Mechanical Properties Assessment of Indigenous Timber Wood Species in Southeastern Nigeria

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Abstract

We examined the mechanical properties of four native wood species in southeastern Nigeria, including *Alstonia congensis*, *Ceiba pentandra*, *Milicia excelsa*, and *Terminalia superba*. The samples were milled and trimmed to standard sizes and subjected to a three-point bending test. The mechanical properties modulus of rupture (MOR) and compression parallel to grain were tested using the Universal Testing Machine, with machine no: 0500-10080. We computed the force at the point of failure, modulus of elasticity and compression parallel to the grain. Here show that the samples from the selected indigenous timber species had significant variations in the mechanical properties, with the highest MOR being 94.185N/mm^2, MOE 3553.098N/mm^2 and compressive strength being 54.224N/mm^2. The flexural and compression strength of *Terminalia superba* wood material was significantly higher relative to *Milicia excelsa*, *Alstonia congensis* and *Ceiba pentandra*. Our findings provide valuable information on the mechanical properties of these species sourced from southeastern Nigeria, which can be used to assess their suitability for a variety of applications.

Introduction

In recent years, there has been a growing concern about the impact of human activities on the environment (FAO, 2016). One of the major areas of concern is the depletion of natural resources, particularly timber wood species. In Umuahia, Abia State, several indigenous timber wood species are used for various purposes. Timber wood has played a significant role in the history of Umuahia, Abia State, Nigeria. For centuries, the people of this region have relied on timber wood for various purposes, including construction, furniture, and other household items. The use of indigenous timber wood species in the region has been particularly important due to their suitability for the local environment and availability.

Nigeria's demand for timber is high due to its importance in the construction industry (Ogunleye et al., 2020). However, the mechanical properties of Nigerian indigenous timber species in southeastern Nigeria are poorly documented, limiting their utilisation and value. Understanding the mechanical properties of these species is essential for the optimal utilisation and management of the resource. In this study, we assessed the mechanical properties of Nigerian indigenous timber species and their implications for the timber industry and biodiversity conservation. Specifically, we determined the bending strength (modulus of rupture, modulus of elasticity) and compressive strength of four indigenous timber species *Milicia excelsa* (Iroko), *Terminalia superba* (Afara), *Ceiba pentandra* (Kapok tree), and *Alstonia congensis* (Egbu) sourced from tropical rainforest ecosystem Umuahia Abia State, Nigeria.

These selected timber species are highly valued for their beauty and versatility, but research on their physical and mechanical properties is limited (Afolayan et al., 2019; Ogunleye et al., 2020). Our findings contribute to the knowledge base on the mechanical properties of Nigerian timber species for the development of mathematical models and simulations that provide insight into the behaviour of wood materials under different conditions and inform decision-making in the timber industry. Furthermore, the findings from our study have implications for biodiversity conservation as the knowledge of mechanical properties can inform sustainable harvesting practices (Akindele et al., 2021).

Materials and Methods

Wood materials of *Milicia excelsa, Alstonia congensis, Terminalia superba* and *Ceiba pentandra* with no insect, termite or rot were sourced from the Umuahia timber sawmill, Abia State (5.5092° N, 7.5333° E). Umuahia timber sawmill comprises wood processing areas and timber wood market outlets.

Four wood samples of each selected indigenous timber species were collected from the sawmill and named systematically. Each test carried out would represent each timber species from the sawmill considered. For instance, a timber species, namely "Milicia", which was sourced, would be named with the code: $\mathbf{M_1}$ while the subscript "1" represents the sample number. For the project, 4 x 6 x 10 ft (100 mm x 150 mm x 3000 mm) sawn timber logs were acquired from the sawmill. For the compression parallel to grain test and the modulus of rupture test, respectively, test pieces were sawn into different specimen sizes (20mm x 20mm x 280mm and 20mm x 20mm x 60mm), as required by BS 373 and the National Centre for Agricultural Mechanization (NCAM) for determining the mechanical properties of structural timbers. The wood materials were dried at 40°C for one hour using the oven in NCAM.

Two samples of dimension 20mm x 20mm x 280mm were used for each timber species’ bending strength and compression strength parallel to grain tests. Three-point bending strength tests for each of the selected timber species using Universal Testing Machine (UTM). The ends of the rectangular test piece were made to be smooth, parallel, and perpendicular to the axis for the testing machines to obtain an accurate result. The failure load for each beam was measured and the bending strength computed based on the equation:

$$f_m = \frac{aF_{max}}{2W} \dots\dots\dots\dots\dots\dots\dots\dots\dots (1)$$

Where a is the distance between the loading position and the nearest support (mm), F_{max} is the maximum load (N), W is the section modulus (mm3), and f_m is the bending strength (N/mm^2).

The load was applied continuously with head movement to maximize force. The support points were spaced 28 cm apart, and the loading rate was 6.604 mm per minute. The average time to failure and the time to failure of each test piece were reported.

For the compression strength test, the load was applied at a 0.635mm/min till maximum load was reached. The time to failure for each test piece was recorded and the compressive strength computed based on the equation:

$$fc_1 0 = \frac{F_{max}}{A}$$

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The bending stress parallel to the grain was determined using the failure stresses from tests (Ozelton and Baird, 1981).

$$f_{bpar=f_m-\frac{2.33\sigma}{2.25}}$$

3

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Where fb_{par} = basic bending stress parallel to the grain

f_m = mean value of the failure stress

σ = standard deviation of the failure stresses

The compressive stress parallel to the grain for the species was computed using the failure stresses based on the equation:

$$C_{bp} = f_m - \frac{2.33\sigma}{1.4}$$

4

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The modulus of elasticity was computed following the method described in Adefemi (2015) based on the equation:

$$E_N = E_{mean} - \frac{2.33\sigma}{\sqrt{N}}(E\_N = E\_mean - 2.33\sigma)\ /\ \sqrt{N}\ldots\ldots\ldots\ldots(5)$$

Where E_N is the minimum statistical value of E appropriate to the number of pieces N acting together (where N = 1, E_N becomes the value for E_{mean}), and σ is the standard deviation (Adefemi, 2015).

Results

The flexural strength of *Terminalia superba* (98.1 ± 14.6 N/mm^2) wood material was significantly higher relative to *Milicia excelsa* (85.4 ± 15.3 N/mm^2), *Alstonia congensis* (58.7 ± 7.4 N/mm^2) and *Ceiba pentandra* (32.4 ± 3.0 N/mm^2) based on the transverse rupture strength measurement ($F_{3,4}$ = 13.4, P = 0.0148, R^2 = 0.91; Table 1, Fig. 1). There was a significant difference in the flexural strength of wood materials sourced from *Terminalia superba* compared to *Milicia excelsa, Alstonia congensis* and *Ceiba pentandra* at yield point ($F_{3,4}$ = 10.11, P = 0.0244, R^2 = 0.88), peak point ($F_{3,4}$ = 13.4, P = 0.0148, R^2 = 0.91) and breakpoint ($F_{3,4}$ = 17.23, P = 0.0094, R^2 = 0.92). The wood material from *Ceiba pentandra* had the least bending strength at the yield point. Compared to *Ceiba pentandra*, the bending strength of *Terminalia superba* at the yield point was 64.733N/mm^2 higher, followed by *Milicia excelsa (*55.991733N/mm^2) but least in *Alstonia congensis* (25.252 N/mm^2) (Table 1, Fig. 1). The bending strength of *Alstonia congensis* (54.70 ± 6.1 N/mm^2), though higher than that of *Ceiba pentandra* (29.4 ± 4.3 N/mm^2), the difference was not statistically significant (P = 0.1238). At the peak, ($F_{3,4}$ = 13.4, P = 0.0148, R^2 = 0.91) and breakpoint ($F_{3,4}$ = 17.23, P = 0.0094, R^2 = 0.93), the bending strength of wood material sourced from *Terminalia superba* was significantly higher relative to *Milicia excelsa, Alstonia congensis* and *Ceiba pentandra* (Table 1).

A significant difference in the bending modulus of the wood samples was observed in the flexural test, with *Terminalia superba* (9490.3 ± 593.6N/mm^2) showing the greatest resistance to bending (stiffness), followed by *Milicia excelsa* (9429.1 ± 1188.1N/mm^2) and *Alstonia congensis* (6318.5 ± 159 N/mm^2), but least in *Ceiba pentandra* (3553.2 ± 204.9 N/mm^2). *Terminalia superba* wood material showed a higher elongation at yield and break points, while *Ceiba pentandra* was most elongated at the breakpoint. However, the differences in the deformation of the wood materials were not statistically significant at yield ($F_{3,4}$ = 0.240, P = 0.8644, R^2 = 0.15), peak ($F_{3,4}$ = 3.171, P = 0.147, R^2 = 0.70) nor at the breakpoint ($F_{3,4}$ = 1.742, P = 0.2964, R^2 = 0.57).

The force required to change the wood materials from elastic deformation to plastic deformation (force at yield; $F_{3,4}$ = 10.11, P = 0.0244, R^2 = 0.88), force at peak ($F_{3,4}$ = 13.4, P = 0.0148, R^2 = 0.91) and the force required to cause a rupture in the wood material (force at the break; $F_{3,4}$ = 17.23, P = 0.0094, R^2 = 0.92) were significantly greatest in *Terminalia superba*, but least in *Ceiba pentandra* (Table 1, Fig. 1). The maximum amount of energy required to cause a plastic deformation (energy to peak; $F_{3,4}$ = 8.849, P = 0.0307, R^2 = 0.87) and the energy required to break (energy to break; $F_{3,4}$ = 6.602, P = 0.049, R^2 = 0.83) the wood samples were significantly higher in *Terminalia superba*, but least *Ceiba pentandra* (Table 1). Though higher energy to yield was observed in wood samples of *Terminalia superba* (8.3 ± 4.5N.m), followed by *Milicia excelsa* (6.6 ± 1.7N.m) and *Alstonia congensis* (4.3 ± 0.7 N.m), compared to *Ceiba pentandra* (2.2 ± 0.4N.m), the differences were not statistically significant ($F_{3,4}$ = 2.331, P = 0.2157, R^2 = 0.63). The 3-point flexural strength test resulted in changes in the volume of the wood materials sourced from the *Terminalia superba*, *Milicia excelsa*, *Alstonia congensis* and *Ceiba pentandra*. Still, the differences were not statistically significant at yield ($F_{3,4}$ = 0.2404, P = 0.8648, R^2 = 0.15), peak ($F_{3,4}$ = 3.17, P = 0.1471, R^2 = 0.70), nor breakpoint ($F_{3,4}$ = 1.741, P = 0.2965, R^2 = 0.56).

Compression strength (parallel to grain) of *Terminalia superba* (2276.7$\pm$493.95N/mm^2) wood materials was significantly higher relative to *Milicia excelsa* (137.001$\pm$380.430N/mm^2*), Alstonia congensis* (719.322$\pm$135.337N/mm^2*), Ceiba pentandra* (475.451$\pm$33.352N/mm^2) based on the young modulus ($F_{3, 4}$ = 12.71, P = 0.01637, R^2 =0.91; Table 2, Fig. 2). There was a significant difference in the compressive strength of wood materials sourced from *Terminalia superba* compared to *Milicia excelsa*, *Alstonia congensis* and *Ceiba pentandra* at stress yield ($F_{3,4}$ = 28.18, *P* = 0.0003, R^2 = 0.9548), stress peak point ($F_{3,4}$ = 27.71, *P* = 0.0038, R^2 = 0.9541) stress breakpoint ($F_{3,4}$ =7.447, *P* = 0.0409 R^2 = 0.8482). The wood material sourced from *Ceiba pentandra* had the least compression strength at the stress yield point; compared to *Ceiba pentandra*. The compressive strength of *Terminalia superba* stress yield point was 34.364N/mm^2, higher followed by *Milicia excelsa* 28.364N/mm^2 but least in *Alstonia congensis* 9.151N/mm^2 (Table 2). The compressive strength of *Alstonia congensis* (21.3751±747N/mm^2) though higher than *Ceiba pentandra* (12.224±1.747N/mm^2). The difference was not statistically significant (*P* = 0.0038). At the stress peak ($F_{3,4}$ = 27.71, *P* = 0.0038, R^2 = 0.9541), breakpoint ($F_{3,4}$ = 27.7, *P* = 0.0038, R^2 = 0.95), the compressive strength of wood material sourced from *Terminalia superba* was significantly higher relative to *Milicia excelsa*, *Alstonia congensis* and *Ceiba pentandra* (Table 2, Fig. 2).

A significant difference in the young modulus of the wood samples was observed in the compression (parallel to grain) test with *Terminalia superba* (2276.664±493.954N/mm^2) showing the highest resistance to compression, followed by *Milicia excelsa* (1373.001±380.430N/mm^2) and *Alstonia congensis* (719.332±135.337N/mm^2) but least in *Ceiba pentandra* (475.451±33.352N/mm^2). *Terminalia superba* wood material showed a higher elongation at yield and break point, while *Ceiba pentandra* was the most elongated at the breakpoint. However, the differences in the deformations of the wood materials were not statistically significant at yield ($F_{3,4}$ = 0.767, *P* = 0.5692, R^2 = 0.3652), peak ($F_{3,4}$ = 4.023, *P* = 0.106, R^2 = 0.7511) nor at a breakpoint ($F_{3,4}$ = 3.136, *P* = 0.1492, R^2 = 0.7017). The force required to change the wood materials from elastic deformation to plastic deformation (force at yield; $F_{3,4}$ = 28.19, *P* = 0.0376, R^2 = 0.9548) force at peak ($F_{3,4}$ = 27.7, *P* = 0.0038, R^2 = 0.9541) and the force required to cause a failure (rupture) in the wood material (force at the break; $F_{3,4}$ = 7.447, *P* = 0.0409, R^2 = 0.8481) were significantly greatest in *Terminalia superba* but least in *Ceiba pentandra* (Table 2).

The maximum energy required to cause a plastic deformation (energy to peak; $F_{3,4}$ = 4.117, *P* = 0.1026, R^2 = 0.76) and the energy required to break (energy to break; $F_{3,4}$ = 7.25, *P* = 0.0428, R^2 = 0.85) wood samples were significantly higher in *Terminalia superba* but least in *Ceiba pentandra* (Table 2). Though higher energy to yield was observed in wood samples of *Terminalia superba* (19.857±4.345N.m), followed by *Milicia excelsa* (19.857±4.345N.m) and *Alstonia congensis* (8.745±1254N.m), compared to *Ceiba pentandra* (4.930±3.897N.m), the differences were not statistically significant ($F_{3,4}$= 9.375, *P* = 0.0278, R^2 = 0.875). The compression (parallel to grain) test resulted in changes in the volume of the wood materials sourced from the *Terminalia superba*, *Milicia excelsa*, *Alstonia congensis* and *Ceiba pentandra.* Still, the differences were not statistically significant at yield ($F_{3,4}$ = 0.767, *P* = 0.5692, R^2 = 0.3652), peak ($F_{3,4}$ = 4.023, *P* = 0.106, R^2 = 0.7511) nor for breakpoints ($F_{3,4}$= 3.136, *P* = 0.1492, R^2 = 0.7017).

Table 1: Bending strength measurements (mean ± standard deviation) of *Terminalia superba*, *Milicia excelsa*, *Alstonia congensis* and *Ceiba pentandra* wood materials.

Species	Bending Strength Yield (N/mm^2)	Bending Strength Peak (N/mm^2)	Bending Strength Break (N/mm^2)	Bending Modulus (N/mm^2)	Def @ Yield (mm^2)	Def @ Peak (mm^2)	Def @ Break (mm^2)	Force @ Yield (N)	Force @ Peak (N)	Force @ Break (N)	Energy to Yield (N.m)	Energy to Break (N.m)	Energy to Peak (N.m)	Transverse Rupture Strength (N/mm^2)	Strain Peak (%)	Strain Yield (%)	Strain Break (%)
Alstonia congensis	54.70±6.1	58.7±7.4	58.6±7.4	6318.5±159	7.3±0.4	8.9±0.9	8.9±0.9	1042±116	1118.5±140.7	1118±140.0	4.3±0.7	6.1±1.5	6.1±1.5	58.7±7.4	1.3±0.1	1.1±0.1	1.3±0.1
Ceiba pentandra	29.4±4.3	32.4±3.0	29.1±7.5	3553.2±204.9	6.9±0.6	9.2±0.9	9.5±1.2	561.0±82.0	616.5±57.3	555.0±142.8	2.2±0.4	3.6±0.4	3.5±0.3	32.4±3.0	1.4±0.1	1.1±0.1	1.4±0.2
Milicia excelsa	85.4±15.3	85.4±15.3	80.4±9.3	9429.1±1188.1	7.3±0.5	7.3±0.5	7.6±0.9	1627.5±292.0	1627.5±292.0	1531.5±177.5	6.6±1.7	7.1±2.2	6.6±1.7	85.4±15.3	1.1±0.1	1.1±0.1	1.2±0.1
Terminalia superba	94.2±20.1	98.1±14.6	98.1±14.6	9490.3±593.6	8.0±2.4	9.3±0.5	9.4±0.5	1794.0±383.3	1869.0±277.2	1868.5±277.9	8.3±4.5	10.4±1.5	10.4±1.5	98.1±14.6	1.4±0.1	1.2±0.4	1.4±0.1

Table 2: Compression parallel to grain strength values (mean ± standard deviation) of wood materials of *Terminalia superba*, *Milicia excelsa*, *Alstonia congensis* and *Ceiba pentandra*.

Species	Density (kg/m^3)	Force @ Peak (N)	Force @ Yield (N)	Force @ Break (N)	Def @ Peak (mm)	Def @ Yield (mm)	Def @ Break (mm)	Strain @ Peak (%)	Strain @ Yield (%)	Strain @ Break (%)	Stress @ Yeild (N/mm^2)	Stress @ Break (N/mm^2)	Stress @ Peak (N/mm^2)	Youngs Mudulus (N/mm^2)	Time to Failure	Energy to Peak (N.m)	Energy to Yield (N.m)	Energy to Break (N.m)	Force (N)
Astonia congensis	416.7	9068±1043.7	8550±698.6	8715.5±1125	2.8±0.1	2.2±0.2	4.3±0.5	4.7±0.1	3.7±0.3	7.2±0.8	21.4±1.7	21.8±2.8	22.7±2.6	719.3±135.3	405.6±46.4	14.1±1.4	8.7±1.3	27±2	8936.5±1018.9
Ceiba pentandra	416.7	5351.5±1190.1	4889.5±1726	4857.5±1207	2.7±0.4	2±0.7	4.1±1.2	4.6±0.6	3.4±1.2	6.8±1.9	12.2±4.3	12.1±3	13.4±3	475.5±33.4	384.1±110	8.4±2.9	4.9±3.9	15.7±8.8	5308.5±1132.1
Milicia excelsa	833.3	16310±2602.2	16235±2552.7	9694±3911.7	2.7±0.2	2.5±0.1	6.3±1.6	4.6±0.4	4.2±0.1	10.4±2.7	40.6±6.4	24.2±9.8	40.8±6.5	1373±380.4	590.8±153.7	23.4±7.7	19.9±4.3	70.1±18.9	16220±2503.2
Terminalia superba	916.7	18635±1336.4	18635±1336.4	16090±2305.2	2±0.4	2±0.4	2.9±0.8	3.3±0.6	3.3±0.6	4.9±1.3	46.6±3.3	40.2±5.8	46.6±3.3	2276.7±494	280.1±78.7	19.4±3.6	19.4±3.6	37±13	19380

Discussion

By using transverse rupture strength measurements at yield, peak and breakpoints, we show a significant variation in the flexural strength of timber materials sourced from the rainforest region of Nigeria, comprising *Terminalia superba*, *Milicia excelsa*, *Alstonia congensis*, and *Ceiba pentandra*. The modulus of rupture represents a member's maximum load-carrying capacity in bending. It is related to the greatest moment borne by the wood materials sourced from the four timber species. The results suggest that *Terminalia superba* is the strongest and most resistant to bending of the four wood materials tested. *Terminalia superba* and *Milicia excelsa* are of high strength and durability, making them ideal for construction and furniture-making, in addition to their desired good resistance to decay and insect attack. *Ceiba pentandra* wood is relatively soft and lightweight compared to other surveyed timber species, making it ideal for use in plywood, paper, and carvings. It has a low modulus of elasticity and modulus of rupture, which limits its use in high-stress applications. *Alstonia congensis* wood is lightweight and straight grained, making it suitable for furniture and panelling. It has a low modulus of elasticity and modulus of rupture, which limits its use in high-stress applications. These four species have varying mechanical properties but have unique characteristics that make them valuable for different applications. These findings could be useful in selecting wood materials for construction or other applications where strength and stiffness are important considerations. The results also highlight the importance of considering the specific properties of different wood materials when selecting them for specific applications.

Modulus of rupture (MOR) as an established criterion for wood strength (Kretschmann and Bendtsen 1992), which represents the ability of wood to withstand applied load until it breaks, is affected by the degree of moisture content (Thybring and Fredriksson 2021), except for *Allanblackia parviflora* sourced from Ghana (Antwi et al. 2014). When the moisture level of wood products falls below the fibre saturation point, the mechanical properties of the material change, resulting in a decrease in strength. In addition to moisture content, anatomical characteristics influence the mechanical properties of wood products. For our study, the samples were collected from timber stored in similar environmental conditions that could create minimal differences in the moisture content of the sample wood materials.

The bending strength value obtained in our study is consistent with the classification of *Milicia excelsa* to the medium static bending strength class reported in Ekundayo et al. (2022), Jamala et al. (2013), Kimpouri (2009), Frake (2021), and despite our wood material being sourced from a different geographical region. However, the bending strength of *Terminalia superba* in our study differed from that reported by Ekundayo et al. (2022), who classified it as having low static bending strength. The bending strength of *Ceiba petandra* falls within the range of the same species sourced from Kwara State (Jimoh and Ibitolu 2009).

The disparity in bending strength values obtained among studies may be due to tree growth conditions, portions of the tree where specimens are obtained, e.g., mature heartwood or sapwood (Frake 2021), density and species (Winnady 1994; Rajamanickam et al. 2021) and felling age due to overlogging (Ogunsanwo and Akinlabi 2011). Also, given the possibility of large strength variations within species and changing supply conditions, the need for continuous evaluation of the strength properties of wood remains relevant in advancing wood utilisation (ASTIM-D143 2009). Furthermore, the reality of variation in wood properties within and between species is a compelling argument for implementing engineering interventions such as glue lamination to achieve superior and more stable mechanical properties in wood suitable for structural application.

Conclusion

The strength of the four indigenous timber species we investigated varied depending on the species, indicating that different species have distinct strength properties. Interestingly, we found that *Alstonia congensis*, a lesser-known wood species, exhibited physical and mechanical properties similar to *Ceiba petandra* and could be an alternative. Wood users can use our quantitative data on the mechanical properties of the four studied indigenous timber species to determine the most appropriate applications in building, construction, and furniture production. It is crucial to conduct further studies on the mechanical qualities of less utilised wood species to address the current over-exploitation of the few economic species whose properties are widely recognised. In addition, implementing afforestation projects to boost the availability of the surveyed species is critical to their preservation, given their high threat level.

Declarations

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Author contributions

ECN conceived the idea, ACS conducted the experiments, ECN analysed the data. ACS and ECN wrote the manuscript.

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Data availability

The data sets analysed during the current study are available from the corresponding author upon request.

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Figures

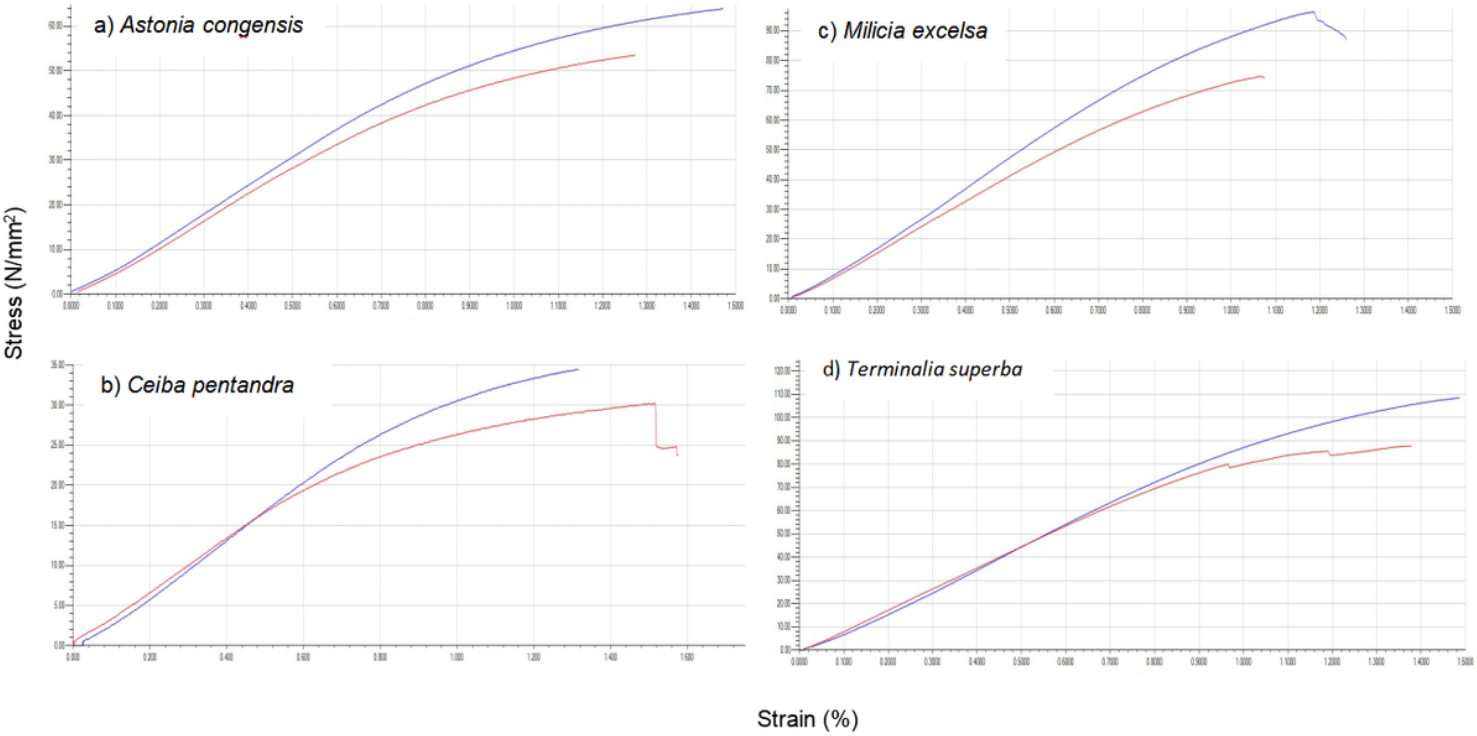

Figure 1

the 3-point flexural test of wood materials sourced from four indigenous timber species.

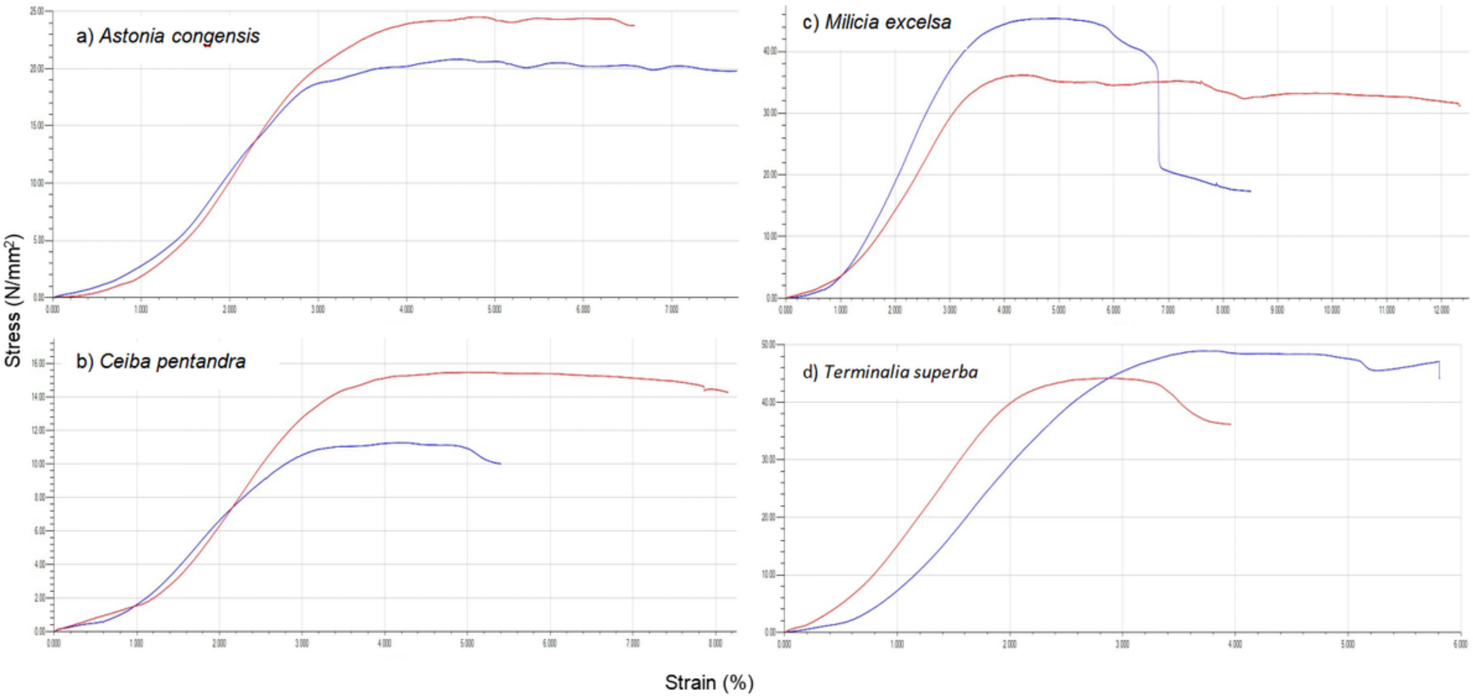

Figure 2

Axial Compression test for wood materials sourced from four indigenous timber species.