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Effects of natural and artificial ageing on the physical and acoustic properties of wood in musical instruments

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ABSTRACT

The reversible and irreversible effects of natural and artificial hydrothermal ageing are reviewed with respect to the hygroscopicity and acoustic properties relevant to the practical quality of wooden musical instruments. Long-term natural ageing reduces the hygroscopicity of wood while improving its acoustic quality, but these changes are partly reversible by exposure to high humidity. Similar reversible changes are observed in hydrothermally treated wood, especially when the wood is heated at an intermediate relative humidity. These reversible changes are attributed to the annealing-like rearrangement of amorphous wood polymers or the temporary closure of micropores, but further investigation is necessary. Color change resulting from natural ageing is shown to be successfully reproducible by oven-heating.

1. Research aims

This article describes the irreversible and reversible effects of both natural and hydrothermal artificial ageing on the properties of wood relevant to the quality of wooden musical instruments. The effects of ageing are usually attributed to irreversible chemical changes in wood polymers, such as the recrystallization of cellulose and depolymerization of hemicelluloses. However, recent investigations suggest that the effects of ageing are partly recoverable by rewetting or moistening in humid conditions. This reversible phenomenon is likely caused by conformational changes during the physical ageing of wood polymers, which should be considered for the appropriate conservation of the properties of old wooden cultural artifacts.

2. Introduction

For musicians and artisans dealing with musical instruments made from wood, the ageing process is not considered degradation but a treatment that improves the acoustic quality and stability of wooden instruments. Old lumber is often priced higher than recently cut wood for making the soundboard and bass bar of stringed instruments. According to Noguchi et al., aged pinewood shows a higher sound velocity (V) and lower loss tangent ($\tan\delta$) than newly cut wood, while the rigidity ratios (E'/G' in which E' is the dynamic Young's modulus and G' is the dynamic shear modulus) of woods of different ages are nearly equal [1]. A higher V and lower $\tan\delta$ increase the amplitude of sound radiation [2,3], and the high E/G ratio of wood creates its characteristic frequency response [4]. Therefore, wooden soundboards become more resonant while maintaining their tone quality with long-term ageing. Moreover, long-term ageing reduces the hygroscopicity of wood in general [5,6]. The reduced hygroscopicity improves the dimensional stability of wood, as well as stabilizing its mechanical and acoustic properties depending on the moisture content. Thus, the empirical approach of musicians and artisans to the effects of ageing on the acoustic quality and stability of wood is well-supported by material analysis.

The enhanced rigidity and reduced damping of aged wood have not yet been fully explained. Noguchi et al. have speculated that cellulose crystallization contributes to the higher E value and lower $\tan\delta$ value of aged wood [1], but this hypothesis was later negated: no significant difference was recognized in the crystallinity of new and aged wood samples [7]. Yokoyama et al. also found equivalent degrees of crystallinity between new and aged woods [6]. According to Inagaki et al., the degree of crystallinity increases by both ageing and hydrothermal treatments, which cause the decomposition of the amorphous regions in cellulose and hemicelluloses; however, the increase of crystallite thickness was confirmed only for hydrothermally treated wood [8]. From these results, the crystallization of cellulose can be concluded to be a minor mechanism for the enhancing effects of ageing. Other

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possible mechanisms include hornification [9], the cross-linking reaction in lignin, and the rearrangement of disordered polysaccharides, but those hypotheses require further experimentation.

Meanwhile, the improved stability or reduced hygroscopicity of aged wood is fully explained by the decomposition of hemicelluloses, which is the most significant chemical change in wood during ageing [10,11]. As hemicelluloses are the most hygroscopic components of wood, their decomposition reduces the hygroscopicity. The decomposition of hemicelluloses also reduces the ductility and toughness of wood; these amorphous polysaccharides are crucial to the tight connections between reinforcing cellulose microfibrils and amorphous matrix polymers [12–14]. In fact, the tensile strength [15], rupture energy in bending [6], impact bending strength [5,16], and cleavage resistance [5] are all significantly reduced by ageing. These adverse effects of ageing are qualitatively similar to those induced by hydrothermal treatment, which involves the remarkable hydrolysis of hemicelluloses [18]. The fragile nature of aged wood must be considered when wooden parts of musical instruments are loaded with strong forces, such as the tension of strings.

In general, the effects of ageing are most frequently explained as results of irreversible changes, such as the decomposition of hemicelluloses. However, recent investigations have suggested that the effects of both natural and artificial hydrothermal ageing can be partly reversed by moistening or rewetting the wood sample [18–20]. These reports imply that the wood ageing process involves some recoverable, i.e., reversible changes in the wood cell wall. The reversible effect of ageing may be related to the effects of seasoning and playing, which must be considered for the appropriate conditioning of old wooden instruments. In this paper, the reversible and irreversible effects of natural and artificial ageing on the physical properties of wood are described. In addition, some recent studies on the color of aged wood are briefly discussed regarding the restoration and imitation of the physical appearance of old wooden musical instruments.

3. The effects of natural ageing

3.1. Change in hygroscopicity

The hygroscopicity of wood sample can be evaluated by the equilibrium moisture content (EMC) at a constant relative humidity (RH). In general, the EMC of wood at an intermediate RH (60–65%) remains unchanged [15] or decreases during long-term ageing [5,6]. Some aged wood shows higher hygroscopicity than new wood [21], but in these cases, the aged wood is similar to submersed (water-logged) wood in terms of moisture sorption characteristics [22]. As submersed lumber is rarely used for musical instruments, these cases are irrelevant to this paper.

The reduced hygroscopicity of aged wood is usually attributed to the decomposition and loss of hygroscopic hemicelluloses. This explanation holds if the effects of ageing are always irreversible. However, the reduced hygroscopicity of aged wood was recently found to be recoverable by a moistening treatment. Fig. 1 shows the relative EMC of aged wood before and after the moistening treatment [19]. In Fig. 1, the EMC values of aged wood are normalized relative to those of recently cut wood under the same conditions. The EMC values of aged wood are always lower than those of recently cut wood, but with moistening at 100% RH for several days, its EMC values are at least partially recovered, especially at low RH. Notably, the different trends in Fig. 1 do not reflect sorption hysteresis, because these EMC values are always determined in the adsorption process. Thus, the effect of ageing is partly reversible with respect to hygroscopicity.

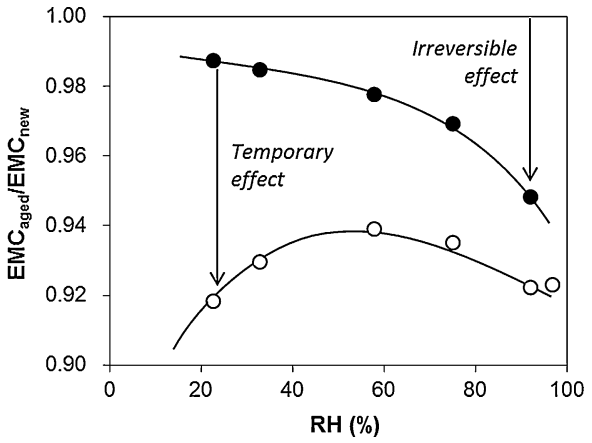

Fig. 1. Relative equilibrium moisture content (EMC) values of aged red pine wood (279 y after cutting) as a function of relative humidity (RH) [19]. Open plots: aged wood as received; filled plots: aged wood previously moistened at 25 °C and 100% RH for several weeks. All EMC values were determined in the adsorption process.

A possible interpretation for the cause of the temporary reduction in hygroscopicity by ageing is the physical ageing or annealing of wood polymers. Figs. 2 and 3 schematically illustrate the fine structure of wood cell wall and the mechanism of internal stress during drying, respectively. The wood cell wall is a composite in which crystalline cellulose fibers are embedded in amorphous matrix substances. The crystalline cellulose is rigid and hydrophobic, whereas the amorphous matrix polymers are swollen with moisture in green state and ready to shrink by drying. As wood dries from its green state (Fig. 3A), the shrinkage of amorphous wood polymers is restricted by the adjacent crystalline cellulose. Therefore, the amorphous polymers are distorted and dry under applied stress, as in the quenching of synthetic polymers (Fig. 3B). Since the amorphous wood polymers are glassy and immobile in dry conditions, the drying stress cannot immediately be relaxed. During long-term ageing, however, it may gradually relax (Fig. 3E) and such an annealing-like rearrangement of wood polymers reduces the hygroscopicity of the wood. On the other hand, the wood polymers recover their initial arrangements once they are re-swollen and plasticized by moisture at high RH (Fig. 3G). Therefore, the hygroscopicity is recovered by moistening and subsequent drying. This hypothesis was originally proposed to explain the temporary reduction in hygroscopicity resulting from oven heating [23], but can be applied to the present case in which the natural ageing process can be regarded as a long-term hydrothermal treatment at ambient temperature. The annealing effect may also account for the reduction in hygroscopicity caused by repeated humidity cycling [24]. Although it is technically difficult to observe the

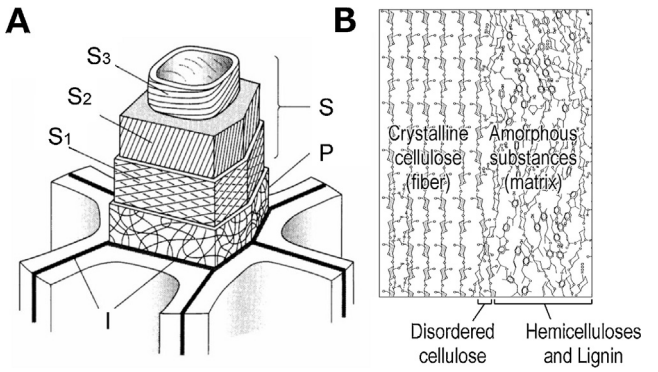

Fig. 2. Multi-layered structure of the wood cell wall (A) and fiber-matrix structure of each layer (B).

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