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Strain Energy Variability as a Function of Moisture Content, Pre-heating Temperature and Loading Rate on African nutmeg (*Monodora myristica*) Seed During Cracking

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Abstract: In this study, the behaviour of strain energy as influenced by moisture content, preheating temperature, and loading rate on African nutmeg seed during cracking was investigated. Using nonlinear regression analysis, empirical models were developed and validated; and these models compared favorably with the experimental data. Furthermore, an analysis of variance indicated that, all three independent variables had a main significant effect on strain energy at 95% confidence level. Therefore, for effective energy utilization and optimum quality assurance, 14% moisture content and 100ºC preheating temperature of the seeds at a loading rate of 2.5 mm/min is recommended.

Key words: African nutmeg, moisture content, preheating temperature, strain energy

INTRODUCTION

One of the intrinsic characteristics of biomaterials, essential to processing, is their viscoelastic behaviour. This unique attribute, as manifested in the load-deformation regime, is needed for predicting the energy requirements, particularly, in the cracking process of seeds and nuts (Burubai *et al.*, 2007). Cracking as a macroscopic phenomena, is a failure of a material which does not necessarily imply the breaking up of that material into pieces but the fracture of molecular bonds dictated by small imperfections at a given level of stress (Vincent, 1999; Hiller and Jeronimides, 1996; Burubai, 2009). Extensive studies show that, for a crack to propagate, energy in form of strain must be provided. This strain energy, otherwise called toughness, is that energy absorbed by the seeds or nuts prior to seed coat rupture per unit of seed volume (Kamyab *et al*., 1998). The concept of fracture mechanics has proposed three modes of tissue failure for biomaterials: cell wall rupture; intercellular debonding and cell relaxation due to migration of the fluids out of the cells during compression (Schoorl and Holt, 1983; McGary, 1993). Moreover, recent research reveals that, the strain energy needed to attain the above modes of tissue failure in biomaterials is dependent on several factors which includes moisture content, loading rate and pre-heating temperature (Khazaei and Mann, 2004); therefore understanding the implications of these conditioning variables on strain energy is not only vital to fruit cracking but for system optimization purposes.

However, African nutmeg (*Monodora myristica*) seed, which has cracking to extract the kernel as its most difficult unit operation, is one of the most important condiments in the West African cuisines. But this time-and-energy consuming unit operation (cracking) is, yet to be mechanized, to reduce the drudgery associated with it because there is lack of scientific information on the influence of certain basic conditioning variables on the toughness of African nutmeg seeds. It is therefore the objective of this study to investigate the effects of moisture content, loading rates and pre-heating temperature on the strain energy (toughness) of African nutmeg seeds during cracking.

MATERIALS AND METHODS

Bulk quantities of fresh African nutmeg seeds were obtained from the popular Sabagreia market in Bayelsa State of Nigeria on the 12th of September, 2010; and the seeds sorted to remove the damaged ones and the remainder stored for experimentation. All experiments were conducted at the National Centre for Agricultural Mechanization (NCAM), Ilorin, Kwara State, Nigeria and an Instron Universal Testing Machine (M4400, Instron Limited, England) controlled by a microcomputer

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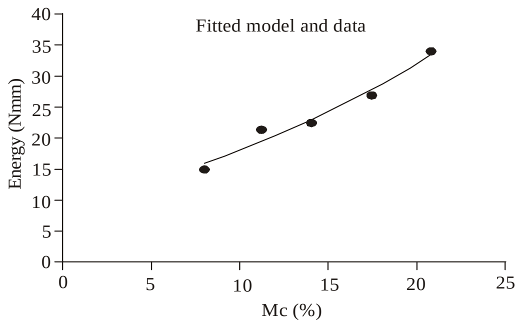

Fig. 1: Experimental and predicted values of strain energy at different moisture contents

Table 1: Summary of statistical output

a: Goodness of fit coefficients					
R (coeff of correlation)				0.984	
R^2 (coeff of determination)				0.968	
SSR				6.374	
b: Anova					
	df	SS	MS	Fisher's F	Pr>F
Regression	1	191.1	191.1	74.92	0.0032
Residual	3	7.651	2.55		
Total	4	198.8			
c: Model parameters					
Parameters		Value		SD	
pr1		1.24		4562269.508	
pr2		0.043		286983.598	
pr3		- 0.222		855856.180	
pr4		1.244		4562269.469	
pr5		0.043		286983.601	
pr6		- 0.222		855856.165	

was used for the compression tests to ascertain the variability of strain energy as influence by the processing variables.

For the effect of moisture content to be studied, five moisture levels of 8.0, 11.2, 14.0, 17.4 and 20.7% (db) at which the nuts (seeds) could be easily cracked were determined using the methods employed by Oje (1993) and Aviara *et al.* (2000). A set of ten samples were then drawn from each of the determined moisture levels and quasi-statically compressed in an axial orientation between two parallel plates, in the Universal Testing Machine (UTM), to evaluate the effect of moisture on strain energy. A loading rate of 2.5 mm/min was applied as described in ASAE standard (S368.4, 2000) and the response data automatically generated from the integrators.

Also, to investigate the effects of loading rates, loading tests were conducted at 1.0, 2.5, 4.0, 5.5, and 7.0 mm/min at 14% (db) moisture level as recommended by ASAE Standard (S368.4, 2000) and applied by Khazaei and Mann (2004). Compression tests were quasi-statically performed between two parallel plates on ten samples for each of the selected loading rates. As testing progressed, data on response of each seed strain energy was automatically obtained from the recorder.

For the influence of preheating temperature, a temperature-controlled heating rig (MTL1, NCAM, Nig), with a cylindrical barrel heating chamber was used. Preheating temperatures of 60, 100, 140, 180 and 220ºC at 14% moisture level and 2.5 mm/min loading rate were selected based on those used by Vincent (1999) and Khazaei and Mann (2004). The thermostat was preset at the required preheating temperature level and allowed to stabilize. Ten samples were then preheated at each of the temperature levels for a constant period of 5minutes. On completion of heating, samples were immediately removed and compressed with the UTM at the specified loading rate. This was done in conformity with ASAE Standard (S368.4, 2000) and data on the variability of strain energy (toughness) was recorded on the integrator until the specimen failed.

Data analysis: The raw data obtained from the experiment was analyzed using the nonlinear regression procedure of Xlstat software (version 10) to generate the models and the coefficients of determination (R^2). Furthermore, an analysis of variance (Anova) was also conducted to ascertain the variability of the regression line at 95% level of probability.

RESULTS AND DISCUSSION

Effect of moisture content on strain energy: As shown in Fig. 1, the increase in moisture content, generally, had a positive correlation with strain energy. At a moisture level of 8.0%, a corresponding strain energy value of 15.1 N.mm was recorded. This strain energy value increased to 34.1 N.mm at a moisture level of 20.7%.This energy absorbing ability may be due to the fibrous nature of African nutmeg seed which on receiving moisture probably improves its dampening effect.

The coefficient of determination (R^2 = 0.968) obtain from the goodness of fit test as indicated in Table 1a

Table 1d: Predictions and residuals

Observations	Weights	MC(%)	Energy (Nmm)	Energy (Model)	Residuals	Standardized residuals
Obs1	1	8.00	15.100	15.969	- 0.323	- 0.202
Obs2	1	11.2	21.600	19.613	1.752	1.097
Obs3	1	14.0	22.500	23.169	- 1.220	- 0.764
Obs4	1	17.4	27.100	28.073	- 1.322	- 0.828
Obs5	1	20.7	34.100	33.572	1.114	0.698

Durbin-Watson statistic: d = 2.494

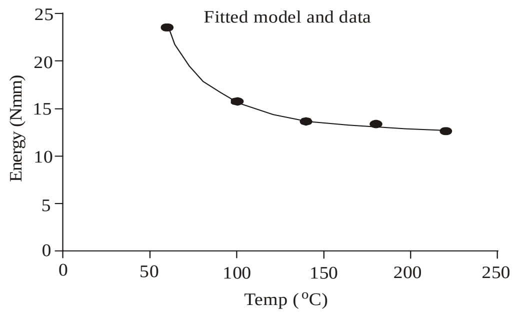

Fig. 2: Experimental and predicted values of strain energy as influenced by temperature

Table 2: Summary of statistical output

a: Goodness of fit coefficients					
R (coeff of correlation)					0.999
R^2 (coeff of determination)					0.998
SSR					0.145
b: Anova					
Source	df	SS	MS	Fisher's F	Pr>F
Model	1	57.6	57.6	7.89	0.067
Residuals	3	21.9	7.3		
Total	4	79.5			

c: Model parameters		
Parameters	Value	SD
pr1	12.02	0.940
pr2	2.303	1.815
pr3	7.57	448.183
pr4	1347.7	175591.349

d: Predictions and residuals					
Observations	Weights	Temp. (ºC)	Energy (Nmm)	Energy (Nmm) (Model)	Residuals
Obs1	1	60.00	023.300	23.305	- 0.005
Obs2	1	100.000	15.600	15.525	0.075
Obs3	1	140.000	13.400	13.641	- 0.241
Obs4	1	180.000	13.200	12.932	0.268
Obs5	1	220.000	12.500	12.597	- 0.097

Durbin-Watson statistic: d =1.637

showsthat 96.8% of the variability of strain energy of African nutmeg seed during cracking is influenced by the amount of moisture present in the seed. An analysis of variance (Anova), in Table 1b, also reveals that since the calculated Fishers F (71.27) is greater than the tabular $F_{0.05,1,3}$(0.0032) value, a highly significant regression of strain energy on moisture content is declared. Mathematically, the developed model for effect of moisture on strain energy is given in Eq. (1) and parameters (pr1 to pr6) are shown in Table 1c, Strain energy

(N.mm) = Exp (pr1+MC*pr2)/ (MC + 1)
^pr3+Exp(pr4+MC*pr5)/(MC + 1)^pr6 (1)
$R^2 = 0.968$

Furthermore, to ascertain the validity of Eq. (1), prediction of strain energy as influence by moisture was made and the predicted values compared favorably with the experimental data (Table 1d). These results are similar to those reported on the effects of moisture content on the physical properties of some agricultural products (Aviara *et al.*, 2000; Khazaei and Mann, 2004).

Effects of pre-heating temperature on strain energy: Figure 2 shows the converse relationship which existed between preheating temperature and strain energy. This means increasing the preheating temperature of African nutmeg seeds during cracking, generally, decreases the strain energy values. Thus, at 60ºC, strain energy of 23.3 N.mm was obtained; this value then declined to 12.5 N.mm, at a corresponding temperature of 220ºC. Various reasons could be attributed to this trend: firstly, African nutmeg seed is composed of cellulose micro-fibrils embedded in an amorphous matrix of hemicelluloses, proteins, lipids and pectic substances. The cellulose micro-fibrils give rigidity and resistance to tearing of the cell walls, while the hemicelluloses, lipids and pectic substances confer plasticity to it which allows it to stretch and absorb energy. Therefore, on application of heat, depolymerization of these celluloses, lipids and pectic substances occurs as exudes of oily substances were observed on the surfaces of the seeds between preheating temperatures of 140-220ºC, thereby making the seeds to loose their cellular integrity and potential toughness (strain energy); secondly, the negative trend could be ascribed to loss of turgor pressure which is responsible for keeping cell walls in a state of elastic stress. This is because, as more heat is applied to the seed, moisture which is occluded in the interstices of the seed is forced to escape either by capillarity or diffusion, and this dehydration phenomenon increases the friability and brittleness of the seeds.

However, in order to ascertain the validity of this negative correlation, an analysis of variance (anova) was conducted. Anova summary in Table 2b shows, that, there is a significant main effect of temperature on strain energy as $F_{cal} = 7.890$ is greater than $F_{0.05,1,3} = 0.06735$, $p<0.05$. The goodness of fit results in Table 2a also indicated a value for coefficient of determination of $R^2 = 0.989$, and this reveals that 98.9% of strain energy is accounted for by preheating temperature. Consequently, the empirical model developed through nonlinear regression is as indicated in Eq. (2) and the parameters (pr1 to pr4) given in Table 2c,

Strain energy (N.mm) = pr1+ (pr4-pr1)/
(1+ (Temp/pr3)^pr2) (2)
$R^2 = 0.989$

These findings are consistent with the investigations of Ramana *et al*. (1992) and Mamman and Umar (2005).

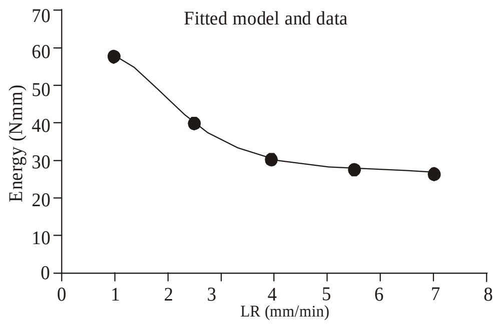

Fig. 3: Experimental and predicted values of strain energy at different loading rates

Table 3: Summary of statistical output

a: Goodness of fit coefficients

R (coeff of correlation)	1.000
R^2 (coeff of determination)	0.999
SSR	0.383

b: Anova

Source	df	SS	MS	Fisher's F	Pr > F
Model	1	562.500	562.500	13.51	0.03
Residuals	3	124.840	41.613		
Total	4	687.340			

c: Model parameters

Parameters	Value	Standard deviation
pr1	26.1	0.580
pr2	3.2	0.385
pr3	2.22	0.062
pr4	60.5	1.043

d: Predictions and residuals

Observations	Weights	LR (mm/min)	Energy (Nmm)	Energy (Nmm) (Model)	Residuals	Standardized residuals
Obs1	1	1.000	58.200	58.203	-0.003	1.008
Obs2	1	2.500	40.100	40.067	0.033	-0.636
Obs3	1	4.000	30.300	30.514	-0.214	-0.992
Obs4	1	5.500	28.300	27.809	0.491	-0.140
Obs5	1	7.000	26.600	26.907	-0.307	0.760

Durbin-Watson statistic: d =1.454

Effect of loading rate on strain energy: The influence of loading rate (otherwise called speed of loading) on strain energy is clearly depicted in Fig. 3. Results have it that, as loading rate increased, strain energy values also responsively decreased. Thus, at 1.0 mm/min, a corresponding strain energy value of 38.2 N.mm was noted. This value decreased to 26.6 N.mm as loading rate was raised to 7.0 mm/min. An explanation to this converse development is that, loading rate is directly proportional to the applied force. Therefore, as loading rate is increased, the unit seed volume is left with lesser time to absorb the resultant energy.

Nonlinear regression statistics in Table 3a also shows that, 99.9% of the variability of strain energy is seriously influenced by loading rate as the coefficient of determination, R^2 is 0.999. Anova summary in Table 3b further confirms this observation, that loading rate has a significant main effect on strain energy since the calculated Fisher's $F_{cal} = 13.52$ is greater than $F_{0.05,1,3} = 0.0348$, $p<0.05$.

The empirical model developed from nonlinear regression for this behaviour is given in Eq. (1) and parameters (pr1 to pr4) in Table 3c as,

$$\text{Strain energy (N.mm)} = pr1 + (pr4 - pr1) / (1 + (LR/pr3)^{\wedge}pr2) \quad (3)$$

$$R^2 = 0.999$$

Results and observations made in this study are in consonance with the works of Bilanski (1966) and Khazaei and Mann (2004), who variously investigated the effects of loading rate on soya beans and sea buckthorn berries respectively.

Technological implications of this study: In an attempt to mechanize the processing of African nutmeg seed, certain vital conditioning variables must be investigated, as they play a crucial role not only to system optimization, but product quality assurance. Essentially, this study has revealed the variability of African nutmeg seed toughness as dictated by changes in seed moisture content, preheating temperature and subsequent loading speeds on the processing bench. It is therefore advised, that, designers of African nutmeg process machines take information herein provided, seriously, because this will aid both energy selection and monetary cost.

CONCLUSION

This study investigated the effect of moisture content, preheating temperature and loading rates on strain energy. It was observed that;

- All the three variables tested had significant main effect on strain energy.
- For proper energy utilization and optimum quality assurance, seed moisture level should be 14% (db).
- A preheating temperature of 100ºC for the seeds at a loading rate of 2.5 mm/min should also be adopted by African nutmeg processors and agricultural engineers in their bid to design cracking machines for this viable crop.

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