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Acoustic properties of modified wood under different humid conditions and their relevance for musical instruments

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ABSTRACT

In musical instrument making, there is a strong need to find alternatives to the traditional endangered and expensive tropical wood species used today. The present study examined whether different commercial and experimental modified wood materials have the necessary acoustic qualities under different humid conditions (dry, standard and wet) to contribute to the use of raw materials for wooden musical instruments. The materials were thermally-modified wood (ash, aspen and birch), acetylated wood (beech, maple and radiata pine), melamine- and phenol formaldehyde-treated beech and furfurylated Scots pine (Kebony Scots pine). Investigations involved physical (density ρ, Equilibrium moisture content *EMC*, volumetric shrinkage) and dynamic elastic testing by a free-free flexural vibration method to determine various acoustic characteristics: specific dynamic modulus (MOE_{dyn}/ρ), damping coefficient ($tan\delta$), speed of sound (c), specific acoustic impedance (z), sound radiation coefficient (R) and acoustic conversion efficiency (*ACE*). The modified materials and especially acetylated wood showed low *EMC* values and high dimensional stability at each humidity level, which are considered important factors for making quality musical instruments. Based on the obtained value ranges of all acoustical properties, the different modified wood materials could find uses in musical instruments where specific characteristics of sound are required. Furthermore, most of the modified materials showed an excellent acoustic performance in the three humid conditions based on a high *ACE* and low $tan\delta$. Furfurylated Scots pine and phenol formaldehyde-treated beech showed an inferior acoustic quality with the lowest *ACE* and the highest $tan\delta$, which is a less favourable combination for most of the musical instruments.

1. Introduction

The quality of a musical instrument depends on the choice of wood materials for the different parts and their harmonized arrangement when it is constructed. The main criteria for makers of musical instruments (wind, string or percussion) to choose wood with superior acoustical performance include dimensional stability, homogeneity of the grain, hardness, flexibility and plasticity. Tropical hardwoods are typically used in musical instruments as they satisfy these criteria [1,2]. For example, ebony is used in fretboards for its high density, lack of grain, elegant contrast and more importantly superiority as sound transmitter; Brazilian rosewood and mahogany are used in violins, bottom and ribs of guitars for their high density and low damping; pernambuco is used in bows of stringed instruments for its excellent flexibility and strength; African blackwood, rosewood, Macassar ebony, granadilla, cocuswood are used in flute, clarinets, piccolos and oboes for their high dimensional stability, high density and fine structure [1,3]. However, those tropical hardwood species are often illegally harvested while some of them (e.g. Brazilian rosewood, some mahogany species, pernambuco) are protected by the Convention on International Trade in Endangered Species, CITES [4].

Nowadays, the demand to replace tropical wood in musical instruments is higher than ever before due to the obvious problem of commercial availability. Even though the musical industry has looked at alternative wood species, which are less expensive and readily available, the traditional woods are still preferred [5,6]. The reason is that they possess inferior acoustical properties and they do not fulfill the required physical, mechanical and chemical properties. Furthermore, their acoustic behavior can change over time under varying moisture conditions [7]. Such alternative wood species used as for example in string instruments are maple or Honduras mahogany for the neck; maple for fretboard; alder, ash, basswood, maple, poplar and walnut for the body; spruce for soundboards [1,8,9]. On the other hand, high quality wood for musical instrument making is getting harder to find as well as more expensive [10]. Since there is a huge potential of using such alternative wood materials in musical instrument industry, the interest in technologies that can ensure the improvement or stabilization of their acoustical properties has been increased [4]. An additional

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potential also exists for restoration and reconstruction of old musical instruments by using the new species in case these technologies could provide them with similar sound characteristics to naturally aged wood.

Musical instrument manufacturers have been trying to minimise the negative characteristics of the wooden raw materials by applying special treatments for a century [4]. However, the question arises today whether the modern wood modification processes can be used to enhance the specific functionalities of inexpensive common wood species needed for various instruments. That could potentially help to satisfy the increasing demand of high-quality wood in this industry and reduce the pressure on endangered, expensive tropical and exotic hardwood species.

Thermal, chemical and impregnation modification of wood has received considerable attention in recent years, mainly as an environmental-friendly alternative to conventional wood preservation [11,12]. Some of these wood modification have been commercialized in different parts of the world. The most important thermal modification process is performed by the ThermoWood® Association (Finland, Sweden), where steam is used as a heat transferring media and the treatment is performed at 185–215 °C for 2–3 h. During the thermal modification process, degradation of hemicelluloses, modification of lignin, redistribution of extractives, increase of cellulose crystallinity and the reduction of hydrophilic hydroxyl (-OH) groups in the cell wall resulted in a significant reduction in the amount of moisture absorption [13,14]. Acetylation is one type of chemical modification and the name of commercial product is Accoya® (The Netherlands) where reaction between the chemical molecule of acetic anhydride and the -OH groups of the wood substrate takes place and generates acetylated wood. This process is a single site reaction, meaning that one acetyl group is attached to one hydroxyl group, without polymerization and results in reduction of moisture absorption [15]. Another type of chemical modification that has also been commercialized is Kebony® (Norway), uses furfural alcohol. After impregnation with furfural alcohol, the wood is heated for the polymerization of the furfural alcohol, so that the resulting polymer is permanently locked into the wood cells giving a better stability [16]. Treatments with silicones/silanes [17,18] have a small industrial capacity (e.g. Sioo, UK/Sweden and OrganoClick, Sweden). Other types of impregnation modification include resin modification (DMDHEU, melamine, phenol formaldehyde) and treatments with waxes, oils and paraffin. In resin modification, a full cell impregnation process with vacuum and pressure steps in closed vessels allows the resin molecules to diffuse in the cell walls and finally curing is accomplished at 70–130 °C. Resin modification ensures high anti-swelling efficiency of wood [19,20]. However, with the exception of DMDHEU under Belmadur® for some years no commercial products are available today.

In principle, wood modification is applied to increase its durability following an alteration in material properties, such as reduced pore size in the cell wall matrix and/or lower cell wall moisture content. As a consequence, additional wood properties are improved which encompass increased dimensional stability, reduced water uptake, improved hardness and resistance to weathering. Usually, static and dynamic mechanical properties remain unchanged or even increase depending on the modification method and intensity [21,22]. The enhanced properties as well as the pleasant appearance of modified wood made it ideal for many interior or exterior uses. A few studies have also been carried out on the acoustical properties of modified wood with aim finding an appropriate suitability and quality balance for making musical instruments. Mild thermal treatments were found to improve the sound characteristics of wood, which are required for musical instruments [4,23–25]. Due to an improved hydrophobicity and dimensional stability, the sound properties of hydrothermally-modified wood became better at humid conditions [26]. Thermally improved wood was suggested for the restoration and reconstruction of old musical instruments as it showed similar sound characteristics to naturally aged wood [27]. Acetylated wood has shown very positive results when used for instruments like violin, piano soundboard, guitar, recorder, bagpipe chanter, trumpet and trombone mouthpieces [6]. Different chemical treatments, such as with a low molecular weight phenolic resin, resorcinol/formaldehyde treatment and saligenin/formaldehyde, resulted in improved sound characteristics of wood by increasing the specific dynamic Young's modulus and decreasing damping ($tan\delta$) without greatly increasing its specific gravity [28].

This paper further report on the acoustical properties of different modified wood materials, especially taking into account variations in humidity that has been little researched so far. It is well known that wood is a hygroscopic material and its dimensions change due to changes of its moisture content. This eventually affects the dimensional stability of wood products, in this case wooden musical instruments and may cause degradation of their tone quality. It is anticipated that the acoustic behavior of modified wood will vary little under different humid conditions.

2. Materials and methods

2.1. Modified wood

In total, nine different types of modified wood were used as to represent the different technologies existing today both at commercial and research levels. Those were experimental material of phenol formaldehyde-treated beech (*Fagus sylvatica* L.) with 25% resin content and melamine-treated beech (*Fagus sylvatica* L.) with 25% resin content (Georg-August University of Goettingen, Germany); commercially produced thermally-modified ash (*Fraxinus excelsior* L.) treated at 200 °C, aspen (*Populus tremula* L.) and birch (*Betula pendula* Roth) treated at 185 °C (ThermoWood®, Helsinki, Finland); commercially produced acetylated beech (*Fagus sylvatica* L.), maple (*Acer* spp.) and radiata pine (*Pinus radiata* D. Don) (Accoya®, Accsys Technologies PLC, Arnhem, The Netherlands); and commercially produced furfurylated Scots pine (*Pinus sylvestris* L.) (Kebony®, Oslo, Norway). Light weight swamp ash (*Fraxinus* spp.), maple (*Acer saccharum* Marshall), alder (*Alnus glutinosa* (L.) Gaertn.) and mahogany (*Swietenia macrophylla* King) wood pieces served as reference materials since they are commonly used for musical instruments. They were provided by the electric guitar company Strandberg guitars AB, Uppsala, Sweden. Test samples were sawn and planed to final dimensions of $12.5 \times 25 \times 350\,mm^3$ (radial × tangential × longitudinal). Four (4) samples were prepared for every type of material giving a total of 52 samples and were left to air-dry at ambient laboratory conditions for 4 weeks. Three (3) different climate conditions were set to simulate dry, standard and wet conditions, specifically 35%, 65% and 85% relative humidity (RH) at a constant temperature of 20 °C. Before testing, all samples were acclimatized at each of the respective conditions in a climate chamber (Binder KMF 115, Binder GmbH, Tuttlingen, Germany) for at least 2 weeks until they achieved a constant weight. From every category, samples were prepared for measuring the moisture content at each climate condition. For the measurement of dimensional changes (volumetric shrinkage), five samples with dimensions of $25 \times 25 \times 0.5\,mm^3$ (radial × tangential × longitudinal) for each radial and tangential shrinkage and five samples with dimensions of $10 \times 10 \times 100\,mm^3$ (radial × tangential × longitudinal) for longitudinal shrinkage were used. The radial, tangential and longitudinal dimensions were measured using an electronic caliper (TESA Valueline iP67, Switzerland) at the closest 0.02 mm on the samples after complete saturation and oven drying at 103 ± 2 °C. Shrinkages in three different directions were calculated and volumetric shrinkage was obtained by adding them together.

2.2. Acoustical properties

The most important acoustical properties of wood materials that are used for musical instruments are the speed of sound (c) within the material, the specific acoustic impedance (z), the sound radiation