WOOD RESEARCH
64 (2): 2019
195-204

STUDY OF THE CORRELATION BETWEEN FIBER AND MECHANICAL PROPERTIES OF WOOD *BORASSUS AETHIOPUM* MART. OF CHAD

Ngargueudedjim Kimtangar, Guersoube Tao
University of N'djamena, Faculty of Exact and Applied Sciences
Laboratory for Study and Research in Industrial Technology
N'djamena, Chad

Guy Edgard Ntamack
University of Ngaoundéré, Faculty of Science, Department of Physics, Group of Mechanics, Materials and Acoustics
Ngaoundéré, Cameroon

(Received September 2018)

ABSTRACT

Palmyra palm (*Borassus aethiopum* Mart.) is a large palm tree whose wood is often used for its mechanical resistance and weathering in buildings in Africa. In this work, the influence of fibre characteristics on the mechanical properties of wood was studied. For this purpose, the mechanical characteristics were determined and study of the micrograph of the sapwood and Duramen which are the useful parts of this wood were carried out. The results of this study show the mechanical properties of the palmyra are very influenced by the number and the mechanical characteristics of the fibres.

The proposed polynomial model of the evolution of the mechanical characteristics gives the good results because the maximum relative mistakes of the prevision are 4.43% for the breaking strength and 0.40% for the Young's modulus.

KEYWORDS: Wood, palmyra, fiber, mechanical characteristics, correlation.

INTRODUCTION

Within the framework of sustainable development, most of the developing countries of the African continent and particularly Chad through the University of N'Djamena took the lead in research on local materials, including palmyra which contributed to socio-economic development.

The palmyra (*Borassus aethiopum* Mart.) is abundant in Chad and is widely used as building material for timber framing, beams and planks in the construction of habitats and fence posts due to its good durability and resistance to moisture and termites (Ngargueudedjim et al. 2015c). It develops a smooth and grey stipe, which at adulthood is 15 to 20 m tall and has an appearance of a slightly thick column at its base and strongly swollen in the top part (Samah et al. 2015). It is a material that is resistant to molluscs and hardly rotten (Samah et al. 2013).

The general objective of this work is to participate in a recovery economy to gain autonomy by using local materials that do not require large investments. Our concern is the development and popularization of palmyra. However, a material is better used if its mechanical characteristics are controlled as a function of the conditions of the environment of use.

The specific objective is to study the correlation between the characteristics of the fibers and the mechanical properties of this wood. The aim is to study the structural (anatomical), micrographic and mechanical characteristics of this wood in Chad, to establish a relationship between the characteristics of the fibers and the mechanical characteristics (breaking strength and Young's modulus).

MATERIALS AND METHODS

Materials

For our experiments, the plant material was taken from a tree trunk of the male palmyra, about 40 years old, cut down in a village named "Houndouma". The geographical coordinates of the sampling site are 11°51.33' north latitude and 15°04.47' east longitude.

From an anatomical point of view, the stipe of a palmyra consists of numerous cribrovascular bundles surrounded by a sheath of sclerenchyma, embedded in the fundamental parenchyma (Detienne 1988). The duramen is the part of the hardest wood, compact and rot-proof. It is connected directly to the bark. The sapwood is the part between the duramen and the heartwood. The chemical characteristics of the palmyra studied are report in the Tab. 1.

Tab. 1: Average values of the chemical characteristics of studied palmyra (Ngargueudedjim et al. 2016, Allarabeye 2010).

	Duramen (%)	Sapwood (%)
Cellulose	63.21	61.89
Lignin	19.36	19.68
Hemicellulose	09.60	11.32

The electron microscope with a maximum magnification of 0.1x was used for the analysis of the longitudinal section and the light optical microscope with a maximum magnification of 0.4x was used for that of the perpendicular section.

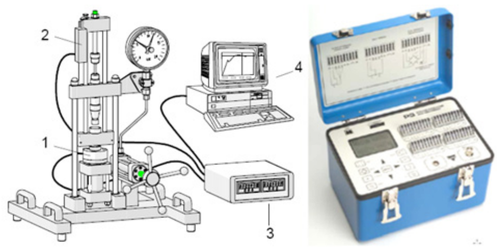
Fig. 1: Fibres of palmyra extracted for the tensile tests (Ngargueudedjim et al. 2016, Allarabeye 2010).

In our study were used the data of the characteristics (Tab. 2) of the fibres extracted from the same palmyra (Fig. 1).

Tab. 2: A characteristic of the Palmyra's fibres (Ngargueudedjim et al. 2016, Allarabeye 2010).

	Sapwood Duramen	Duramen
Section (mm^2)	0.72 ± 0.23	0.72 ± 0.15
Strain (%)	1.6 ± 0.7	1.3 ± 0.3
Breaking strength tensile (MPa)	219 ± 85	184 ± 77
Young's modulus tensile (MPa)	16 800 ± 8 800	17000 ± 1500

The universal testing machine type WP 300 (Fig. 2a) with maximum capacities 20 kN in force and 200 $cm \cdot min^{-1}$ in speed of movement was used for the mechanical characterization (Young's modulus and breaking strength).



(a) (b)

Fig. 2: WP 300 universal testing machine connected to a computer. (a) Universal testing machine type WP 300: 1) load cell on the principle of strain gauges, 2) electronic displacement sensor, 3) measuring amplifier with digital display of test force and elongation and integrated serial interface for connecting to a PC, 4) PC with analysis software and printer. (b) Model P3 strain indicator and recorder.

This device, controlled by a computer, makes it possible to record the data of the tests and to plot the stress-strain curves automatically. It directly gives the values of the breaking strength and the Young's modulus in compression.

Methods

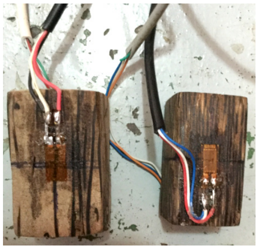
The samples are extracted from the part of the duramen and the part of the sapwood of the palmyra. They have not undergone any chemical treatment.

For the microscopic study, we made two types of cutting: a section parallel to the direction of the fibers (longitudinal section) and a section perpendicular to the direction of the fibres. After cutting the samples, the surfaces to be observed are polished with fine-grained abrasive paper (P400 and P800) and then cleaned with a wet cloth.

We have counted the primary fibers contained in the cross section of 2 x 2 cm of each image obtained from the perpendicular section of the duramen and the sapwood.

The dimensions of our samples for the compression tests are measured with a calliper rule and their weights are obtained using a Mettler PM4600 Delta range electric scale.

Seven samples of sapwood and seven samples of duramen were prepared. After their machining milling to dimensions 2.5 x 2.5 x 4.0 cm the two adjacent side surfaces to receive the gauges were polished to P800 sandpaper. The alignment pins of the gauges on the surfaces have been drawn in pencil hard lead. These surfaces have been degreased, cleaned and dried in the open air under the sun. The gauges are cleaned resin solvent and neutralized before being glued with the M200 cyanoacrylate superglue. Next, the connecting wires are welded on each gauge in quarter of the Wheatstone bridge mounting (Fig. 3).



(a) (b)

Fig. 3: Test specimen with gauges, (a) sapwood, (b) duramen.

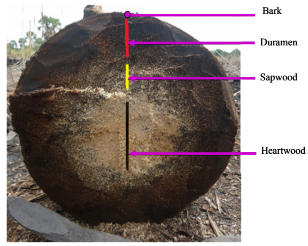


Fig. 4: Diagram showing the proportions of sapwood and duramen in a palmyra slat.

To prevent the erosion of borders and ensure the proper distribution and alignment of the load, a square steel plate side 30 mm and 5 mm thick is placed on each of the two charging tips of the specimen. Each sample was subjected to compression tests in the longitudinal direction of the fibres.

From a mechanical point of view, palmyra is an orthotropic material that has three main directions (longitudinal, radial and transverse or circumferential). Its elastic behaviour, as for any composite material, is characterized by the material tensor of the elastic compliance which connects the state of the deformations to the state of the constraints in the orthonormal basis $(\vec{L}, \vec{R}, \vec{T})$.

The laws of behaviour applied to rough wood are:

$$\varepsilon_{ij} = S_{ijkl}\sigma_{kl} \tag{1}$$

$$\sigma_{ij} = C_{ijkl}\varepsilon_{kl} \tag{2}$$

In these relationships:
σ_{ij} - the stress tensor,
ε_{ij} - the tensor of the deformations,
S_{ijkl} - the flexibility matrix,
C_{ijkl} - the stiffness tensor.

On the macroscopic scale, wood is considered as linear elastic, homogeneous and cylindrical orthotropic (transverse isotropic). The Young's modulus in the direction i $(\vec{L}, \vec{R}, \vec{T})$ is the ratio of the stress imposed σ_{ij} on the corresponding deformation ε_{ij};

$$E_{ij} = \frac{1}{S_{ij}} \tag{3}$$

From an analysis of the different types of trend curves obtained by drawing the curves Breaking stress - Number of fibres and Young's modulus - Number of fibres from our results of compression tests in the longitudinal direction of the fibres, we choose to use a second-order polynomial evolution for expressing this correlation. The proposed equation is:

$\sigma_{r\,\mathrm{mod}}(N) = a_1 N^2 + b_1 N + c_1$ (For the breaking stress (strength)) (4)

$E_{\mathrm{mod}}(N) = a_2 N^2 + b_2 N + c_2$ (For the Young's modulus) (5)

In these relationships:

$a_1 = \alpha_1 \sigma_m / N_m^2$, $b_1 = \beta_1 \sigma_m / N_m$, $c_1 = \gamma_1 \sigma_m$, $a_2 = \alpha_2 \sigma_m / N_m^2$, $b_2 = \beta_2 \sigma_m / N_m$, $c_2 = \gamma_2 \sigma_m$;

where: σ_m - the mean breaking strength of the extracted fibres in the sapwood and the duramen, respectively (Tab. 3),
N_m - the mean number of the fibres into the tested samples of the sapwood and the duramen, respectively (Tab. 3),
α_1, β_1, γ_1, α_2, β_2 and γ_2 - pure constants which will be determined by numerical adjustment.

In Chad, palmyra laths are widely used as beams in the construction of traditional clothes (Guersoubé 2016). As they contain in their thickness about 1/3 of the sapwood and 2/3 of the duramen (Fig. 4), their mechanical characteristics will be estimated as follows form those of these two parts:

We defined the relative mistake between the mean values experiment and polynomial model by:

$ER_{\sigma r}(\%) = 100(\sigma_{r\exp} - \sigma_{\mathrm{mod}}) / \sigma_{r\exp}$ (For the breaking stress) (6)

$ER_{\sigma r}(\%) = 100(\sigma_{r\exp} - E_{\mathrm{mod}}) / \sigma_{r\exp}$ (For the Young's modulus) (7)

RESULTS AND DISCUSSION

Fig. 5 shows that in the longitudinal direction, the palmyra consists of the fibers embedded in the parenchyma matrix. These fibers are made up of individual cells or base cells. The cells consist of microcrystalline fibrils based on cellulose and connected on an entire layer by lignin and hemicelluloses. Several of these layers are celluloses and lignin stacked together forming multilayer cell walls.

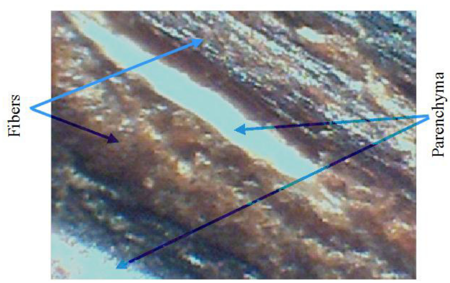


Fig. 5: Longitudinal section of the duramen.

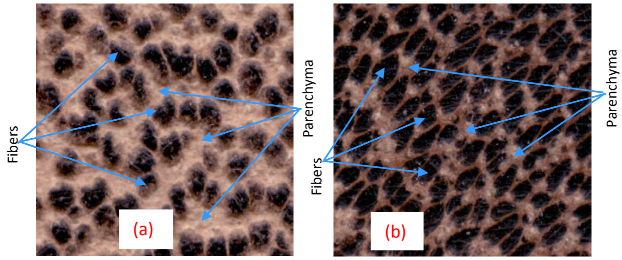


Fig. 6: Perpendicular sections: (a) sapwood, (b) duramen.

Fig. 6 shows the image of a perpendicular section of the sapwood and duramen. We obtain, in average values for a sample of section 2 x 2 cm, 180 fibres for the sapwood (Fig. 6a) and 351 fibres for the duramen (Fig. 6b). The fibers are therefore denser in duramen than in sapwood.

The wood palmyra is constituted of two basic components: the fibers and the parenchyma. The parenchyma constitute a cement (matrix) occupying the space between the fibres which represent the reinforcements of the wood (Fig. 5 and 6). The high rates of the lignin and hemicellulose in the palmyra (Tab. 1) contribute to its resistance. Main constituent of the fiber, cellulose gives the palmyra its structure very dense in fibers and very compact as well as its great resistance to chemical and physical degradations. This resistance to degradation is reinforced by lignin, which is a stable biopolymer with respect to heat and physical and biological modification agents of the cell structure (Felby et al. 2002).

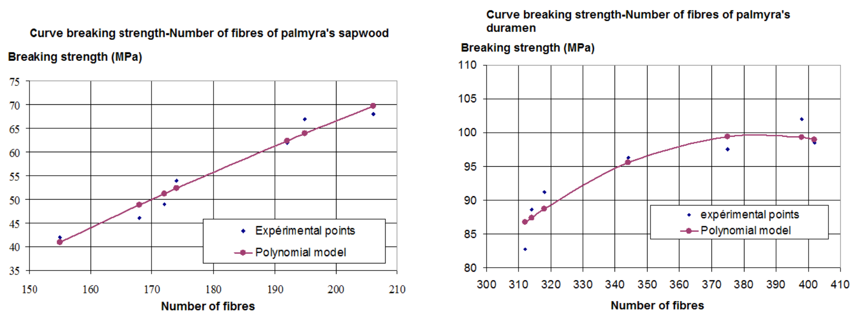
Tab. 3 summarizes the number of the fibers and the density of each sample of sapwood and duramen obtained from duramen and sapwood at 13.2% content moisture. This table shows that the mean density of the duramen is higher than that of the sapwood. This is due to the fact that during the growth of Borassus, its structure densities from outside to inside. At the rate of 12%, it worth is 848.5 kg·m^{-3} for the Duramen and 476.23 kg·m^{-3} for the sapwood. These values make it possible to classify the duramen in the category of heavy wood and sapwood in the category of light wood because its modulus is less than 10 000 MPa. In the longitudinal direction the palmyra is presented as a rigid and resistant material. In the radial direction its resistance is low. In this direction, the microfibrile which are perpendicular to the axis of compressive stress would constitute points of weakness (Ngargueudedjim et al. 2015a, 2016, Ahonou et al. 2004, Boussari 2008, Ahoussinou and Orounla 2010). Moreover, it is observed that the majority of the fibers are oriented along the axis of the trunk. This gives it a fibrous reinforcement in the longitudinal direction and an important value of Young's modulus. The fibers which are not oriented along the axis of the trunk are twisted forming of woody rays, which induce reinforcement in the radial direction (Ngargueudedjim et al. 2015b, Bos et al. 2002).

Tab.3: Tensile strength and Young's modulus of sapwood and duramen in longitudinal compression.

Sapwood								
N° Sample	1	2	3	4	5	6	7	Average
Numbers of fibers	155	168	172	174	192	195	206	180
$\sigma_{rupture}$ (MPa)	42	46	49	54	62	67	68	55.43
E (MPa)	5012	4927	5025	5195	5210	5145	5204	5102.57
Average volume (mm^3)								9614.50 ± 3507.27
Average weight (10^{-3}kg)								4.81 ± 1.48

Duramen								
N° Sample	1	2	3	4	5	6	7	Average
Numbers of fibers	312	314	318	344	375	398	402	351
$\sigma_{rupture}$ (MPa)	82.80	88.60	91.21	96.30	97.52	102.00	98.50	93.85
E (MPa)	6102.70	6004.30	6087.50	6175.15	6248.00	6301.15	6387.50	6186.61
Average volume (mm^3)								9417.00 ± 3462
Average weight (10^{-3}kg)								8.00 ± 3

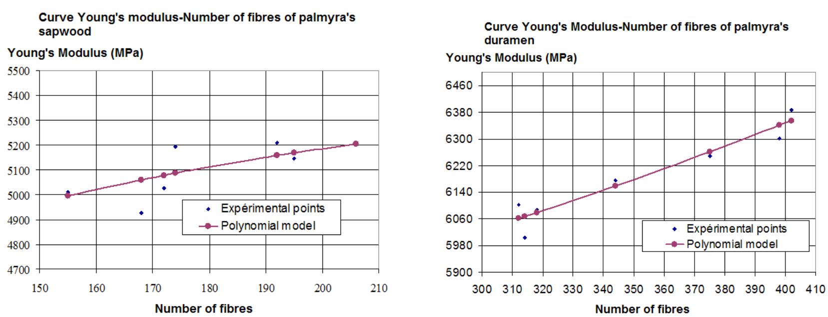
Fig. 7 shows the curves of evolution of the breaking strength of the sapwood and the duramen as a function of the number of fibers.



(a) (b)

Fig. 7: Curves of evolution of the experimental and polynomial breaking strengths in longitudinal compression of the sapwood (a) and the duramen (b) as a function of the number and the mean breaking strength of the fibres of tested samples.

Fig. 8 shows the curves of evolution of the breaking strength of the sapwood and the duramen as a function of the number and the mean breaking strength of the fibres of tested samples. Fig. 9 gives the curves of evolution of the breaking strength and the Young's modulus of the palmyra as a function of the number and the mean breaking strength (a), the number and the man Young's modulus (b) of the fibres of tested samples, respectively.



(a) (b)

Fig. 8: Curves of evolution of the experimental and polynomial Young's modulus in longitudinal compression of the sapwood (a) and the duramen (b) as a function of the number and the mean Young's modulus of the fibres of tested samples.

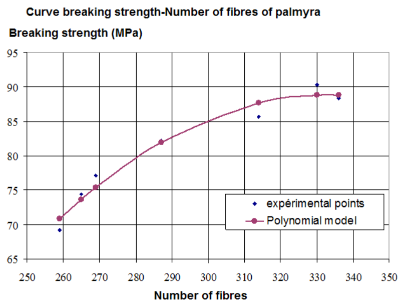


Fig. 9: Curves of evolution of the experimental and polynomial of the breaking strength in longitudinal compression of the palmyra as a function of the number and the breaking strength of fibers of tested samples.

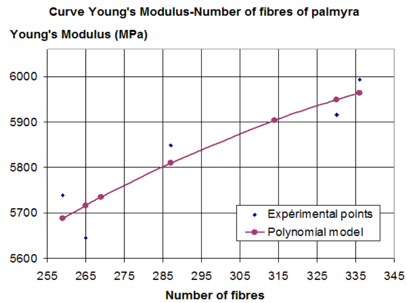


Fig. 10: Curves of evolution of the experimental and polynomial of the Young's modulus in longitudinal compression of the palmyra as a function of the number and the Young's modulus of fibers of tested samples.

Tab. 4: Mean values of mechanical characteristics obtained.

Type of sample	Sapwood			Duramen			Palmyra		
	Experimental value	Polynomial model value	Relative mistake	Experimental value	Polynomial model value	Relative mistake	Experimental value	Polynomial model value	Relative mistake
Breaking strength (MPa)	55.43 ± 10.39	55.63 ± 10.03	0.36%	93.85 ± 6.64	98.01 ± 5.88	4.43%	81.04 ± 7.77	81.00 ± 7.71	0.05%
Young's modulus (MPa)	5102.57 ± 113.44	5107.00 ± 72.61	0.10%	6186.61 ± 133.84	6189.08 ± 128.74	0.40%	5825.27 ± 123.18	5823.75 ± 115.32	0.03%

The values of the relative mistake are in the Tab. 4 shows that the polynomial model may be used validly for determining the breaking strength and the Young's modulus of the palmyra.

CONCLUSION

The determination of the various mechanical characteristics of the palmyra of Chad constitutes an indispensable tool for the implementation of strategies of its rational use. The microscopic study shows that the root wood consists of a matrix and fibers embedded in this matrix. The analysis of the proportion of the fibers shows that the fibers are denser in the duramen than in the sapwood. The different mechanical tests have shown that the duramen is the part of palmyra which resists better than the sapwood in the longitudinal compression. In this study can be concluded that the breaking strength and the Young's modulus of studied palmyra are strongly depend on the number and characteristics of the fibers. The proposed polynomial model of the evolution of the mechanical characteristics gives the good results because the maximum relative mistake of the prediction is less than 5%.

REFERENCES

1. Ahonou, N., Houinsou, S.W., Gbaguidi, A.G., Zohoun, S., 2004: Determination of some physical and mechanical characteristics of *Borassus aethiopum*. DIT memory, EPAC/ UAC (Benin), 103 pp.
2. Ahoussinou, I., Orounla, M., 2010: Theoretical determination of Borassus wood sections in just slightly flexed and loaded beams. Design Engineer memory, EPAC / UAC (Benin), 203 pp.
3. Allarabeye, N., 2010: Structural, physico-chemical and mechanical characterization of the palmyra. Master thesis. University Institute of Sciences and Techniques of Abéché (IUSTA), 59 pp.
4. Bos, H.L., Van Den Oever, M.J.A, Peters, O.C.J.J., 2002: Tensile and compressive properties of flax fibers. Journal of Materials Science 37: 1683-1692.
5. Boussari, A., 2008: Physical and mechanical characterization of wood *Borassus Aethiopum*. Design Engineer memory EPA / UAC (Benin), 203 pp.
6. Detienne, P., 1988: Illustrated course of wood anatomy. Technical Center Forester Tropical. CIRAD, 47 pp.
7. Felby, C., Hassingboe, J., Lund, M., 2002: Pilot-scale production of fiber boards made by laccase oxidized wood fibers. Board properties and evidence for cross-linking of lignin. Enzyme and Microbial Technology 31(6): 736-741.
8. Guersoube, T., 2016: Study of the fiber-mechanical correlation of *Borassus aethiopum* Mart (Palmyra) wood from Chad. Master's thesis, University of Ngaoundéré / University of N'Djamena, 64 pp.
9. Ngargueudedjim, K., Bassan B., Nadjitononn, N., Allarabeyen, N., Annouarn, D.M., Abdel-rahimn, M., Soh Fotsingn, B., Foguen, M., Destrebecqn, J.F., Moutoun, P.R., Jeromen, D., 2015a: Mechanical characteristics of Tall-palm (*Borassus aethiopum* Mart., Arecaceae) of Chad/Central Africa. International Journal of Engineering and Technical Research (IJETR) 3(9): 125-128.
10. Ngargueudedjim, K., Mbayngone, E., Nadjitonon, N., Bassa, B., Allarabeye, N., Destrebecq, J.F., Moutou, P.R., Roudier, A., 2016: Anatomical and chemical characteristics of tall-palm (*Borassus aethiopum* Mart., Arecaceae) of Chad / Central Africa. International Journal of Innovation and Scientific Research 20(1): 129-137.
11. Ngargueudedjim, K., Allarabeye, N., Charles, T.K., Destrebecq, J.F., Moutou, P.R., Robert, J.L, 2015b: Mechanical characteristics of fiber palmyra. Global Journal of Researches in Engineering: G Industrial Engineering 15(3): 14-22.
12. Ngargueudedjim, K., Ngarmaïm, N., Bassa, B., Allarabeye, N., Annouar, D., Abdel-Rahim, M., Soh Fotsing, B., Fogué, M., 2015c : Physical characteristics of tall-palm (*Borassus aethiopum* Mart., *Arecaceae*) of Chad / Central Africa. International Journal of Innovation and Applied Studies 13(3): 553-560. .
13. Samah, O.D., Amey, B.K., Neglo, K., 2015: Determination of mechanical characteristics and reaction to fire of "RÔNIER (*Borassus aethiopum* Mart.) of Togo. African Journal of Environmental Science and Technology 9(2): 80-85.
14. Samah, O.D., Amey, B.K., Vianou, A., Sanya, E., Atcholi, E.K., 2013: Characterization of the palmyra (*Borassus aethiopum*) "Cocker". Caspian Journal: Management and High Technologies 3(23): 140-146.

*Ngargueudedjim Kimtangar, Guersoube Tao
University of N'djamena
Faculty of Exact and Applied Sciences
Laboratory for Study and Research in Industrial Technology
Pb 1027 N'djamena
Chad
Phone: (+235) 66270673/99963448
*Corresponding author: kimta_ernest@yahoo.fr

Guy Edgard Ntamack
University of Ngaoundéré
Department of Physics
Faculty of Sciences
Group of Mechanics, Materials and Acoustics
B.P. 454 Ngaoundéré
Cameroon