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EXPERIMENTAL CHARACTERISATION OF THE MECHANICAL PROPERTIES AND MICROSTRUCTURE OF ACROCOMIA MEXICANA FRUIT FROM THE YUCATAN PENINSULA IN MEXICO

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ABSTRACT

A study of the mechanical properties and microstructure at different drying conditions of the Cocoyol fruit endocarp of Acrocomia Mexicana palm found in the Yucatan Peninsula in Mexico was performed. Quasi-static uniaxial compression was carried out on endocarp samples. The experimental results showed that the fruit exhibited an average peak force and displacement at failure of 4.23 kN and 2.43 mm, respectively. The average energy absorbed by the fruits before failure was 6.06 J. Optical and scanning electron microscopy of cross-sections of the equatorial region revealed that the endocarp has complex hierarchical structure. The micrographs showed that the structure is made of bundles of randomly oriented tubes and bubble-like cells, showing entangled network of hollow micro channels, which are in the order of tens of microns. The results and the microstructure presented herein encourage further research for bioinspired man-made materials.

KEYWORDS

Biomaterial, acrocomia, peak-force-at-failure, microstructure.

INTRODUCTION

The demand for new materials, which possess outstanding mechanical performance and are lightweight, for modern engineering applications is growing rapidly. Innovative engineering design is necessary to address the competing constraints of light weight on one hand, and high strength on the other hand. Structural biological materials such as wood, bone and abalone shells, are an excellent source for inspiration (Barthelat 2007) considering that evolutionary developments have resulted in high-performance lightweight composites structures, made of relatively weak and mundane constituents (Meyers et al. 2008; Espinosa et al. 2009). Bioinspired materials design has gained considerable interest during the past decade, mainly due to the growth of interdisciplinary interactions between biologists, chemists, physicists and materials scientists (Chen et al. 2012).

Many biological materials have outstanding mechanical performance due to their hierarchical structure that spans several scales. An example of a hierarchical structured material is nacre, commonly known as the mother-of-pearl, which is a natural multi-layered composite material that have excellent mechanical properties due to its brick-like structure, the waviness of the layers and the multiple interfaces between layers (Espinosa et al. 2009). A recent study shows that nacre structure can be used as inspiration for protective man-made structures (Flores-Johnson et al. 2014).

Hierarchical structure in fruit walls has already been reported as a mechanism that promotes energy absorption and these fruit structures are models for the design of impact resistance materials (Seidel et al. 2010). Pomelo (Citrus Maxima) can dissipate considerable amounts of kinetic energy due to its foam-like peel that have regular arrangement of vascular bundles and interconnected cells (Thielen et al. 2013). Hierarchical structure in macadamia nutshells containing randomly oriented bundles of several rod-like cells has been also reported (Jennings and Macmillan 1986; Wang and Mai 1994).

Macaw palm (*Acrocomia aculeata* (Jacq.) Lodd. ex Martius), from the palm family Arecaceae, is widely distributed in the American continent including Mexico, Antilles, Brazil, Argentina, Uruguay and Paraguay (Moura et al. 2009). This palm has been extensively studied because its fruits can generate more than 5000 kg of oil per hectare (Moura et al. 2009) that can be used as biofuel. Although it is well known that the endocarp of the this fruit is extremely hard (Ribeiro et al. 2011), its mechanical properties have not been investigated.

This work is motivated by the lack of knowledge in the study of the mechanical properties and microstructure of the Cocoyol fruit, from the palm family Arecaceae, found in the Yucatan Peninsula in Mexico. The present paper addresses this problem by presenting a study of the uniaxial compression behaviour and the microstructure of this fruit.

MATERIALS AND METHODS

Fruit Specimens

Cocoyol fruit (*Acrocomia Mexicana* Karw. ex Mart. (Colunga-GarcíaMarín and Zizumbo-Villarreal 2004)) racemes, commonly found in the Yucatan Peninsula (Ramírez Hernández et al. 2013), were harvested from trees located 50-km east from Merida, Mexico, the capital city of Yucatan state (Fig. 1). Thirty-six fruits of similar size were selected and divided into four groups. Three groups were separately dried at 80 °C in an oven for 24, 48 and 72 h. After drying, exocarp and mesocarp were removed from around the endocarp, which was used for the compression test (Fig. 2). The fruit endocarp had an average diameter of 21.72±0.54 mm. Figure 2 shows the cross-section of the fruits for illustration purposes; however, whole specimens were used for the compression test described in the next Section.

Compression Test

Unconfined uniaxial compression tests were carried out on a universal testing machine (Shimadzu AG-1), equipped with a 100-kN load cell. The tests were performed at room temperature at a cross-head speed of 5 mm/min. This methodology has been used to test other palm fruits (Visalberghi et al. 2008) and also nutshells (Braga et al. 1999; Ogunsina et al. 2008). The energy absorbed was determined by measuring the area under the force-deformation curve, from the origin to the failure point.

Microscopy

Surface examination of the samples was performed using an optical microscope using two different magnifications, i.e., 60X and 200X. Samples for microscope were prepared by sanding the surface of the cross-section with 1500 grit SiC abrasive paper. Scanning electron microscopy (SEM) was also performed on fracture surfaces using a JEOL JSM-6360 LV.

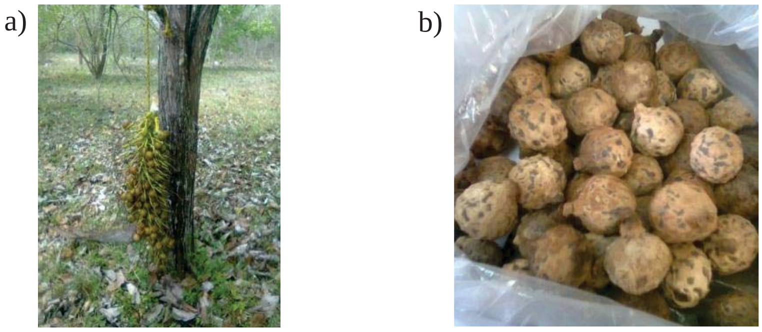

Figure 1. a) Cocoyol fruit raceme; b) Cocoyol fruits after drying and peeling.

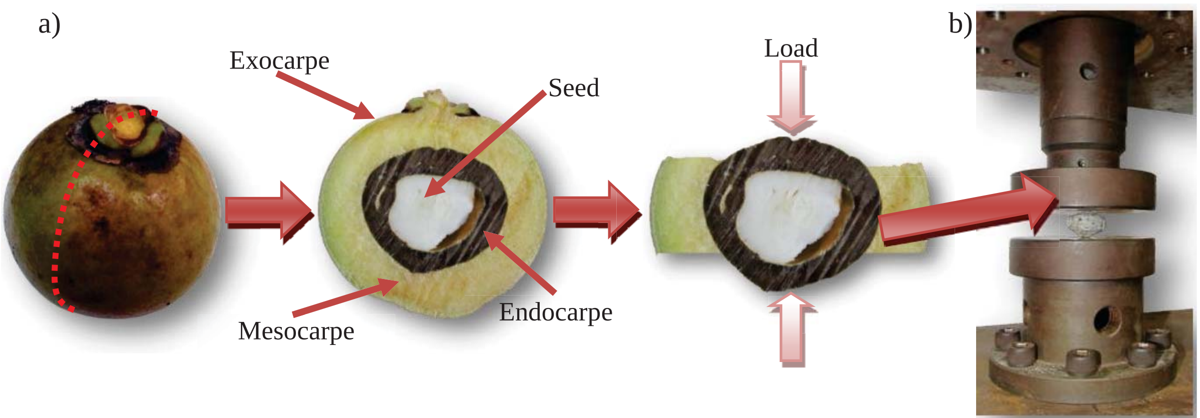

Figure 2. a) Cross-section of Cocoyol fruit for compression test; b) Compression tests setup.

RESULTS AND DISCUSSION

Compression Tests

Figure 3 shows typical load (*F)* versus displacement (*d)* curves for different drying conditions. It can be seen that the peak load and displacement at failure are somewhat similar. Each curve consists of an initial apparent elastic regime ($0<d<1$), followed by an apparent plastic region with lower stiffness ($0<d<2.5$), which terminates catastrophically indicating failure of the fruit. Table 1 shows the mechanical properties obtained for different drying condition groups (9 samples per group). It can be seen from Table 1 that the drying conditions does not affect substantially the mechanical properties of the fruit; however, slightly better performance is observed for the non-dried fruits.

In Fig. 3, typical force-displacement curves for Dika (Ogunsina et al. 2008) and Dura (Koya and Faborode 2005) nuts are also shown. Table 2 shows the mechanical and geometrical properties of these nuts, the Cocoyol fruit and the Tucum fruit (Visalberghi et al. 2008). It can be seen that the Cocoyol has the highest peak load at failure and stiffness. The absorbed energy for the cocoyol is less than that for the Dika nut; however the Cocoyol has the lowest shell thickness and the lowest diameter. A qualitative comparison of the nuts performance is reported in Table 2. For these types of nuts, it has been reported that a larger cracking force is required for larger diameters (Koya and Faborode 2005; Visalberghi et al. 2008). Hence, the Cocoyol has a very good performance.

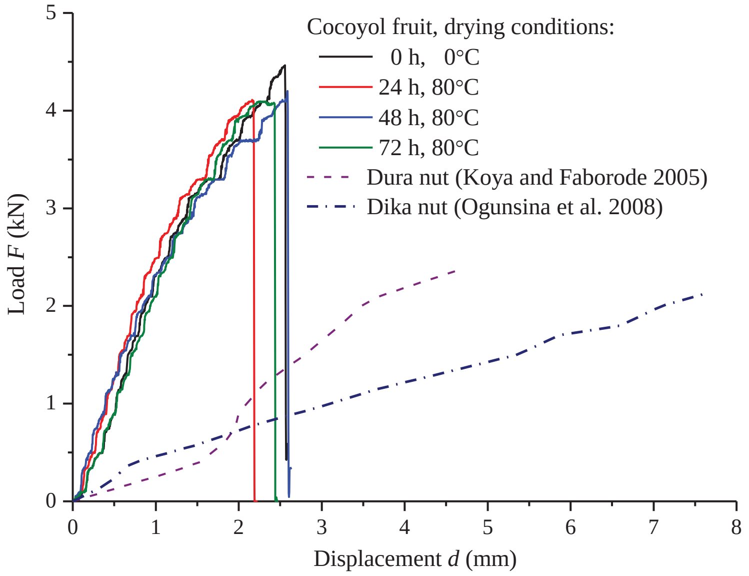

Figure 3. Typical uniaxial compression load-displacement curves for various drying conditions.

Table 1. Mechanical properties.

Drying conditions	Maximum load (kN)	Maximum displacement (mm)	Absorbed energy (J)
0h, 0 °C	4.58±0.41	2.53±0.45	6.83±1.05
24h, 80 °C	4.30±0.53	2.25±0.28	5.47±1.19
48h, 80 °C	4.12±0.43	2.55±0.38	6.15±1.54
72h, 80 °C	4.15±0.19	2.38±0.54	5.80±1.19

Table 2. Geometrical and mechanical properties of Cocoyol fruit, Dura nut (Koya and Faborode 2005), Dika nut (Ogunsina et al. 2008) and Tucum fruit (Visalberghi et al. 2008).

Fruit	Average geometric diameter (mm)	Shell thickness (mm)	Max. load (kN)	Max. displacement (mm)	Absorbed energy (J)
Cocoyol	21.72	3.01	4.58	2.53	6.83
Dura nut	27.70	3.30	2.25	~4.6	~5.6
Dika nut	28.65	3.03	2.06	~8.5	8.7
Tucum	28.16	4.12	4.15	-	-

Microscopy

Figure 4 shows micrographs of the cross-section of the fruit. It can be seen that microstructure consists of bundles of randomly oriented tubes and bubble-like cells, showing entangled network of hollow microchannels, which are in the order of tens of microns. A similar microstructure has been reported for macadamia nuts (Jennings and Macmillan 1986; Wang and Mai 1994). Figure 5a shows a SEM image of the fruit surface, in which, well-defined microchannels and bubble-like cells can be seen. Figure 5b shows a SEM image of a fracture surface after testing. It can be seen that the microchannels are hollow in the top-left area of the image; however, the microchannels seem to be solid in the left-bottom area of the image. It is believed that the microchannels have a finite length as suggested in Figures 4d and 5a, and that depending on the loading conditions, the fruit walls may fracture either at the microchannels walls or at the boundary between adjacent cells.

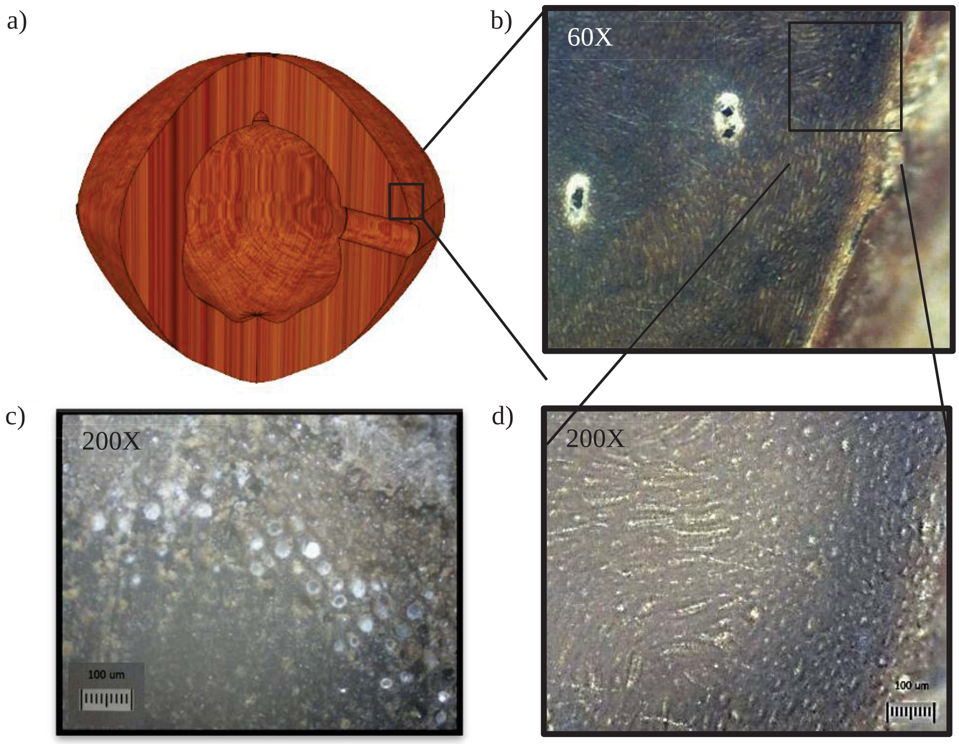

Figure 4. a) Schematic of fruit endocarp; b) optical micrograph of the cross-section (magnification 60X); c) optical micrograph of the cross-section showing hollow bubbles (magnification 200X); d) optical micrograph of the cross-section showing tubes and bubble-like cells (magnification 200X).

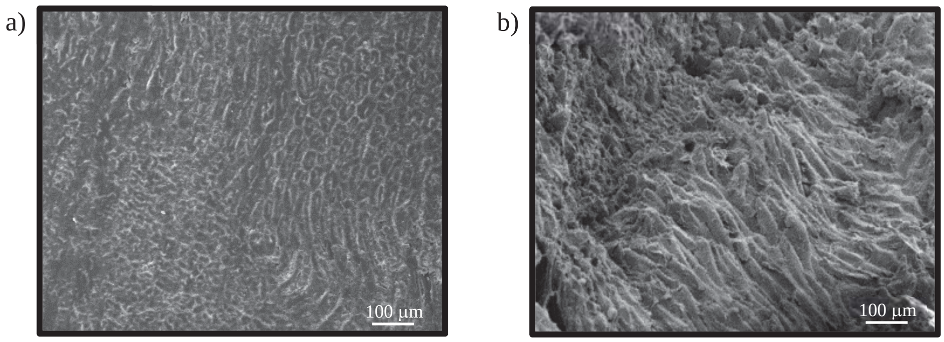

Figure 5. SEM micrographs of fruit endocarp: a) cross-section; b) fracture surface.

CONCLUSIONS

A study of the mechanical properties and microstructure at different drying conditions of the Acrocomia Mexicana palm fruit found in Yucatan Peninsula, Mexico was presented. Quasi-static compression results showed that the fruit exhibit an average peak force and displacement at failure of 4.23 kN and 2.43 mm, respectively, and an average energy absorbed at failure of 6.06 J. The average peak force was higher than that of similar fruits compared herein. Optical and scanning electron microscopy of cross-sections of the equatorial region revealed that the endocarp has a complex hierarchical structure made of bundles of randomly oriented tubes and bubble-like cells. The results and the microstructure presented herein encourage further research for bioinspired man-made materials.

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