Characterization of acoustic and mechanical properties of common tropical woods used in classical guitars

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**Abstract**

There is a need of substitution woods for the use in musical instruments because of the limited availability of some commonly used tropical tonewoods. Before substitutions can be found, it is necessary to know about the required properties. Hence, in this paper acoustical, mechanical and physical properties of four common tropical hardwoods (Indian rosewood, ziricote, African blackwood and ebony) were determined because there are less literature values for some properties available, e.g. internal friction, hardness or swelling behaviour. The acoustic properties were determined by means of experimental modal analysis, the mechanical properties by means of static bending tests and tests of the Brinell hardness. For the swelling behaviour the volume swelling and also the differential swelling coefficients were determined. With the results it is possible to look for new 'tonewoods' or to specifically modified woods, e.g. thermally treated wood, to substitute tropical wood species.

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**Introduction**

Tropical hardwoods, such as ebony or rosewood, are common wood species for the use in musical instruments, such as classical guitars. This is owing to the high stiffness and dimensional stability as well as the excellent colour nuances. Furthermore, the wood must be stored for a long time, sometimes for decades, to achieve suitable properties, in particular high resonance qualities and reduced growth stresses, for the use in high-quality acoustic guitars (natural wood aging). In addition to the much higher costs, the availability of those ‘tonewoods’ is significantly reduced. According to the CITES Convention, the trade with some tropical hardwoods is limited [1]. At the 17th CITES Conference held in Johannesburg (South Africa), it was decided that all existing Dalbergia species not listed in CITES Annex I are listed in CITES Annex II. Thus, these wood species, including the products consisting of these wood species, are tradeable to a limited extent worldwide. Hence, there is a need of substitute materials for such applications. In consequence, new woods were employed in the past [2]. Ziricote, for example, is a substitution of Indian rosewood – the common wood used for back and sides of classical guitars. Another example is African blackwood which substitutes ebony as standard material for fretboards.

Most of the “new woods” are also tropical species. Thus, it is necessary to look forward to find other suitable native woods for the use in classical guitars.

Important properties to determine the suitability of wood for guitar making are not only acoustic properties but also mechanical properties and sorption behaviour. The acoustic characteristics of wood can be described by means of dynamic Young's modulus ($E'$), damping also called internal friction or loss coefficient ($Q'/C_0$), dynamic shear modulus ($G'$) or speed of sound ($c$) and tested non-destructive via ultrasonic testing or modal analysis [3,4]. Additional acoustic properties like impedance ($z$) or sound radiation coefficient ($R$) are directly related to density ($\rho$) and dynamic Young's modulus [4]. Furthermore, Young's modulus ($E$), modulus of rupture (MOR) and Brinell hardness (HB) reflect the mechanical behaviour. The swelling properties can be characterized by means of the volume swelling ($a_v$) and differential swelling coefficient ($q$).

Not every tonewood, such as Indian rosewood, is well studied, which sometimes makes it very difficult to find data for the specified properties to decide whether a wood species is suitable or not.

It is essential to characterize the wood species actually used for classical guitar making to find other suitable woods afterwards. The aim of this work is to fill the gap in research and to determine the acoustical, mechanical and sorption properties of wood species used as back and sides material and for fretboards.
Material and methods

The heartwood of four species: Indian rosewood (*Dalbergia latifolia* Roxb.), ziricote (*Cordia dodecandra* DC), African blackwood (*Dalbergia melanoxylon* Roxb.) and ebony (*Diospyros crassiflora* Hiern.) was investigated. The wood was provided by a classical guitar manufacturer. The dimension of one specimen was 190 mm (longitudinal) × 28 mm (radial) × 6.5 mm (tangential). The number of specimens varied between 20 and 30 of each species and each testing method. The specimens were conditioned at 20°C and 65% relative humidity (RH) until constant mass was reached. All investigations were conducted at 20°C and 65% relative humidity. The EMC and volume swelling were measured compared to oven-dry mass at 80°C to avoid possible alterations in properties of the specimens owing to a thermal influence at 103°C (according to EN 13183-1). The dynamic Young’s modulus (E₁) was calculated with the resonant frequency for a rectangular cross section:

\[ E₁ = \frac{\rho l^2 f_R^2}{4F_1(m)} \left(1 + \frac{l^2}{F_1(m)} + \frac{1}{F_2(m)} \frac{sE_A}{G} - \frac{4\pi^2 s^2 \rho f^2}{G} \right) \]  

where \( E₁ \) is the apparent Young’s modulus, \( l \) is the radius of gyration of a cross section, \( l \) is the length of the test specimen, values of \( F_1(m) \) and \( F_2(m) \) for the first bending mode are 49.98 and 12.30, \( s = 1.2 \) is the shear deflection coefficient for a rectangular cross section, \( G \) is the shear modulus calculated from the first torsion mode, \( \rho \) is the density, \( f_R \) is the resonance frequency of the first bending mode.

For a beam of a rectangular cross section, the radius of gyration \( r \) is calculated according to Eq. (2):

\[ r^2 = \frac{h^2}{12} \]  

where \( h \) is the thickness of the specimen. The dynamic Young’s modulus \( E₁ \) is calculated in several iterations where the apparent Young’s modulus \( E_A \) is the result of the previous iteration step. As the starting point, \( E_A \) was calculated by using the Euler-Bernoulli theory as a first approximation according to Eq. (3):

\[ E_A = \frac{4\pi^2 l^2 l^2 f^2}{m^2} \]  

where \( m = 4.73 \) is a constant corresponding to the first bending mode of a free flexural vibration.

The dynamic shear modulus \( G_l \) in LR plane was determined by using the first torsion mode according to the Euler-Bernoulli equation for a rectangular cross section:

\[ G_l = \frac{\rho l^2 (h^2 + b^2) f_l^2}{3c_3 h^2} \]  

where \( b \) is the width of the specimen, \( f_l \) is the resonance frequency of the first torsion mode and \( c_3 \) is a constant depending on the ratio \( b/h \) \( (c_3 = 0.281) \).

The damping of wood can be described by the flexural internal friction \( Q^{-1} \) and was calculated using the peak frequency \( f \) and the half-value width of the resonance peak \( \Delta f \) shown in Fig. 2 according to Brémaud [8]:

\[ Q^{-1} = \frac{\Delta f}{f_R} \]
The determination of the static bending properties (Young’s modulus – E and modulus of rupture – MOR) was performed in accordance to DIN 52186 as three point bending test. The span was 150 mm, and the load was supplied to the centre of the span.

The Brinell hardness (HB) test was measured perpendicularly to the grain in tangential direction in accordance to DIN EN 1534. The hardness was calculated by using the equation from Grekin [9]:

$$HB = \frac{F}{\pi D h}$$

(6)

where $F = 1000$ N is the applied force, $D = 10$ mm is the diameter of indenter and $h$ is the depth of the indentation.

**Results and discussion**

Table 1 shows the physical properties such as density, EMC, differential swelling coefficient and volume swelling of the different wood species. As mentioned above, ziricote is a substitute to rosewood and African blackwood to ebony. It is obvious that the densities of ziricote compared to rosewood and African blackwood compared to ebony are higher. Related to literature the densities are in the same range, which is important to compare especially the mechanical properties. The EMC of rosewood, ziricote and African blackwood is in the same range, but the value for ebony is 30% higher, which has an influence on the swelling behaviour. The volume swelling of ebony is nearly twice the value of the other tested woods. Ziricote shows the lowest volume swelling. The literature values for each wood species are higher than the measured values. This is because of the fact that the literature values are the maximum volume shrinkage measured from the fibre saturation point to the oven-dry stage as desorption. In this study, the volume swelling was determined between oven-dry state and 85% RH as adsorption.

The differential swelling coefficient specifies the increase of dimension due to the increase of 1% moisture content. Indian rosewood shows a distinctive anisotropy between the radial and tangential swelling coefficient. Furthermore, ebony has the highest values for swelling in tangential and radial dimension.

Table 2 shows a comparison of the mean values of E, MOR, HB, $E$, $Q^{-1}$ and $G_{0LR}$ of each wood species studied, which are in the range of 13.3–19.5 GPa, 142–219 MPa, 13–20.8 GPa, 0.0076–0.0098 and 1.6–2.5 GPa, respectively. The Young’s modulus and the MOR from the static bending test of rosewood and ziricote are in the same range. This does also apply to African blackwood and ebony. The measured values for ziricote are significantly higher than the literature values.

The mean value of Brinell hardness for ziricote and African blackwood is much higher than for rosewood and ebony. African blackwood shows the highest HB. For the use as fretboard material, the hardness of wood is an important quality factor. A high value indicates a good abrasion resistance due to strings scratching on the fretboard surface while guitar playing.

Fig. 3 describes the relationship between the dynamic Young’s modulus and the density. It shows the higher the density the higher Young’s modulus. The tested wood species are divided into two groups: one for back and side material (rosewood, ziricote)

### Table 1

| Species                  | Indian rosewood | Ziricote | African blackwood | Ebony |
|--------------------------|-----------------|----------|-------------------|-------|
| $\rho$ (kg m$^{-3}$)     | 20              | 20       | 20                | 20    |
| $m$                      | 793             | 1002     | 1268              | 1140  |
| CV (%)                   | 6               | 9        | 3                 | 5     |
| Literature               | 640–910         | (560) 805–950 | 900–1300         | 900–1300 |
| EMC (%)                  | m               | 7.7      | 6.5               | 6.9   |
| CV (%)                   | 12              | 16       | 11                | 10.5  |
| Literature $\beta_v$     | 6.77            | 5.40     | 5.17              | 12.24 |
| $\alpha_v$ (%)           | m               | 12       | 19                | 28    |
| CV (%)                   | 8.5 [11,12]     | 9.8 [12] | 7.6–7.7 [11,12]  | 14.8–19.6 [11,13,18] |
| $q_{\text{rad}}$ (3/%)   | m               | 0.19     | 0.28              | 0.27  |
| CV (%)                   | 0.39            | 0.36     | 0.34              | 0.45  |
| $q_{\text{tan}}$ (3/%)   | m               | 16       | 29                | 15    |
| CV (%)                   | 13              | 16       | 25                | 22    |

- $Q^{-1} = 1 - f_2 - f_1$ is the difference between the resonance frequencies.
- $f_1$ and $f_2$ are the resonance frequencies.
- $\delta$ is the phase angle.
- $\tan \delta$ is the tangent of the phase angle.

Fig. 2. Determination of internal friction $Q^{-1}$ according to Brémaud [8].
and one for fretboards (blackwood, ebony), which are in the range of 700–1100 kg m$^{-3}$; 9–18 GPa and 1000–1300 kg m$^{-3}$; 14–26 GPa, respectively.

Young’s modulus found from EMA indicates a good relationship to Young’s modulus found from static bending test with a maximal deviation of 9% and is shown in Fig. 4. These results are similar to those obtained by Haines et al. [10].

Soundboards of stringed instruments need to have a high E/G ratio [16,19]. That means, a high elastic anisotropy contributes to sound radiation of the top plate because of a higher mobility of the vibration modes. For fretboards the E/G ratio should be far less pronounced than for soundboards. It’s necessary to have also a high Young’s modulus and shear modulus. A high shear modulus counteracts torsion of the guitar neck because of the different string tensions. A low shear modulus tends to result in a torsional twisting of the neck while playing. Thus, string buzzing and other disturbing noises while playing can occur. Therefore, woods for fretboards need to have a high shear modulus like African blackwood with 2.5 GPa. But also ebony with 1.65 GPa shows a high value even if it is 35% lower than that of African blackwood. In literature it is hard to find values for the dynamic shear modulus of such tropical hardwoods and of possible alternative woods.

Damping is a very important property of woods used for musical instruments because it withdraws the energy owing to internal friction, which otherwise is available for sound radiation [8,15,16,19]. Ziricote has the lowest damping value followed by African blackwood. But all studied woods exhibit a good damping behaviour with a maximal value of 0.0098.

**Table 2**

| Species                   | Indian rosewood | Ziricote | African blackwood | Ebony |
|---------------------------|-----------------|----------|-------------------|-------|
| E (GPa)                   | 13.3            | 13.3     | 14.5              | 15.5  |
| CV (%)                    | 22              | 15       | 14                | 17    |
| Literature                | 11–14[11,12,17] | 10.9[13] | 17.9–20.6[11–13] | 13.4–17.7[11–13] |
| MOR (MPa)                 | 146             | 142      | 219               | 191   |
| CV (%)                    | 15              | 21       | 9                 | 21    |
| Literature                | 115–132[11,12,17] | 113[17] | 170–214[11–13] | 130–188[11–13,17] |
| HB (MPa)                  | 43              | 70       | 112               | 58    |
| CV (%)                    | 14              | 20       | 16                | 10    |
| Literature                | 35[11]          | –        | 98[11]            | 84[11] |
| N                         | 20              | 20       | 20                | 20    |
| E’ (GPa)                  | 13.0            | 13.6     | 17.2              | 20.8  |
| CV (%)                    | 23              | 15       | 14                | 15    |
| Literature                | 9.5–17[8,15,16] | 13.8–16.2[14] | 20.6[8] | 15.5[18] |
| Q$^{-1}$ (10$^{-3}$)      | 9.6             | 7.6      | 8.1               | 9.8   |
| CV (%)                    | 11              | 12       | 13                | 17    |
| Literature                | 6.05–8.9[8,15,16] | –        | 5.8[8]            | 8.1[18] |
| GLR’ (GPa)                | 1.64            | 1.61     | 2.51              | 1.65  |
| CV (%)                    | 12              | 14       | 11                | 10    |
| Literature                | 1.5–2.7[15]     | –        | –                 | –     |

![Fig. 3. Relationship between Dynamic Young's modulus and density for tested wood species; solid ellipse – group for back and side woods; dashed ellipse – group for fretboard woods.](image)
Table 3 lists an overview of European wood species as possible substitution woods for the use in classical guitars. The data on wood properties were derived from literature. Comparing the results listed in Tables 1 and 2 with the literature data in Table 3 makes it possible to assign the woods useful for fretboards or back and sides. Sycamore and cherry are potentially suitable for back and sides and beech, hornbeam, pear, plum and sorb-tree may be possible for fretboards. Service tree and European walnut are suitable for both back or sides and fretboards. Woods used as fretboard material need to have a high density, hardness, dark colour and low swelling and shrinkage due to humidity changes. Indian rosewood has the lowest hardness of the tested wood species with 43 MPa. But there are only a few European wood species with HB greater than 40 MPa. Only European walnut and hornbeam listed in Table 3 have similar values compared to rosewood and ebony. Further investigations have to manage the questions, how to increase the hardness of such woods. Another question to solve is how to decrease swelling and shrinkage of European woods compared to the tested tropical hardwoods. The highest swelling behaviour has ebony with a volume swelling of 12.2% or, as described in literature, with 14.8–19.6% maximum shrinkage. The other tested woods have only a swelling of 5.2–6.8% or from literature with 7.6–9.8% maximum shrinkage. This is only half of the value of ebony. Woods used for back and sides of a guitar need to have similar values. Plum and sycamore show the lowest swelling values of the listed woods in Table 3 with 11.5–11.8% maximum shrinkage. All other listed species have much higher values. It’s a matter of fact that thermal modification could reduce the swelling behaviour in dependence of the modification parameters: temperature, time and atmospheric condition [20].

![Graph](https://example.com/graph.png)

**Fig. 4.** Comparison of Young’s modulus found from EMA with those obtained from static bending test for all tested specimens.

| Species             | Uses  | $\rho$ (kg m$^{-3}$) | $E'$ (GPa) | $E$ (GPa) | GLR$^0$ (GPa) | MOR (MPa) | $Q^{-1}$ ($10^{-3}$) | HB (MPa) | $\beta_v$ (%) |
|---------------------|-------|----------------------|------------|-----------|---------------|-----------|---------------------|----------|---------------|
| European walnut     | B&S   | 640–693 [11,22,24]   | 11.2 [24]  | 11.2–13   | 1.38 [24]     | 147 [11]  | 52 [11]             | 13.4–14 [11] |
| Sycamore            | B&S   | 630–640 [8,11,22]    | 6.8 [13]   | 9.4–10.5  | 95 [11]       | 16.1 [13] | 27 [11]             | 11.5–11.8 [11]|
| Beech               | F     | 690–720 [11,20,23,25]| 9.6–11.5   | 13.7–16   | 1.24 [25]     | 123 [11]  | 7 [20]              | 17.5–17.9 [11]|
| Hornbeam            | F     | 740–830 [11,21,23]   | 15.4 [8]   | 14.5–16.2 | 160 [11]      | 9.5 [8]   | 29–45               | 18.8 [11] |
| Pear                | F     | 690–740 [11,8]       | 6.8 [8]    | 8–8.2     | 98 [11]       | 14.9–16.7 | 32 [11]             | 13.6–14.7 [11]|
| European cherry     | B&S   | 560–630 [11,23,24]   | 8.2–10.8   | 10–11     | 1.11 [24]     | 83 [11]   | 10 [8]              | 13.7–14 [11] |
| Plum                | F     | 619 [22]             |            |           |               |           |                     | 12.1 [22] |
| Service tree        | F, B&S| 630–870 [11]         |           | 10–13.4   | 108 [11]      | 21–27 [11]| 16.8–17.5           |          |
| Sorbus domestica L. | F     | 810 [8]              |           | 15.6 [8]  |               |           |                     | 9.9 [8]   |

Table 3 Possible European woods for the use as fretboard (F) and for back and sides (B&S) of a classical guitar and important properties – density ($\rho$), dynamic Young’s modulus ($E'$), Young’s modulus ($E$), dynamic shear modulus in LR plane (GLR$^0$), modulus of rupture (MOR), damping coefficient ($Q^{-1}$), Brinell hardness (HB), maximum volume shrinkage ($\beta_v$).
change to darker nuances is a quite acceptable side effect. In further work, suitable alternative ‘tonewoods’ for the use as fretboard and for back and sides of a classical guitar will be investigated applying the results of this work. In addition, an option is to modify possible woods thermally or chemically to improve their acoustical, mechanical and swelling properties. Zauer et al. [20] show that the acoustical and mechanical properties of beech improve significantly owing to thermal modification.

Conclusion

This work determines values for important acoustical, mechanical and physical properties of: Indian rosewood, ziricote, African blackwood and ebony as a basis of their substitution with native wood species in high quality classical guitars. In this case, the substitution woods may be modified native wood species which have similar properties compared to the tropical wood species usually used in components of classical guitars. The investigations show that ebony has a significantly higher equilibrium moisture content and swelling behaviour than the other wood species studied. Furthermore, Indian rosewood has the most pronounced anisotropy between the swelling coefficient in radial and tangential direction. African blackwood has the best mechanical properties owing to the highest raw density and is a favourite for the use in fretboards. All investigated wood species exhibit a relatively low damping, which is an important factor for the use in components of classical guitars. In addition to the investigations, important acoustical and mechanical properties of European wood species as possible substitution wood species for the use in back and sides as well as in fretboards of classical guitars were shown.

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