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Article

Assessment of Wooden Foundation Piles after 125 Years of Service

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Abstract: Buildings on piles have been constructed in Ljubljana since the Bronze Age. The piles were made of different types of wood. In the present study, piles that were erected about 125 years ago were investigated. Investors tend to renovate a building; therefore, the piles were analysed to assess the structural condition of the building. The building showed no signs of damage. To gain access to the piles, a 2 m thick layer of soil was removed. On-site, the following analyses were carried out: drilling resistance with a resistograph and a screw withdrawal test. Part of the piles was isolated and light microscopy, scanning electron microscopy, infrared spectroscopy, dynamic vapour sorption, density analysis, and chemical analysis were performed. Microscopic analysis revealed that the piles were made from the wood of Scots pine (*Pinus sylvestris*). The results indicate that the wood was severely degraded, mainly by soft-rot fungi and bacteria, resulting in a significant deterioration of its mechanical properties.

Keywords: piles; waterlogged wood; soft rot; decay; microscopy

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1. Introduction

Wood is one of the most important building materials that has been used for several thousand years [1]. Similar to other building applications, the use of wood for piles has a long history. In the Alpine region, this construction technique has been used for about 7000 years [2]. Among other regions, Ljubljana and its surroundings are recognised as one of the places with the longest tradition of using wooden piles [3]. The southern part of Ljubljana has been built on piles since Roman times, while pilings in Ljubljana Moor have their origin in Bronze Age. Traditionally, pilings were made by hammering down wooden stakes vertically into the marsh soil at even intervals. For this purpose, piles with dimensions between 25 cm and 35 cm are commonly used to support the foundations and to transfer the load more in-depth into the soil [4]. In the Bronze Age, the Ljubljana Moor piles were mainly made of oak (*Quercus robur, Q. petraea, Q. cerris*) and ash (*Fraxinus excelsior and F. ornus*). At the same time, the wood of *Sorbus aucuparia* (rowan), *Carpinus betulus* (hornbeam), *Alnus glutionosa* (black alder), and *Corylus avellana* (hazel) were less frequently used [5]. Afterwards, timber logs of softwood species (pine, spruce or larch) were frequently used for foundation piles [6]. In the recent periods, the pilings in Ljubljana are predominately made of Scots pine (*Pinus sylvestris*), sweet chestnut (*Castanea sativa*), and black alder. In the Bronze Age, pilings were made for building shelters above the water or moor. Still later, this construction technique was used to reclaim marshes and settle wastelands [6,7]. Thus, the use of piles somehow enables constructions even on unstable soil.

Wooden piles in waterlogged conditions have a long service life [8,9]. Many historical cities near rivers, waterfronts, and the sea still stand on the original wooden piles [6], such as Stockholm, Hamburg, Amsterdam, Trondheim, Venice, Saint Petersburg, Ljubljana, etc. [10]. In recent decades, biological damage to a considerable number of wooden foundations across Europe has been identified. Therefore, it is of great importance to understand the performance of waterlogged wood to enable safe homes for citizens and predict the future performance of buildings.

Submerged wood was once considered safe from any form of fungal decay due to the absence of oxygen [8]. However, it has been known for decades that wood in below-ground applications is exposed to a variety of the decay organisms [11,12]. The prevalent type of decay in the ground contact is soft rot. Soft-rot organisms preferentially attack hemicellulose and cellulose in the S2 layer of the secondary cell wall, forming longitudinal cavities (Type 1) or eroding the wood cell wall from the lumen surface in hardwoods (Type 2) or the S2 in conifers. Fungi that cause soft rot are taxonomically classified into Ascomycota and Deuteromycota [13]. Soft rot was initially characterised as a soft, decayed surface of the wood in contact with excessive moisture [14]. Common fungi that cause soft rot include *Chaetomium globosum* and *Alternaria alternata* [15]. Soft-rot fungi colonise wood under conditions that are too cold, too hot, or too moist for white or brown rot fungi. Soft- rot fungi are less aggressive decomposers than white- and brown-rot fungi; therefore, decomposition is slower under soil conditions than above ground or in the air–soil transition zone [16]. In addition to fungi, some bacteria are also known to cause decay in soil by causing tunneling, erosion, or cavitation [17]. Bacterial decomposition in soil and above ground is slower than decomposition caused by fungi in similar applications [18].

Various techniques have been developed to assess the condition of waterlogged wood [19]. The basic principles are based on visual assessments and the use of simple tools such as needles and a knife [20]. The mechanical properties of piles in situ can also be assessed using resistance drilling and penetrometers such as the pylodine. These techniques are concerned with wood density, which is closely related to porosity and maximum water content [21]. There are numerous reports on the use of a wide range of analytical techniques, from pH measurements [22] to thermogravimetric techniques (TGA, DSC, DMA) [23,24] to X-ray-based measurements (XRD) and spectroscopic and chromatographic methods (FTIR, HPLC, GCMS) [25,26]. Some of the classical tools in wood analysis are different types of microscopy (SEM, confocal, light microscopy) and imaging techniques (MRI) [25]. The choice of technique depends on the expected results and the hypothesis. Moreover, it should be taken into account that the research object is a cultural heritage; therefore, less invasive techniques are preferred.

The respective manuscript aims to analyse the properties of wooden piles installed 125 years ago. During the period in question, many buildings were built or reconstructed in Ljubljana, as Ljubljana was affected by a devastating earthquake that destroyed several buildings. Thus, the respective case study could serve as an assessment of the state of other piles in Ljubljana. Moreover, many of these buildings are considered part of the cultural heritage, and therefore the protection of wooden piles is important to protect objects of cultural significance.

2. Materials and Methods

2.1. Material

An 1895 building (old school) (Figure 1) was analysed in detail before renovation. Due to the soft terrain, the building was constructed on wooden foundation piles. The piles were 2 m below ground level and were constantly wet. After 125 years, the top layer (2 m deep) of soil was removed, and five piles were examined in several locations (at the edges) of the building. The water level was about 50 cm above the piles at the time of the measurements. Pieces of wood were cut from the piles with an axe and knife. Multiple samples (2–3) per pile were isolated to represent the pile conditions. Isolated samples were put in plastic bags with an excess of water to prevent drying. Samples were stored at 5 °C approximately 2 h after isolation and kept in the fridge until the analysis. Samples were of uneven shape. The volume varied between 2 cm^3 to 10 cm^3. For comparison, the sapwood of Scots pine (*Pinus sylvestris*) was used.

Figure 1. Old school in Ljubljana prior to renovation.

2.2. Resistograph and Screw Withdrawal Measurements

The structural condition of the wooden foundation piles was quantified by resistograph measurements (PD 500, IML, Wiesloch, Germany). The resistograph analysis was carried out in October 2020. A resistograph is a high-resolution needle-drill resistance measuring device. A thin, steel needle is driven into the wood. During drilling, the energy required is measured as a function of the depth of the needle. The resistograph instrument provides a high linear correlation between the readings and the wood's density being drilled through. Even internal decay can be easily detected. A 1.5 mm diameter drilling needle with a needle tip diameter of 2.0 mm was used [27,28]. Multiple measurements were taken on five piles. On the same piles, screw withdrawal measurements were also performed using a Fakopp instrument (Fakopp Enterprise Bt, Agfalva, Hungary). The screw size was 4 mm in diameter, and the length of the threads was 18 mm. Since the withdrawal force depends slightly on the test speed, a speed of 0.5 mm/s was used. At the end of the measurement, the maximum force was determined [29]. For comparison, measurements were performed on wet Scots pine wood as well.

2.3. Density and DVS Analysis

The envelope density of oven-dry wood was determined using GeoPyc 1365 (Micromeritics, Unterschleissheim, Germany). The envelope density was measured on 15 wood samples (average dry mass 0.7 g). The GeoPyc is a dry and void-filling method using a free-flowing solid, compression, and a displacement measurement technique. Instead of Hg, a free-flowing solid Dry Flo (registered trademark, Micromeritics Instrument Corporation) was used. First, the sample chamber was filled with Dry Flo only; under rotating movement and the desired pressure, the volume of sand was calculated. Second, the sample was positioned in Dry Flo, and the sand was agitated and gently consolidated around the sample. The envelope volume of the sample was calculated from the difference in volume between the two measurements. A 19.1 mm inner diameter chamber was chosen to perform the envelope density determination of the wooden samples. A recommended consolidation force of 28 N and a conversion factor of 0.1284 cm^3/mm was used for this chamber. As recommended by the operating manual, this force was low enough not to damage the wood structure [30,31].

The sorption isotherms of the pile sample were determined using a DVS Intrinsic instrument (DVS Intrinsic, Surface Measurement Systems Ltd., London, UK). Before the experiment, the sample was conditioned for at least 24 h at 20 ± 0.2 °C and 1 ± 1% RH. For analysis, a small amount (approximately 40 mg) of the milled sample was placed on the sample holder and suspended in a microbalance within a sealed, thermostatically controlled chamber in which a constant flow of dry compressed air was passed over the sample at a flow rate of 200 cm^3/s and a temperature of 25 ± 0.1 °C throughout the RH range. The DVS method was set to 20 steps of 5% between 0% and 95% RH for both the sorption and desorption steps. Two full isothermal runs were performed to capture the material's sorption behaviour fully; however, only one cycle is presented in the respective study. The instrument held a constant target RH until the rate of change of sample moisture content (dm/dt) was less than 0.002% per minute for 10 min. The run time, target RH, actual RH, and sample weight was recorded every 20 s throughout the isothermal run. Sorption and desorption isotherms were constructed by plotting the change in equilibrium moisture content (EMC) against relative humidity (RH). Additionally, the drying dynamics were determined for the water-saturated sample. A small piece of wet wood (approximately 45 mg) was placed on the sample holder and exposed in the chamber with the conditions described above. The only difference was that in this case the sample was passed over with compressed air of 0% RH until the rate of change of the sample moisture content (dm/dt) was less than 0.002% per minute over a period of 10 min.

2.4. Chemical Analysis

Diffuse reflectance infrared Fourier transform spectra (DRIFT) were recorded between 4000 cm^{-1} and 450 cm^{-1} with a PerkinElmer FTIR Spectrum Two spectrometer (Waltham, MA, USA) using diamond ATR (PerkinElmer, Waltham, MA, USA). The spectra were recorded at a resolution of 1 cm^{-1} and 16 scans. FTIR spectra were normalised based on the lignin peak at 1505 cm^{-1} [32].

For the determination of Klasson lignin, 1 g of the sample was used. The sample was placed in a 50 mL beaker and mixed with 72% H_2SO_4. After 2 h, the mixture was diluted with distilled water to obtain a 3% aqueous H_2SO_4 solution and heated for another 4 h. The next day, the solution was filtered through filter paper. The filter paper containing the lignin was dried at 103 ± 2 °C for 24 h and weighed. Then, the lignin content was calculated [33,34]. The lignin content was determined on three parallel samples from three poles.

The pH of the wood was determined by an extraction method. Wood samples (2 g) were ground into sawdust that could pass through a 40-mesh sieve. The sawdust was then immediately added to 50 mL of boiling deionised water (pH = 6.5) and stirred for 5 min in an Erlenmeyer flask with reflux. The mixture stood in the closed Erlenmeyer flask for 30 min and was then rapidly cooled to room temperature. The extract was then filtered, and the pH of the solution was measured using a glass electrode [35]. The experiment was carried out in three parallel measurements.

2.5. Microscopic Analysis

Light microscopy was performed on specimens oriented in all three anatomical planes and containing at least one tree ring. The specimens were dehydrated in a graded ethanol series (70, 90, 95, and 100%), cleaned with D-limonene, and embedded in paraffin blocks (tissue processor Leica TP1020-1, Nussloch, Germany). Thin sections (9 μm thick) were cut using a semi-automatic rotary microtome RM 2245 (Leica, Nussloch, Germany), stained with a safranin and astra blue solution and mounted in Euparal (Gladwick St, Compton, CA 90220, USA). Slides were observed under a Nikon Eclipse 800 light microscope and photomicrographs were taken by a digital camera (DS-Fi1) connected to a NISElements BR 3 image analysis system (Melville, NY, USA).

Scanning electron microscopy (SEM) was performed to reveal detailed anatomical features of the three-dimensional structure of the wood. Specimens were cut into 1 cm^3 cubes, ensuring that they were oriented in all three anatomical planes. The surfaces were planed using a sliding microtome equipped with a new disposable blade. Specimens were dried and coated with gold (Q150R ES Coating System Quorum technologies, Laughton, UK) for 30 s at 20 mA intensity. SEM micrographs were then taken at high vacuum and low voltage (between 5 and 12.5 kV). A large field detector (LFD) and a concentric backscatter detector (CBS) were used in an FEI Quanta 250 SEM microscope (Hillsboro, OR, USA). Observations were performed at a working distance between 8 and 10 mm. Energydispersive X-ray spectroscopy (EDX) analysis was made using a TEAM EDS analysis system (EDAX, AMETEK Inc., Berwyn, PA, USA). The point analysis, performed at a voltage of 20 kV, allowed the identification of the elements present on the sample surface, in particular, we detected calcium (by X-ray energy Kα at 3.69 keV), sulfur (by X-ray energy Kα at 2.30 keV), and iron (by X-ray energy Kα at 6.39 keV).

3. Results and Discussion

The soil in the vicinity of the piles was classified as histosol and humic gleysol on clay. The layer from which samples were isolated was moist, unstructured, smeary, clayey, mineral, strongly carbonate (type 5Y4/1). The pH was about 8 [36]. It should be noted that the soil layers in the marginal areas were mixed during construction and remediation works. Therefore, this layer contained more organic material (peat) and construction debris than the surrounding soil. The average temperature at 100 cm depth varied from 3.7 °C (February) to 20.1 °C (August) (Figure 2).

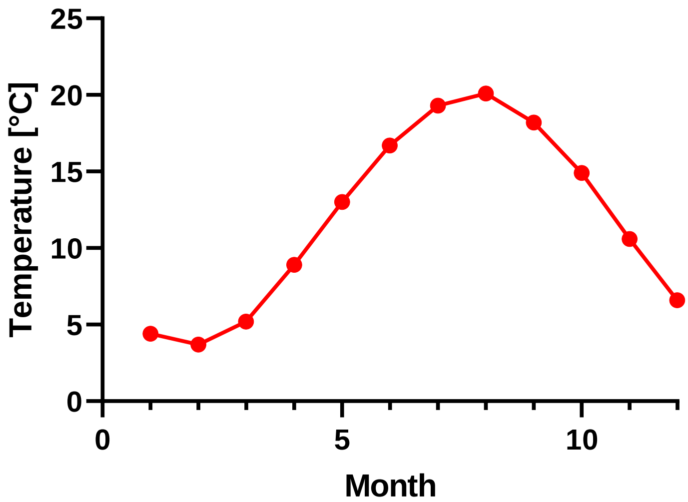

Figure 2. Average soil temperature 100 cm below the layer in Ljubljana in the period between 1961–2016 [37].

The structural health of the piles was assessed with resistograph and screw withdrawal force measurements. These measurements were carried out in situ. Resistance drilling is frequently used for decay assessment, but in the respective study, data were linked to chemical composition as well. It should be taken into account that the wood was saturated with water. It is well known that wood's mechanical properties are significantly affected by moisture content (MC) [38]. However, increased MC is not the only reason for a decrease in mechanical properties. The blue curve in Figure 3 represents the typical resistograph curve. This reference curve was determined on a freshly cut Scots pine (*Pinus sylvestris*) representative beam [39]. MC of this beam was above fibre saturation to have comparable moisture conditions with wooden piles. The annual rings and the pith were resolved in the respective curves. The red curves in Figure 3 represent measurements taken on the piles. Three typical measurements are shown. Measurement one (Figure 3, pile 1) shows the pile where one part of the pile was severely degraded while the other part was less degraded. Although the heartwood of Scots pine has better durability than sapwood [40,41], no difference was found between the degradation rate of sapwood and heartwood. However, as shown in the other resistograph measurements (Figure 3, piles 1 and 2), all piles' parts were significantly degraded. As can be seen from resistograph measurements, pile 3 was less degraded. As the piles were located in comparable conditions, we could not determine the reasons for this difference. The key reason is presumably heterogeneity of the wood used and variations in micro-locations. It should be considered that piles were not in direct contact with each other.

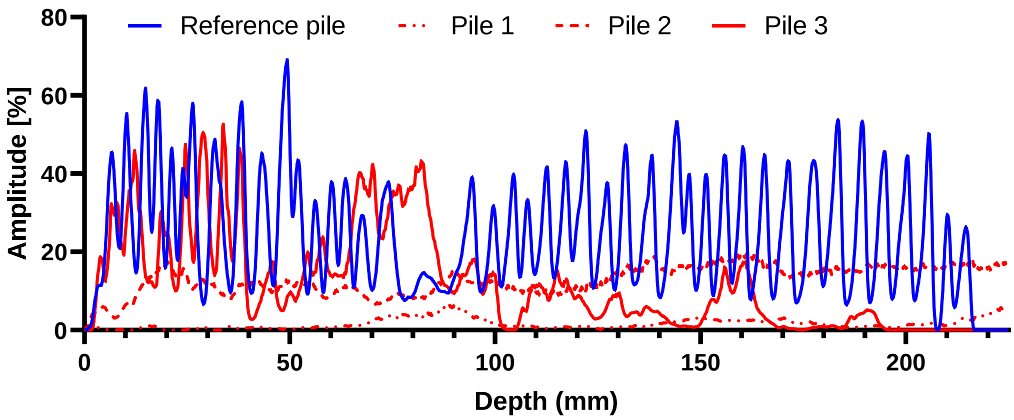

Figure 3. Resistograph analysis of pine piles and reference Scots pine trunk.

Resistograph measurements were in line with the screw withdrawal force (SWF) measurements. The SWF determined on the reference pine beam was 2060 N, while the SWF determined on wooden piles was only 272 N (Figure 4). This value was about 13% of the value determined on fresh wood. Both methods, resistograph and SWF, indicate that the wood was significantly degraded. However, it should be considered that the measurements were made on the upper part of the wooden piles. Literature data indicate that the upper parts are more exposed to biodegradation than the part of the piles deeper in the soil [6]. It can therefore be assumed that the worst part of the piles was analysed.

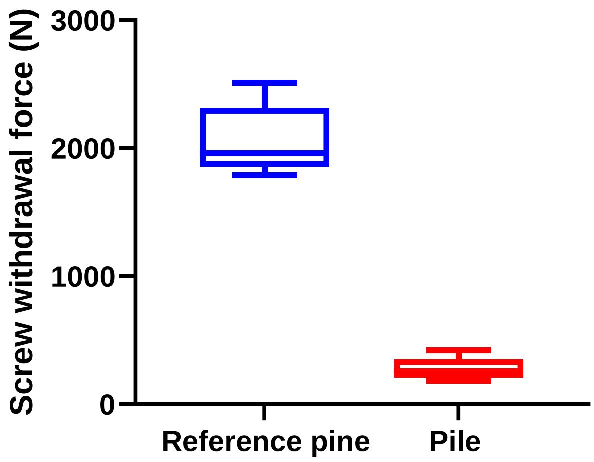

Figure 4. Screw withdrawal force measurements on pine pile and reference Scots pine trunk.

The decay of the piles was also confirmed visually. When isolated, the colour of the wood was white, and after a few minutes, it became grey. The wood had a fibrous, spongy texture, with no distinct odour. Cutting was easy, and the wood did not present much resistance. Decay is usually reflected in density, especially since the wood was saturated with water and carefully dried to prevent collapse before densities were determined. The density of the reference pine was 532 kg/m^3. This value is in line with literature data [42]. However, the density of the wood from the piles was significantly lower. The average density of the wood from the piles was 296 kg/m^3 (Figure 5A). This confirms that the piles were highly degraded. Chemical analysis confirmed the results obtained by the other methods of investigation. The lignin content in the pinewood was 26.7% (Figure 5B). However, due to the general depletion of cellulose and hemicelluloses [13], the piles' relative lignin content increased (58.8%). These values are still slightly lower than the lignin content in the Bronze Age piles from a nearby location. The lignin content in 4500- to 5700-year-old Bronze Age piles ranged from 63.8% to 70.3% [43]. The pH of the degraded wood was 7.1 and corresponded with the pH of the surrounding soil [36]. On the other hand, the pH of reference Scots pine sapwood (pH = 4.68) and heartwood (pH = 5.02) was considerably lower. Scots pine pH values were in line with literature data [44].

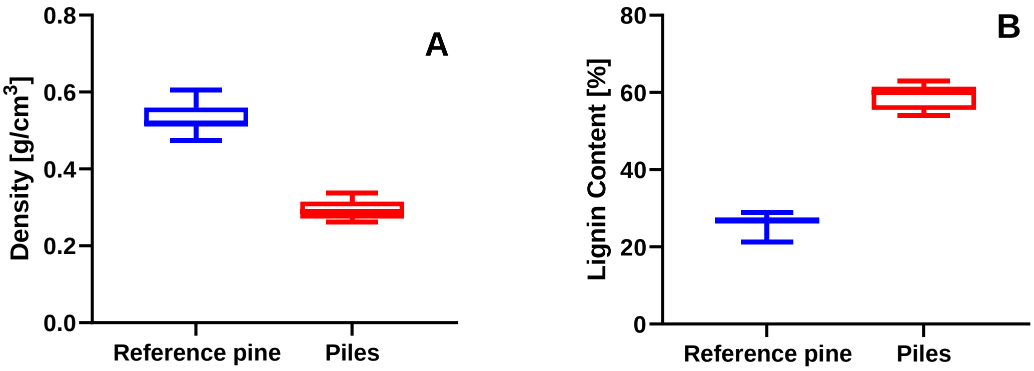

Figure 5. The density (**A**) and lignin content (**B**) of oven-dried pine pile and reference Scots pine sapwood.

The degradation of cellulose and hemicelluloses was also reflected in the FTIR spectra (Figure 6). The most notable change was the disappearance of the 1725 cm^{-1} peak, which was assigned to C=O stretching in hemicelluloses [32]. Additionally, changes were also observed in other peaks assigned to cellulose and hemicelluloses, namely: 1453 cm^{-1}, 1230 cm^{-1}, 1160 cm^{-1}, 1050 cm^{-1}, and 895 cm^{-1} [45,46]. Peaks assigned to lignin were less affected (Figure 6). This is in line with the lignin content and typical patterns of soft-rot decay [47].

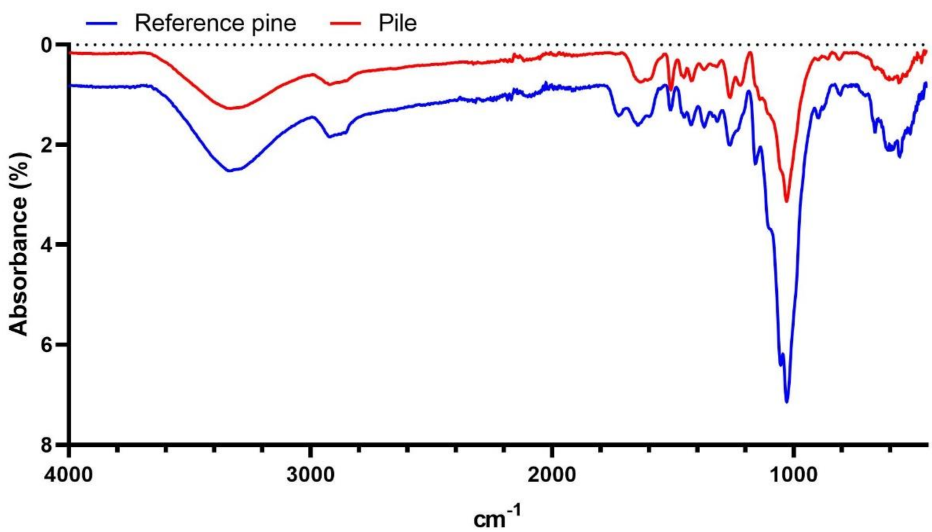

Figure 6. FTIR spectra of pine pile and reference Scots pine sapwood.

The moisture content of waterlogged wood was very high. DVS analysis showed that the MC of waterlogged wood ranged from 450% to 500% (Figure 7B). This is typical of water-saturated wood as it decomposes and reduces density (Figure 5). Similar high MCs are also reported in the literature [8,43]. As shown in Figure 7B, the mass loss during drying in the DVS device was linear, indicating that the water was not bound in the wood. Drying slowed down below fibre saturation. The wooden piles' chemical changes were reflected in the increased equilibrium moisture content during both sorption and desorption cycles. For example, the reference pine's EMC at 95% RH was 25.93%, while the EMC of the pile at the same RH was 23.79%. Similar differences were also observed at other RH (Figure 7A). This phenomenon has been reported previously [12,48] and may be attributed to partial depolymerisation of lignin, greater amorphous cellulose content, and consequent greater availability of OH groups [49].

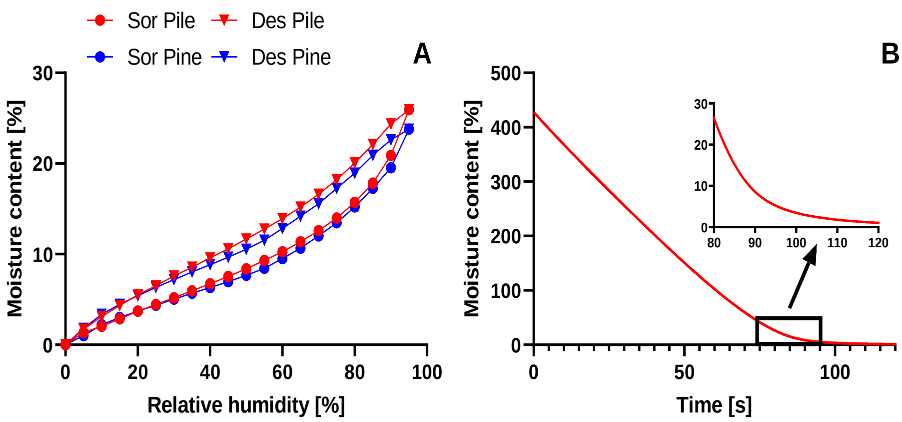

Figure 7. (**A**) Sorption (Sor) and desorption (Des) curves of pine pile and reference Scots pine sapwood. (**B**) Drying pattern of the fresh pile sample.

Finally, the degradation of the wood was confirmed by light and scanning electron microscopy. Light microscopy analysis confirmed that the piles were made of Scots pine (Figure 8). Predominantly in the latewood cells, the typical soft-rot decay pattern can be seen as described previously [17]. The S2 layer was absent in most of the tracheids, except for a very few latewood tracheids.

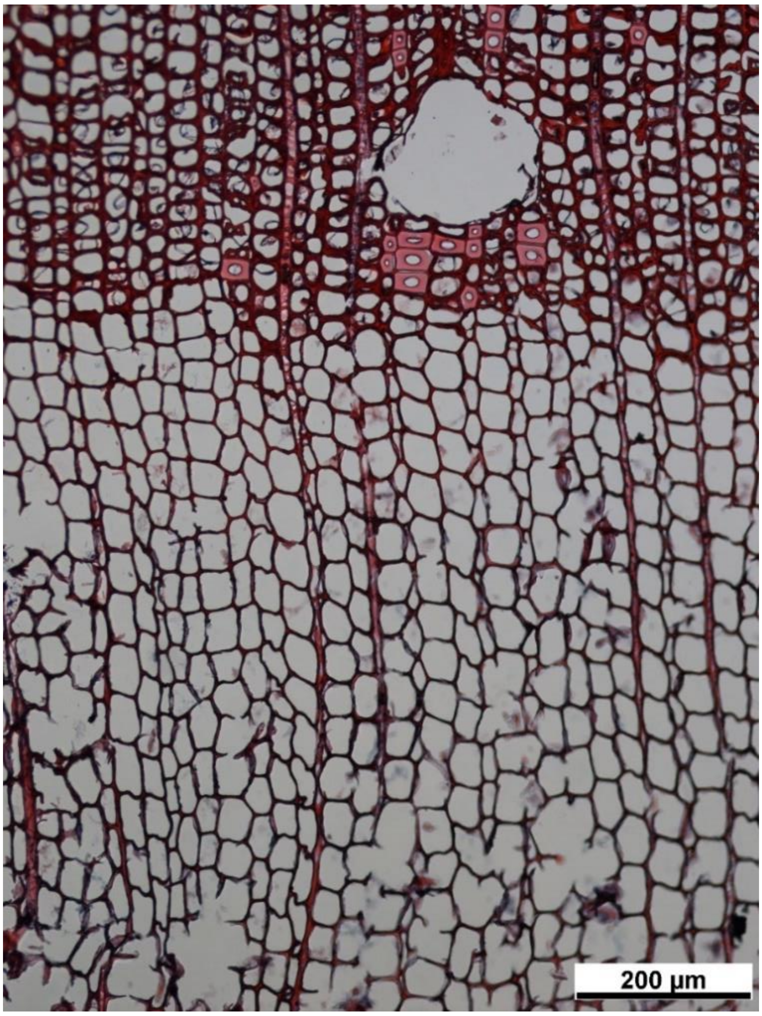

Figure 8. Light microscope image of the cross-section of a 125-year-old wooden pile.

The SEM analysis proved the typical soft-rot decay, as can be seen in Figures 9 and 10. The S2 layer in the tracheids of the latewood was wholly decayed. In contrast, the middle lamellas were less affected. This was consistent with the chemical analysis. Middle lamellas were predominately lignin, whereas more cellulose was present in the S2 layer of tracheids [44]. The S2 layer was too degraded to distinguish between Type I and Type II soft rot.

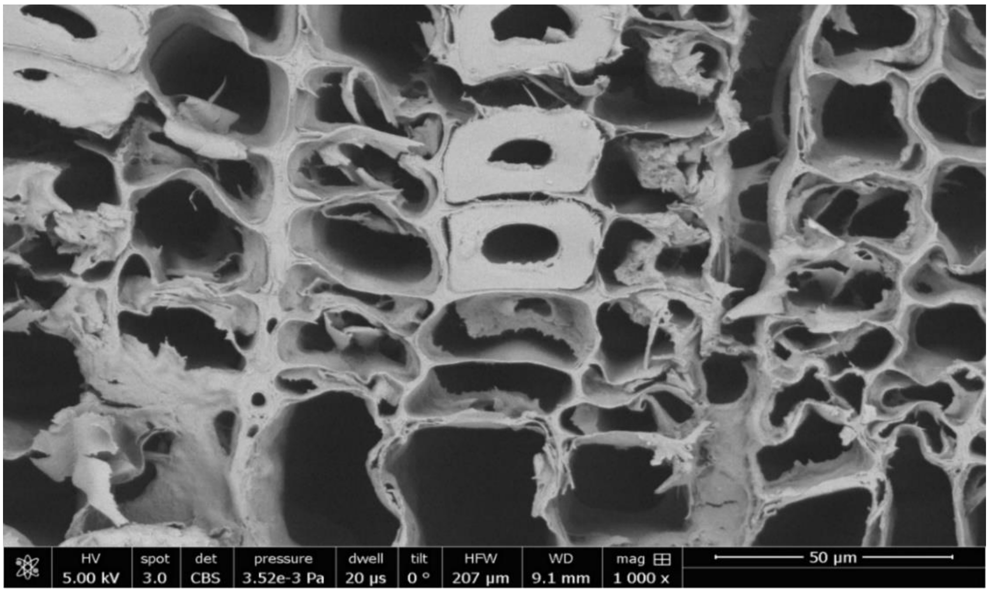

Figure 9. Scanning electron microscopy image of the cross-section of the latewood cells of the wooden pile.

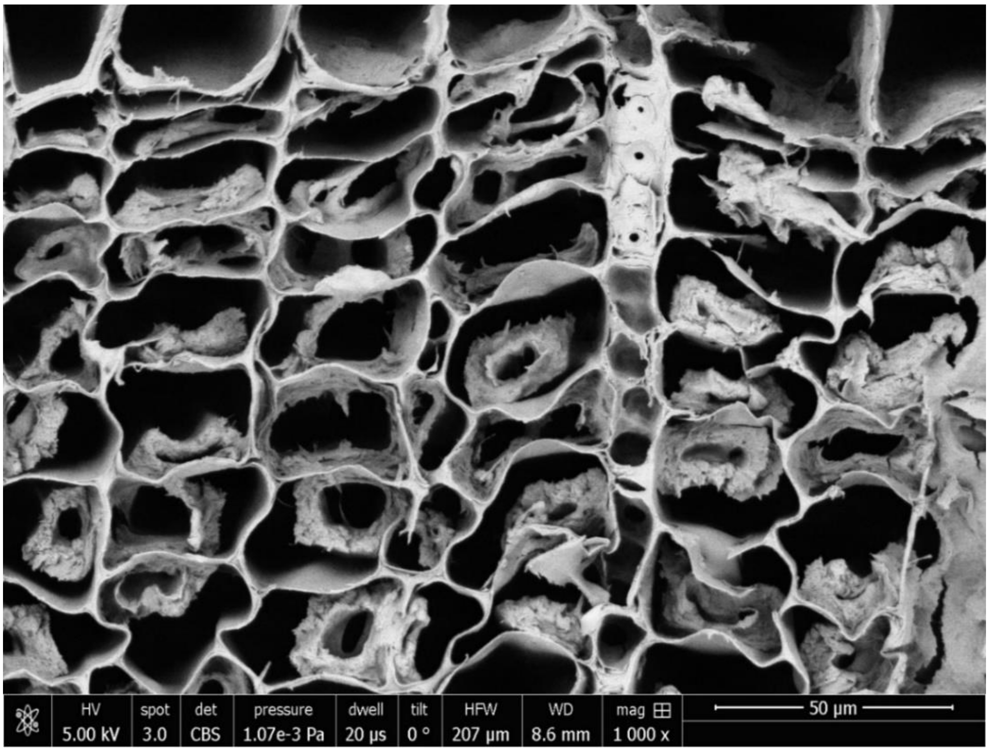

Figure 10. Scanning electron microscopy image of the cross-section of the latewood cells of the wooden pile.

Although no bacteria were detectable in the degraded wood, we noted several spherical structures in the wood cell walls (Figure 11). EDX analysis of the crystals confirmed the presence of sulfur, iron, and calcium. Chemical analysis of the crystals showed that these structures could be of bacterial origin [50]. This process is known as biomineralisation, the chemical alteration of an environment by microbial activity leading to minerals' precipitation. The most important bacteria associated with biomineralisation belong to the *Bacillus* sp. *and Lysinibacillus* sp. More than 60 different biological minerals have been reported as a result of biomineralisation [51]. However, these minerals are not an explicit confirmation of bacterial decay, but an indication that the bacteria were somehow involved in the respective piles' degradation.

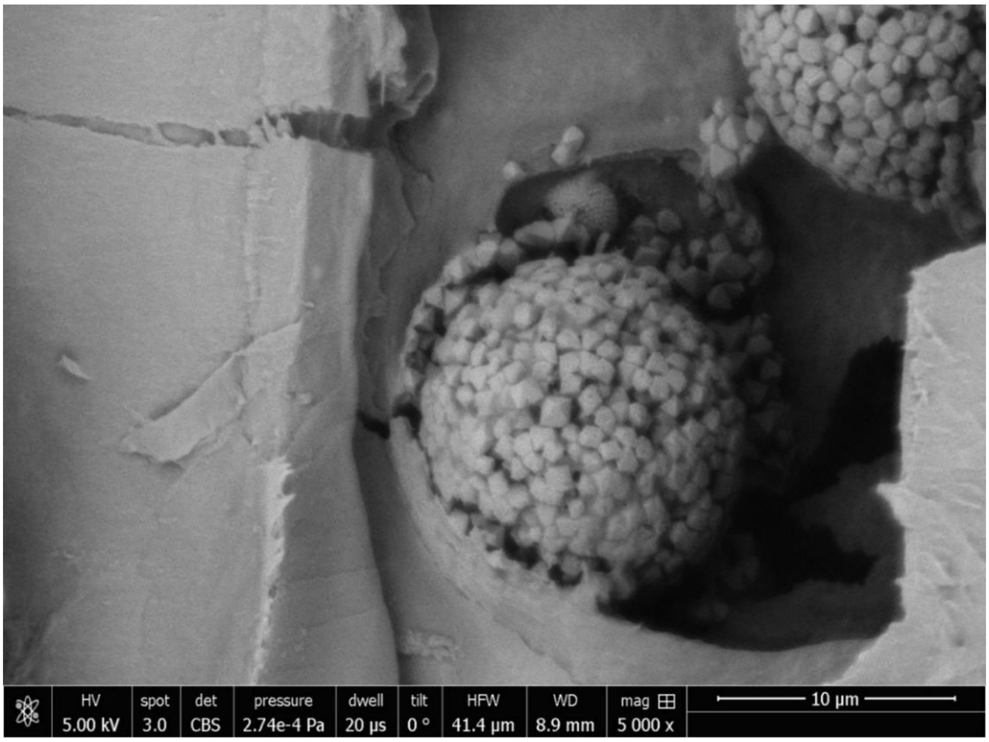

Figure 11. Scanning electron microscopy image of the spherical form in the wood cells.

It has been reported in the literature that artificial mineralization of wood yields materials with improved mechanical properties compared to natural wood when mineralization is carried out to a higher degree [52]. Wood modification processes have been developed that take advantage of this principle and are used to consolidate building materials [53]. However, in waterlogged piles, mineralization does not appear to be sufficient enough to lead to significantly improved mechanical properties. However, further studies could clarify the role of deposited crystals on the mechanical properties of waterlogged wood. On the other hand, the bacteria associated with mineralization to strengthen the wood could be increased with the biological mechanisms. The consolidation of a foundation is a challenging task. Different strategies have been developed depending on the historical value and quality of the structure. First, the mass of a building should not be increased, which should be considered during renovation. If necessary, concrete beams should be placed under the building and new piles should be installed under the beams to support the building.

4. Conclusions

One hundred and twenty-five years of exposure of Scots pine piles to waterlogged conditions in Ljubljana resulted in severe degradation. The waterlogged wood became saturated with water. SEM and light microscopy confirmed that soft rot was the main cause of wood decay in the buried piles. Soft rot is typical for waterlogged wood, but the decay of the piles in question was more rapid than reported in some of the previous case studies. The decay resulted in reduced density, a relative increase in lignin content, and a loss of mechanical properties. Chemical and morphological changes resulted in increased hygroscopicity. Due to the degradation of the piles, special attention should be paid to the reconstruction of the building. Only low-density material should be used, and the piles should be consolidated somehow.

Based on the analysis performed, we can conclude that resistance drilling provides useful insight into waterlogged piles. Microscopy and FTIR could serve as an additional method of validation. Suppose the measurements cannot be made by resistance drilling. In this case, screw withdrawal could be used as a partial alternative, as the results reflect only the properties of the outer parts of the piles.

In Ljubljana and its surroundings, there are about 10,000 buildings constructed in the corresponding period. Approximately 30% of them were built on piles. It can be assumed that these buildings face the same problems as the corresponding case study.

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