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Triaxial variation of the modulus of elasticity in the thermos-elastic field of six species of tropical woods

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Abstract

This work highlights the effect of temperature on the modulus of elasticity following the orthotropic axis of six species of tropical woods: assamela, bibolo, doussié, iroko, movingui, and sapelli of scientific names *Azelia*, *Pericopsiselata*, *Distemonanthus benthamianus*, *Entandrophragma cylindricum*, *Milicia excelsa*, and *Lovoatrichilioides* respectively. The four-point bending and compression tests were conducted to determine the failure loads, which can help further tests performed in elastic domain. In order to determine the Young's modulus in the thermoselastic field, the above tests were carried out at different levels of loads and temperature; the samples of 20 × 20 × 340 mm dimensions for bending tests and 20 × 20 × 60 mm dimensions for compression tests according to current standards. The strains were read by means of two strain gauges, connected to the strain gauge bridge. Test results under the different constant thermo-hydric conditions showed an increase in the longitudinal, radial and tangential MOE of all six species as the temperature increased from 22°C to 40°C, and a regression above 40°C. In terms of lost in elastic modulus, due to the temperature, the tests showed the following classification: *movingui* < *sapelli* < *iroko* ≈ *bibolo* ≈ *assamela* < *doussie*. Those results may be crucial while selecting the wood species for a typical use in a range of temperature.

KEYWORDS: MOE, orthotropic axis, Mechanical Tests, thermos-elastic.

Introduction

Wooden structures are often used in environments where humidity and temperature are variable. As an orthotropic and hygroscopic material, the use of wood in structures is subject to a multitude of inconveniences due to its highly variable nature and complex interaction with its environment (Merakeb et al., 2006; Armstrong et al., 1962; Dinh et al., 2011). This interaction impacts the mechanical properties of wood, in particular the MOE, which is the main mechanical property used to characterise the wood material. Taking into account the effects of temperature rise on the mechanical behaviour of load-bearing structures would avoid their premature rupture which is the cause of deforestation

Since 1941, various research studies on several European and American wood species have been carried out to determine:

- (i) the influence of temperature on MOE: indeed, the MOE of hardwood decreases with increasing temperature (Thunnell, 1941; Sulzberger, 1953; Hisada, 1981a).
- (ii) the influence of moisture content on MOE: MOE has been shown to decrease with increasing moisture content (Goulet et al. and Ouellet, 1968; Takemura, 1972; Kawai et al., 1979; Guitard, 1987).
- (iii) the combined influence of the two factors leads to a non-linear decrease in MOE (Lessard, 1978; Gerhards, 1982; Ranta-Maunus, 1992). Most of the studies cited above were carried out on wood from European and American forests. Unfortunately, many locally used tropical wood species are not sufficiently studied in our region. Unfortunately, many locally used tropical wood species are not sufficiently studied in our region. Therefore, it is necessary to produce a data bank for their safe use. For the above reason, the final objective of the current work is to

The final objective of the current work is to:

- perform an explicit study of the impact of temperature on the modulus of elasticity of six threatened tropical wood species (Julve et al., 2003; Cerutti et al., 2013) in the three orthotropic directions
- To establish the order of magnitude between the moduli of elasticity according to the three directions of tropical wood in order to deduce the preferred direction of stress.
- To make a comparative study of the species studied in relation to their resistance to the effects of temperature.

Materials and Methods

In this section, we present the different materials and methods used for each type of loading. The tests are carried out at different load and temperature levels until the specimens break.

Material

The tests are performed on samples of the above species. Two dimensions are used:

- 20 x 20 x 320 mm according to NF-B51-008 for 4-point bending tests (NF-B51-008, 1987a, NFB 51-003, 1985a);
- 20 x 20 x 60 mm according to NF-51-007 for parallel, radial and tangential compression tests (NF-51-007, 1985e).

Figure 1 shows the arrangement of the samples preparation.

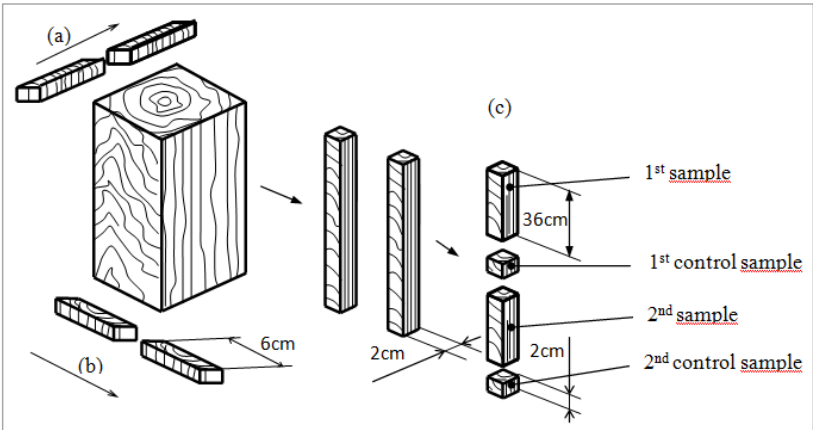


Figure 1: Illustration of samples orientations: (a) radial, (b) tangential, and (c) longitudinal directions.

To reach hygroscopic equilibrium, the samples were stored inside the laboratory (Figure 2), to undergo natural drying for about three months. They were stacked on drying rods to enhance air drying by air ventilation.



Figure 2: Drying of the specimen.

Experimental

Four-point bending device

The bending device was designed for specimens dimensions of 340 mm in length and 20 mm x 20 mm in cross-section. They are mechanically acted upon by simple supports made of 30 mm diameter steel cylinders which minimise local punching; one of the end supports being rotatable and the other fixed. Motion outside the bending plane of the samples is prevented.

- To determine the four-point bending failure load, the bending device is placed under the hydraulic press rod and the normal stress on the specimen is deduced from the cylinder pressure (Figure 3a).
- For the determination of the EOM, the stress is applied by means of the marked masses (Figure 3b).

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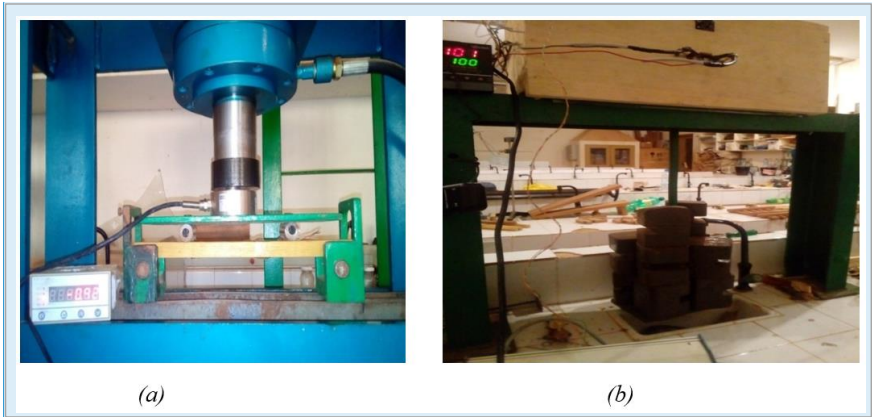


Figure 3: Testing machine and bending device for (a) rupture tests, and (b) 4-point bending test for the determination of Young's modulus at ambient temperature.

Compression Device

As in 4-point bending, the hydraulic press is used to determine the failure loads in parallel, radial and tangential compression. For the various MOEs in compression, the device in Figure 4 was designed.

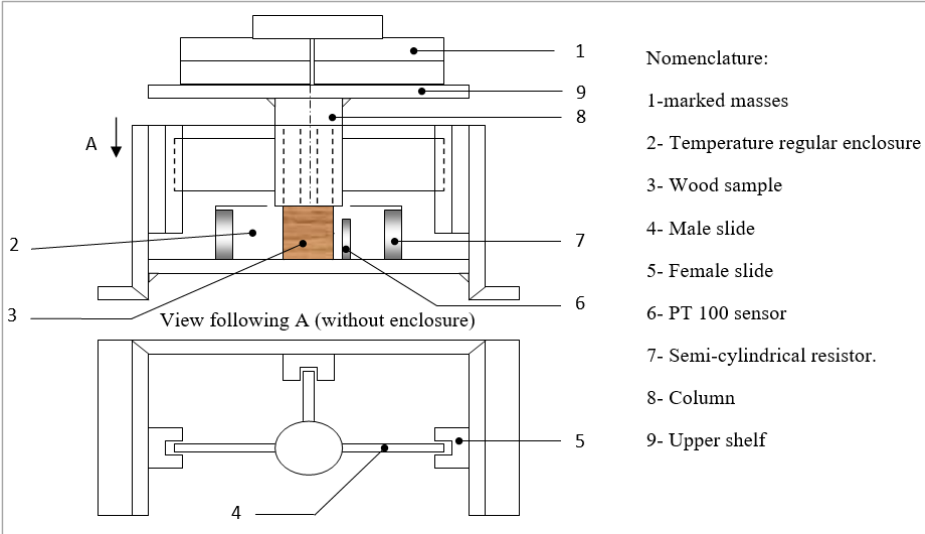


Figure 4: Compression device with a temperature-controlled enclosure with a regulated temperature.

All mechanical tests were carried out in a temperature controlled environment. For this reason, an adiabatic chamber enveloped the operational part of the bending and compression devices in order to minimise heat exchange with the outside environment. Inside the chamber, two hemispherical resistors were fixed, associated in series and arranged to even out the temperature in the chamber. The PT100 sensor is also placed in the chamber and close to the sample. Equipped with its components (Figure 5)

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which are connected to the Maxwell temperature controller, these chambers allow experimentation in an environment ranging from 23 to 105°C.



Figure 5: The electronic components of the regulated temperature enclosure.

Experimental method of determination of MOE.

In order to obtain the EOM, it is necessary to plot the stress-strain curve corresponding to a chosen temperature level.

- **Strain at different loads and temperature levels.**

At laboratory temperature T_0 , the sample is placed on the bending device which is positioned under the column of the compression device. The whole assembly (devices and sample) is packed in the above adiabatic chamber (Figure 3b) and the variator is set and stabilised at the desired temperature T . After the temperature in the chamber has stabilised and the sample has reached hygroscopic equilibrium, the ten identical labelled masses (5 kg) are successively placed on the tray (Figure 3b, Figure 4). During this one and a half minute phase, the strain is recorded for each set of marked masses deposited. The ten marked masses are then removed from the tray within 30 seconds and the temperature is adjusted to the next value within three minutes. At each temperature level, the specimen is tested in the same way up to the temperature of 100°C.

- **Normal stress developed in the middle of the sample**

If the strain is read directly from the digital display, the stress is deduced from the theory of the beam in strength of materials.

A fictitious section dividing the specimen into two trunks makes it possible to obtain a model of the cohesive actions and those transmitted by cylindrical roller supports on the section of the test specimen (Figure 6).

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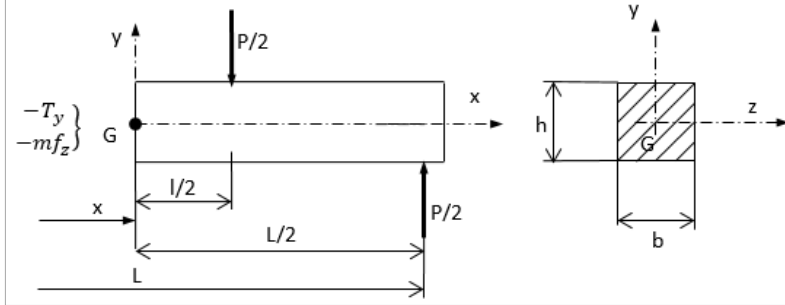


Figure 6: Modelling of actions on the test specimen.

From the nullity of the sum of the moments on the isolated part (right section) (Figure 6), it appears that the bending moment is:

$$mf_z = \frac{P(L-l)}{4} \quad (1)$$

where L is the span length of the beam, l the length between the internal rollers and p the weight of the masses.

The stress of a point M located at a distance y from the mean line due to the bending moment is :

$$\sigma = \frac{mf_z}{I_{Gz}} y$$

with I_{Gz} is the quadratic moment having a maximum value at the point of attachment of the gauges, i.e. for $y=h/2$

$$\sigma_{maxi} = \frac{3P(L-l)}{2h^3} \quad (3)$$

with h the thickness of sample.

In compression, the normal stress is obtained by:

$$\sigma = \frac{g}{b^2} m \quad (4)$$

where m is the total mass on the top plate and b is the cross-sectional dimension of the specimen .

This stress must be plotted for each temperature level as a function of the strain read on the bridge. This plot allows us to determine the MOE E_L , E_R , E_T in the elastic and linear deformation domain, and their evolution as a function of temperature.

Results and Discussions

Moisture content of the specimen at the beginning of the tests

The moisture content of the species, obtained according to NFB 51-004, is useful for comparing the experimental results of the different EOMs with those presented in the literature (NFB 51-004, 1985b).

Table 1: Moisture content of tested wood species.

	Doussié	Assamela	Movingui	Sapelli	Iroko	Bibolo
Moisture content (%)	9.99	11.87	13.60	16.28	12.56	9.30

Breaking load

It makes it possible to locate the elastic domain where the deformations are reversible (Sales, 1977).

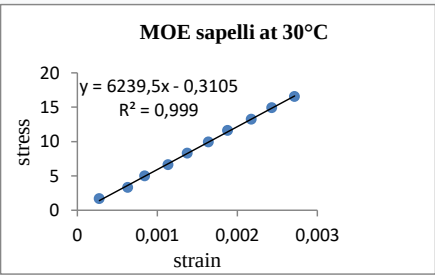
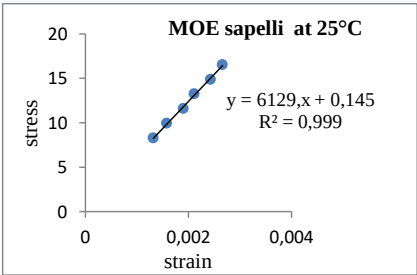
Table 2: Failure load of the studied wood species.

		Failure load (N)					
		Sapelli	Movingui	Assamela	Doussié	Iroko	Bibolo
Four-point bending test		224	293	304	384	219	181
Compression test	Longitudnal direction	2 405	2 528	2 609	3 018	2 202	1 916
	Radial direction	381	371	438	408	386	323
	Tangential direction	252	260	329	357	255	216

Table 2 shows that the failure load varies according to the orthotropic direction of the wood. Its value is higher in the fibre direction than in the transverse directions. Reduced to 12% according to the formula developed by Guitard in 1987 between 6°c and 20°c, its order of value in the fibre direction is 4.5 to 6.7 times that in the radial direction and 7.9 to 9.8 times that in the tangential direction. Almost similar proportions are observed in the literature (Pluinage et al., 1992, Baar et al., 2015, Pierrejean et al., 2017, Talla et al., 2020).

Longitudinal MOE in four-point bending

By varying the load and temperature of the experiment, the stress-strain curves can be plotted at different temperature ranges (Figure 7).



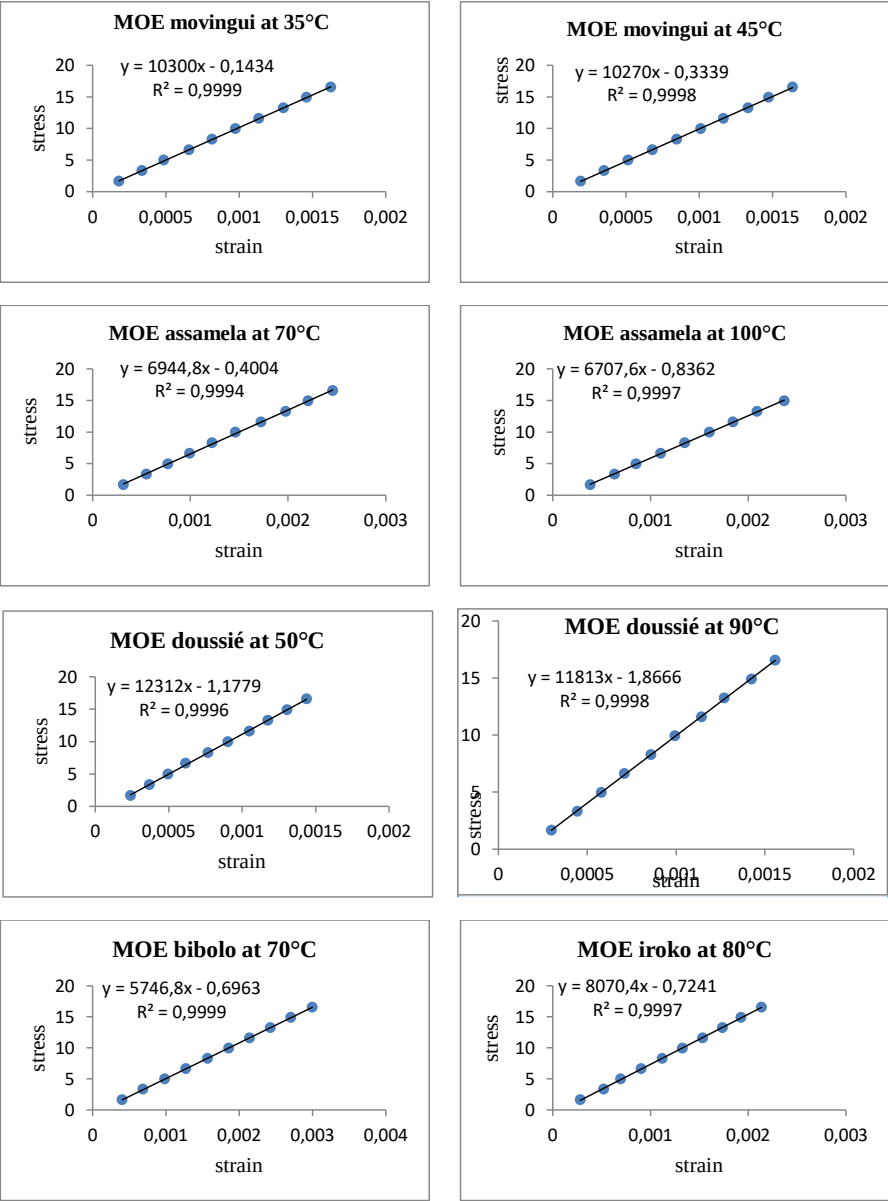


Figure 7: some stress-strain curves of the six species woods studied

The slopes of these lines represent the longitudinal MOE of the six wood species. The same work was done for all other temperature levels.

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Influence of temperature on the longitudinal MOE.

To better appreciate the variation of the longitudinal modulus of elasticity, MOE-temperature curves were plotted. (Figure 8)

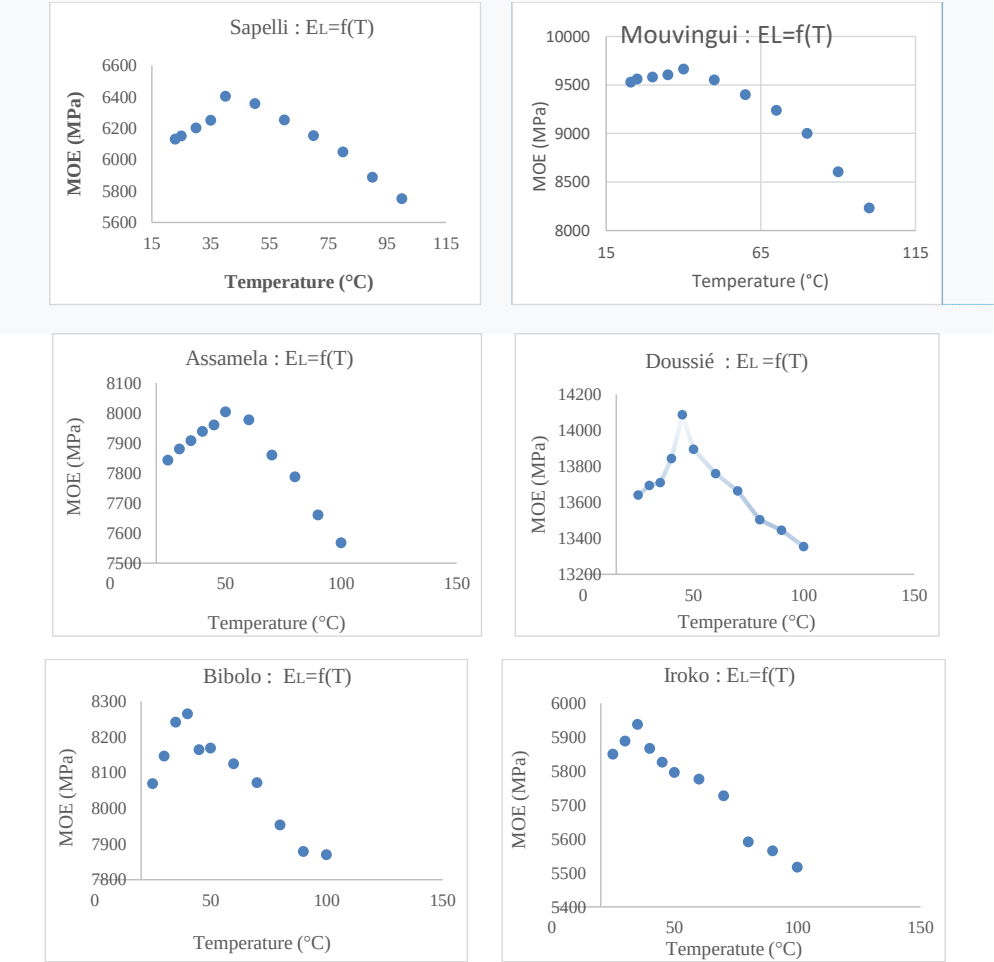


Figure 8: Variation of the longitudinal modulus of elasticity of six tropical wood species with temperature.

The experimental results are close to the modulus of elasticity formulation established in the literature (Lessard, 1977; Merakeb et al, 2006; Navi et al., 2015). Indeed, a significant increase in modulus is observed in the range of 22°C to 40°C. Above 40°C, a decreasing modulus is observed for all six species. Finally, these curves show an optimal use of the species around the range 35°C-45°C. In order to classify the strength of the six tropical wood species, a comparative development of their relative MOE was performed on the same graph.

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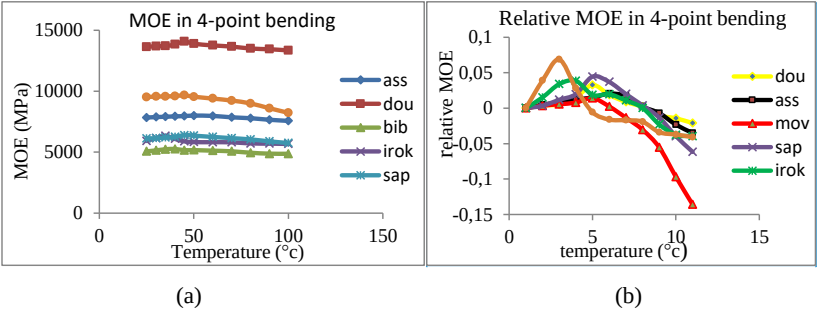


Figure 9: Comparative relationship of (a) absolute and (b) relative parallel moduli of elasticity of six wood species.

The group of curves in Figure 9a shows the evolution of the Young's moduli of the six species as a function of temperature. It appears that $E_{dou} > E_{mov} > E_{ass} > E_{sap} > E_{iro} > E_{bib}$. This order of magnitude is maintained at all temperature levels. We find that heat has a greater effect on the longitudinal MOE of Movingui than the other five species. This effect would be related to the relative speed of desorption. In fact, this relative desorption rate is higher in Movingui than in the other five species.

Variation of MOE in compression of six tropical wood species

As in 4-point bending, the load on the compression device (Figure 4) and the temperature are used to plot the stress-strain curves along each axis. The moduli of elasticity are deduced from these curves using Hooke's law. Figures 10 to 15 show the evolution of the average values of the MOE along each axis.

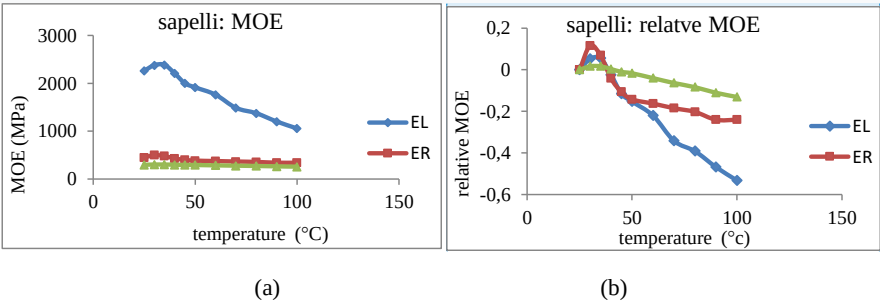
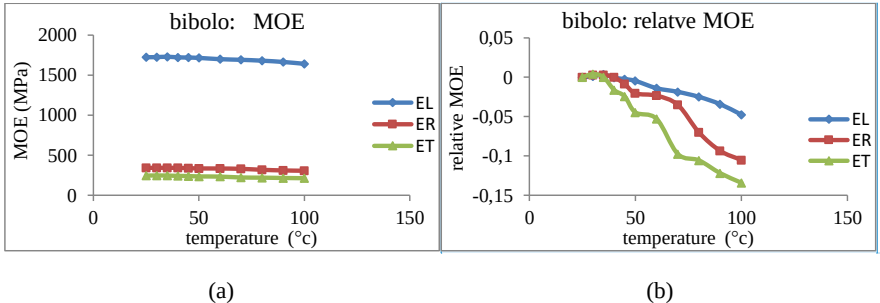


Figure 10: Comparative relationship of (a) absolute and (b) relative elastic modulus in compression of sapelli



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Figure 11: Comparative relationship of (a) absolute and (b) relative elastic modulus in compression of bibolo

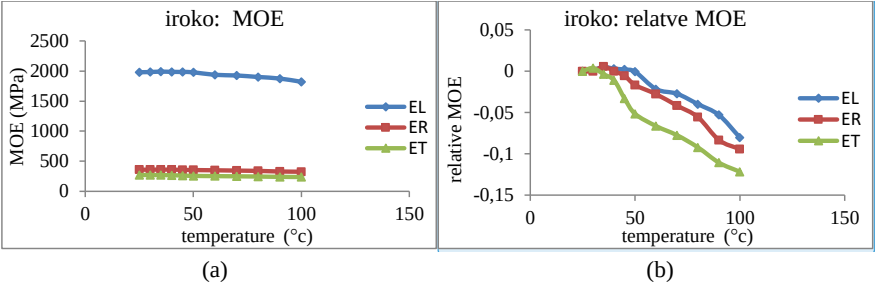


Figure 12: Comparative relationship of (a) absolute and (b) relative elastic modulus in compression of iroko

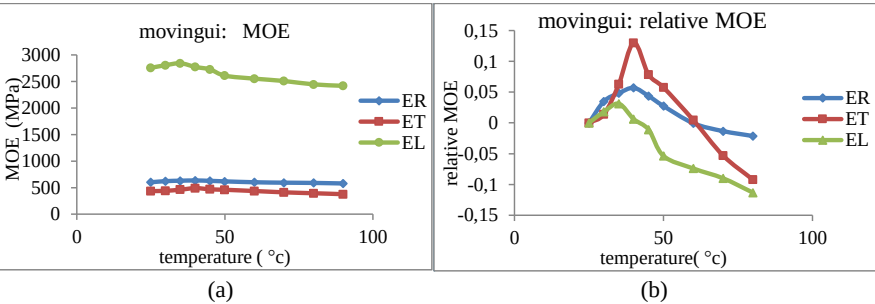


Figure 13: Comparative relationship of (a) absolute and (b) relative elastic modulus in compression of Movingui

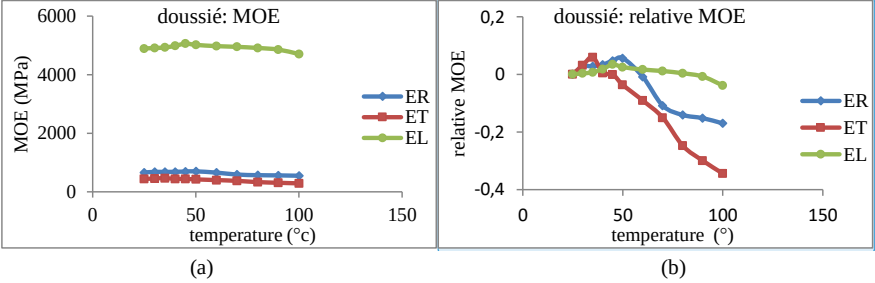
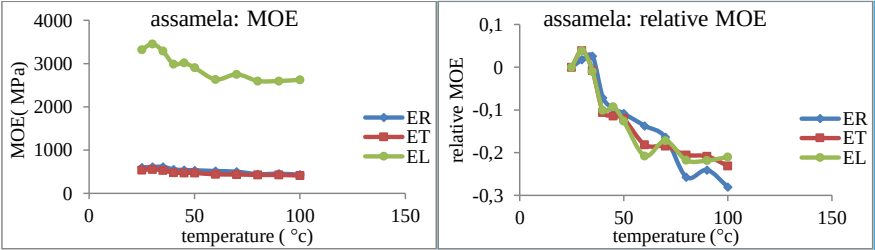


Figure 14: Comparative relationship of (a) absolute and (b) relative elastic modulus in compression of doussié.

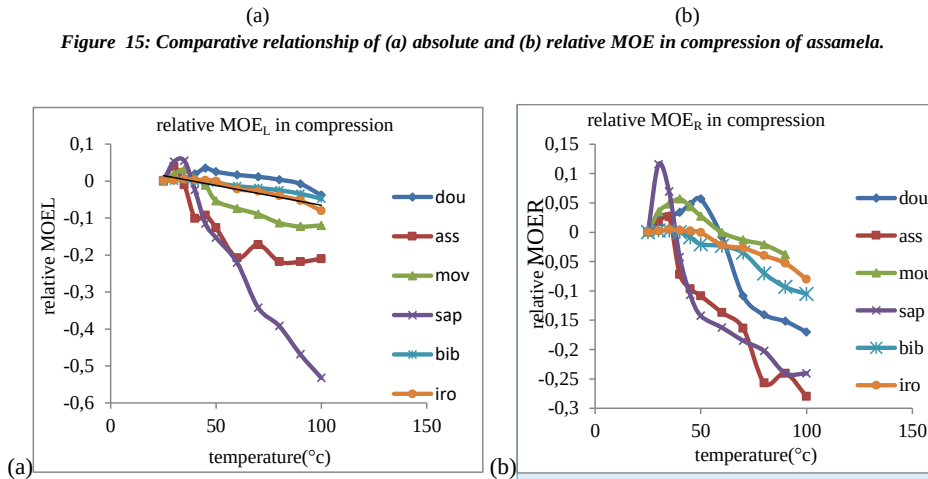


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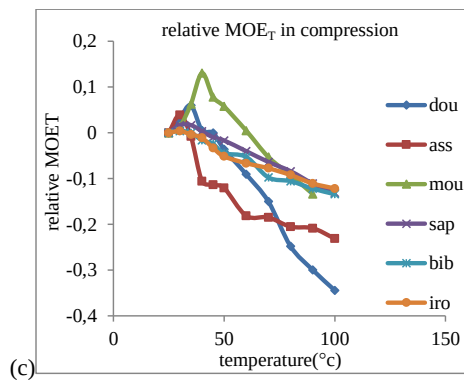
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MOE and Index L etc MOEL



The behaviour of wood is similar in the directions parallel and transverse to the fibres (Figure 10a to 15a). The increase in temperature within the wood material causes a triaxial increase in its deformation. This increase is more pronounced in the transverse plane than in the longitudinal direction (see Figure 16a, 16b and 16c). Wood is more deformable in the tangential direction, followed by the radial and longitudinal directions. In contrast, the MOE varies in the opposite sense, i.e. the EL modulus is greater than the E_T and E_R moduli, with E_R greater than E_T (Figures 10a to 15a, Figures 16a, 16b and 16c). This behaviour reflects the anisotropy of wood reported in the literature, notably by Kollmann and Côté (Kollmann et al., 1968), (Siimes, 1967), Gerhards (1982), (Bodig, 1992), (Wei, 2020) and (Sheikh, 2020)

The comparative curves (Figures 10b to 15b) of the relative MOE show that heat has more impact on sapelli, doussié and assamela than the other three species. It also shows a fluctuating variation in the modulus of sapelli and movingui.

A slight increase of the different modules can be observed up to a T_M (temperature for which the MOE is maximum). This temperature is between 35°C and 45°C. Above this temperature value, the effects are

reversed. It is also observed that the temperature of change of effect on the MOE depends on the orthotropic direction of wood and also on the type of wood.

Conclusion

The influence of temperature on the MOE and strength of six tropical wood species was investigated. The 4-point bending and compression tests were carried out for temperatures ranging from 25°C to 100°C with an increment of 5 to 10°C. At different temperature levels, we obtained the following results:

*A slight increase in the modulus of elasticity of the six species along the three axes, from 23°C up to a temperature T_M (temperature where the MOE is maximum), followed by a considerable decrease (in this second phase, the variation of the MOE is similar to that of softwoods in the literature). This is justified by the fact that as temperature increases, the effects of the water gradient initially dominate over those of temperature. As temperature continues to increase, their effects are reversed. This behaviour justifies an optimal use of these species around the temperature T_M .

* Temperature has a greater impact on transverse than longitudinal moduli of elasticity: at the same test conditions, the MOE in the longitudinal direction is much higher than the radial and tangential MOEs; the order of magnitude is 7.5 to 9.6% for the tangential MOE (E_T) and 4.7 to 6.7 for the radial MOE (E_R). This result was also obtained in the literature for softwoods with a difference in the range of variation of the modulus ratios.

*Finally, the increasing order of resistance to temperature effects is: movingui < sapelli < iroko $\approx$ bibolo $\approx$ assamela < doussie.

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