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Effects of Frequency, Temperature and Test Duration in the Viscoelasticity of Brazilian Hardwoods Used in Handmade Musical Instruments.

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This study aims to make a comprehensive analysis on the viscoelastic behavior of typical tropical hardwoods and its influences in making musical instruments. For that a Dynamic-Mechanical Analysis was done and the mechanical parameters dependence on test control parameters like temperature, frequency and test duration time were measured. For *Dalbergia Nigra* the final value of Module of Elasticity (MOE) was 17551.0MPa and 0.022020 for tangent delta (tg(δ)), but a great variation in those parameters was observed during the tests, for all species the MOE increases and tg(δ) decreases, even with constant temperatures, which may be caused by water loss. Besides that, a discussion was made relating the obtained data and historical knowledge about the usages of the studied woods for musical instruments manufacture, and density was shown as the main variable for that purpose.

Keywords: *Brazilian Hardwoods, Dynamic-Mechanical Analysis of Wood, Viscoelasticity of Wood.*

1. Introduction

Wood itself has numerous properties that makes it attractive for human kind, such as its thermal comfort, that makes possible the construction of warm houses for harsh winters[1, 2], its mechanical properties makes it useful for making musical instruments[3] and furniture[4], and its electrical resistance is widely used in electric poles[5]. One of the most interesting features of such a versatile material is its renewable production and natural degradation, that makes it an important ally of sustainable practices. Aiming to increase it uses in new Eco-friendly technologies this material is been researched nowadays for many different purposes, from cross-laminated timber[6] and others wooden panels, to the development of bio based nanomaterials with nanocelluloses crystals and fibers[7].

To analyze such material it is crucial to have a previous knowledge about wood structure, known also as wood anatomy[8, 9]. First of all a basic division is made related to differences between angiosperm and gymnosperm trees, called hardwood and softwood respectively, it is necessary to have in mind that this is not directly related with strength properties of the wood, as it is just a historical definition.

As we can see in Figure 1 a) softwoods are formed mainly by just one kind of cell, the tracheid, which is responsible for giving support for the tree to stand, for transporting water and nutrients, and also for the storage of those resources. It is visible also on the bottom of the figure some resin canal, usually present in gymnosperms.

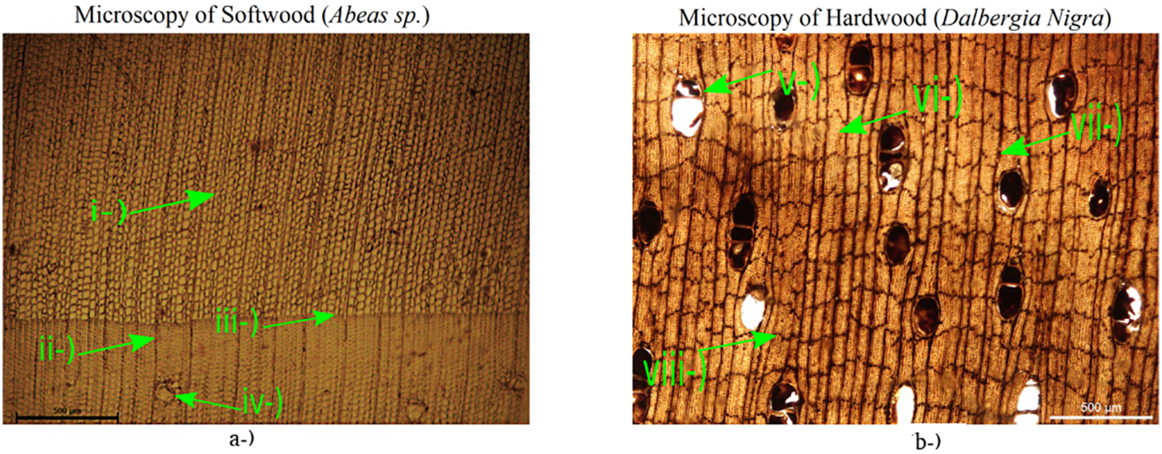
Microscopy of Softwood (*Abeas sp.*)
Microscopy of Hardwood (*Dalbergia Nigra*)
a-)
b-)

Figure 1. A) Softwood and Hardwood microscopy is shown, the arrows point to tracheid (i), rays 920, growth rings marks (iii) and oil deposition (iv). B) A hardwood sample microscopy, the arrows point to vessels (v), fibers (vi), rays (vii) and axial parenchyma (viii).

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There are also noticeable growing rings, easily seen in softwood but also present in part of hardwood species, their presence is a result of the difference in wood structure when grown in different conditions of rain period, temperature and insolation, changing the thickness of fibers and tracheid cell walls and vessels and parenchyma configuration for hardwoods. This variation defines earlywood and latewood, the first one is grown in spring, when the wood is returning to activity, the second one is grown close to winter; they can have great differences in their mechanical properties.

For hardwoods, in Figure 1 b), there are different types of structures for each one of the usages cited for tracheid. Fibers, the main matrix of hardwoods, give strength to the trunk and are formed by cellulosic cell walls, this is also where the majority of the tree's water is storage. For transporting nutrients there are the vessels, structures with thin cell wall and a large space inside; at last for storage function there is the parenchyma cells, which can appear involving vessels or in a diffuse way through matrix.

As all biological systems, these groups have exceptions, rare cases of hardwoods with tracheid-like cells and softwoods with vessels, moreover the appearance of others structures such as oil depositions and crystal formations can occur in several different ways and compositions. Both softwood and hardwood have also a radial structure, the rays, responsible for delivering the sources from phloem to xylem (from outside to the inside).

A broad range of combinations between structures and forms of organization results in samples with many different properties, furthermore the physical properties can vary between trees of the same species, and within a single tree. The drying process, the season management and techniques used can vary it as well. This is the reason why there are particular usages for distinct species and the motivation for best *luthiers* to choose carefully the board for their instruments.

To better understand of the viscoelastic properties of the samples, the complex elastic module parallel of the fibers was measured. The idea of this complex module is a generalization of Young's Modulus[10], taking into account also the dissipation of energy and the delay on material response to an impulse, and it can be written as follows:

$$\mathrm{E}^* = \mathrm{E}' + \mathrm{E}'' = |\mathrm{E}^*|.\cos(\delta) + i.|\mathrm{E}^*|.\sin(\delta) \quad (1)$$

Where *i* is the unit imaginary number, E' is the Young's Module, E'' is the Loss Factor and the angle delta is a phase which represents the delay between stress and strain, it can also see if the material is more solid-like or liquid-like. A delta value of 0° represents no dissipation and the material is an ideal solid, when the value of delta is 90° there is no energy saved in form of elastic energy, and the material can be seen as an ideal liquid, with no solid structure, which would represent a less energetic state where the material tends to return. With this angle, we can also define the:

$$\tan(\delta) = \mathrm{E}'/\mathrm{E}'' \quad (2)$$

Which expresses quantity of this relation.

The main idea of the chosen Dynamic-Mechanical test is to apply oscillating displacements in the sample, with small amplitude (close to 10 µm in our tests) in an accurate system that controls the necessary force, measuring the costs of sustaining the movement and the restaurateur force as a material response.

The goal of this research is to identify the dependence of those viscoelastic parameters in temperature, frequency and oscillation time, besides that we propose an analysis about the difference of the wood chosen to be used in each part of an acoustic guitar crossing the knowledge of a *luthier* and our data.

2. Methods

For this study 30 samples of 15 tropical hardwood species were used, they were chosen with the objective of studying Brazilian›s trees that are used in manufacturing musical instruments. We looked for using a wide range of different densities, aiming to include all the functions of wood in the distinct parts of an acoustic guitar.

It is accepted in wood mechanics literature that one of the most important factors in the mechanical parameters is density[11]; therefore, we were able to test the real dependence of those parameters in density and see which properties are needed for each different part of the instrument, giving us a better notion of its acoustics.

For the complete viscoelastic analysis of those specimen was used the DMA 242 – Netzsch, which makes a Dynamic-Mechanical Analysis in numerous possibilities of mechanical supports commonly used. We chose to do a 3-point bending flexural test, mainly because for this test it was possible to make analysis with samples as thick 5 mm (other tests needed a much thinner extraction), so the samples used had the dimensions of 50x5x5 mm and their fibers were parallel with the longest axes.

It is necessary in DMA the configuration of parameters like frequencies of oscillation, temperature, test duration, amplitude of force, maximum displacement and others. The last two were fixed as recommended by Netzsch, and the rest were varied changing the focus of analysis.

At first, two tests were done for all the samples, one short (15 minutes) and one long (1 hour and 10 minutes). In the first one only higher frequencies were applied (the possible range of frequencies is from 0.025 Hz to 50 Hz, so the "higher frequencies" is a range from 10 Hz to 50 Hz), and on the second one a complete spectroscopy was made, using the full range.

Furthermore, the temperature varied in the range from -10°C to 45ºC for the same frequencies used in the 1 hour test, this variation of temperature was expected not to modify irreversibly the samples. Those temperatures were achieved by the use of liquid nitrogen and a resistance inside the test box, while a thermocouple close to the sample controlled the local temperature and aided to control the entry of nitrogen or heat that was generated.

At last, a destructive test was made with part of the samples, increasing the temperature until 200°C, which could represent the wood before and after it becomes over-dried.

3. Results and Discussion

At first we will discuss some general aspects of the obtained data, Tables 1 e 2 perform the roles of it. It contains some species names, their densities and mechanical properties for selected frequencies, temperatures and minutes of test. After that some graphs are shown of the main results of *Cedrela sp.,* the same general behavior was seen for all others species. All plot follows the same main setup: the points marked with a square are Young's Modulus data, a star for Tangent delta, and a circle for temperature. The different styles of lines represents different frequencies of oscillation, once are shown graphs from different setups the lines are not the same for each frequency in all the figures, this also results in different absolute values of the parameters in the table, the columns marked (*) are from a different setup than those that are not marked.

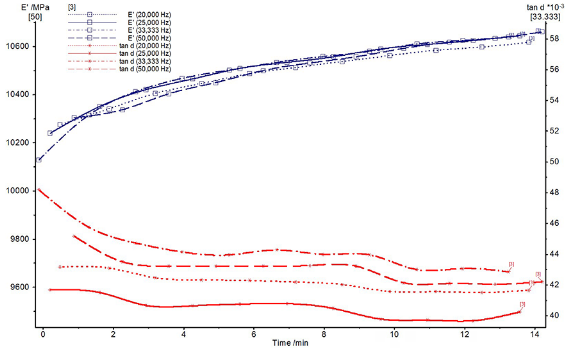

Figure 2. Mechanical spectroscopy of *Cedrela sp*. over 15 minutes.

Table 1 and 2 show a great variation of measured properties between species and also within same sample. This happens because of natural changes on environment conditions that were not controlled, such as temperature, air moisture, year season, and so on. Therefore it would be inaccurate to compare the obtained data with each other or to previous work in literature. With this in view, the discussions presented in this sections is focused on the variation of mechanical properties in control parameters.

Table 1. Elastic Modulus spectroscopy and variance with temperature

Species Name and Sample Identification	Density [g/cm^3]	Modulus of Elasticity (Young's Modulus) [MPa]					
		10 min. 0.025 Hz	55 min. 0.025 Hz	15 min. 50 Hz	60 min. 50 Hz	-8 °C 50 Hz*	40 °C 50 Hz*
Dalbergia nigra 1	1.12(3)	15573.8	16004.9	17220.6	17551.0	13124.5	12364.5
Dalbergia nigra 2	1.16(3)	16031.5	16585.7	17669.1	18094.1	18771.3	18107.8
Cordia goeldiana 1	0.70(2)	9008.6	9530.6	9877.8	10301.7	7678.3	6985.5
Cordia goeldiana 2	0.74(3)	5440.3	6278.3	6081.3	7242.8	10714.8	10394.1
Ocotea porosa 1	0.82(3)	7561.8	7742.5	8307.6	8399.2	9464.6	7752.7
Ocotea prosa 2	0.78(3)	6154.4	6196.4	6913.4	7038.4	8246.8	6822.0
Balfourodendron riedelianon 1	0.93(3)	11265.9	11546.6	12315.3	12504.6	13518.3	11922.4
Balfourodendron riedelianon 2	0.95(3)	9242.7	9419.1	10064.9	10223.8	11721.2	10122.8
Cedrela sp. 1	0.68(2)	7747.9	8023.1	8753.3	8980.6	12597.4	10990.7

Table 2. Tangent Delta spectroscopy and variance with temperature

Species Name and Sample Identification	Density [g/cm³]	Tangent Delta					
		10 min 0.025 Hz	55 min 0.025 Hz	15 min 50 Hz	60 min 50 Hz	-8 °C 50 Hz*	40 °C 50 Hz*
Dalbergia nigra 1	1.12(3)	0.06254	0.05445	0.01580	0.02022	0.03990	0.03682
Dalbergia nigra 2	1.16(3)	0.06276	0.05676	0.02060	0.01882	0.02453	0.02433
Cordia goeldiana 1	0.70(2)	0.08158	0.07083	0.04431	0.03651	0.02845	0.02933
Cordia goeldiana 2	0.74(3)	0.09786	0.08662	0.09300	0.06005	0.04111	0.02600
Ocotea porosa 1	0.82(3)	0.06350	0.05914	0.03450	0.03453	0.03716	0.03880
Ocotea prosa 2	0.78(3)	0.06615	0.06002	0.03516	0.03254	0.03402	0.03681
Balfourodendron riedelianon 1	0.93(3)	0.06402	0.06785	0.03780	0.03770	0.03713	0.03369
Balfourodendron riedelianon 2	0.95(3)	0.06687	0.06517	0.03630	0.03841	0.03516	0.03227
Cedrela sp. 1	0.68(2)	0.07753	0.06625	0.03903	0.03698	0.04070	0.02796

The first general behavior that appears in the Fig. 2 and 3 is an increase of the Young's Modules and a decrease in tangent delta during the test. In Fig.4 when the samples were cooled to -10°C the samples became harder and with less dissipation. After being heated to 40°C the mechanical properties tended to the same asymptotic value near of the final values measured on the first graph.

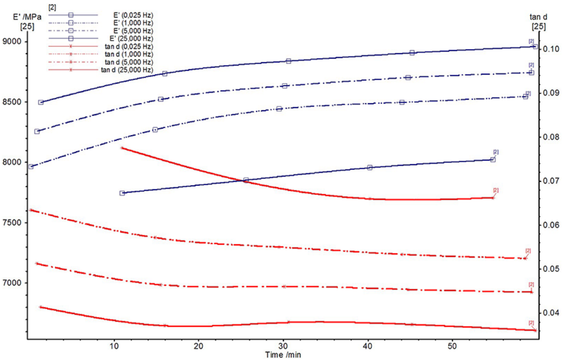

Figure 3. Mechanical spectroscopy of *Cedrela sp*. over 1 hour.

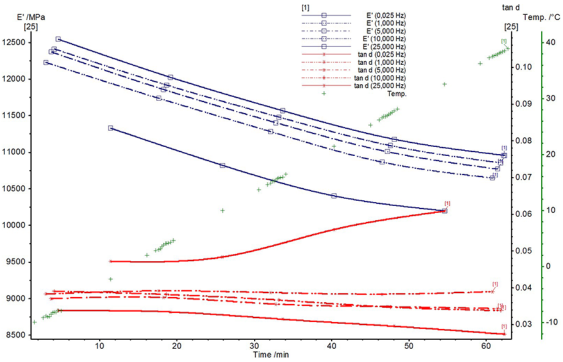

Figure 4. Mechanical spectroscopy of *Cedrela sp*. from -10°C to 50°C.

The water inside the structure of the material was the main cause of this change on dynamics behavior, as it varied with temperature increases the Young's Module on wood in temperatures below 0°C, and in the tests without temperature variance a water loss was responsible for a gain on rigidity. The variance of water was noted measuring the weight of each sample before and after the tests, the difference was around 1% of the initial mass. An interesting form to control the drying process in the samples is to calculate the derivative of mechanical parameters with respect to time, at the end of test it decreases and tends to zero, showing that all the water that could be withdrawn from the sample was already gone.

The Fig.5 contains the information of the heating process in wood, a great difference is seen again when comparing higher and lower frequencies, for lower than 1 Hz a decreases of E' occurs until 100°C, when it starts to go up until the end of the test.

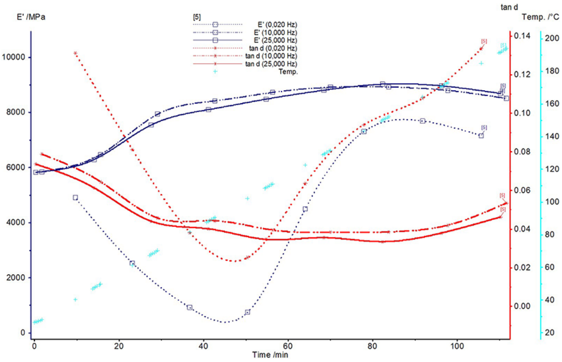

Figure 5. Mechanical spectroscopy of *Cedrela sp*. up to 200°C.

Analyzing Fig.6 it is noted a great variation on mechanical properties at very low frequencies (below 5 Hz). This may be caused by a change of wavelength scale or a change on the response of some of the numerous different cells existent in wood.

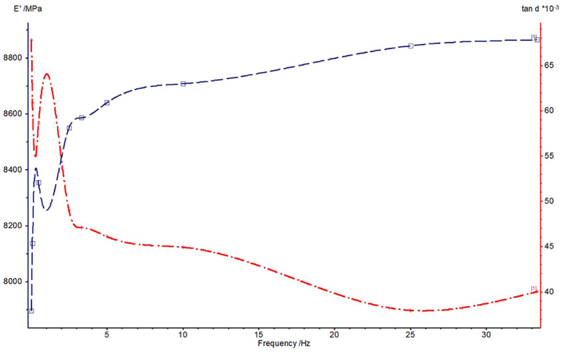

Figure 6. Young's Modulus and Tangent Delta dependence on frequency for *Cedrela sp*.

At last in Fig.7 a linear regression was done to see the main dependence of mechanical properties on density, it was noted that Young's Modulus increases with density, but a great fluctuation shows that other factors can influence it as well.

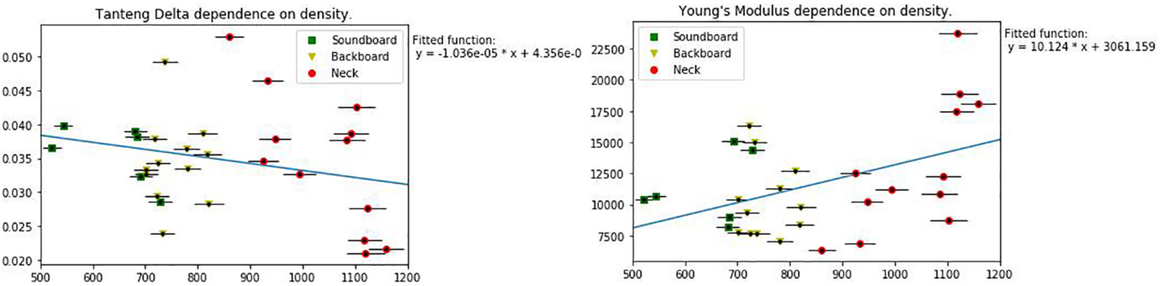

Figure 7. Curve fit of mechanical properties dependence on density for all species and their uses in acoustic guitars

4. Conclusion

The viscoelastic properties of wood showed to be strongly related with the hygroscopic behavior of this material, so the variance of moisture was the main cause of modifications on mechanical parameters and the dynamic-mechanical analysis was extremely efficient to measure its evolution at several conditions. An important divergence on mechanical performance was seen for very low frequencies, both tests, with and without temperature variance, showed a extensive contrasts, which can be related to different parts of wood structure responding differently for each frequency. At last it was concluded that Young's modulus has a higher dependence on density than tangent delta, and for musical instruments until now the weight of a species is its most important properties for choosing it to different functions on a guitar construction, but a great fluctuation of mechanical parameters could be the cause of the large range of qualities available.

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