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Changes in strength of Scots pine wood (*Pinus silvestris* L.) decayed by brown rot (*Coniophora puteana*) and white rot (*Trametes versicolor*)

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HIGHLIGHTS

- The initial stage of fungi development influences wood strength properties.
- Different rate for white- and brown-rot were found.
- Decrease of strength properties was quantified.
- Brown-rot causes more drastic decrease of wood strength.

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ABSTRACT

Alterations in static bending strength, compressive strength parallel to the grain and the modulus of elasticity (MOE) of Scots pine (*Pinus sylvestris* L.) wood decayed by the white-rot fungus (*Trametes versicolor*) and the brown-rot fungus (*Coniophora puteana*) were investigated. The drastic decrease of the bending strength was observed for the initial phase of the decay and the changes were exponential. A 50% decrease in the property was found for 7% of mass loss in the case of brown rot and 20% for white rot. A linear decrease in compressive strength was observed with an increasing mass loss. White rot caused a 50% decrease of compression strength for the mass loss of ca. 30%, while for the brown rot the same decrease was observed for 20% of mass loss. The slowest linear changes were observed for the modulus of elasticity (MOE). In the case of white rot the MOE values were reduced by ca. 50% for a mass loss of 40%, while for brown rot a 50% decrease in the property was found in a mass decrease as low as 20%.

1. Introduction

The deterioration of wood by fungal decay results in changes in chemical structure and mechanical properties. Traditionally, fungal deterioration of wood is quantified by mass loss. This parameter, however, does not relate well to wood strength, which is the most important wood property from a practical point of view. Strength loss at the incipient stages of decay may occur without observable mass loss [1–5]. Incipient fungal colonization can be detected by non-destructive methods such as immunoassays [6], polymerase chain reaction [7], by measuring modulus of elasticity (MOE) [7,8] or semi-destructive methods like microtensile strength tests [9]. Although, non-destructive methods are useful for detecting fungal infestation of wood, they are generally unable to provide information on changes in strength properties. Reliable information on strength properties of decayed wood can be only obtained by destructive methods [2–4,10–13]. Data concerning strength properties is usually very general and does not indicate a change in properties during decay, especially in the early stages of the fungi development. Usually, the data concerns one, long period of decay causing a huge decrease in strength. Moreover, such an approach was unable to characterize the dynamics of the strength decrease. However, some reports indicate that changes in wood strength properties of up to 50% occur in the early stages of fungal growth, corresponding to mass losses of only 0–5% [2,3,11,14].

Destructive measurements resulted in the exact values of strength, though this approach does not allow observing changes which occur for the same element. On the contrary, the modulus

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of elasticity (MOE) is a mechanical property that can be used for repeated measurements on the same specimens in order to depict the course of wood decay. Therefore, the property is used in long-term studies, especially in field tests and it can be applied for predicting wood decay influence on a decrease of wood strength. According to some studies, minor changes of the MOE are observed in the early stages of decay, i.e. for mass loss from 0% to 7%, the relative decrease of the MOE ranged from (−)2.4% to 15.5%, and the rate of change is twice lower than the rate of change in the bending strength, i.e. for mass loss from 0% to 7% the relative change of the strength is from 0% to 16–42% depending on the wood species [11]. Other observations reported rapid changes in the MOE in the first stages of wood decomposition (for ca. 1% of mass loss the relative decrease of the MOE for brown rot was 9–20% depending on wood species and 5–7% for white rot.), followed by their slowdown [6,20].

The compressive strength parallel to the grain is often used to estimate the effects of fungal decay, especially in historical artifacts. The preparation of small decayed samples is relatively easy. Therefore, the test is more frequently applied than bending strength tests. The previously reported results confirm the linear nature of the changes in the compressive strength of wood decay development [6,10,14,21,22]. However, different rates of changes were observed for brown and white rot, i.e. for the mass loss from 0% to 7% registered for brown rot, the decrease of bending strength was 25–45% depending on the species of wood and fungi, while the same mass loss observed for white rot was associated with a decrease of compression strength of 6–14% depending on the species of wood and fungi.

Bending strength is a property which is rarely used for investigating wood decay. It is primary due to the size of samples and problems related to obtaining uniformly decayed large samples. Only a few studies showed rapid changes of the static bending strength already in initial stages of decay [6,20,21].

Also, alteration of wood strength is rarely related to changes in chemical composition. It is believed that wood ultrastructure and chemical composition, determine wood strength. Therefore the effects of fungal degradation on strength properties should be considered, in the context of such changes in physical and chemical properties. Some research [18,19] showed the relationship between the changes in ultrastructure of wood degraded by brown rot and white rot fungi on the stiffness of wood. The relationship between the chemical and mechanical effects of fungal decay was rarely investigated [1,3,5,9,15]. Some researchers [1,3,15] attributed the decrease of strength properties in early stages of the decay to hemicelluloses decomposition without cellulose decay. Our earlier findings [16,17] obtained for the same test material as investigated in the present study, indicated that cellulose was also degraded at the early stages of decay. It was also observed that the degree of polymerization (from DP 6000 to DP 1800) and α-cellulose content in all cellulose decreased from 60% to 20% for the mass loss from 0% to 7%.

Unlike previous papers, the present study provides results of investigations made for large samples of dimensions adhering to standards and the material at different stages of decay. Static bending strength, compressive strength parallel to the grain and modulus of elasticity were measured in the same material which was also used to determine changes in chemical composition and the degree of polymerization (DP) of cellulose [16,17].

The objective of the present study was to determine the rate of strength change in Scots pine wood exposed to the white-rot fungus *Trametes versicolor* or the brown-rot fungus *Coniophora puteana* using measurement of static bending strength, compressive strength parallel to the grain and modulus of elasticity in static bending.

2. Materials and methods

A single trunk of Scots pine tree *Pinus silvestris* (L.) with a diameter of 500 mm and length of 4500 mm, was used to prepare the samples. For the tests, samples of wood with a dimension of 20 × 20 × 300 mm were made from sapwood. After cutting, the samples were dried in an oven, at 105 °C, to measure the initial dry mass.

Test fungi were grown on a malt-agar medium. The malt-agar medium was prepared and sterilized for 25 min at 121 °C in an autoclave according to PN-EN 113:1996/A1:2005 standard [23]. A 300 ml medium was transferred to the 1000 ml measurement cylinder, before adding mycelium. Two test fungi were used, i.e. the brown-rot *Coniophora puteana* (Schum.: Fr.) P. Karst. isolate Eb.97, and the white-rot *Trametes versicolor* (L.: Fr.) Pilát. isolate Poznan. Brown rot was selected as it is the predominant type of wood decay in construction. Brown rot fungi mainly decompose the polysaccharides (cellulose and hemicelluloses) – the framework of the wood, leaving amorphous lignin almost undecomposed. Within a short period of attack, decomposition of the framework substances causes a reduction in the mechanical strength. White rot fungi are able to decompose lignin as well as other cell wall components (polysaccharides). At equal mass loss, white rot does not cause as much reduction in strength as brown rot, because the cellulose framework is not attacked as much. Although, white rot is less frequent in wooden construction, as it occurs most often in standing and felled forest trees, white rot fungus was selected in order to compare it to brown rot.

Strains of the fungi were inoculated on malt agar. The inoculation samples were pre-incubated in small Petri-dishes for 3–6 weeks. After 2 weeks in a climatic chamber at a temperature of 20 °C and a relative humidity of 65%, it covered the entire surface of the medium. All fungi were taken from the collection of the Department of Wood Preservation, University of Life Science in Warsaw.

The wood samples were sterilized and placed in 1000 ml measuring cylinders, filled with 300 ml malt agar and covered with mycelium of the fungi (Fig. 1). Glass supports were placed between the samples and agar media. It was made to avoid a direct moisture flow between the agar and the test material. The samples were subjected to two different species of fungi, twenty six different incubation periods and one control.

The samples were incubated with fungi at temperature of 20 °C and a relative humidity of 65%. Three replicates for each incubation time were prepared. A total of 78 samples exposed to *C. puteana* were incubated for a maximum of 26 weeks and 3 samples were harvested every week. Similarly, 78 samples were exposed to *T. versicolor* and were incubated for a maximum of 52 weeks and again 3 samples were harvested every second week.

The samples were dried to a moisture content of 0% and the mass loss was calculated. Control samples were stored at a temperature of 20 °C and a relative humidity of 65%. Thus two series' of samples with ascending mass loss by fungal decay were obtained to be applied for the strength tests. Mass losses caused by *C. puteana* ranged from 0% to 29% and from 0% to 51% in the case of *T. versicolor*. After drying, samples were transferred to a climate controlled room at a temperature of 20 °C and a relative humidity of 65%, so that they reached a moisture content of 12%. The strength tests were conducted on wood with a moisture content of 12%.

The decayed samples were subjected to MOE and strength determination. A five-ton INSTRON testing machine was used in the examination. MOE and bending strength tests was conducted on long wood samples with dimensions of 20 × 20 × 300 mm. The examination of bending strength was executed according to the procedure provided by the ISO 3133:1975 standard [24] and of the MOE according to the ISO 3349:1975 standard [25].

Compressive strength tests were conducted on smaller wood samples with dimensions of 20 × 20 × 30 mm that were cut out of defect free clear parts of long samples after previous strength tests. The examination of the compression strength parallel to grain was made according to the procedure of the ISO 3787:1976 standard [26].

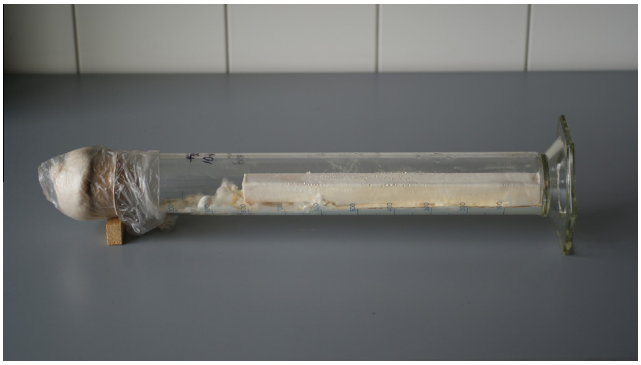

Fig. 1. Set up of the decay tests with wood samples on malt agar media.

3. Results and discussion

3.1. Changes in static bending strength

The changes in the static bending strength as caused by fungi are shown in Fig. 2. Both fungi caused a rapid decrease in strength, in the early stages of decay. The results indicate a high loss of wood strength already at the initial, barely noticeable stage of fungi development. The decrease in the strength by 50% was accompanied by a 20% mass loss of wood, decayed by *T. versicolor*. The relation was described by the exponential model $y = 115.27 \cdot e^{-0.0322x}$, with the coefficient of determination $R^2 = 0.88$. The fungus *C. puteana* caused a 50% drop in strength with a mass loss of about 7%. Further mass losses (20–25%) were associated with almost complete strength loss (10% of the initial value). These changes were also described by the exponential model $y = 110.8 \cdot e^{-0.1088x}$, with the coefficient of determination $R^2 = 0.86$.

On the base of the obtained results it can be concluded that the fastest changes during white rot and brown rot development were most profoundly related to static bending strength. In both cases, a rapid decrease in the strength was already found at the initial stages of wood decay. Our results are consistent with previous findings [10,15,20,21]. Although some studies [1–3,6,11] suggest that depolymerization of polysaccharides with a degree of polymerization lower than 200 (i.e. mainly hemicelluloses) is the main factor responsible for rapid changes in strength properties of wood at an early stage of decay, the reported results seem to be valid, only in such cases where fungi start to utilize the nutritional components from hemicelluloses. However, it is evident from our earlier studies [16,17] that decomposition of cellulose represented by a decrease of α-cellulose content and a decrease in the degree of polymerization has the highest importance on the reduction of wood tensile strength. It was especially noticeable for the brown-rot when for the mass loss from 0% to 7% was associated with the relative decrease of cellulose of 20% but the content of the most common structural component, i.e. α-cellulose decreased of 40% and the average degree of polymerization was reduced from 6000 to 1800 [16,17]. For white-rot the slower reduction of the strength properties can be explained by a more uniform decomposition of ordered cellulose and amorphous lignin. It was observed for the mass loss from 0% to 20% that the cellulose content was decreased by ca. 15% and its ordering did not change significantly. The degree of polymerization was reduced from DP 6000 to DP 5700.

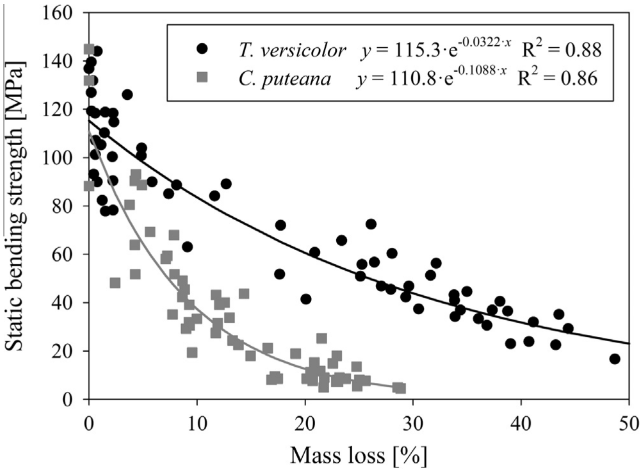

Fig. 2. Relationship between the mass loss and bending strength of Scots pine wood decayed by white rot (*Trametes versicolor*) and brown rot (*Coniophora puteana*).

3.2. Changes in compressive strength parallel to the grain

The obtained results of wood compressive strength parallel to the grain, are shown in Fig. 3. In this test, the decrease in the strength was linear. However, rapid changes were not observable at the initial stages of wood decay. The white rot fungus *T. versicolor* caused a reduction of the compressive strength by an average of 1.1% per 1% of mass loss, while the brown-rot fungus *C. puteana* caused similar changes at a rate of 2% per 1% of mass loss. The regression equations describing the results were as follows: $y = 66.416 - 1.1812x$ ($R^2 = 0.88$) and $y = 68.681 - 1.8893x$ ($R^2 = 0.87$), for white rot and brown rot, respectively. The results obtained are consistent with the data of others [6,10,14,21]. The rapid changes in the degree of polymerization of cellulose did not have such a significant influence on compression strength. It is because lignin and not cellulose is responsible for the compression load transfer within wood. On the other hand the degradation of hemicelluloses and cellulose is undoubtedly responsible for decreasing solidity of wood tissue, which has to lead to internal deformations and buckling. This results in a decrease of the wood's ability to transfer shear stress and thus reduces wood strength.

3.3. Changes in the MOE determined during static bending

The results of the MOE changes were presented as a function of the duration of wood exposure to fungi, represented as mass loss (Fig. 4). For both fungi species used, i.e. *T. versicolor* and *C. puteana*, a clear decrease in the MOE was found, and it was caused by progressive wood decay represented by mass loss. The changes in the MOE in both cases, i.e. white and brown decay, were linear in trend and dependent on an increasing degree of wood decay. The following linear models were separately fitted to both sets of the results: $y = 10324 - 124.2x$ ($R^2 = 0.49$) and $y = 10352.4 - 278.3x$ ($R^2 = 0.39$), for white rot and brown rot, respectively. No rapid changes were observed at any stage of the fungi development. The rate of the MOE decrease was *about* 1.2% per 1% of the sample mass loss in the case of white rot and about 2.7% per 1% of the sample mass loss in the case of brown rot. Nevertheless, the obtained data can be related to the changes of the compressive strength only. When wood strength was determined from static bending, a 50% decrease in strength was observed at the initial stage of decay, corresponding to only 5–7% of mass loss. In spite of the above observation it is widely considered for sound wood that

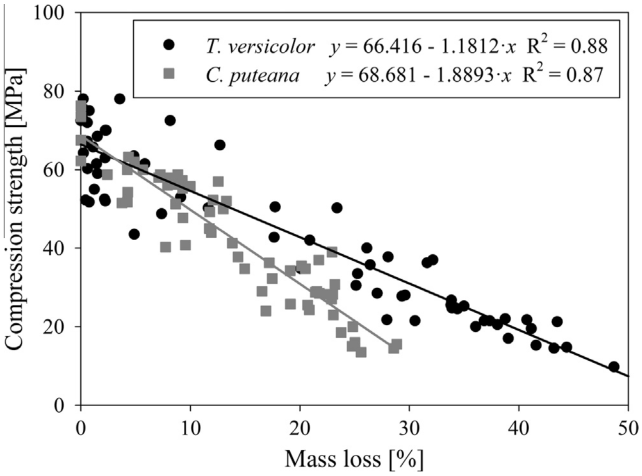

Fig. 3. Relationship between the mass loss and compression strength of Scots pine wood decayed by white rot (*Trametes versicolor*) and brown rot (*Coniophora puteana*).

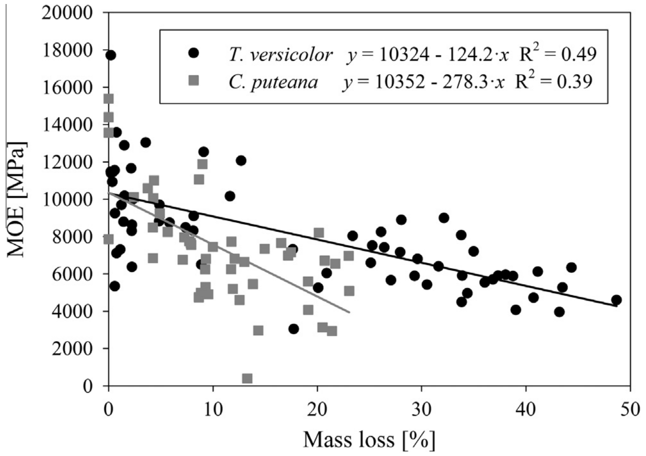

Fig. 4. Relationship between the mass loss and MOE measured in static bending for Scots pine wood decayed by white rot (*Trametes versicolor*) and brown rot (*Coniophora puteana*).

the MOE is correlated with strength. However, the correlation seems to be not valid for decayed wood. As it was depicted in Figs. 2 and 4 the obtained relations are characterized by different intensity of changes. The changes of the bending strength of wood decayed by brown-rot fungi are exponential with a distinct decrease of 50% for mass loss from 0% to 7%. Whereas the MOE changes seem to be linear with a much lower intensity of decrease, e.g. for brown-rot a 50% decrease of MOE was observed for a mass loss of 20%. Another problem related to obtaining a correlation between the bending strength and MOE of decayed wood is the high scatter of the results.

From a practical point of view in this case, the measurement of the MOE gives very limited information on wood decay and none on its strength. Moreover, wood properties of the same species differ due to habitat, climatic conditions and the position in the trunk. It concerns different wood properties, i.e. density, anatomical structure, chemical and physical properties. It implies a high scatter of results of measurements especially the ones obtained for mechanical and strength properties of sound and decayed wood. The only advantage of this method is the possibility of repetition of tests for the same samples and comparison of the results at different stages of decay.

4. Conclusions

1. The most rapid changes in the investigated wood properties during fungi decay, were found in static bending strength. The drastic decrease of the bending strength was observed for the initial phase of the decay and the changes were exponential. A 50% decrease of the property was found for 7% of mass loss in the case of brown rot and 20% for white rot.
2. The compression strength parallel to the grain was much slower in responding to wood decay. White rot caused a 50% decrease in the property for the mass loss of ca. 30%, while for the brown rot, the same decrease was observed for 20% of mass loss.
3. The slowest changes were observed for the modulus of elasticity (MOE) as determined during bending. In the case of white rot the MOE values were reduced by ca. 50% for the mass loss of 40%, while for brown rot a 50% decrease of the property was found with a mass decrease as low as 20%. However, the decrease of the MOE values did not properly describe changes in the strength properties as induced by fungi decay.
4. Brown rot caused a drastic decrease in static bending strength even at the initial stage of decay. It has a practical significance when considering the performance of wooden constructions.
5. Although, methods of identification at the initial phase of decay are available (e.g. the MOE), the standard tests of strength properties are of special importance for determining the decrease of wood strength.

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