Effect of moisture content on some mechanical and frictional properties of mucuna bean (mucuna crens) relevant to its cracking

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Abstract: Some mechanical properties of mucuna bean seed were studied at different moisture levels to provide relevant data for development of cracking machine for the seed. The frictional coefficient of the seed on five structural surfaces (plywood, aluminum, glass, steel, and wood) was determined using the incline plane method. The mechanical properties were determined using a Universal Testing Machine. The coefficients of friction of the seed on the respective structural surfaces were observed to have increased with increasing moisture levels. The force to crack the seed on its major axis decreased from 1595.1 to 244.9 N as moisture level increased from 4.79% to 18.53% (dry basis), with a similar trend also observed on the minor axis. The deformation on both axes decreased as moisture level increased. The stress on the major and minor axes respectively increased from 2.79 to 21.61 N mm^{-2} and 5.12 to 21.01 N mm^{-2}, as moisture level decreased. The force required to crack the seed and energy to break on both axes decreased as moisture level increased. The stress on the major and minor axes increased with moisture level. Regression equations were used to establish relationship between the properties measured and the moisture level of the seed.

Keywords: moisture content, coefficient of friction, cracking force, energy to break, stress, deformation

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1 Introduction

Mucuna bean seed is of huge nutritional and medicinal potential. It is dominant in tropical regions of Africa and Asia. The seed and hair of the bean pod have been widely used traditionally and commercially for various purposes in Nigeria and the by extension West Africa. Mucuna bean can be harvested and consumed by humans for the following medicinal purposes: prevention of kidney stones, blood cleansing, treatment of urinary tract infection, the expulsion of excessive gases from the body system, stimulation of the central nervous system, reduction of blood pressure in humans, menstrual cycle stimulation, and also as a worm expeller. Lampariello et al. (2012) in their study, opined that a similar product (velvet bean) is rich in crude protein, essential fatty acids, starch and amino acids. They also reported that anti-microbial properties of the seed may be potent in the treatment of skin diseases. Janardhanan et al. (2003) also studied the nutritional properties of five varieties of the mucuna seed in India. Their findings revealed some anti-nutrients present in the seed such as L-Dopa and phytic acid. A study on some engineering properties of the seed is essential, considering the high demand for the seed in the market for consumption as food by humans and other applications. The traditional means of cracking the seed involves soaking in water for a

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period of two to four days, before the pods are easily removed. The process is quite tedious and time-consuming, and it is believed to be the reason why some locals have lost interest in post-harvest processing of the seed, despite its huge food and medicinal value. Figure 1 shows an array of the seed after harvesting.

Figure 1 Mucuna bean seeds

The ability to efficiently designing a mechanical device for cracking of the seed is dependent on knowledge of the engineering properties of the seed. Altuntaş et al. (2004) studied some physical properties of Fenugreek seed. Mohite et al. (2019) also studied the influence of moisture content on some engineering properties of tamarind seed. The moisture content of the seed will also play a key role since the seeds are usually soaked in water for days. The frictional properties of agricultural bio-materials which include angle of repose, and coefficient of friction are essential in the design of hoppers for agricultural and food processing machines.

Many authors have reported the coefficient of friction of agricultural materials on different structural surfaces, such as Fathollahzadeh and Rajabipour (2008) for wild pistachio, Özarslan (2002) for cotton, Dursun and Dursun (2005) for caper seed, Gupta and Das (1997) for sunflower, and Baryeh and Mangope (2003) for pigeon pea. Many others have also analyzed these properties as a function of moisture levels: Adejumo et al. (2005) for okra; Tunde-Akintunde et al. (2007) for melon; Shafiee et al. (2009) for dragon head seed; Wandkar et al. (2012) for soyabean; Esref (2007) for lentil and Ozturk and Esen (2008) for barley. Tavakoli et al. (2009) in studying moisture dependent engineering properties of barley observed that the static coefficient of friction of the grains increased linearly against various structural surfaces (plywood, glass, and galvanized iron steel) as moisture content increased. This agreed with the findings of Koocheki et al. (2007) for watermelon seed and Karimi et al. (2009) for tiger nut. Malik and Saini (2016) examined the effect of dehulling and moisture content on engineering properties of sunflower seed and reported that the coefficient of friction was highest on plywood as structural surface (0.69) at a moisture level of 25% (dry basis) and lowest when glass was used as structural surface (0.28) at a moisture level of 7.6% (dry basis). Aderinlewo et al. (2018) studied some physical and mechanical properties of the shell and kernel of Nigerian Dura and Tenera oil palm varieties. Their findings revealed that the coefficient of friction ranged from 0.59 to 0.80 on the four respective structural surfaces used (galvanized steel, mild steel, plywood, and plastic) at a moisture level of 4.5% and 5.0% for the shell and kernel. Alibas and Koksai (2015) in examining the effect of moisture content on physical, mechanical, and rheological properties of soyabean seed observed that the coefficient of friction on aluminum, stainless steel, galvanized iron, glass, and plywood increased with increasing moisture content. Togo et al. (2018) also reported a similar trend in his study of selected physical and mechanical properties of Alfalfa seed. Bamgboye and Adejumo (2011) studied some mechanical properties of roselle seed as a function of moisture content. The behavior of the grain due to compression was analyzed using a software texture analyzer. It was also observed that the mechanical properties of the seed increased with an increase in moisture content (8.8% to 10%) dry basis.

The compressive force, yield stress and young's modulus increased from 23.45 to 49.05 N, 17.0 to 38.15 N mm^{-2} and 216.03 to 374.11 N mm^{-2} respectively with the increasing moisture level. A similar trend was obtained by Ahmadi et al. (2009) for apricot. Taheri-Garavand et al. (2012) reported that the rupture force and energy of hemp seed decreased from 36.65 to 18.67 N and 10.25 to 5.4 mJ^{-1} respectively as moisture level increased from 5.39% to 27.12% (dry basis). Awolu and Oluwafemi (2013) while examining the effect of moisture content on the mechanical properties of Dika fruit and nut, reported variation in force at peak, deformation at peak, energy at peak, deformation at break, energy at break, force to break and young's modulus, as moisture level of the fruit increased from 5% to 20% (dry basis). Shashikumar et al. (2018) in studying the influence of moisture content and compression axis on Physico-chemical properties of *Shorea robusta* seeds observed that at a moisture variation of 6.38% to 21.95% (dry basis), the values of hardness, deformation at hardness and energy for rupture were higher in the minor than the major axis. Oduma et al. (2016) reported that the rupture force of African Oil Bean seed decreased with increase in moisture content, while the seed was observed to deform more with increase in moisture content. Palilo et al. (2018) studied some physical and mechanical properties of selected common beans.

2 Materials and methods

Fresh samples of the seed were obtained from a local market in Uyo, Akwa Ibom State Nigeria. The seeds were manually clean to remove foreign materials and dirt. Hundreds of samples were randomly selected for various experiments by employing a random sampling method, as utilized by Alonge and Etim (2011) in their study on African Oil Bean Seed. Experiments were conducted at the National Center for Agricultural Mechanization (NCAM), Ilorin, and the Department of Agricultural and Food Engineering of the University of Uyo. The moisture content of the seed was determined using the ASABE standard. A laboratory oven (Binder ED 56 Model) was used to dry the various samples at six different levels to enable analysis of the effect of moisture content on the mechanical properties of the seed. The initial weight (g) of the seed was determined using an electronic weighing balance (NANBEI – NBT A200 Model) of 0.0lg sensitivity. The moisture content was determined from the relationship in equation1:

$$Moisture\ Content\ (M.C.\%\ dry\ basis) = \frac{Initial\ Weight\ (g) - Final\ Weight\ (g)}{Final\ Weight\ (g)} \quad (1)$$

The coefficient of friction of the seed on different structural surfaces was determined using the inclined plane method (Palilo et al, 2018; Onwe et al., 2020). The five structural surfaces used were; electroplated steel, plywood, glass, aluminum, and rough wood. As the seeds were placed on each of the structural surfaces, the inclined plane was gradually raised and the angle of inclination at which the seed began sliding was read off.

The tangent of the tilt angle was reported as the coefficient of friction of the seed.

$$\mu = tan\,\theta \quad (2)$$

where, μ = Coefficient of friction, and

θ = tilt angle of the friction device in degrees.

Mechanical properties were determined by the use of a Universal Testing Machine (UTM – Instron 3382, 100KN Floor Model), which was connected to a display monitor. The resistance of the seed to compression was determined. The method involved subjecting individual seeds to compression in its natural resting position on the major and minor axes. The seeds were loaded between two parallel flat plates at a compression speed of 3 mm min-1 as shown in Figure 2.

Figure 2 Cracking of the seed by compression using a UTM

Oduma et al. (2016) in a similar study for African oil bean seed used 2.5mm min^{-1}. The behavior of the seed to compression was analysed with the aid of the software texture analyzer. The software graphic interface produced force deformation curves for various treatments and showed eventual rupture of the seed with the variation of forces during deformation. Mechanical properties of the seed namely: force to crack on major and minor axes of the seed; deformation on the major and minor axis of the seed; stress on the major and minor axes of the seed; and energy to break upon cracking on the major and minor axes of the seed were obtained from the graphical display of the texture analyzer. This method was utilized by Bamgboye and Adejumo (2011) for roselle seed and Onwe et al. (2020) for African star apple. All experiments were conducted at six moisture levels and replicated thrice. Analysis of variance (ANOVA) and comparison of means was performed using the EXCEL Program. The relationship between the properties of the seed and moisture levels were established. Model coefficients were determined by using EXCEL routines. The coefficient of determination (R^2) was also obtained. The effect of moisture content on these properties was also analyzed.

Table 1 Analysis of variance on coefficient of friction of the seed

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	0.008	4	0	2.18	0.101	2.76
Within Groups	0.024	25	0			
Total	0.032	29				

3 Results and discussion

3.1 Coefficient of friction

The coefficient of friction of the seed increased as moisture level increased. The values ranged from 0.25 to 0.277 (plywood), 0.231 to 0.298 (aluminum), 0.205 to 0.287 (glass), 0.218 to 0.313 (galvanized steel) and 0.249 to 0.329 (rough wood). Plywood and aluminum as structural surfaces had a friction coefficient of 0.205, while rough wood recorded the highest as 0.329. Mathematical relationships linking the coefficient of friction on different structural surfaces with moisture levels were established as in Equations 3 to 7:

$$\mu_p = 0.005m + 0.183\ (R^2 = 0.992) \tag{3}$$

$$\mu_a = 0.004m + 0.213\ (R^2 = 0.93) \tag{4}$$

$$\mu_g = 0.006m + 0.17\ (R^2 = 0.983) \tag{5}$$

$$\mu_s = 0.006m + 0.19\ (R^2 = 0.993) \tag{6}$$

$$\mu_w = 0.005m + 0.228\ (R^2 = 0.972) \tag{7}$$

Where μ_p, μ_a, μ_g, μ_s and μ_w were coefficients of friction of the seed on plywood, aluminum, glass, steel, and rough wood structural surfaces respectively, while m is the moisture content. The results obtained were not in close proximity with what was obtained by Gowda et al. (1990), Paksoy and Aydin (2006), Özarslan (2002) and Coşkuner and Karababa (2005) for soybean, pea, cotton and flaxseed respectively. The high value agreed that the coefficient of friction of the seed on the different structural surfaces showed a positive correlation with moisture content (dry basis). The *p*-value (>0.05) from Table 1, revealed that the moisture of content did not have a significant effect on the coefficient of friction of the seed.

A graphical representation of the coefficient of friction on the different structural surfaces at the respective moisture levels is as shown in Figure 3.

3.2 Force to crack the seed

The force required to crack the seed on its major and minor axes decreased as moisture content increased. These findings were inconsonant with results obtained by Darvishi (2012), Ezeoha et al. (2012), and Ahmadi et al. (2009) for white sesame, palm kernel, and fennel seed respectively. At 18.53% moisture level (dry basis), about fifty percent of the seed loaded into the UTM were partially cracked, because the seed pods and the cotyledon in most cases were separated as a result of an increase in moisture content (dry basis). A mathematical expression relating the moisture level of the seed with force required to crack the seed on its major axis was obtained as in Equation 8:

$$Fmax = 2029 - 100.1m\ (R^2 = 0.998) \tag{8}$$

Where: F_{max}=Force required to crack the seed (N) and m=Moisture content (% dry basis)

A relationship between the force to crack the seed on its major and minor axes is as represented in Figure 4.

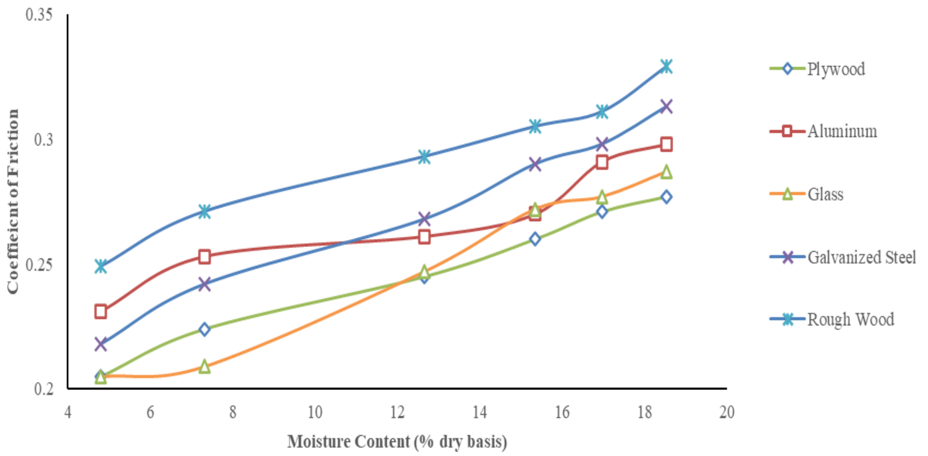

Figure 3 Relationship between coefficient of friction and moisture content

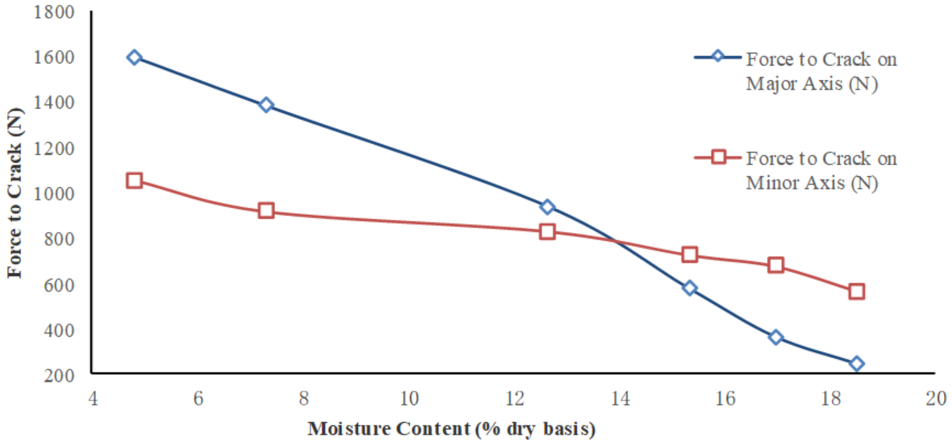

Figure 4 Relationship between cracking force and moisture content

A mathematical expression linking the peak force on the minor axis with moisture content was developed as in Equation 9:

$$Fmin = 1185 - 31.38m\ (R^2 = 0.971) \qquad (9)$$

Where: F_{min}= Force required to crack the seed on the minor axis (N) and

m=Moisture content (% dry basis)

The cracking force recorded on the minor axis (567.1 N) at a moisture level of 18.53% (dry basis) was greater than what was obtained on the major axis (244.9 N). This clearly showed that, when the seeds are dried over a period of time, cracking tends to likely be more achievable on the major axis than the minor axis. Similar trends were reported by Bamgboye and Adejumo (2011), Sadiku and Bamgboye (2014) and Tunde-Akintunde et al. (2007) for roselle, locust bean, and melon seed respectively.

3.3 Deformation on major and minor axes

The deformation on the major and minor axes increased with increasing moisture content (dry basis). The values ranged from 0.694 to 5.426 at the various moisture levels, and a relationship linking the two is as established in Figure 5.

The value ranged from 0.054 to 8.774mm at the different moisture levels. A mathematical expression relating the pair was developed as in Equation 10:

$$d = 12.5 - 0.655m\ (R^2 = 0.942) \qquad (10)$$

where: d=Deformation (mm) and

m=Moisture content

At the various moisture levels, an increase of 81% was recorded against the 160% obtained for the major orientation. A similar analysis was reported by Afzalinia and Roberge (2007) for some selected crops and African star apple (Onwe et al., 2020).

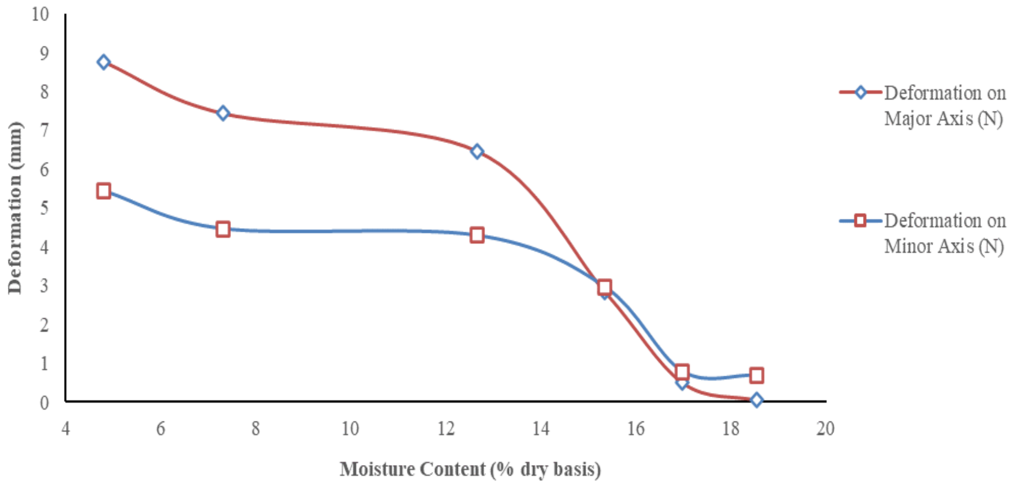

Figure 5 Relationship between deformation and moisture content

3.4 Relationship between force and deformation

The relationship between force and deformation on both the major and minor axes of the seed was determined. A positive correlation was obtained between the force required to break the seed and deformation on the major axis as in Figure 6.

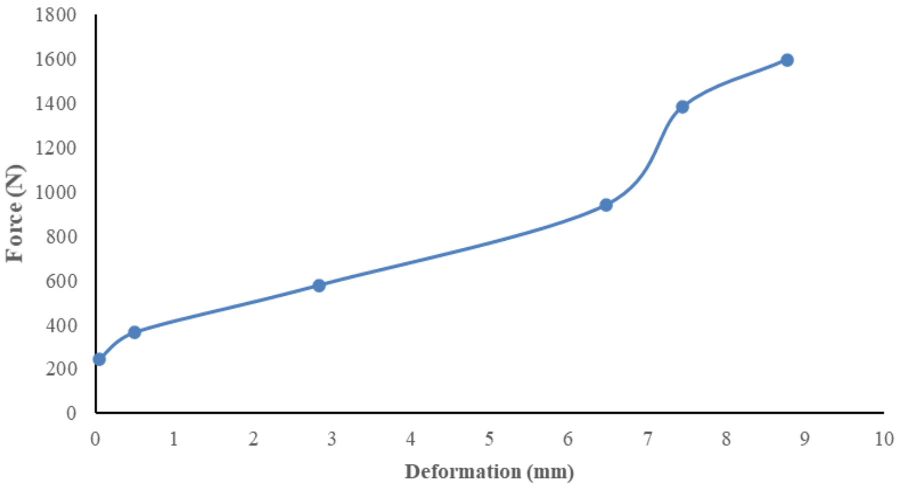

Figure 6 Relationship between force and deformation on major axis

A mathematical model relating the two variables was established as expressed in Equation 11:

$$F_{maj} = 238.1 + 143.2d \ (R^2 = 0.953) \quad (11)$$

Where F_{maj} = Force required to crack the seed on the major axis(N) and d = deformation (mm).

The deformation of the seed upon cracking on its minor axis increased with cracking force as showed in Figure 7.

This agreed with the findings for African oil bean seed (Oduma et al., 2016). It was observed that as the seed continually deformed, the force required to crack the seed on its major and minor axes also correspondingly increased. A mathematical expression was developed for the variables as given in Equation 12:

$$Fmin = 538.2 + 82.7d \ (R^2 = 0.881) \quad (12)$$

where F_{min} = Force required to crack the seed on its minor axis (N) and

d = deformation on the minor axis (mm)

The coefficient of determination (R^2) on the major axis (0.953) was higher than that on the minor axis (0.881). The R^2 values meant that the force to crack the seed and deformation showed a positive correlation on the major axis than the minor.

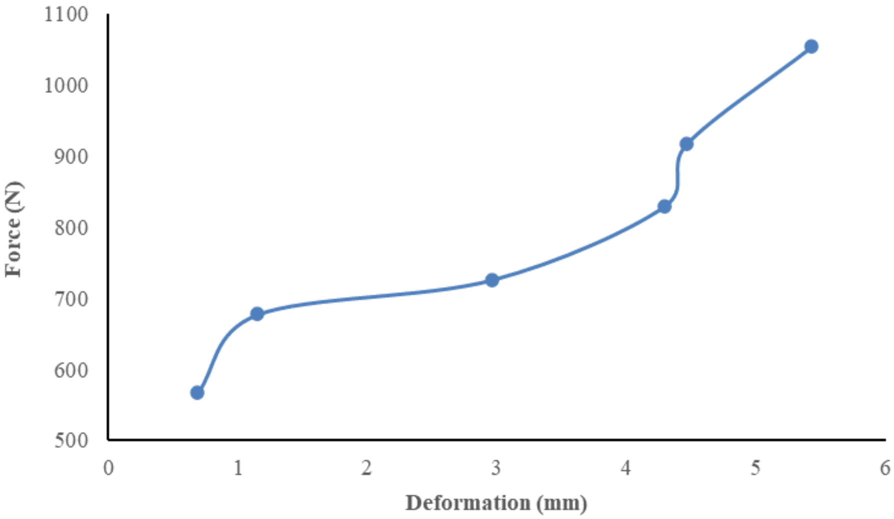

Figure 7 Relationship between force and deformation on minor axis

3.5 Stress and energy

The stress on the major and minor axes of the seed on cracking increases with increasing moisture content as captured in Figure 8. The Energy to break on the major and minor axes of the seed upon cracking decreased as moisture content increased as showed in Figure 9.

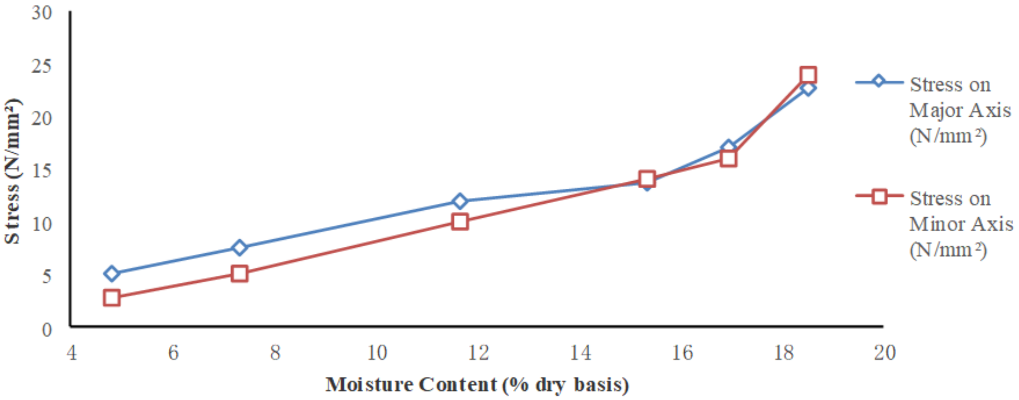

Figure 8 Relationship between stress and moisture content

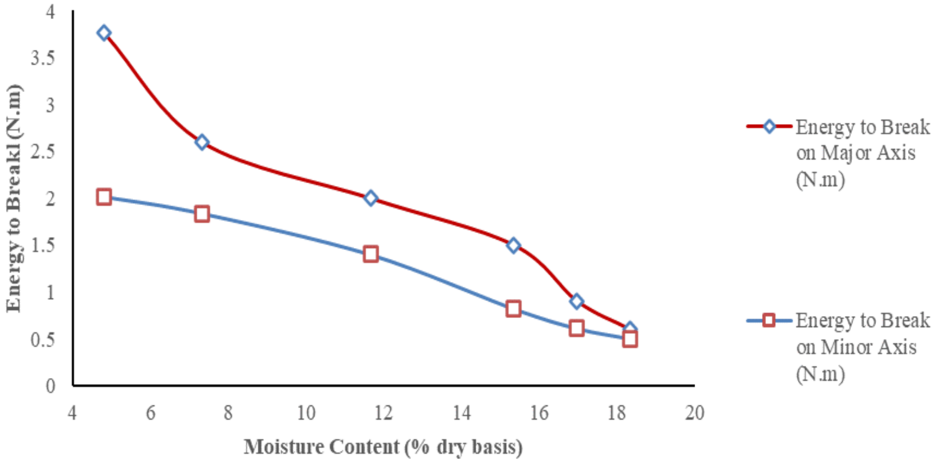

Figure 9 Relationship between energy to break and moisture content

4 Conclusions

The effect of moisture content on some mechanical and frictional properties of mucuna bean relevant to its cracking was studied. A Universal Testing Machine (UTM) was used for the purpose of the experiment. The coefficient of friction of the seed on different structural surfaces tested showed the friction coefficient increased as moisture content increased. The force required to crack the seed on its major and minor axes respectively decreased as moisture level increased. Similar trend was also observed for the deformation. The stress on the major and minor axes of the seed when subjected to cracking increased as moisture level increased, while energy required for cracking of the seed decreased as moisture level decreased. It is recommended that further studies be done on the mechanical properties of the seed not captured in the study to help provide relevant data which could be useful in the design of cracking machine for the seed to enhance its nutritional and health benefits.

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