Venice lagoon aimed at preserving the lagoon environment and monitoring the stability of buildings. For that purpose, a partnership was established among CORILA, University of Ca' Foscari, University of Padova, Soprintendenza Belle Arti e Paesaggio per Venezia e Laguna and CNR-IVALSA in order to study and characterize the foundation piles of Venice. Main object of this research was the *Church of Santa Maria Maggiore*, and in particular its lateral front.

Aim of present work was evaluating the state of preservation of the foundation woodpiles from the Church of Santa Maria Maggiore in Venice, also including the measurement of the residual parallel-to-grain compressive strength in wet conditions. An additional aim of the work was assessing the effect of the considered diagnostic parameters on the residual strength, thus identifying those to be possibly used in models able to predict the woodpiles compressive strength.

2. Materials and methods

2.1. Sampling and labelling

Samples were taken from the woodpile portions found in the core drills obtained from the S. Maria Maggiore Church's foundations[2] (Fig. 1a). These core drills were inclined 85° in respect to the ground (Fig. 1b). Wooden piles studied in the present work were found in core drills 2, 4 and 5, at different depth from the ground level. They were called S2, S4 and S5, respectively. In the labelling of samples, the depth was also associated to each core drill number: for instance, the label S2/-290/-320 was assigned to a sample taken from core drill 2 and found

[1] http://www.corila.it/?language=en.

[2] Core drills were carried out by S.P.G. – Sacchetto Perforazioni Geotecnica s.r.l.