Physical and mechanical properties of Ayous wood (*Triplochiton scleroxylon*) from Cameroon

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Abstract
The present study deals with Ayous wood from the East Cameroon forest reserve in the locality of Abong-Mbang. The water absorption rate of Ayous wood and the absorption kinetics were evaluated. Ayous wood reached its absorption saturation around 28 days. The primary diffusion coefficient was found to be 1.51 x 10^{-11} m^2/s with a standard deviation of 0.23x10^{-11} m^2/s while the saturation absorption rate is 144% with a standard deviation of 16.3%. About the modeling of kinetic absorption, many models were tested, and (Sikame, 2014) was the best model for our experiments. In order to determine the mechanical properties, four point bending and compression test were done through the three orthotropic directions. It is found that the modulus of elasticity value is 8792.75 MPa with a standard deviation of 527 MPa and the fracture stress (σ_l) value is 53.6 MPa with a standard deviation of 8 MPa. Longitudinal, radial and tangential compressive stress are 31.51 MPa, 29.15 MPa and 31.4 MPa respectively, with standard deviations of 4.34MPa, 4.52 MPa and 4.23 MPa.

Keywords: Absorption kinetics, diffusion coefficient, orthotropic directions, modulus of elasticity, modulus of rupture.

1. Introduction

Wood is a material derived from trees. Its production constitutes a great wealth for central African economy (Kisito, 2008). It is a biological composite, constituted of fibers as reinforcement, embedded in lignin as matrix. (Pot, 2012). The fibers orientation leads to three orthotropic directions: radial, longitudinal and transversal. It is a natural material that has several advantageous characteristics such as its lightness, ease of absorbing and releasing water. The water absorption by wood assumes great importance, especially in the structure uses of wood (Baronas, 2001), but a technological problem that limits its valuation resides in its mechanical variability. Indeed, unlike other common building materials, wood is a living material whose properties are governed by nature. There may therefore be a variability of properties between trees of the same species. This is due to the presence of singularities such as knots, slots, and wire slope. It is therefore important to first determine the performance of each wood species before it is used in a construction application.

The aim of the present work is to characterize Ayous (*Tripochiton scleroxylon*), a species intensively used in building construction as formwork for reinforced concrete, or structure elements. When this wood is used as formwork, it is influenced by climatic variations (rain and heat) due to its exposure on construction sites. It is therefore subjected to sorption phenomena

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(Saifouni, 2014). The knowledge of its absorption kinetics is fundamental for the understanding of its behavior under various conditions.

2. Materials and methods

2.1 Sampling

The wood we have worked on, is Ayous (*Tripochiton scleroxylon*), a tropical wood of the Eastern region of Cameroon in the locality of Abong-Mbang. In order to obtain results that validate the methods used, a set of 1205 specimens were tested. Three trees have been chosen in this species that have a diameter between 30 cm and 43 cm. They are straight and have few defects. This sampling allows a certain representativeness of the species studied.

Figure 1: Tree trunks and sawing along longitudinal, radial and transverse directions

Figure 2: Test specimens

2.2 Hygroscopic behavior

The absorption rate is determined by gravimetric method. This test was conducted by immersing sample in the water, removing it every two days and deducting the amount of water absorbed. If M_i is the initial weight of the sample, and Mt the actual value measured, then the equation 1 gives the absorption rate (Scida, 2010).

$$\mathrm{TA(t)} = \frac{Mt - M_i}{M_i} \times 100 \quad (1)$$

Where TA(t) is the absorption rate.

Figure 3: Hygroscopic measurement: (a) precision balance, (b) soaking tank

If M_∞ is the weight at saturation, the absorption ratio is calculated using equation 2.

$$MR(t) = \frac{Mt - M_i}{M_\infty - M_i} \times 100 \tag{2}$$

Where $MR(t)$ is the absorption ratio.

From the mathematical point of view, the problem of water absorption by wood can be treated as a diffusion problem based on the Fick's second law of diffusion. The absorption kinetics of this wood species and the mathematical model of this absorption kinetics are then determined by testing several empirical models from the literature under Matlab software.

The Fick diffusion coefficient gives a linear relationship between water flow through the porosity and the concentration gradient (Crank, 1956).

$$J_j = -\rho D_{ij} \nabla c_j \tag{3}$$

where Jj is the diffusion flux, of which the dimension is the amount of substance per unit area time in $kg.m^{-2}s^{-1}$ and ρ the mass per unit volume in $kg\ m^{-3}$

Dij is the binary diffusion coefficient or diffusivity in $m^{-2}s^{-1}$
∇ is the symbol for the mathematical gradient.
cj is the mass fraction.

In this expression the diffusion coefficient Dij is given by equation 4

$$Dij = \pi \left(\frac{K}{4M_\infty}\right)^2 \tag{4}$$

Where K is the slope of the linear part of the curve defined by equation 5

$$wt = \left(\frac{\sqrt{t}}{h}\right) \tag{5}$$

wt is the water content at time t.

2.3 Mechanical behavior

Bending test

In order to determine the modulus of elasticity as well as the bending stress, four-point bending test is carried out according to the standard NF B 51-016 1987(Seram, 1987), as shown in Figure 4. The test is carried out using prismatic specimens of 360 mm length and 20 mm x 20 mm square cross-section, a compression press, a test stands and two pressure gauges. For this purpose, we made a support and loading device that was adapted to the existing press.

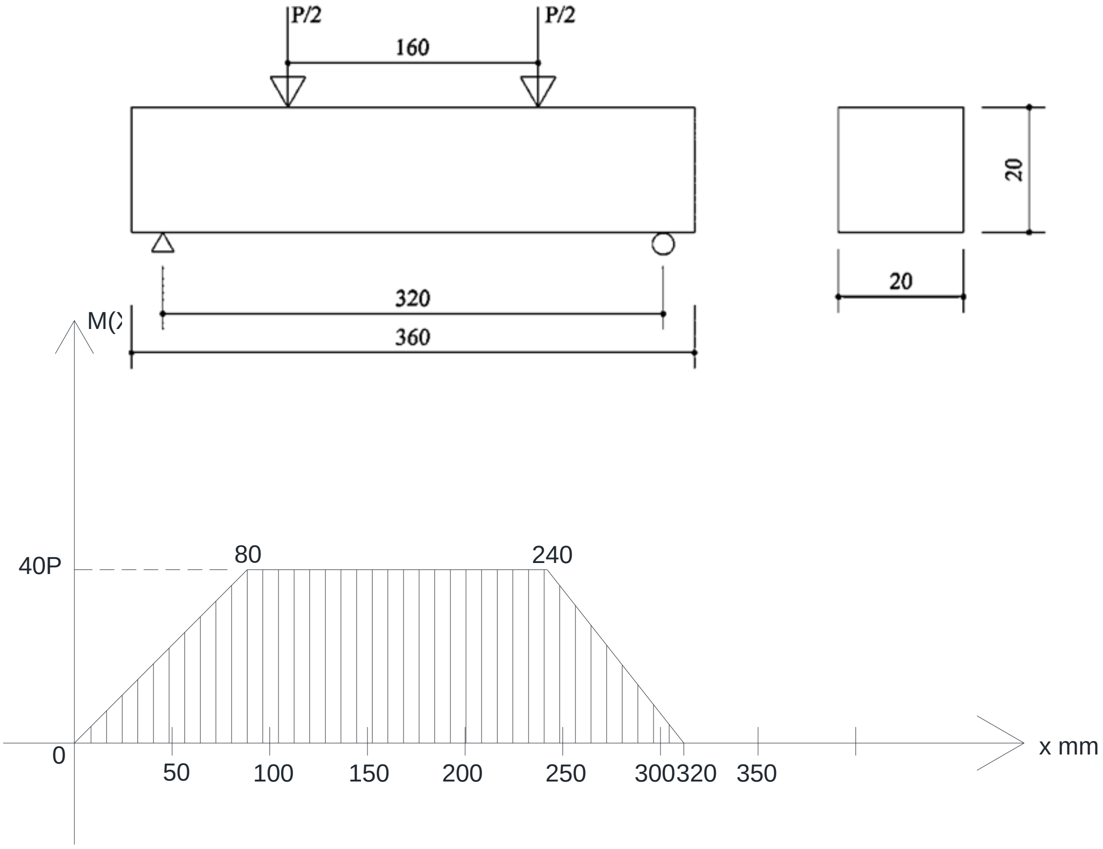


Figure 4: Bending moment

The modulus of elasticity and the bending tensile stress are derived by equation 6.

$$\mathrm{MOE} = \frac{pl^3}{48I\Delta_{max}}\left[\frac{3(l-a)}{2l} - \frac{(l-a)^3}{l^3}\right] \tag{6}$$

MOE : modulus of elasticity

I: quadratic moment of the section of the sample

Δ: maximal deflexion obtained from the test.

P maximal load

a: dimension of the section of the sample (a= 20 mm)

l: the distance between supports (320 mm)

The maximum bending moment is given by equation 7

$$M_{max} = \frac{p}{2}a \tag{7}$$

M_{max}: the maximum bending moment.

Equation 8 gives the maximal static bending stress.

$$\sigma_{max} = \frac{3pa}{b^3} \tag{8}$$

σ_{max} : the maximal static bending stress

Compression test

The compression test is conducted by standard NFB 51-007 (Seram, 1987). The test method is based on the following principle: the chosen test (compression) aims to impose a uniform uni-axial stress state on a prismatic specimen and, by measuring the resulting deformations, to evaluate the elastic compliances expressed in the reference frame linked to the specimen. The samples are taken through the three orthotropic directions according to the Figure 5.

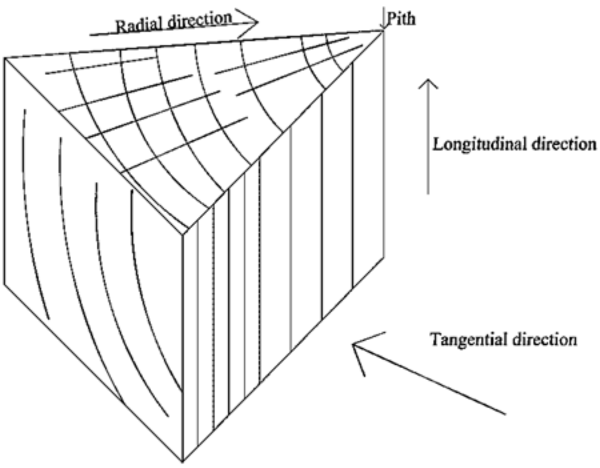
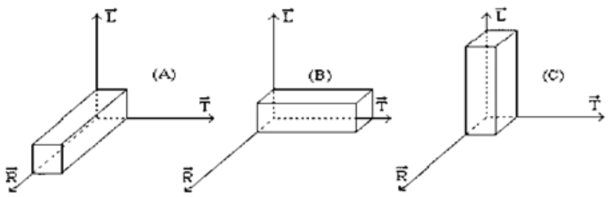


Figure 5: The three orthotropic directions of wood

The practice is to use three specimens as shown in Figure 6 below.

(a)



(b)

Figure 6: The three specimens in the three directions (a), Test machine and specimen loading mode in compression (b)

For each test, if P is the maximum force applied to the specimen, the stress is given by equation 9

$$\sigma = \frac{P}{b^2} \tag{9}$$

Where b^2 is the section of the sample. ($20x20mm^2$). The modulus of elasticity is then given by.

$$\text{MOE} = \frac{PL}{b^2 \Delta L} \tag{10}$$

Where P is the maximum force applied to the specimen, and L the length of the sample
Where ΔL is the variation of the length of the sample under the maximum force P.

3. Results and discussion

3.1 Hygroscopic behavior

The water absorption kinetics was studied. The graph of the absorption kinetics curve is shown in Figure 7. This figure shows the variation of water absorption ratio with time. It appears that the saturation happens in twenty-eight days. The rate of absorption is 144% with a standard deviation of 16.3%.

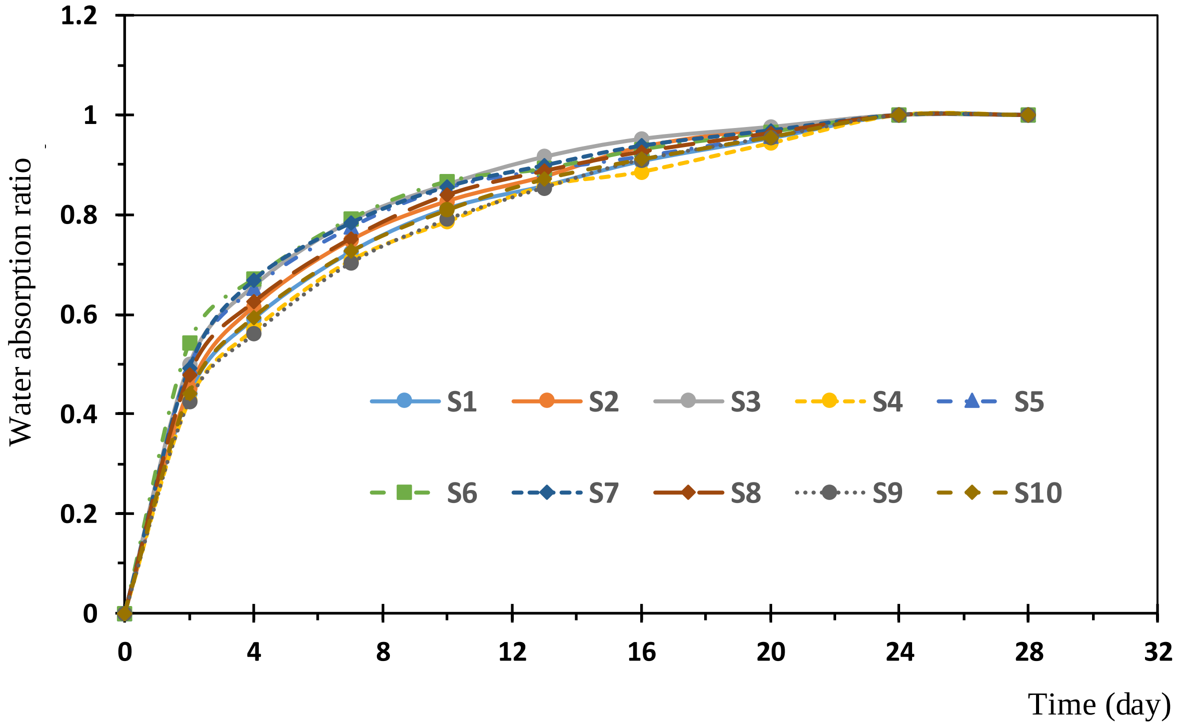


Figure 7: Absorption kinetics of Ayous wood

The modelling of the absorption kinetics was done in Matlab using models from the literature. Figure 8 presents this modelling.

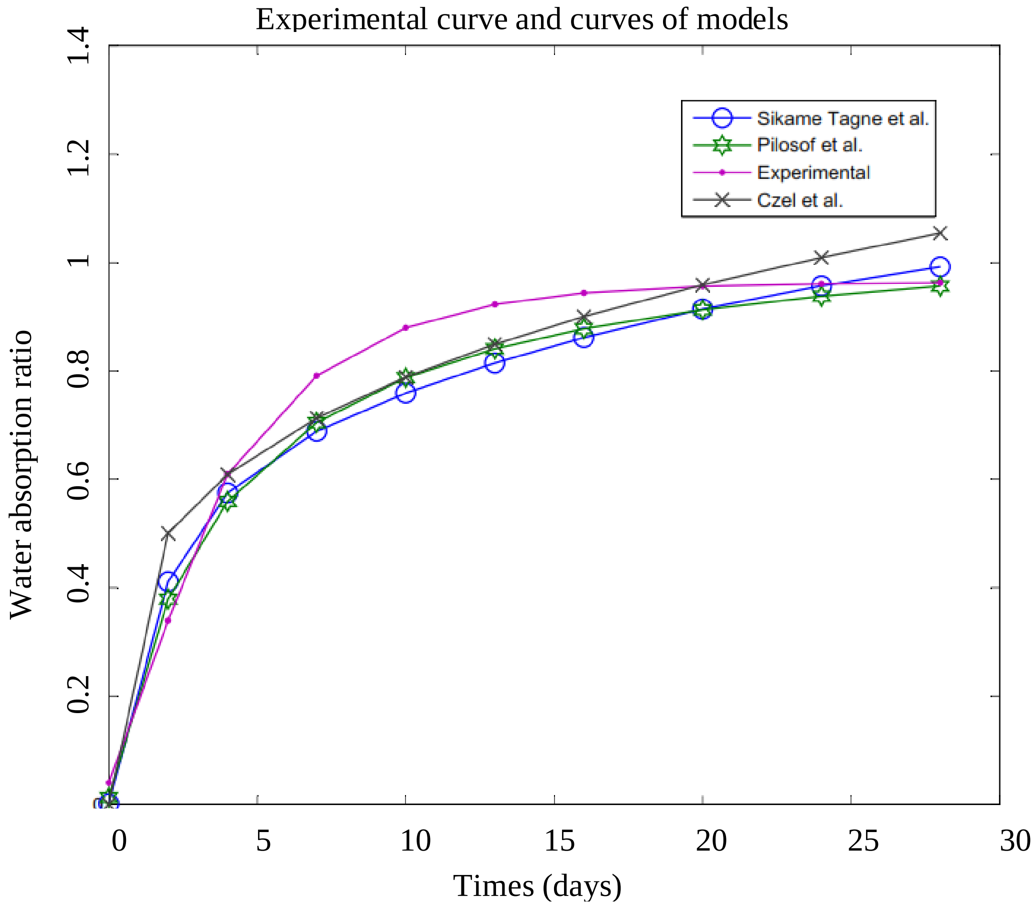


Figure 8: Experimental curve of Ayous wood and curves of models

To evaluate the goodness of fit of each model, two criteria were used. Coefficient of determination (R-square) and root mean square error (RMSE), as given in the table 1.

Table 1: Distribution of the average parameter model of the absorption kinetics of Ayous wood

Model names	Goodness of fit		
	R-square	Adjusted R-square	RMSE
(Sikame ,2014) G(x)= c-a.exp(-k.x)-b.exp(-m.x)	0.9979	0.9962	0.01959
(Pilosof, 1987) G(x)=a+ $\frac{b.x}{c+x}$	0.9853	0.9811	0.04378
Experimental	0.9980	0.9974	0.01622
(Czel ,2008) G(x)=a.x^m	0.9339	0.9258	0.08672

G is the model equation

The root mean square error (RMSE) is given by equation 11

$$RMSE = \sqrt[2]{\frac{\sum_1^n (m_{ci}-m_{ei})^2}{n}} \quad (11)$$

Where m_{ci} is the theoretical mass, m_{ei} is the predicted mass, n the number of observations
The mathematical model that best describes the absorption kinetics of Ayous wood is the Sikame model (2014) given by equation 12 below.

$$G(x) = c - a\,.\exp(-k.x) - b.\exp(-m.x) \tag{12}$$

Where a b and c are constants and k and m are the scattering parameters.

Table 2: Coefficients of Sikame Model.

Coefficients (with 95% confidence bounds)	Values
a	0.001366
b	0.002965
c	1.04
k	0.1756
m	0.203

The corrected primary scattering coefficient deduced from this absorption kinetics is $1.51.10^{-11}$ m²/s. This value is in the order of magnitude of the diffusion coefficients of woods of the same characteristic in the literature. It is experimentally proven that the diffusion coefficient of medium-heavy tropical woods varies from 10^{-13} m²/s to 10^{-11} m²/s while that of heavy woods varies from 10^{-14} m²/s to 10^{-12} m²/s with a relative error of 10%. The diffusion coefficient of tropical woods is lower than the diffusion coefficients of temperate woods and also differs according to the density (Khazaei, 2008). The heavier the wood, the lower its diffusion coefficient, i.e. the more difficult it is to lose water (Nsouandele, 2009).

3.2 Mechanical properties of wood in 4-point bending

Its maximum deflexion value Δ is 10.73 mm with a standard deviation of 0.69 mm. The 4-point bending test produced the curve given by figure 9. From this curve we determine the value of the longitudinal modulus of elasticity MOE= 8792.75 MPa.

It should be noted that this value of modulus of elasticity is within the range of moduli of elasticity of this species given in the literature 7260 MPa with a standard deviation of 1574 MPa (Gérard, 1998).

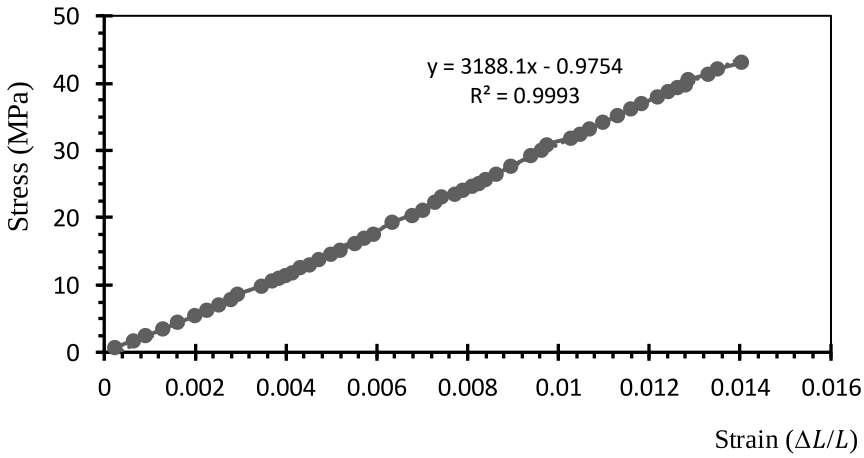
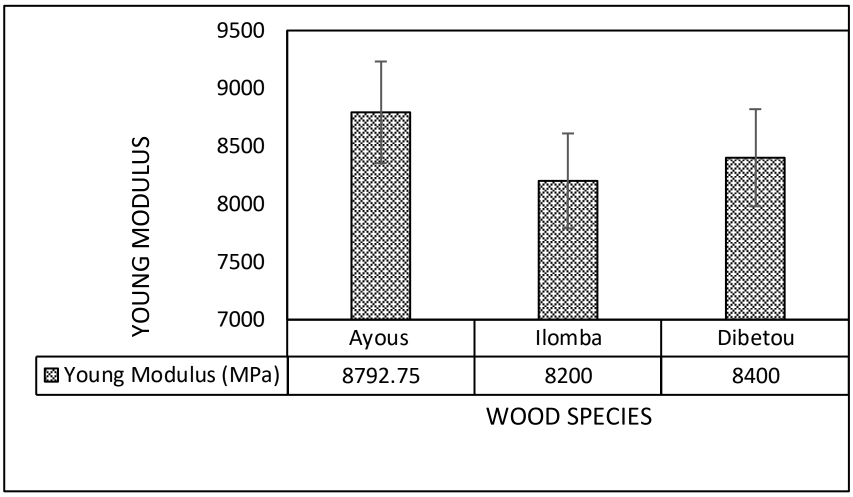


Figure 9: Four point bending test, evaluation of modulus of elasticity

(a)



(b)

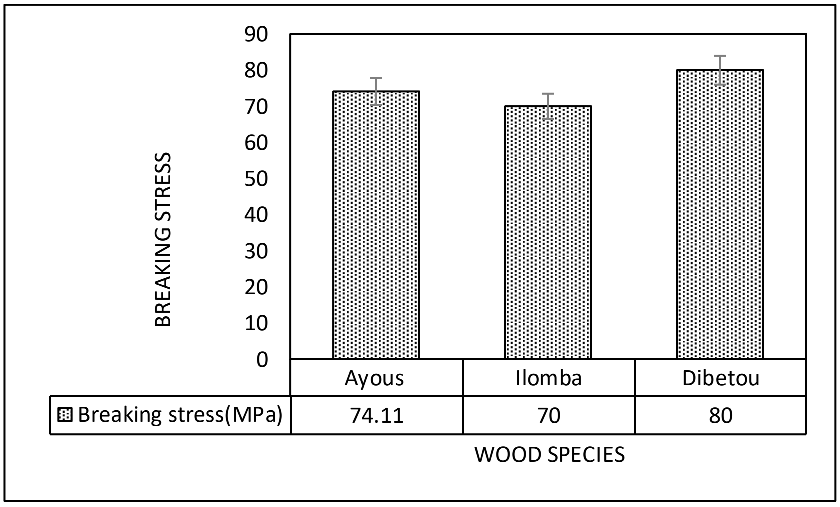


Figure 10: Comparison of modulus of elasticity of Ayous wood with other species (a) Longitudinal breaking stress of some species (b)

A static bending modulus or modulus of elasticity of 8792.75 MPa with a standard deviation of 527 MPa is obtained for this species, as well as a comparison with other similar woods (softwoods) in the literature. In this test, the bending stress parallel to the grain was determined to be 74.11 MPa. This value is high compared to other similar woods in the literature, namely Ilomba and Dibetou with similar densities (Gérard, 1998).

Table 3: Fracture stress and modulus of elasticity for the four point bending test.

Four point bending test	Fracture stress in MPa (SD)	Modulus of elasticity in MPa (SD)
	53.6 (8)	8792.75(527)

3.2 Uni-axial compression test

This uniaxial compression test allowed us to draw the curves below.

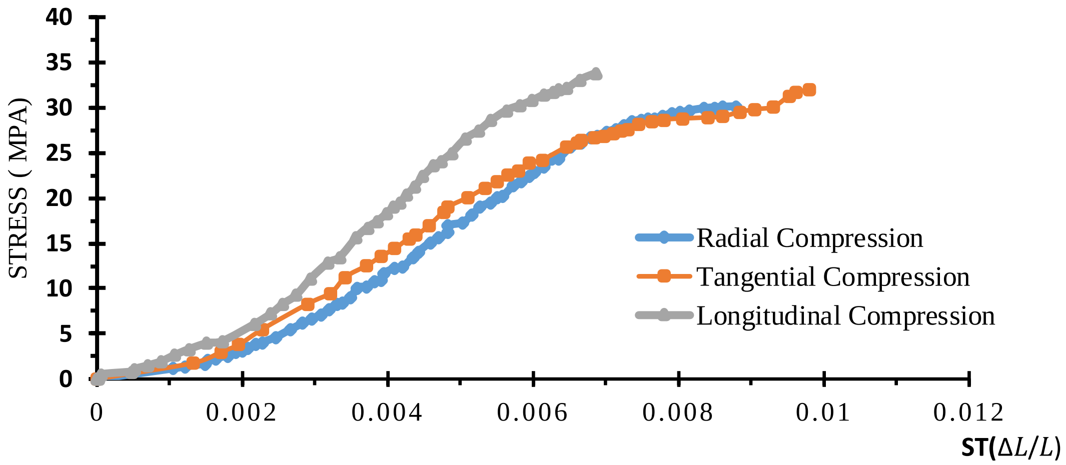


Figure 11: Uni-axial compression test: radial compression, tangential compression, longitudinal compression.

The values for modulus of elasticity and stress at break from this test are given in the table 4.

Table 4: Stress at break and modulus of elasticity in compression

	Compressive stress in MPa (SD)	Modulus of elasticity in MPa (SD)
Longitudinal compression	31.51 (4.34)	6529 (510)
Radial compression	29.15 (4.52)	4041 (309)
Tangential compression	31.49 (4.23)	4029 (301)

Based on these results, we observed that the modulus of elasticity in longitudinal compression is greater than the moduli of elasticity in radial and tangential compression. This value of longitudinal modulus is also within the range of moduli of elasticity of this species given in the literature 7260 MPa with a standard deviation of 1574 MPa (Gérard, 1998).
This reflects the use of this species in structures in the longitudinal direction (parallel to the grain).

4. Conclusion

The main objectives were to characterize the kinetics of Ayous wood and its mechanical behavior. Water diffusion in this species has shown that its water absorption rate is high in the first eight days of the test, and gradually decreases to stabilize at saturation absorption around 28 days. This absorption rate is 144% with a standard deviation of 0.163%. The process that led to the determination of this value consisted of successive weighing carried out on average every 02(two) days until saturation (mass stabilization). When we use Matlab software the model of Sikame is the one that best fits the absorption kinetics of this species. The correlation coefficient is R^2= 0.9979 and the RMSE value equal to 0.01959. This model value is close to the experimental value which is 0.01622. The average primary diffusion coefficient is $1.15.10^{-11} m^2/s$. The four point bending test revealed a tensile stress of 53.6 MPa and a modulus of elasticity of 8792.75 MPa.The uni-axial test revealed a longitudinal compressive strength of

31.51 MPa, a tangential compressive strength of 31.49 MPa, and a radial compressive strength of 29.15 MPa. The moduli of deformation in the different directions in compression are: EL = 6529 MPa, Er = 4041 MPa Et = 4029 MPa.

In future work, it will be necessary to study a creep ratio behavior of this species (viscoelastic and mechano-sorptive behavior).

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