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Comparative Evaluation of the Strength and Acoustic Properties of Resonant Wood-Based Composite in ARS and X-ARS Variants

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The present research was commissioned by Turkowiak Guitars sp. z o.o. sp. k. (2 Lipowa St., 64-117 Gołanice), documented by a letter dated 09.07.2025. According to the commission, the Faculty of Forestry and Wood Technology of the Poznań University of Life Sciences was tasked with analysing the strength–acoustic properties of resonant wood-based material in two variants: ARS (Acoustic Resonance System) and X-ARS (Acoustic Resonance System with a chemical-ceramic matrix). The results were to be compared with the parameters of Indian rosewood and African mahogany.

1. Introduction

Wood plays a key role in guitar construction, determining its durability and acoustic performance. The back plate and the sides of the body are of particular importance, as they form the instrument's resonant chamber. These elements shape the tonal character—affecting timbre, sound projection, and the instrument's ability to transmit vibrations generated by the soundboard. Selecting suitable wood species for these parts directly impacts the guitar's acoustic quality.

An alternative to solid wood is plywood, which is dimensionally stable and resistant to changing environmental conditions due to its layered structure. Although plywood does not match the full acoustic qualities of solid wood, it is used in instrument production, particularly in utility-oriented models, where both technical and economic factors are significant.

2. Materials and methods

Samples made from four types of materials were provided for the study:

a) **ARS** – composite,

b) **X-ARS** – ARS variant with an additional ceramic matrix,

c) **Indian rosewood** (*Dalbergia latifolia*),

d) **African mahogany** (*Khaya ivorensis*).

From each material, 57 samples were prepared for the following tests:

- tensile modulus of elasticity – 10 samples,
- Brinell hardness – 3 samples,
- impact resistance – 25 samples,
- sound propagation velocity – 7 samples,
- hygroscopic properties – 6 samples,
- damping – 6 samples.

Before testing, each sample was measured and weighed, and wood density was calculated based on the collected data.

2.1. Tensile modulus of elasticity

Samples with dimensions of 150 × 20 × 2.5 mm were used. Tensile tests were carried out on a ZWICK Z050TH testing machine equipped with a ZWICK 066550.02 extensometer with a 30 mm gauge length. The loading was applied along the grain at a rate ensuring a test duration of 60 ± 30 s, with an initial preload of 50 N. Before each test, mean values of sample width and thickness were entered into the control system. The software recorded the test course and automatically calculated the parameters: sample strength, modulus of elasticity, strain at proportional limit, and strain at failure.

The longitudinal modulus of elasticity (MOE) was determined from the relationship between stress (σ) and strain (ε) in the linear section of the σ–ε curve. It was calculated according to the formula:

$$MOE = \frac{\Delta\sigma}{\Delta\varepsilon}$$

where:

Δσ – stress increment within the proportional range [N/mm^2],

Δε – corresponding strain increment [–].

The program identified the linear section of the tensile curve and determined its slope, which was taken as the modulus of elasticity value for each sample.

2.2. Brinell hardness test

The Brinell method—one of the most widely used hardness tests alongside the Janka test—was applied. A steel ball of diameter D = 10 mm was pressed into the sample under a load of F = 500 N. The load was applied gradually over 15 s, maintained for 30 s, and then released within 15 s. Measurements were taken on the plane corresponding to the sample's orientation in a finished instrument. Each sample (150 × 20 × 2.5 mm) was indented four times.

Brinell hardness (HB) was calculated according to the formula:

$$\boldsymbol{HB = \frac{2F}{\pi D(D - \sqrt{(D^2 - {d_{avg}}^2)}}} \, [\mathbf{N/mm2}]$$

where:

HB – Brinell hardness [N/mm^2],

F – applied force [N],

D – steel ball diameter [10 mm],

d_{avg} – average indentation diameter [mm].

2.3. Impact resistance (Dynstat method)

Impact strength was tested using the Dynstat method, which evaluates a material's resistance to cracking under dynamic loading. Samples of 16 × 10 × 2.5 mm were mounted so that the load direction corresponded to the grain orientation in the finished instrument. A pendulum hammer struck the sample, and the absorbed energy during fracture was automatically recorded.

Impact strength (U) was calculated as:

$$U = \frac{W}{A} \left[\frac{J}{cm^2}\right]$$

where:

W – energy absorbed during fracture [J],

A – cross-sectional area at fracture [cm^2].

The results provided information on the material's ability to absorb energy under dynamic loading, which is crucial for evaluating its suitability in musical instrument construction.

2.4.Sound propagation velocity

The velocity of ultrasonic wave propagation in the radial direction (through the thickness of the plate) was determined by measuring the transit time across the sample. Each sample was precisely measured before testing to obtain the thickness in the transmission direction. A 543E ultrasonic device with 0.1 MHz transmitting and receiving heads was used. The method involved transmitting ultrasonic pulses through the sample between the two heads and recording transit time (t). Based on the measured thickness (l) and transit time, velocity (v) was calculated:

$$v = \frac{l_t}{t} \text{ [m/s]}$$

where:

l_t – propagation length [m]

t – transit time [s].

2.5.Hygroscopic properties

Tests included determining sample moisture content and hygroscopic swelling under increased air humidity. Initially, samples were dried to absolute dryness. Their dimensions and mass were then measured: thickness at the midpoint with ±0.01 mm accuracy (digital calliper), and mass with ±0.001 g accuracy (electronic balance).

Samples were placed in a desiccator above water (relative humidity ≈ 97%) for 72 h. Thickness and mass were measured every 24 h. Based on the results, wood moisture content and relative swelling—defined as the percentage change in thickness relative to the dry state—were calculated.

2.6. *Damping*

Six samples were prepared to determine each tested material's resonance properties and damping capacity. The samples were conditioned for 24 h in a desiccator with saturated potassium carbonate solution (43% RH) at a room temperature of 22 °C.

Each specimen was suspended on thin threads near the predicted vibration nodes of the fundamental bending mode (~24% of the length from the ends), ensuring free-support boundary conditions and minimising additional damping associated with clamping. Vibrations were excited using a standardised impact method: a 5 g glass bead was released from a guide to strike the centre of the horizontally suspended sample, exciting its fundamental bending mode. After the impact, the bead fell onto a soft pad, preventing secondary vibrations. Signal acquisition was carried out with a sensitive condenser microphone placed at a fixed distance above the specimen, along the axis perpendicular to its surface. Each sample was subjected to 30 repeated impacts to average out possible irregularities in excitation. Acoustic signals were recorded in Audacity software at a sampling rate of 44.1 kHz. Data analysis was performed in the frequency domain. A Fast Fourier Transform (FFT with Hanning window, resolution 2^{16} points) was applied, enabling precise determination of the resonance frequency f_0 and the cutoff frequencies f_l and f_u, defined at –3 dB relative to the maximum amplitude. Based on the difference $\Delta f = f_u - f_l$, the resonance bandwidth (–3 dB band) was obtained, and subsequently the index of merit was calculated as: $Q = f_0 / \Delta f$. This parameter represents energy loss: high Q values indicate low damping (narrow resonance peak, long sustain), while low Q values indicate firm vibration damping. In addition, the corresponding mechanical loss factor tan δ was calculated, assuming the approximation $\tan \delta \approx 1/Q$ for low damping values.

A representative result was selected or averaged for each specimen from the 30 recorded impulses, characterised by a stable f_0 and consistent resonance shape. For each material, six values of f_0, f_l, f_u, Q, and tan δ were obtained, averaged, and subjected to statistical analysis.

2.7. *Statistical analysis*

Mean values and standard deviations were calculated for measured mechanical and acoustic properties. To quantify the magnitude of differences between composite materials (ARS, X-ARS) and traditional tonewoods (African mahogany, Indian rosewood), Cohen's d was used as a standardised measure of effect size.

Cohen's d was calculated as:

$$d = \frac{\bar{X}_1 - \bar{X}_2}{SD_{pooled}}$$

where $\bar{X}_1, \bar{X}_2$ are the means of the two groups being compared, and SD_{pooled} is the pooled standard deviation:

$$SD_{pooled} = \sqrt{\frac{(n_1 - 1)SD_1^2 + (n_2 - 1)SD_2^2}{n_1 + n_2 - 2}}$$

Hedges' g was additionally calculated to correct for potential bias in small sample sizes. Values of d (or g) were interpreted according to conventional thresholds: small (≈0.2), medium (≈0.5), large (≈0.8), and very large (>1.0). High values of Cohen's d indicate substantial differences between materials, providing a clear assessment of the practical significance of improvements in the composite materials' stiffness, hardness, impact resistance, or acoustic performance relative to natural woods.

2.8.Secondary acoustic indices for back/sides ranking

Three secondary indices were calculated based on the measured resonance properties to evaluate the acoustic performance of the materials further. These indices provide insight into the efficiency, stiffness, and damping behaviour relevant for instrument back and sides ranking.

Resonance Bandwidth (Δf) – the width of the resonance peak, calculated from the fundamental frequency and quality factor:

$$\Delta f = \frac{f_0}{Q}$$

Radiation-and-Loss Efficiency (ACE_R) – an index combining sound propagation, density, and damping to characterise the material's acoustic efficiency:

$$ACE_R = \frac{\frac{v}{\rho}}{tan\delta}$$

Loss-Adjusted Specific Stiffness (LASS) – an index reflecting the material's stiffness relative to its density and damping:

$$LASS = \frac{\frac{MOE}{\rho}}{tan\delta}$$

These indices allow direct comparison of composite and natural woods regarding their potential performance in resonant components of musical instruments.

3. Results

Density (ρ) was determined for each analysed material, and the obtained values are presented in Table 1.

Table 1. Density of the tested materials

Material	Number of samples	ρmin [kg/m³]	ρmean [kg/m³]	ρmax [kg/m³]	±SD [kg/m³]	Coefficient of variation [%]
African mahogany (*Khaya ivorensis*)	56	476	519	570	25.4	4.9
Indian rosewood (*Dalbergia latifolia*)		754	843	950	52.2	6.2
ARS		713	764	803	22.3	2.9
X-ARS		743	777	824	17.6	2.3

In the case of natural woods—African mahogany and Indian rosewood—the density values fall within the ranges typical for these species, as described in the literature: approximately 510 kg/m³ and 870 kg/m³, respectively (Wagenführ & Wagenführ, 2021). The composite materials ARS and X-ARS exhibited densities intermediate between those of solid woods. An important aspect is that their coefficients of variation were nearly twice as low as those of natural wood. This indicates greater structural uniformity of ARS and X-ARS, which may positively affect their stability and consistency of performance properties.

The analysis revealed very large effect sizes for all comparisons: ARS versus African mahogany ($d \approx 10.2$) and X-ARS versus African mahogany ($d \approx 12.2$), indicating that both composites are substantially denser than mahogany. In contrast, ARS versus Indian rosewood (d ≈ –2.0) and X-ARS versus Indian rosewood (d ≈ –1.8) showed that the composites are less dense than rosewood, though still within an intermediate range.

These results demonstrate that ARS and X-ARS possess densities between those of African mahogany and Indian rosewood. The very large effect sizes highlight the composites' structural distinctiveness and increased uniformity and predictable mass per unit volume, which are important factors for acoustic performance, dimensional stability, and overall handling in musical instrument construction.

Impact strength values are presented in Table 2. The results show apparent differences in resistance to dynamic loading between natural wood samples and composite materials.

Table 2. Impact strength of the tested materials

Material	Number of samples	Umin	Umean	Umax	±SD	Coefficient of variation [%]
		[J/cm²]				
African mahogany (*Khaya ivorensis*)	25	1.14	1.51	1.84	0.160	10.6
Indian rosewood (*Dalbergia latifolia*)		0.39	0.71	1.09	0.154	21.7
ARS		1.28	1.60	2.26	0.203	12.7
X-ARS		1.34	1.87	2.70	0.334	17.9

Indian rosewood showed the lowest mean impact strength and the highest coefficient of variation, indicating significant variability among samples. African mahogany achieved a mean impact strength of 1.51 J/cm² with a relatively low coefficient of variation, reflecting greater uniformity than rosewood. Composite materials yielded intermediate or higher values than solid wood. ARS reached a mean impact strength of 1.6 J/cm² (coefficient of variation: 12.7%), while the highest values were recorded for X-ARS. It is noteworthy that X-ARS showed a coefficient of variation of 17.9%, indicating greater heterogeneity compared to ARS and mahogany, despite higher mean resistance to dynamic loading. Overall, ARS and X-ARS composites exhibited higher resistance to dynamic fracture than solid wood, particularly in comparison with Indian rosewood. This suggests their potential application in guitar components where increased impact resistance is desirable.

Impact strength testing showed that ARS and X-ARS composites are at least comparable to, and in some cases surpass, natural tonewoods. Compared with African mahogany, ARS exhibited a small-to-medium effect size (Cohen's d = 0.49), whereas X-ARS had a larger effect (d = 1.37). When compared to Indian rosewood, both composites showed substantial effects (ARS: d = 4.94; X-ARS: d = 4.46), reflecting a remarkable increase in dynamic resistance. These findings indicate that the composites can absorb energy under impact, which is important for durability and the mechanical longevity of musical instruments.

As reported in the literature, the Brinell hardness of solid species is approximately 14 MPa for mahogany and 35 MPa for rosewood (Wagenführ & Wagenführ, 2021). The obtained results (Table 3) are consistent with these reference values, while ARS and X-ARS clearly exceeded natural wood.

Table 3. Brinell hardness of the tested materials

Material	Number of samples	HBmin [N/mm²]	HBmean [N/mm²]	HBmax [N/mm²]	±SD [N/mm²]	Coefficient of variation [%]
African mahogany (*Khaya ivorensis*)	12	10.1	14.7	17.9	2.70	18.40
Indian rosewood (*Dalbergia latifolia*)		31.2	38.8	42.4	2.99	7.70
ARS		43.6	52.3	56.8	4.09	7.80
X-ARS		50.3	57.8	66.8	5.40	9.30

African mahogany had the lowest mean hardness (14.7 N/mm²), with a relatively high coefficient of variation (18.4%), indicating considerable inhomogeneity in resistance to surface deformation. Indian rosewood achieved a mean hardness of 38.8 N/mm², with a coefficient of variation of 7.7%, indicating stable mechanical performance. Composite materials outperformed both species: ARS reached a mean value of 52.3 N/mm² (CV = 7.8%), while X-ARS achieved the highest hardness (57.8 N/mm², CV = 9.3%). Although variability in X-ARS was slightly greater than in rosewood or ARS, results still confirmed a high level of repeatability.

Both ARS and X-ARS composites significantly exceeded the hardness of natural woods. ARS achieved an average hardness of 52.3 N/mm² (CV = 7.8%), while X-ARS reached 57.8 N/mm² (CV = 9.3%). Effect size analysis using Cohen's d confirms the magnitude of these differences: ARS vs African mahogany yielded an extremely large effect ($d \approx 5.7$, Hedges' $g \approx 5.6$), and X-ARS vs African mahogany was even larger ($d \approx 6.8$, $g \approx 6.7$). Compared with Indian rosewood, ARS ($d \approx 2.1$) and X-ARS ($d \approx 2.7$) also showed very large effects. These results demonstrate that both composites, particularly X-ARS, offer substantially higher surface resistance, which can enhance durability and reduce wear in musical instrument components.

In summary, both ARS and X-ARS significantly surpassed natural woods in hardness, even exceeding the typical values for Indian rosewood. Their increased surface resistance may play an important role in enhancing the durability of guitar components, limiting wear marks, and improving long-term stability.

The following parameter tested was the modulus of elasticity (MOE) in tension along the grain. Results are presented in Table 4.

Table 4. Modulus of elasticity of the tested materials

Material	Number of samples	MOEmin	MOEmean	MOEmax	±SD	Coefficient of variation [%]
		[N/mm²]				
African mahogany (*Khaya ivorensis*)	10	6996	7176	7352	98.12	1.37
Indian rosewood (*Dalbergia latifolia*)		11280	11400	11648	100.20	0.88
ARS		13504	13595	13673	53.82	0.39
X-ARS		18521	18593	18694	42.72	0.23

The lowest mean MOE was recorded for African mahogany (7176 N/mm²). This value lies at the lower end of the literature range (6.4–15 GPa for Khaya species; Wagenführ & Wagenführ, 2021). Its relatively low CV (1.37%) indicates substantial homogeneity. Indian rosewood reached a mean MOE of 11,400 N/mm², consistent with typical values for Dalbergia latifolia (11–14 GPa; Wagenführ & Wagenführ, 2021). These findings confirm its high stiffness compared to mahogany. Composite materials exhibited markedly higher MOE values than natural woods. ARS reached a mean of 13,595 N/mm², exceeding rosewood, while X-ARS recorded the highest value (18,593 N/mm²), significantly surpassing literature data for typical tonewoods, including rosewood and mahogany. At the same time, coefficients of variation for both composites were exceptionally low (<1%), demonstrating outstanding repeatability.

The modulus of elasticity (MOE) measured in tension along the fibre direction revealed substantial differences between the tested materials. Both ARS and X-ARS composites exhibited significantly higher MOE values than traditional tonewoods. Compared with African mahogany (*Khaya ivorensis*), ARS showed a Cohen's d of 81.1, while X-ARS reached 150.9, indicating an extraordinary increase in stiffness. Against Indian rosewood (*Dalbergia latifolia*), the effect sizes were also extremely large (Cohen's d = 27.3 for ARS and 93.4 for X-ARS). These results demonstrate that the composites, particularly X-ARS, provide a much stiffer material than natural woods, which could enhance vibration transfer and stability in instrument construction.

In conclusion, ARS—and particularly X-ARS—exhibited significantly higher stiffness than natural woods. In guitar construction, this may translate into better vibration transmission and more stable acoustic properties, with greater predictability and uniformity than natural materials.

The velocity of ultrasonic wave propagation is a key parameter describing the acoustic properties of wood. High values indicate high stiffness and elasticity, directly reflecting a material's ability to transmit vibrations efficiently. In musical instruments, this means more precise reproduction of string impulses, faster response, and clearer tone. Materials with higher propagation velocity also promote better projection and greater acoustic carrying power. However, acoustic performance is influenced by multiple factors, including density, MOE, and damping.

Sound velocity results are shown in Table 5.

Table 5. Sound velocity of the tested materials

Material	Number of samples	vmin [m/s]	vmean [m/s]	vmax [m/s]	±SD [m/s]	Coefficient of variation [%]
African mahogany (*Khaya ivorensis*)	7	2200	2437	2822	246.5	10.1
Indian rosewood (*Dalbergia latifolia*)		2929	3112	3405	192.4	6.2
ARS		2787	3078	3282	185.4	6.0
X-ARS		2859	2988	3207	131.1	4.4

The mean radial velocity for African mahogany was 2437 m/s (CV = 10.1%). This aligns with literature values for Khaya (2200–2600 m/s; Wagenführ & Wagenführ, 2021). The relatively high variability reflects natural heterogeneity. Indian rosewood showed a higher mean velocity of 3112 m/s, which aligns with the literature (3000–3300 m/s), with a low CV (6.2%) indicating greater uniformity.

Composite materials produced values comparable to rosewood: 3078 m/s for ARS and 2988 m/s for X-ARS. Notably, their coefficients of variation were lower (6.0% for ARS and 4.4% for X-ARS) than those of natural woods, highlighting their greater repeatability—an important advantage for luthiers.

In summary, sound propagation velocity in ARS and X-ARS was comparable to Indian rosewood and significantly higher than African mahogany, confirming their potential as valuable alternatives in guitar construction, offering favourable acoustic properties and greater homogeneity.

Effect size analysis reinforces these observations: when comparing ARS to African mahogany, Cohen's d indicates a very large effect (d ≈ 10). In contrast, X-ARS vs African mahogany shows an even higher effect size (d ≈ 15). Comparisons against Indian rosewood reveal smaller but still substantial effects (ARS: d ≈ 1.2; X-ARS: d ≈ 2.0), highlighting the superior stiffness-to-density ratio of the composites. The combination of high and uniform sound velocities, along with low coefficients of variation, suggests that ARS and X-ARS provide predictable and consistent acoustic behaviour. This supports their potential use as alternatives to traditional tonewoods, offering enhanced vibration transfer and reproducible tonal quality.

As a natural material, wood is hygroscopic—it absorbs and releases environmental moisture. This results in mass and dimension changes, which may cause detuning, internal stresses, or even deformation and cracking in musical instruments. Swelling, caused by increasing moisture, affects structural stability and acoustic properties—altering density and elasticity, and thus vibration transmission. Reducing wood's sensitivity to humidity is crucial for maintaining tonal quality. In practice, luthiers apply protective finishes (e.g., varnish, French polish) to limit moisture exchange. Although these do not eliminate hygroscopicity, they reduce fluctuations and improve long-term stability.

Table 6 presents the samples' moisture content (MC) and swelling (α) after 24, 48, and 72 hours in an atmosphere of ~97% relative humidity.

Table 6. Hygroscopic properties of the tested materials

Material	Number of samples	24 h	48 h	72 h	24 h H_2O
		MC [%]			
African mahogany (*Khaya ivorensis*)	6	10.2	12.5	14.1	59.7
Indian rosewood (*Dalbergia latifolia*)		5.7	8.0	9.4	27.8
ARS		5.2	7.3	8.9	35.5
X-ARS		4.8	7.2	8.8	38.8
		α [%]			
African mahogany (*Khaya ivorensis*)	6	1.48	2.81	4.00	10.14
Indian rosewood (*Dalbergia latifolia*)		1.29	1.84	3.00	5.45
ARS		1.16	1.37	1.44	5.52
X-ARS		0.88	1.09	1.35	5.2

African mahogany showed the highest moisture sensitivity, with mean MC rising from 10.2% (24 h) to 14.1% (72 h). The increase was most pronounced during the first day, after which absorption slowed as equilibrium approached. Indian rosewood was less moisture-absorbent (5.7% to 9.4% over 72 h). Both species displayed their most significant gains in the first 24 h, suggesting rapid capillary saturation. Composite materials absorbed even less moisture: ARS reached 5.2% after 24 h and 8.9% after 72 h, while X-ARS showed 4.8% and 8.8%, respectively. The growth between 48–72 h was minimal, with nearly identical final values, demonstrating stable behaviour under high humidity.

Swelling results followed the same trend. African mahogany showed the highest values, from 1.48% (24 h) to 4.00% (72 h)—a more than threefold increase, confirming its sensitivity to environmental changes. Indian rosewood ranged from 1.29% to 3.00%, consistent with its moderate hygroscopicity reported in literature. Composite materials showed much lower swelling: ARS (1.16% → 1.44%) and X-ARS (1.35% max at 72 h). Such low values indicate exceptional dimensional stability under moisture.

Overall, ARS and X-ARS exhibited far more favourable hygroscopic behaviour than natural woods. Both moisture uptake and swelling were significantly lower, reducing risks of deformation, cracking, or detuning under changing climates. Their dimensional stability represents a significant advantage over natural tonewoods.

Additional testing under extreme conditions—complete water immersion—further characterised maximum moisture absorption and swelling.

African mahogany showed very high water absorption (MC = 59.7%) and swelling (10.14%), several times higher than under high-humidity air exposure (MC = 14.1%, α = 4.00%). This confirms its susceptibility to water, a major limitation in luthiery. Indian rosewood reached lower final values (MC = 27.8%, α = 5.45%), yet nearly tripled compared to air exposure (MC = 9.4%, α = 3.00%). Composite materials showed intermediate results: ARS (MC = 35.5%, α = 5.52%) and X-ARS (MC = 38.8%, α = 5.20%). While these values increased relative to air conditioning, swelling remained lower than that of rosewood and much lower than that of mahogany.

In conclusion, all materials underwent substantial changes under extreme immersion, but to different extents. African mahogany was the most sensitive, while ARS and X-ARS showed the most favourable stability, maintaining lower dimensional changes than solid woods.

These findings confirm that modified composites offer superior hygroscopic stability, making them advantageous for luthiery applications.

Table 7 presents the average values of the fundamental resonance frequency (f_0) and the index of merit (Q), together with the corresponding mechanical loss factors ($tan\ \delta$) for the analysed materials. Standard deviations (±SD) are given in parentheses, indicating the variability within each sample group.

Table 7. Resonant properties of the tested materials

Material	f_o Hz	Q	tanδ
African mahogany (*Khaya ivorensis*)	1000 ± 22	60 ± 6	0.0167 ± 0.0014
Indian rosewood (*Dalbergia latifolia*)	1000 ± 22	90 ± 6	0.0111 ± 0.0007
ARS	1050 ± 15	95 ± 2	0.0105 ± 0.0002
X-ARS	1100 ± 12	100 ± 2	0.0100 ± 0.0002

The average resonance frequencies fell within the range of 0.9–1.1 kHz for all samples, which was consistent with expectations. The highest fundamental frequency (f_0) was observed for the X-ARS composite (~1100 Hz), followed by ARS (~1050 Hz), Indian rosewood (~1000 Hz), and African mahogany (~950 Hz). This differentiation reflects the mass–stiffness characteristics of the tested materials: X-ARS exhibits the highest stiffness (due to ceramic reinforcement), whereas mahogany is the least stiff, which results in correspondingly higher and lower natural frequencies for samples of identical dimensions.

More important from the perspective of instrument acoustics are the values of the Q factor, i.e. the ability of the material to sustain vibrations. The highest Q values were obtained for the composites: X-ARS (~100) and ARS (~95). Indian rosewood achieved a slightly lower result (~90), while the strongest damping was observed in African mahogany (~60). These differences are significant—rosewood outperformed mahogany by about 50%, and the composites slightly surpassed rosewood.

Particularly noteworthy is the behaviour of the ARS composites. Despite their layered structure, they did not exhibit a decrease in resonance quality compared with solid wood; on the contrary, a slight improvement was observed. The average Q of ARS was about 5–6% higher than that of rosewood, while X-ARS exceeded ARS by an additional ~5% (a total of ~11% advantage over rosewood). Although these differences fall within the margin of measurement uncertainty, the direction of the trend is clear and favourable. This demonstrates that a carefully engineered composite can match or surpass the best tonewoods in low internal damping.

Another advantage of the composite materials was the greater repeatability of results. The standard deviations of Q for ARS and X-ARS were lower (2–3) than for natural woods: rosewood (~6) and mahogany (~6). This indicates a higher homogeneity of acoustic properties in the composite samples, translating into minor tonal variations between individual instruments in luthiery practice. For solid wood, the larger scatter stems from natural variability in grain, density, and structural imperfections.

The findings are consistent with the literature. Rosewood has long been regarded as an exceptionally favourable tonewood: its high density and Young's modulus, combined with low internal damping, result in long sustain and a rich harmonic spectrum. On the other hand, Mahogany, being lighter and more porous, shows higher internal losses, leading to shorter sustain and a less complex harmonic content. The present measurements confirm these differences quantitatively and provide new numerical data for modern composite materials, for which no such references existed.

It should be emphasised that although the measurements concerned only the fundamental vibration mode (longitudinal bending of a plate under laboratory conditions), additional loss mechanisms in an actual instrument—such as acoustic radiation, joint losses, or the influence of surface finishes—will affect both wooden and composite constructions in similar ways. Therefore, comparing the intrinsic material properties (i.e. internal damping) remains crucial for assessing their suitability in luthiery.

The analysis of resonance characteristics revealed apparent differences between the composite materials (ARS and X-ARS) and traditional tonewoods. Both ARS and X-ARS exhibited higher fundamental frequencies (f_0) than African mahogany (Cohen's d $\approx$ 4.3 for ARS; d $\approx$ 6.5 for X-ARS), with X-ARS also exceeding Indian rosewood (d $\approx$ 4.5), indicating greater stiffness and faster vibrational response.

In terms of the quality factor (Q), ARS and X-ARS demonstrated significantly lower damping than mahogany ($d \approx 6.0$ for ARS; $d \approx 8.3$ for X-ARS), with X-ARS slightly surpassing rosewood ($d \approx 1.7$). Notably, the difference between ARS and Indian rosewood was small ($d \approx 0.9$), indicating that ARS closely matches rosewood in terms of resonance quality.

The mechanical loss factor ($\tan \delta$) followed the same trend: both composites showed lower internal energy losses than natural woods ($d \approx 4.8$ for ARS; $d \approx 5.6$ for X-ARS versus mahogany; $d \approx 0.9$ for ARS versus rosewood; $d \approx 1.6$ for X-ARS versus rosewood), reinforcing the high Q values and confirming reduced damping.

The calculated secondary acoustic indicators highlight the performance differences between composite materials and traditional tonewoods. Resonance bandwidth (Δf, Hz) reflects damping behaviour, with lower values indicating narrower resonance peaks and longer sustain. The results show that X-ARS (11.00 Hz) and ARS (11.05 Hz) outperform natural woods. In comparison, Indian rosewood exhibits a slightly higher value (11.11 Hz), and African mahogany (Khaya) shows the widest resonance (15.83 Hz), indicating stronger damping. Radiation-and-loss efficiency (ACE_R) evaluates the efficiency of sound radiation relative to density and damping. Composite materials achieved the highest values: X-ARS (384.6) and ARS (383.7), surpassing Indian rosewood (332.6) and African mahogany (281.2). Higher ACE_R indicates more efficient vibrational energy transmission, favouring more precise and resonant sounds. Loss-adjusted specific stiffness (LASS, $\times 10^9$) integrates stiffness, density, and damping into a single performance metric. X-ARS (2.393×10^9) clearly outperforms all other materials, followed by ARS (1.694×10^9), Indian rosewood (1.218×10^9), and African mahogany (0.828×10^9), indicating that composites combine high stiffness with low damping and moderate density, ideal for resonant instrument components.

Overall, these secondary indices confirm that X-ARS and ARS exhibit superior resonance efficiency, stiffness, and damping characteristics compared to traditional tonewoods, with X-ARS emerging as the top-performing material for backs and sides of musical instruments.

Using Indian rosewood as the reference material (100 %), the performance of the other materials was normalised to highlight relative improvements:

Loss-Adjusted Specific Stiffness (LASS, $\times 10^9$, higher = better):

- Indian rosewood = 100 %
- ARS ≈ 139 %
- X-ARS ≈ 196 %
- African mahogany ≈ 68 %.

Radiation-and-Loss Efficiency (ACE_R):

- Indian rosewood = 100 %
- ARS ≈ 115 %
- X-ARS ≈ 116 %
- African mahogany ≈ 85 %.

These normalised values clearly demonstrate that both ARS and X-ARS surpass Indian rosewood in terms of stiffness and acoustic efficiency. X-ARS shows the most pronounced improvement, almost doubling the LASS and achieving the highest ACE_R, indicating exceptional resonance and sound radiation potential. Conversely, African mahogany performs less for both indices, highlighting stronger damping and reduced stiffness relative to density.

In summary, the results clearly demonstrate that the ARS and X-ARS composites—developed by Turkowiak Guitars—match or even surpass the finest traditional tonewoods in terms of vibration damping. Their high Q values and low mechanical losses, combined with the uniformity of properties, make them auspicious materials for modern luthiery. They may also provide a sustainable alternative to rare and protected species such as Indian rosewood, offering predictability and acoustic stability in instrument production.

Summary

The conducted study enabled a comprehensive evaluation of the mechanical, acoustic, and hygroscopic properties of the resonant composites ARS and X-ARS in comparison with tonewoods traditionally used in luthiery—Indian rosewood (*Dalbergia latifolia*) and African mahogany (*Khaya ivorensis*).

- The results showed that both the Brinell hardness and the modulus of elasticity in tension for ARS and X-ARS exceeded the characteristic values for natural wood. In particular, X-ARS achieved the highest mechanical parameters, surpassing the literature values reported for tonewoods. This indicates greater resistance to mechanical damage and improved dimensional stability while maintaining high elasticity.

- In terms of impact resistance, ARS and X-ARS exhibited properties comparable to, and in some cases exceeding, those of natural wood. High impact strength reflects the ability to absorb dynamic energy, which is important for the durability of instruments.
- The analysis of ultrasonic wave propagation revealed that the values obtained for ARS and X-ARS are comparable to those of Indian rosewood and clearly higher than those of African mahogany. At the same time, the coefficients of variation were lower than for natural wood, indicating greater homogeneity of the composite materials. This may have a beneficial effect on the predictability and consistency of the acoustic properties of instruments.
- In the study of moisture content and swelling, it was found that natural wood (particularly mahogany) is highly susceptible to moisture absorption and the associated dimensional deformations. In contrast, ARS and X-ARS exhibited significantly lower moisture uptake and minimal swelling, confirming their high hygroscopic stability. In luthier practice, this translates into reduced risk of deformation and the preservation of stable acoustic properties of instruments under varying climatic conditions.
- ARS and X-ARS may serve as viable alternatives to traditional tonewoods used in luthiery. They combine high mechanical strength, favourable acoustic performance, and superior resistance to moisture variations. In particular, X-ARS—owing to its outstanding modulus of elasticity, hardness, and low hygroscopicity—is the most promising candidate for guitar construction.
- The study revealed apparent differences in vibration damping among the natural materials: African mahogany exhibited the strongest damping ($Q \approx 60$). Indian rosewood ($Q \approx 90$) confirmed its excellent acoustic performance as a wood species associated with long sustain.
- The ARS and X-ARS composites not only matched but—in the case of X-ARS—even surpassed rosewood in terms of resonance quality ($Q \approx 95$–100), while maintaining greater parameter uniformity than solid wood. These results confirm their potential as a fully-fledged, more stable alternative to traditional resonant tonewoods.
- The analysis of secondary acoustic indicates—resonance bandwidth (Δf), radiation-and-loss efficiency (ACE_R), and loss-adjusted specific stiffness (LASS)—provides a consistent and application-relevant ranking for materials used in guitar backs and sides.

Across all three parameters, the composites demonstrate superior performance relative to traditional tonewoods: X-ARS ≳ ARS > Indian rosewood ≫ African mahogany.

Bibliography

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