Influence of moisture content and loading orientation on some mechanical properties of *Mucuna flagellipes* nut

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Abstract

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The effects of moisture content and loading orientation on some strength properties of *Mucuna flagellipes* nut namely, bioyield, yield and rupture points; bioyield, compressive and rupture strengths; and moduli of elasticity, resilience, toughness and stiffness were determined at lateral and longitudinal axial loading, using a Testometric Universal Testing Machine (UTM). In the moisture range of 3.38–10.7% (d.b.), bioyield, yield and rupture points of the nut decreased from 1,137 to 755 N, 1,157 to 790 N and 685 to 365 N, respectively, when loading was on the lateral axis, and increased from 1,090 to 1,888 N, 1,092 to 1,918 N and 420 to 1,215 N on longitudinal loading. Bioyield strength (1.83–1.41 N/mm^2), compressive strength (1.85–1.44 N/mm^2) and rupture strength (1.03–0.74 N/mm^2), decreased with increase in moisture content under lateral loading, but increased from 4.05 to 8.17 N/mm^2, 4.15 to 8.45 N/mm^2 and 2.6 to 6.3 N/mm^2, respectively, as the moisture content increased in the above range, under longitudinal loading. The elasticity, toughness and stiffness moduli of the nut decreased (23–16.6 N/mm^2, 0.615–0.525 J and 272.8–250 N/mm, respectively) with increase in moisture content under lateral loading, and increased (34.5–66.56 N/mm^2, 0.508–0.69 J and 246–369 N/mm, respectively) with moisture content on longitudinal loading. On the above loading orientations, modulus of resilience increased from 0.166 to 0.355 J, and 0.255 to 0.576 J respectively, with moisture content. The properties were higher on the longitudinal than lateral axial loading. Second order polynomial equations relating these properties to moisture content were established.

Keywords: bioyield; compressive tests; modulus of elasticity; rupture; strength properties; Nigeria

Mucuna flagellipes is a climbing tree crop that belongs to the legume family Fabaceae. It is found mainly in the Tropical Rainforest of Nigeria and was noted to be grown as an important food crop in other parts of Africa and Asia (Dako, Hill 1977; Iyayi, Egharevba 1998). The nut contains a kernel with approximately 20% protein and 70% carbohydrate and an oil content of 3.77% (Ajayi et al. 2006). The kernel therefore serves as a very good source of protein and edible oil. Gum extracted from *Mucuna flagellipes* kernel was shown to possess high emulsion properties and pseudoplasticity (Onweluzo et al. 2004), which suggests its suitability as a stabilizer and emulsifier in oil-water emulsions like mayonnaise and salad dressings as well as in meat emulsions and as thickening agent in foods (Nwokocha, Williams 2009). As a result, the flour of *Mucuna flagellipes* kernel is usually applied as a thickening agent in soups (Anumnu 1990; Ene-Obong, Carnovale 1992; Versteeg et al. 1998).

The processing of *Mucuna flagellipes* nut involves cracking it using a hard object to extract the kernel. This is then boiled in water, ground and mixed with palm oil to form a yellow loose powder which is packaged in transparent polyethylene bags for marketing or use as thickening agent in soup. The present methods of carrying out the above operations are not only labour and time consuming but also wasteful. A proper understanding of the mechanical properties of *Mucuna flagellipes* nut is necessary in the design and development of its postharvest processing machines and equipment.

Several investigators (ANAZODO 1982; ANAZODO, CHIKWENDU 1983; DINRIFO, FABORODE 1993; ABBOTT, MASSIE 1995; CENKOWSKI et al. 1995; ABBOTT, LU 1996; KING 1996; MAW et al. 1996; KHAZAEI, MANN 2004; MAMMAN et al. 2005; RYBINSKI et al. 2009; AVIARA, AJIKASHILE 2011; MANUWA, MUHAMMAD 2011) studied the mechanical properties of different agricultural and food materials. ANAZODO and NORRIS (1981) noted that the modulus of elasticity, crushing strength and modulus of toughness of corncob decreased with increase in moisture content. MISRA and YOUNG (1981) showed the modulus of elasticity of soya bean decreased parabolically with increase in moisture content. Similar results were reported for cowpea (PAPPAS et al. 1988), yellow dent corn kernels (WAANANEN, OKOS 1988), cashew nuts (OLOSO, CLARKE 1993) and wheat (KANG et al. 1995).

AVIARA et al. (2010) studied the moisture dependent physical properties of *Mucuna flagellipes* nut relevant in bulk handling and mechanical processing but little information appears to exist on the moisture dependence of the nut's mechanical properties. The objective of this study was therefore to determine the mechanical properties of *Mucuna flagellipes* nut and investigate their variation with moisture content and loading orientation. The mechanical properties include bioyield, yield and rupture points; bioyield, compressive and rupture strengths, moduli of elasticity, resilience, toughness and stiffness.

MATERIAL AND METHODS

Sample preparation

For the purpose of this work, a bulk quantity of *Mucuna flagellipes* nut at stable market storage moisture condition was purchased from the Monday market, Maiduguri, Nigeria. The nuts were cleaned and graded by hand picking to separate the good from the damaged ones. The separated nuts were preserved at the initial moisture condition by storing them in air tight polythene bags.

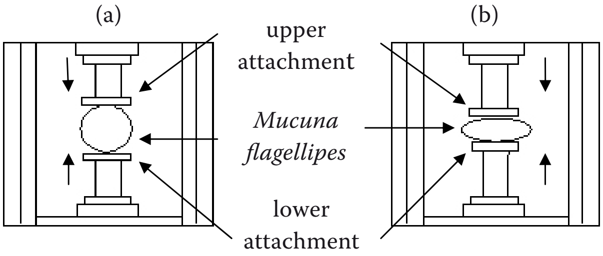

Fig. 1. Compression of *Mucuna flagellipes* nut at (a) longitudinal and (b) lateral loading orientations using the Universal Testing Machine

Moisture content of *Mucuna flagellipes* nut was determined using the oven method described by AVIARA et al. (1999). Samples were dried in an oven set at 105°C for 7 h. Four moisture levels were used to investigate the effect of moisture content on the mechanical properties. Nut samples of desired moisture levels were prepared by conditioning the samples using the method of EZEIKE (1986). This involved soaking of different bulk samples in clean water for a period of 1–4 h, but for *Mucuna flagellipes*, soaking was carried out for 16, 32 and 48 h, because trial tests suggested that below these periods of time, no appreciable moisture variation would be obtained. Soaking was then followed by spreading the samples out in a thin layer to dry in natural air for about eight hours. After this, the samples were sealed in polyethylene bags and stored in that condition for a further 24 h. This enabled stable and uniform moisture content of the samples to be achieved.

Experimental procedure

Compression tests were conducted on nuts at different moisture levels using a Testometric Universal Testing Machine (UTM) (Testometric Company Ltd., Lancashire, UK) controlled by a micro-computer. Two loading orientations namely longitudinal (Fig. 1a) and lateral (Fig. 1b) were used. The nuts were compressed at the cross head speed of 10 mm/min. As the compression began and progressed, a load-deformation curve was plotted automatically in relation to the response of each nut to compression. Thirty randomly selected nuts were tested at each loading orientation and nut moisture content. This was replicated three times. The load-deformation curves obtained were analyzed for:

(1) bioyield point, yield point and rupture point;
(2) bioyield strength, compressive strength, rupture strength;
(3) modulus of elasticity, modulus of stiffness, modulus of resilience and modulus of toughness.

Bioyield was the point on the force-deformation curve at which the compressed nut shell weakened and failed internally without cracking outwardly. At this point, an increase in deformation resulted from either a decrease or no change in force (Mohsenin 1986) and the nut was considered to have failed in its internal cellular structure (Anazodo 1982). Yield point was the point on the force-deformation curve at which the nut shell just began to tear (Aviara et al. 2007). Rupture point was the point on the force deformation curve at which the nut shell completely got broken and torn with the kernel exposed (Anazodo 1982; Mohsenin 1986).

Bioyield strength was taken as the stress at which the nut shell failed in its internal cellular structure. Compressive strength was the stress at which the nut shell began to tear. Rupture strength was taken as the stress at which the nut shell got completely broken.

Modulus of elasticity was taken as the ratio of the stress to the strain up to bioyield. Modulus of stiffness was determined as the ratio of the average maximum force to the average maximum deformation at failure (Dinrifo, Faborode 1993). It was calculated from the force-deformation data of *Mucuna flagellipes* nut following the method reported by Mamman et al. (2005) and Aviara et al. (2007). The modulus of resilience which is the area under the force-deformation curve up to bioyield (Zoerb, Hall 1960; Mohsenin, Gohlich 1962) was determined from the force-deformation curve using a similar method to that of Haque et al. (2001). Modulus of toughness which is the area under the force-deformation curve up to failure (Zoerb, Hall 1960; Mohsenin, Gohlich 1962) was determined from the force-deformation curve using a similar method to that which was followed by Haque et al. (2001). The average of each property at both loading orientations was determined and regressed against moisture content.

RESULTS AND DISCUSSION

Mechanical property – moisture content relationship

This work was carried out within the *Mucuna flagellipes* nut moisture range of 3.38–10.70% (d.b.). The values of the mechanical properties of the nut were found to be a function of moisture content. The relationships existing between the properties and moisture content at both lateral and longitudinal loading orientations were best expressed using polynomial equations of the second order. These equations are of the form

$$Y = a + bK + cK^2 \qquad (1)$$

where:

Y – mechanical property
a, b, c – regression coefficients
K – moisture content (%, d.b.)

The coefficients of term in the equation for each property are presented in Table 1. The equations were found to have very high coefficients of determination ($R^2 > 0.9$), which indicate that they described the relationships reasonably.

Bioyield, yield and rupture points

The bioyield, yield and rupture points of *Mucuna flagellipes* nut at different moisture contents and axis of loading are presented in Table 2. Under lateral loading, the bioyield, yield and rupture points of the nut decreased from 1,137 to 755 N, 1,157 to 790 N and 685 to 365 N, respectively as the moisture content increased from 3.38 to 10.7% (d.b.). On the longitudinal orientation, the bioyield, yield and rupture points of the nut increased from 1,090 to 1,888N, 1,092 to 1,918 N and 420 to 1,215 N in the above moisture range. The values of bioyield, yield and rupture points suggest that the nut would require lesser force level to get it cracked when loaded on the lateral axis than on the longitudinal axis. Second order polynomial equations with coefficients of term presented in Table 1, gave the best fit for the relationship existing between the bioyield, yield and rupture points and nut moisture content at different loading axes.

Bioyield, compressive and rupture strengths

The bioyield, compressive and rupture strengths of the nut at different moisture contents and loading orientation are presented in Table 2. From this Table, it can be seen that the bioyield, compressive and rupture strengths of the nut decreased from 1.83 to 1.41 N/mm^2, 1.85 to 1.44 N/mm^2 and 1.03 to 0.74 N/mm^2, respec-

Table 1. Coefficients of terms in the general equation expressing the mechanical properties of *Mucuna flagellipes* nut as a function of moisture content (%, d.b.)

Property	Loading orientation	Coefficients			R^2
		a	*b*	*c*	
Bioyield point (N)	lateral	+1.824	−258.1	+14.90	0.963
	longitudinal	−57.31	+421.7	−22.59	0.981
Yield point (N)	lateral	+1.779	−241.6	+14.04	0.963
	longitudinal	−112.3	+442.7	−23.82	0.98
Rupture point (N)	lateral	+1.156	−172.6	+9.272	0.989
	longitudinal	−894.5	+490.2	−27.61	0.969
Bioyield strength (N/mm^2)	lateral	+2.762	−0.357	+0.021	0.967
	longitudinal	−2.779	+2.547	+0.143	0.969
Compressive strength (N/mm^2)	lateral	+2.804	−0.362	+0.022	0.961
	longitudinal	−2.745	+2.562	−0.142	0.937
Rupture strength (N/mm^2)	lateral	+1.540	−0.189	+0.010	0.988
	longitudinal	−2.945	+2.043	−0.111	0.982
Modulus of elasticity (N/mm^2)	lateral	+33.23	−3.779	+0.209	0.985
	longitudinal	−12.09	+17.10	−0.917	0.985
Modulus of resilience (J)	lateral	−0.176	+0.128	−0.007	0.97
	longitudinal	−0.184	+0.160	−0.008	0.981
Modulus of toughness (J)	lateral	+0.745	−0.047	−0.002	0.988
	longitudinal	+0.267	0.086	−0.004	0.994
Modulus of stiffness (N/mm)	lateral	+301.1	−10.21	+0.510	0.994
	longitudinal	+56.91	+69.94	−3.84	0.978

tively with increase in moisture content under lateral loading. On the other hand and under longitudinal loading, the properties increased with increase in moisture content from 4.05 to 8.17 N/mm^2 (bioyield strength), 4.15 to 8.45 N/mm^2 (compressive strength) and 2.6 to 6.3 N/mm^2 (rupture strength). The strength of *Mucuna flagellipes* nut was higher on longitudinal loading than at lateral loading. This may be due to smaller contact areas that occurred during loading on the longitudinal axis and it confirms the higher resistance of the nut to cracking expected at this loading orientation. The relationship existing between the bioyield, compressive and rupture strengths of the nut can be adequately represented by second order polynomial equations with the coefficients of term presented in Table 1.

Moduli of elasticity, toughness and stiffness

The moduli of elasticity, toughness and stiffness of *Mucuna flagellipes* nut in the moisture range 3.38–10.7% (d.b.) and at different loading orientation are presented in Table 2. For lateral loading, the moduli of elasticity, toughness and stiffness decreased from 23 to 16.6 N/mm^2, 0.615 to 0.525 J and 272.8 to 250 N/mm, respectively, as the nut moisture content increased in the above range. Under longitudinal loading, the moduli of elasticity, toughness and stiffness increased from 34.5 to 66.56 N/mm^2, 0.508 to 0.69 J and 246 to 369 N/mm respectively, in the above moisture range.

The relationship existing between the moduli of elasticity, toughness and stiffness of the nut and moisture content at different axis of loading could be expressed using the second order polynomial equations with coefficients of term presented in Table 1.

Modulus of resilience

Table 2 also shows that the modulus of resilience of *Mucuna flagellipes* nut increased from 0.166 to 0.355 J for lateral loading and from 0.255 to 0.576 J

Table 2. Mechanical properties of *Mucuna flagellipes* nut at different moisture contents and loading orientations

Properties	Moisture content (%, d.b.)							
	lateral loading				longitudinal loading			
	3.38	5.75	8.28	10.7	3.38	5.75	8.28	10.7
Bioyield point (N)	1,137 (2.87)*	792 (0.28)	750 (0.310)	755 (0.11)	1,090 (1.45)	1,678 (1.12)	1,829 (1.04)	1,888 (1.5)
Yield point (N)	1,157 (1.15)	817 (0.41)	780 (0.22)	790 (0.07)	1,092 (1.07)	1,708 (1.23)	1,858 (1.17)	1,918 (1.28)
Rupture Point (N)	685 (0.42)	453 (0.5)	380 (0.14)	365 (0.09)	420 (1.16)	1,088 (1.2)	1,195 (1.08)	1,215 (1.14)
Bioyield strength (N/mm^2)	1.83 (0.03)	1.38 (0.01)	1.34 (0.01)	1.41 (0.025)	4.05 (0.2)	7.52 (0.04)	8.07 (0.012)	8.17 (0.05)
Compressive strength (N/mm^2)	1.85 (0.015)	1.4 (0.02)	1.37 (0.01)	1.44 (0.02)	4.15 (0.02)	7.65 (0.1)	8.3 (0.042)	8.45 (0.015)
Rupture strength (N/mm^2)	1.03 (0.004)	0.79 (0.001)	0.728 (0.001)	0.74 (0.002)	2.6 (0.008)	5.4 (0.1)	6.1 (0.02)	6.3 (0.04)
Modulus of elasticity (N/mm^2)	23 (0.011)	18 (0.02)	16.7 (0.01)	16.6 (0.018)	34.5 (0.01)	58 (0.022)	64.54 (0.011)	66.56 (0.022)
Modulus of toughness (J)	0.615 (0.004)	0.55 (0.001)	0.53 (0.001)	0.525 (0.001)	0.508 (0.001)	0.627 (0.002)	0.675 (0.001)	0.69 (0.001)
Modulus of stiffness (N/mm)	272.8 (1.02)	258.4 (1.01)	252.5 (1.01)	250 (0.98)	246 (1.01)	342 (0.88)	363 (1.02)	369 (1.01)
Modulus of resilience (J)	0.166 (0.003)	0.335 (0.001)	0.36 (0.001)	0.355 (0.001)	0.255 (0.001)	0.484 (0.003)	0.545 (0.003)	0.576 (0.001)

numbers in parentheses are standard deviations

for longitudinal loading in the moisture range of 3.38–10.7% (d.b.).

The relationship existing between modulus of resilience and nut moisture content was found to be parabolic. This result would be helpful in determining the ability of the nuts to withstand loading on each other during storage. Second order polynomial equations with coefficients of term presented in Table 1, were found to appropriately describe the relationship existing between modulus of resilience and the nut moisture content during compressive loading on both lateral and longitudinal orientations.

Generalization of the effect of moisture content and loading orientation on the mechanical properties of *Mucuna flagellipes* nut

The results reported in this study show that moisture content and axis of loading have substantial influence on the mechanical properties of *Mucuna flagellipes* nut. All the mechanical properties showed similar trend with increase in moisture content by decreasing when loaded laterally and increasing when loaded longitudinally except the modulus of resilience that increased under both loading orientations. Similar relationships between moisture content and some mechanical properties under lateral and longitudinal loading orientations were reported by Anazodo and Norris (1981), Misra and Young (1981), Oloso and Clarke (1993), Kang et al. (1995) and Mamman et al. (2005) for corn cob, soy beans, cashew nuts, wheat and *Balanites aegyptiaca* nuts, respectively. Second order polynomial models relating each of the properties to nut moisture content confirmed the behavior of the mechanical properties. At all moisture levels, the mechanical properties studied were higher when the nut was loaded longitudinally than when it was loaded axially. This could imply that the binding forces within the nut shell may be weaker at the lateral axis than at the longitudinal axis; hence the nut would be easier to crack when loaded laterally.

The decrease of the mechanical properties of the nut with moisture content under lateral loading suggests that to save energy and make for high efficiency, the nut should be cracked at high moisture contents. But cracking at high moisture contents could crush the kernels and result in reduction in quality. Since product quality is very important, it may be recommended that the nut should be cracked on lateral orientation at low moisture content between 5.75 and 8.28% (d.b.), so that intact kernels could be obtained, because within this moisture range, it was observed that the minima and maxima values of the properties occurred.

CONCLUSIONS

The investigation of the mechanical properties of *Mucuna flagellipes* nut revealed the following.

(1) Bioyield, yield and rupture points as well as bioyield, compressive and rupture strengths of the nut decreased parabolically under lateral loading and increased under longitudinal loading as the moisture content increased within the range of 3.38–10.7% (d.b.).

(2) Moduli of elasticity, toughness and stiffness decreased with increase in moisture content under lateral loading, and increased with moisture content at longitudinal loading.

(3) The modulus of resilience of the nut increased with increase in moisture content under both lateral and longitudinal loading orientations.

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