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Microwave Characterization of Chadian Palmyra Wood (*Borassus aethiopum*)

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Original Research Article

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Abstract: The palmyra (*Borassus aethiopum*) is a palm native to tropical regions of Africa. It is a tall palm, capable of growing up to 30m high. Its anatomical structure shows that it is a composite material consisting of long fibers visible to the naked eye. The fibers are oriented parallel to the direction of growth of the trunk giving the palmyra a high mechanical resistance. In Chad (Central Africa), its wood is widely used in the construction of traditional and modern houses. Unfortunately, there is very little scientific research about the palmyra characteristics. In this article, we propose a microwave analysis of the anisotropic properties of the palmyra wood aged of about 30 years. A free-space transmission ellipsometry is used for this purpose. The experimental measurements performed at microwave frequency (10 GHz) are presented and discussed.
Keywords: Palmyra (*Borassus aethiopum*), palmyra wood, microwave characterization, ellipsometry, free space method, nondestructive testing, anisotropy.

INTRODUCTION

The palmyra palm whose scientific name is *Borassus aethiopum* is a woody tree of the family of *borassus* that is typically found in Africa in the Sahelian and sub-Sahelian areas [1, 2]. The adult African palmyra includes male and female subjects. Its trunk (or stem) has a cylindrical shape of about 30 to 40 cm in diameter, and can reach 15 to 30 m in height [3]. The palmyra wood is of high mechanical strength and is very resistant to fire and pathogens attack [3, 4].

That is why it is mostly used as frames and structures in traditional and even modern buildings in Africa [3-5]. Recently, it was also used in carpentry, in the manufacture of furniture [5]. In Chad, the Palmyra palm is found in the Sudano-Sahelian zone [6-9]. Even though, this palmyra is widely used in construction work, there are however very few scientific and technical works that have been done to justify its rational and optimal use in Chad.

The aim of this study is to determine the anisotropic properties of the palmyra wood using a free space transmission ellipsometry [10, 11]. We measure the modification of the polarization of the transmitted wave at microwave frequency (10 GHz). The method has an advantage to be nondestructive, contactless and suitable for industrials applications. This study will contribute to develop a database that can be useful for the physico-chemical and mechanical studies of the palmyra which are already undertaken in the LERTI laboratory at the University of N'Djamena (Chad).

MATERIALS AND METHODS

Location and structures of the studied Palmyra wood

This work was done in Chad; an African country located in the Central Africa and lies between latitudes 15°00' North and longitudes 19°00' East.

For this study, the palmyra wood is taken from a male *borassus* of about 30 years old with an average height of 16m in Malfana village (area of Mandalia Local Government, Chad). Malfana is located about 60km in the south of N'Djamena (the capital of Chad) at longitudes 15°15.113' East and latitudes 11°11.771' North (Fig-1).

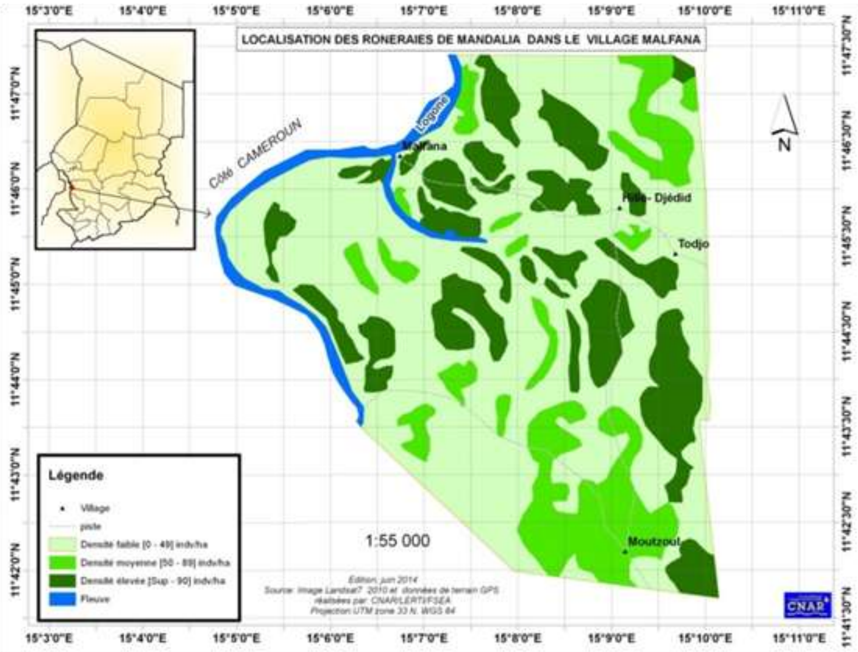

Fig-1: Location of palmyra palms in Malfana village (source CNAR, Chad) [5]

The palmyra wood has a very different anatomical structure than other trees species. Unlike other woods whose heartwood (the very old and hard part of the wood) is in the heart of the trunk, palmyra's heartwood is located between the bark and the sapwood [5]. The inner part (called heart or marrow) is usually soft, whitish and spongy, it rots quickly. The heartwood is mostly dark brown in color, hard, compact, dense and rot-proof. The sapwood structure lies in between the heartwood and the heart. This is shown in figure 2.

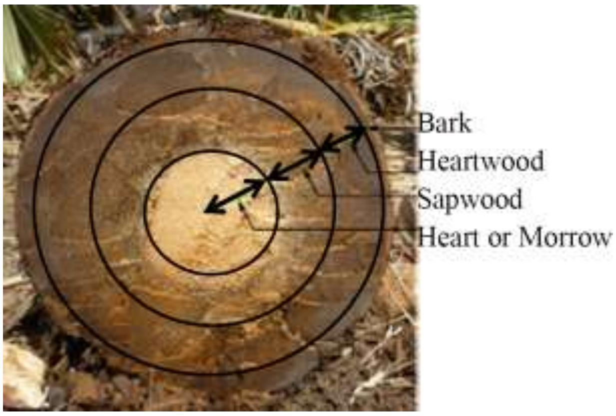

Fig-2: A cross section of the trunk of the Malfana's palmyra tree [9]

Chemical studies of Malfana's palmyra showed that it is essentially constituted of 65.66% of cellulose, 23.66% of lignin, 9.33% of hemicellulose and 1.35% of extractives such as starch and proteins [5].

The useful part of Malfana's palmyra is extended over 8 m and has an average diameter of 34cm. From that part, four blocks of 1.20m were brought for laboratory tests. One of the blocks was used to extract our samples.

Samples preparation

Generally, the description of the wood timber structure requires observation on three perpendiculars planes: the transverse, radial and tangential planes (Fig-3).

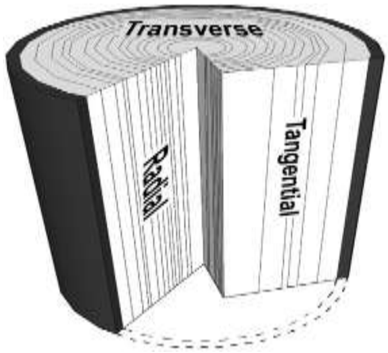

Fig-3: Transverse, radial and tangential planes of the wood timber

For our study, palmyra samples were sawn in the transverse and tangential planes. Four samples were sawn in the tangential plane and two in the transverse plane. The machining of the samples was achieved through a milling machine available in the Mechanical Workshop in the Department of Technology (University of N'Djamena, Chad).

Samples sawn in the tangential plane are rectangular in shape (Fig-4) and are named Tang01, Tang02, Tang03 and Tang04. The three first samples consist of a mixture of heartwood and sapwood while the last one is essentially taken from the bark.

Fig-4: Samples in the tangential plane

Samples sawn in the transverse plane are circular in form (Fig-5) and are named Trans01 and Trans02.

Fig-5: Samples in the transverse plane

Samples dimensions are summarized in Table-1 and Table-2.

Table-1: Dimension of samples in the tangential plane

Samples	Tang01	Tang02	Tang03	Tang04
Thickness (cm)	4	3	1.5	1
Length (cm)	35	30	25	20
Width (cm)	25	25	22	18

Table-2: Dimension of samples in the transverse plane

Samples	Trans01	Trans02
Thickness (cm)	7	4
Diameter (cm)	32	32

Theoretical analysis

Wood is an anisotropic media which anisotropy is characterized by the orientation of its fibers [12-14]. The later are more or less oriented in a single direction. As wood is transparent to microwaves, a linearly polarized wave in the parallel or perpendicular direction to the fibers keeps its polarization but undergoes different attenuation in both directions. But, if this polarization is tilted to a certain angle to the fibers direction, it will decompose into these two directions (parallel and perpendicular to the fibers) resulting in an elliptic polarization [15] (Fig-6**)**. This can be observed using a transmission ellipsometry.

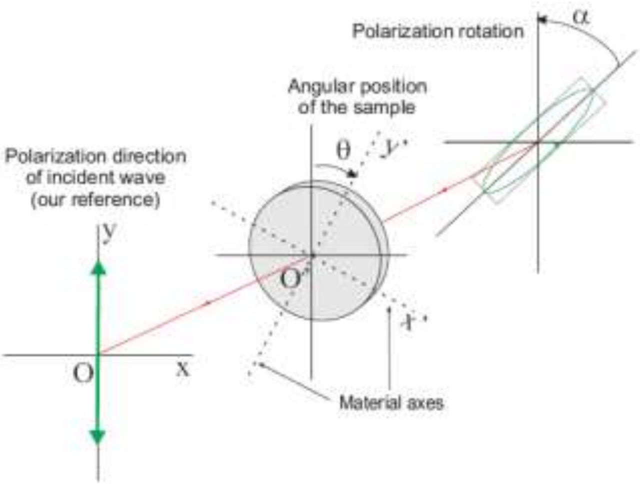

Fig-6: Elliptic polarization in anisotropic media [10]

The two directions known as material axes are related to two different electromagnetic complex indexes $n_1 = n_1^{'} - jn_1^{''}$ and $n_2 = n_2^{'} - jn_2^{''}$. The ratio of the transmission coefficients in the two directions can be expressed in its complex form as:

$$\frac{t_1}{t_2} = \tan\psi \exp(j\delta) \quad (1)$$

Where,

δ: ellipsometric parameter related to the difference in phase;

ψ: ellipsometric parameter related to the difference in magnitude.

These two parameters are also related to the birefringence $\Delta n'$ and the dichroism $\Delta n''$ by:

$$\Delta n' = n_2^{'} - n_1^{'} = \frac{c}{2\pi fd}\delta \quad (2)$$

$$\Delta n'' = n_2^{''} - n_1^{''} = \frac{c}{2\pi fd}\ln(\tan\psi) \quad (3)$$

Where,

f: wave frequency;

d: sample's thickness;

c: speed of light.

The rotation α of the major axis of the ellipse referred to the direction of the incident polarization is given by:

$$\alpha = \frac{1}{2}\arctan\left[\frac{2\tan\theta\tan\psi\cos\delta}{\tan^2\psi - \tan^2\delta}\right] - \theta \quad (4)$$

This model made for homogeneous anisotropic material it here applied to heterogeneous material such as palmyra wood.

EXPERIMENTAL SETUP

The transmission measurement was performed using an ellipsometric workbench made up of a pair of circular horn antennas forming an emitter and a receiver (Fig-7). The measured sample is horizontally placed in between so that its central point is aligned with the antennas axes.

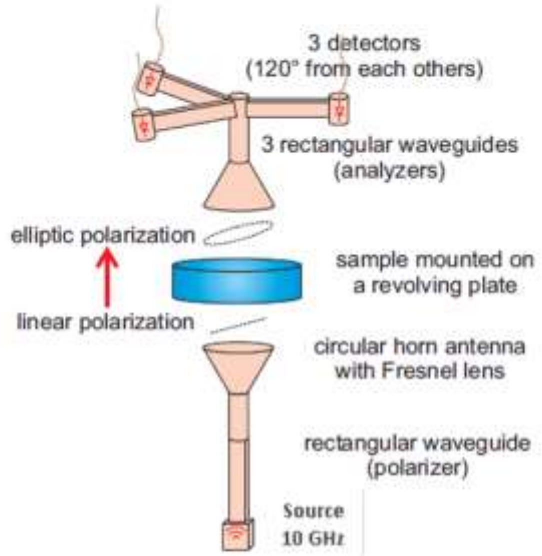

Fig-7: The ellipsometric workbench [10]

The emitter is made of a Gunn source (10 GHz), a rectangular waveguide used as polarizer and a circular horn antenna with Fresnel lens. The rectangular waveguide polarized the electric field **E** of the transmitted wave parallel to its small side, since only the fundamental mode TE_{10} propagates. The resulting beams are then collimated by the Fresnel lens forming a plane wave with a beam width of 16 cm. Thus, at least 20 cm wide samples are needed to avoid the diffraction effects. The dimensions of our samples described above are sufficient for the measurement.

The receiver is also equipped with a circular horn antenna connected to a circular waveguide on which three detectors directed at 120° from each others are perpendicularly connected through portions of rectangular waveguides. Energy is maximal in the detector placed parallel to the direction of the incident polarization. The two other detectors receive quarter of that energy.

The three detectors after their calibration constitute a set of analyzers, which provides the energy of the electric field in each direction (I_1, I_2, and I_3). From these three values it is possible to determine the equation of the ellipse and calculate its rotation α.

Measurement technique

The measurement is based on the changes in the polarization of the transmitted (or incident) plane wave through the sample. When rotating, the sample is located by its angular position θ referred to the direction of the incident polarization (Fig-6). The emergent wave is elliptically polarized and its polarization state is determined from the energy values I_1, I_2, and I_3 of the electric field. Using equation (5), we calculate the rotation α of the emerging wave with respect to the initial direction of the transmitted plane wave for different angular position θ of the sample.

$$\alpha = \frac{1}{2}\arctan\left[\frac{\sqrt{3}(I_3 - I_2)}{2I_1 - I_2 - I_3}\right] \quad (5)$$

A numerical least-square method is then used to find the ellipsometric parameters (δ and ψ) that best fit the model in equation (4). From these parameters, we deduce the anisotropy $\Delta n = n_2 - n_1 = \Delta n' - j\Delta n''$ in the material using equations (2) and (3).

RESULTS AND DISCUSSIONS

The rotation of the emergent polarization α of the samples is measured by the ellipsometric workbench for different angular positions $\theta \in [0°; 720°]$ (i.e. 2 turn with step 10°). The rotations of some few samples are shown in figure 8. The maximal amplitude α_{Max} of these rotations reflects samples anisotropy and their values are summarized in Table-3.

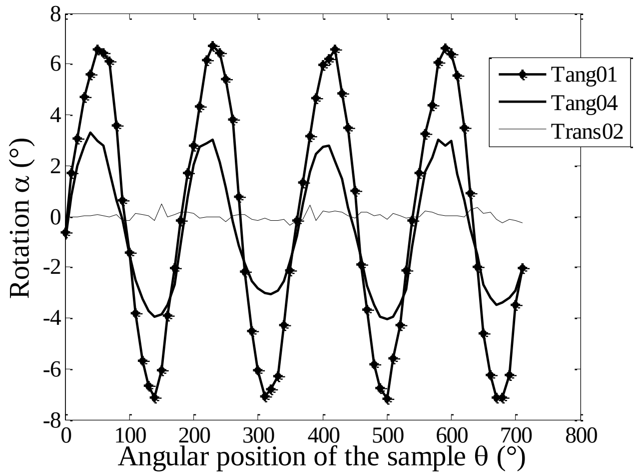

Fig-8: Rotation of the emergent polarization *α* (°) against the angular position of the sample *θ* (°) for samples Tang01, Tang04 and Trans02

Table-3: Samples maximal rotation and anisotropy

Samples	Tang01	Tang02	Tang03	Tang04	Trans01	Trans02
d (cm)	4.0	3.0	1.5	1.0	7.0	4.0
α_{Max} (°)	6.67	5.70	3.08	3.00	0.40	0.20

We can see that samples in the tangential plane have larger maximum rotations (between 3 and 7 degrees) than those in the transverse plane (less than 0.5°).

From this first result, we can qualitatively conclude that samples in the tangential plane show a relatively large anisotropy compared to those in the transverse plane which rather have an isotropic behavior.

In order to determine the rate of anisotropy in the samples, the ellipsometric parameters δ and ψ were found using a least-square method. Rotation curves in Fig-9 and Fig-10 were adjusted using the theoretical model given in equation (4).

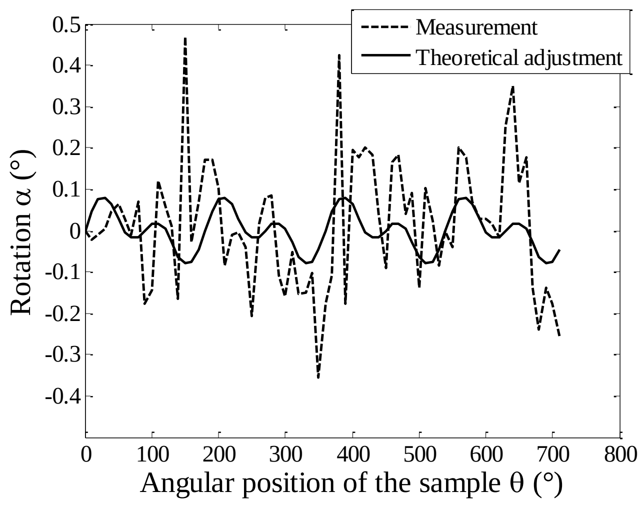

Fig-9: Theoretical adjustment for a sample in the transverse plane (example: sample Trans02).

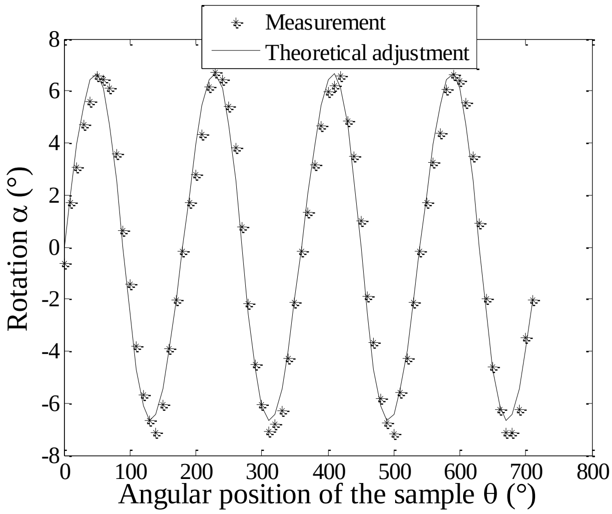

Fig-10: Theoretical adjustment for a sample in the tangential plane (example: sample Tang01).

The sample's anisotropies are summarized in Table 4.

Table-4: Samples anisotropy

Samples	Tang01	Tang02	Tang03	Tang04	Trans01	Trans02
δ (°)	0.0008	0.0016	-0.0100	11.5047	-0.0039	4.7229
ψ (°)	51.6371	50.3542	47.5412	48.3560	44.8487	45.0452
$\Delta n'$	0.0000	0.0000	0.0000	0.0958	0.0000	0.0098
$\Delta n''$	0.0279	0.0299	0.0282	0.0560	-0.0003	0.0001

Figure-9 shows a theoretical adjustment for sample Trans02 in the transverse plane. The adjusted curve does not match the measured one; this is normal because sample Trans02 behaves like an isotropic material and does not match the model. Nevertheless, the numerical program runs normally for several values of δ and ψ starting near 0° and 45° and the result is given in Table-4. Samples in the transverse plane (i.e. Trans01 and Trans02) have low values of $\Delta n'$ and $\Delta n''$ close to zero. This confirms the isotropic nature of these two samples.

Figure-10 shows a theoretical adjustment for sample Tang01 in the tangential plane. The consistency between the measurement and the adjustment is significant for samples in the tangential plane. Values of δ and ψ that best fit the curves were obtained. These values enabled us to calculate the dichroism $\Delta n'$ and the birefringence $\Delta n''$ for all the samples in the tangential plane. Their values are given in Table-4. From that table, we can see that the characteristic of samples Tang01, Tang02 and Tang03 are virtually identical since their anisotropy is almost the same ($\Delta n'$=0 with an average $\Delta n''$ of 0.0287). This is normal because these three samples were all taken from a mixture of heartwood and sapwood. However, sample Tang04 has a different characteristic than the three others ($\Delta n'$=0.0958 and $\Delta n''$=0.0560) because it was exclusively taken from the bark.

This method enables us to differentiate two types of wood, one taken from the bark and another from a mixture of hardwood and sapwood.

CONCLUSION

In this paper, we have presented an experimental result on palmyra wood sawn in the tangential and transverse planes. The measurements were performed using a transmission ellipsometry at microwave frequency (10 GHz).

The variation of the rotation of the emergent wave against the rotation of the samples allowed us to observe a very low rotation in the transverse plane and a high rotation in the tangential plane. The values of the measured maximum rotations allowed us to highlight the presence of a strong anisotropy in samples in the tangential plane compared to those in the transverse plane which have rather an isotropic behavior.

The adjustment of these rotations with theoretical curves enabled us to extract the ellipsometric parameters of each samples and allowed us to assess the rate of anisotropy in the palmyra wood through the values of the birefringence and the dichroism. This has enabled us to differentiate the palmyra wood from the bark to those from heartwood and sapwood. Further work on the palmyra wood might be focused on the correlation of ellipsometric results with mechanical Young's modulus data.

For a complete characterization of the palmyra wood, an absolute index measurement must be carried out. But this requires a more complex measurement techniques and theoretical analysis that are currently undertaken in the Hubert Curien laboratory. The aim is to develop a non-destructive measurement system that no needs sample preparation.

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