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Compressive Properties of Cocoa Beans Considering the Effect of Moisture Content Variations

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ABSTRACT

The compressive properties of premium quality cocoa beans from Ghana considering the effect of moisture content in the moisture range of 7% to 22 % (w.b) were studied. The results of the study demonstrated that the displacement at maximum load or the deformation and the crushing energy had more positive linear function with moisture content and increased significantly from 0.80 mm to 1.87 mm and from 13.0 mJ to 200 mJ respectively. The compressive strain and Young's Modulus decreased significantly in linear relationship with very high correlation coefficient within the confines of the moisture content, which increased from 0.009 to 0.0045 mm/mm, and 1300 MPa to 205 MPa respectively. The compressive stress however decreased exponentially with increasing moisture content from 1.5 MPa to 0.3 MPa. The increase in deformation and subsequent decrease in compressive stress and strain of the cocoa bean, as the moisture content increased, shows that the energy absorption capability of wet cocoa bean is higher than the dry ones leading to higher mechanical strength to rupture during the lateral compressive loading. These findings provide useful information for food and agricultural engineers in the design of suitable cocoa beans crackers.

Keywords: *Cocoa bean, Deformation, Compressive stress, Compressive strain, Crushing energy.*

1. INTRODUCTION

Cocoa (Theobroma Cacao) is an ancient crop of the lowland tropical forest, which originated from the Southern and Central America (Lefeber et al, 2011). In West Africa, cocoa is one of the most important cash crops. Globally, Ghana's cocoa bean production is ranked second in the world after her western neighbour Côte d'Ivoire (Faostat, 2005). The cocoa beans from Ghana are also viewed as the best premium quality in the world (Ntiamoah and Afrane, 2008). The cocoa crop does not only serve as the major source of revenue for farmers', accounting for about 70–100% of annual household incomes (Ntiamoah, 2008) but also the provision of socio-economic infrastructure in Ghana(COCOBOD, 2004). The cocoa industry continues to employ about 60% of the national agricultural labour force in the country (Appiah, 2004). Ghana's cocoa beans are usually processed into chocolate, cocoa powder, cocoa liquor, cocoa butter, and cake. Cocoa is a popular raw material in the pharmaceutical, cosmetics, and the food industries. Studies show that the cocoa bean contains flavonoids with antioxidant properties that can reduce blood clot and the risk of stroke and cardiovascular attacks (ICCO, 2011). The crop is very low in cholesterol and a good source of protein, potassium, zinc, and dietary fibres. In view of this, the government of Ghana is committed to ensuring the country processes more of the cocoa beans into downstream products for both the local and international markets (Awua, 2002).

Freshly harvested cocoa beans have been found to have an unpleasant and astringent flavour, hence it is extremely essential to ferment, dry, and roast raw cocoa beans to obtain the desired organoleptic properties (Beckett, 2009; Vuyst et al, 2009; Thompson et al, 2007). The drying of cocoa beans is associated with moisture content changes accompanied by shrinkage and volume changes (Gereke and Niemz, 2010). The hydroscopicity of cocoa beans affects its physical and mechanical properties. The knowledge of mechanical properties provides the basis for avoiding failure in engineering applications. From an engineering point of view, information and data on the mechanical properties of cocoa beans are necessary in the mechanization of various unit operations involved in the post-harvest processing. It also helps in the development of optimization parameters for efficient and effective processing equipment (Burubai et al, 2007). Compressive and other engineering properties are important in many problems associated with the design of machines and the analysis of the behaviour of the product during unit operations such as drying, cleaning, sorting, crushing, and milling (Akaaimo and Raji, 2006). The solutions to problems of these processes involve knowledge of the compressive and other engineering properties (Irtwange, 2002). This was supported by Kutte (2001) that in the design of any agricultural handling and processing machine, properties of the crop must be taken into account. It is reported that production of cocoa beans jumped from 20% to 35% in the 2004/2005 harvesting season in Ghana (Ntiamoah and Afrane, 2008). The increase in cocoa bean production has called for design of processing machines in the processing of the beans into finished products. In the mechanization of the unit operations involved in the cocoa industry, the compressive properties of the beans play an essential role in the design of optimized cocoa bean processing machines.

Compressive properties including rupture force, deformation, compressive strain and stress, and young's modulus, and crushing energy used for the cocoa bean are useful information in designing cocoa bean grinding machines. Studies have shown that compressive properties are influenced by a number of factors such as the cultivar or variety, temperature, and moisture content of the cocoa beans (Delwiche, 2000; Shitanda et al, 2002). The rupture force indicates the minimum force required for shelling the nut and grinding the bean (Sirissomboon et al, 2007; Galedar et al, 2009). The deformation at rupture point can be used for the determination of the gap size between the surfaces to compress the bean for shelling. Processing of cocoa bean into powder is greatly related to the external forces exerted on each bean between the grinding or crushing surfaces. Therefore, a study of the correlation between the forces on a single cocoa bean is needed for a better understanding of milling. In a similar research by Saiedirad et al (2008) involving small, medium, and large cumin seeds, the energy absorbed at seed rupture increased from 1.8 to 8.6 mJ and 7.6 to 14.6 mJ, with increase in moisture content from 5.7% to 15% d.b., for quasi-statically loaded vertical and horizontal orientations, respectively. At moisture content of 15% d.b the maximum crushing energy of 15. 3 mJ was found for small cumin seeds under horizontal loading, whereas the minimum energy of 1.73 mJ was observed for large seed with 5.7 % moisture content under vertical loading. The study of deformation and crushing energy by Altuntas and Karadag (2006) along the X, Y, and Z- axes for sainfoin seed were found to be 8.94%, 1.71% and 9.97% and 1.97, 0.46 and 0.71 mJ along the respective axes. The specific deformation and energy for grasspea seed were 27.53%, 0.29%, and 14.03%; and 187.20, 29.25, and 38.77 mJ for along X, Y, and Z axes respectively. The mean values of deformation and crushing energy for bitter vetch seed were observed for X, Y, and Z axes to be 7.60%, 1.62%, 1.93% and 10.14, 4.42, and 0.86 mJ respectively.

The compressive behaviour of industrial hemp stalks (Khan et al, 2010), rough rice (Shitanda et al, 2002; Corrêa et al, 2007), pulse seeds (Rybiński et al, 2009), sea buckthorn berries (Khazaei and Mann, 2004), wheat (Kalkan and Kara, 2011), and wood (Gereke and Niemz, 2010) have been investigated. Galedar et al (2009) studied the force required to cause deformation and subsequent rupture and crushing energy in pistachio nuts and kernel. It was reported that a nut breaking force varied from 23.05 to 188.76 N with a crushing energy varying from 24.73 to 441.06 mJ when the nuts were compressed. In another study, Isik and Unal (2007) found that the shelling resistance of white speckled red kidney bean decreased as a function of increasing moisture content from 98.26 to 53.67 N. It has been revealed by Shitanda et al, (2002) that the compression behaviour of agricultural materials does not obey the Hookes law in the same way metals do. The scientific literature is flooded with moisture-dependent physical properties of agricultural materials including jatropha fruits (Pradhan et al, 2009), millet (Baryeh, 2002), and wheat (Kalkan and Kara, 2011). Negligible information is available on compressive properties of cash crops such as cocoa bean, shea nuts etc. Bart-Plange and Baryeh (2002) studied the physical properties of category B cocoa bean considering the effect of moisture content. Therefore, the objective of this research was to investigate the effect of moisture content on the compressive properties (deformation at rupture point, compressive stress and strain, young's modulus, and crushing energy) of cocoa beans that are relevant for the design of processing equipment.

2. MATERIALS AND METHODS

Preparation of Sample

Cocoa beans of good quality were obtained from the 2004/2005 harvesting season from the warehouse of the Quality Control Division of the Ghana Cocoa Board and the Kuapa Kokoo Limited, a cocoa buying company in Kumasi, Ghana. The cocoa had been prepared for export to the international market making it very suitable for the study. The initial moisture content of 7.00%wb was determined by keeping a ground sample of 5g in the oven set at a temperature of 130^0 for two hours (Bart-Plange and Baryeh, 2003). The desired moisture content for higher values were obtained by adding distilled water of mass following equation [1]

$$M_w = \frac{Mi(m_f - m_i)}{(100 - m_i)} \tag{1}$$

The prepared samples were sealed in airtight polythene bags and kept in a refrigerator at 5 ^oC for one week to allow the moisture to diffuse uniformly into the beans.

Prior to using the beans they were taken out of the refrigerator and allowed to warm up to room temperature. Similar approaches have been used by Aviara et al.(1999) for guna seed, Deshpande et al.(1993) for soybean, and Singh and Goswami (1996) for cumin seed. After conditioning the samples to the desired moisture levels of 7, 10, 14, 18 and 22%, the dimensional properties were determined for four replicates and the mean values calculated.

Determination of Principal Dimensions

The average size was determined based on 100 randomly selected seeds. To determine the average size of the seed, a sample of 100 seeds were randomly picked and the three principal dimensions namely, Length *(a),* width, *(b)* and thickness *(c)* axes were measured using a micrometer screw gauge with an accuracy of 0.01mm. The width and thickness were measured perpendicular to the major axis. The geometric mean diameter *(Dg)* or equivalent diameter *(De)* as used by some researchers was calculated using the following relationship (Mohsenin, 1980):

$$D_g = (abc)^{1/3} \tag{2}$$

The Sphericity index (Ø) of were calculated using the following formula (Mohsenin, 1987).

$$\emptyset = \frac{(abc)^{1/3}}{a} \tag{3}$$

Determination of Compressive Properties

The compression test was conducted on the cocoa beans at five moisture content levels (7%, 10%, 14%, 18, 22% w.b) using the Instron Universal Testing Machine (IUTM) controlled by a micro- computer. Prior to the compression test, the linear dimensions and the sphericity of the cocoa beans were measured. During a compressive test, the cocoa bean was placed laterally on the stable up platform and was compressed with a motion probe at a constant speed until the specimen fractured. The data acquisition system generated the rupture load and the displacement automatically during the compression. The load-displacement curve was used to derive the compressive properties of cocoa beans. The maximum compressive load, the load at which the bean fractures was determined by the ratio of peak load of the displacement curve. Treating the cocoa bean as a sphere the maximum compressive stress, strain, and crushing energy were determined using the following equation:

$$\sigma_{max} = \frac{P_{max}}{dL} \tag{4}$$

$$\varepsilon_{max} = \frac{\delta l}{l} \tag{5}$$

$$E_c = \frac{P}{2} \times \Delta D \tag{6}$$

Where σ_{max} is the maximum compressive stress in MPa, P_{max} is the maximum load in N, d is the mean diameter in mm, and L is the mean length in mm. ε_{max} is maximum compressive strain in mm/mm, l is the mean width of the specimen in mm, ΔD is the displacement interval in mm, E_c is the crushing energy in J,

An analysis of variance (ANOVA) was performed to examine the effects of experimental factors and their interactions using SPSS 2007. Means of treatments were compared using Fisher's least significant difference. Regression analysis was performed on the data to examine the trends of compressive properties in relation to the cocoa bean moisture content with MS excel. A significant level of probability $p < 0.05$ was used for all analysis. All measurements were replicated four times.

3. RESULTS AND DISCUSSION

Table 1 shows the mean linear dimensions- length, width, thickness, effective mean diameter and sphericity of the cocoa bean specimen used for the compression test. The mean linear dimensions increased from 21.47 to 22.08 mm, 12.01 to 12.65 mm, 7.27 to 7.32mm, and 12.26 to 12.61 for various principal dimensions of length, width, thickness, and effective diameter respectively (Fig. 1). Related studies, which investigated the effect of moisture content on these principal dimensions reported similar trends for wheat (Kalkan and Mara, 2011; Al-Mahasneh and Rababah, 2007), millet (Baryeh, 2002), sugar beet seed (Dursun et al, 2007). The sphericity values increased from 0.57 to 0.58. In the moisture content range of 8.0-22% w.b, Kalkan and Mara (2011) reported an increased of sphericity values from 0.60 to 0.61, from 0.54 to 0.56, from 0.53 to 0.54 for Pehlivan, Kiziltan-91, and Cesit-1252 wheat cultivars respectively. In the same study, other wheat cultivars like Bayraktar-2000 (0.58-0.58) and Kirik (0.56-0.56) did not show any variation in sphericity with moisture content. The mean values of the principal dimensions recorded in this experiment agree with what Bart-Plange and Baryeh (2003) reported for category B cocoa beans within the moisture content range studied.
The compressive strength of the cocoa bean was described by the natural rest position of the bean (lateral orientation). The variation of cocoa bean moisture content versus displacement at maximum load is shown in Fig. 2. From Fig 2, it can be clearly seen that the displacement at maximum load or the deformation of the cocoa beans

increased with increase in moisture content from 0.80 mm to 1.87 mm. The trend of the variation illustrates that as moisture content increases, the maximum deformation of the bean also increased. In a study by Kalkan and Kara (2011) the deformation at rupture point of wheat grains was found not to show any regular variation with the moisture content. In faba bean grain, Altuntas and Yildiz (2007) studied the deformation in the moisture content range from 9.89% to 25.08% d.b. and reported that specific deformation increased with moisture content from 6.81% to 36.76%; 5.93% to 44.41%. and 14.90% to 49.89% along the X-,Y-, and Z-axes, respectively. In this present study, the relationship between deformation and bean moisture content (equation 7) was best described by a linear function with a very high correlation coefficient of 0.99 .

$$D_{max} = (72.80M + 264.19) \times 10^{-3} \tag{7}$$

Figure 3 illustrate the variation of compressive stress and strain against the cocoa bean moisture content. It is possible to verify that maximum lateral compression stress exponentially decreased with increase in moisture content from 1.5 MPa to 0.3 MPa when the moisture content increased from 7% to 22% (w.b). There was a similar reduction in compressive strain from 0.009 to 0.0045 mm/mm as moisture content increased. However, the decrease in compressive strain was better explained by a linear relationship. The influences of cocoa bean moisture content on the compressive stress and strain were well expressed by the following equation, which had high correlation coefficient ranging between 0.91 and 0.99. Gereke and Niemz (2010) reported a decrease in the compressive stress of cross laminated solid wood panels in the moisture range of 10 to 13%. Delwiche (2000) found a decrease in maximum compressive stress as wheat kernel moisture content increases in the range of 3 to 28 % (d.b). Comparing the compressive stress values recorded in this study with other authors' results, it was lower than the 36 MPa reported by Shitanda et al (2002) for compressive stress of long grain rice at moisture content of 15% (w.b), 25.7 MPa for compressive stress of wheat at 14% (d.b) (Delwiche, 2000). The compressive stress and strain correlation as a function of moisture content are depicted in equations 8 and 9 respectively.

$$\sigma_{max} = 3.3215\exp(-0.108\text{M}) \tag{8}$$

$$\varepsilon_{max} = -0.0003\text{M} + 0.011 \tag{9}$$

The decreasing trend of lateral compressive stress and strain may have been caused by the interactions between the starch and protein matrix in the cocoa beans. These inherent properties of the cocoa beans may have decreased the toughness of the beans as the moisture content increased (Dobraszczyk, 1994). The decrease of compressive stress and strain, and increase of deformation capability of the cocoa bean as the moisture content increased support the hypothesis that the energy absorption capability of wet cocoa bean is higher than the dry ones leading to higher mechanical strength to rupture during the lateral compressive loading (Saiedirad et al , 2008).

The variation of Young's modulus considering the influence of moisture content is shown in figure 4. The increase of moisture content decreased the Young's modulus linearly with a negative slope. The values of the Young's modulus decreased from 1300 MPa to 205 MPa as the moisture content increased from 7 % to 22% (w.b). The experimental values recorded were highly correlated with R^2 of 0.955. The regression equation between cocoa bean moisture content and Youngs modulus was as shown in equation 10. A reported study by Delwiche (2000) suggests a similar decrease in Young's modulus as wheat kernel moisture content increased in the range of 3 to 28 % (d.b).

$$\text{E} = -67.099\text{M} + 1708.8 \tag{10}$$

The inverse relationship between cocoa bean hardness and moisture content arising from the cleaving action of water as it diffuses through the intermolecular spaces of the bean, may have caused swelling and weakening of the cohesive forces, which resulted in the lowering of the compressive stress and strain. This further explains the reduction in young's modulus as the moisture content was increased due to their closeness of relativity in measurement.

The energy requirement for crushing (E_c, mJ) of the cocoa bean with the bean moisture content is displayed in figure 3. With increasing cocoa bean moisture content, more energy was required for compression of the bean in lateral compression direction. The crushing energy increased from 13.0 mJ to 200.0 mJ when the moisture content increased from 7% to 22% (w.b). The regression between E and moisture content followed a linear function with a positive slope. Data for energy requirement were highly related to moisture content with coefficient of correlation, R^2 of 0.925 Eq[11]. The crushing energy for faba bean was found to increase quadratically in the moisture content range of 9.89% to 25.08% d.b. from 203.83 to 681.56 mJ; 135.63 to 651.03 mJ and 217.93 to 1090.6 mJ for X-,Y-, and Z-axes, respectively (Altuntas and Yildiz , 2007). Kang et al (1995) reported that the mean values of bio-yield strain and crushing energy to bioyield of wheat decreased as the moisture content increased at a loading rate of 1-250 mm/min. similarly, in a study by Singh and

Goswami (1998), maximum energy absorbed for cumin seed was found to be 14.8 and 204.0 mJ at the moisture content of 7% d.b in the horizontal and vertical orientations, respectively.

$$E_c = 14.4M - 109.6 \tag{11}$$

Intuitively, the crushing energy was expected to reduce considering the explanation above but was not the case. On the contrary, there was an increase in crushing energy as moisture content increased. This trend may have been due to the increase in bean coat plasticity as moisture content was increased (Mabille, 2001). Dziki (2008) observed an increase in crushing energy for whole wheat kernel from 78 to 178 kJ/kg within a moisture content range of 10 to 20%. Similarly, Khan et al (2010) found a linear function relationship between energy requirements and stem diameter to laterally compress hemp stalk with R^2 values ranging between 0.71 and 0.82. Since crushing operation is expected to be done with minimum energy and maximum bean quality (Galedar, 2009), it can be concluded that compression of cocoa beans at lower moisture content would be better.

4. CONCLUSION

The following conclusions can be drawn from the present study:

1. The mean linear dimensions slightly increased from 21.47 to 22.08 mm, 12.01 to 12.65 mm, 7.27 to 7.32mm, and 12.26 to 12.61 for length, width, thickness, and effective diameter respectively.
2. The sphericity values increased with increasing moisture content from 0.57 to 0.58.
3. The deformation increased linearly with increase in moisture content from 0.80 mm to 1.87 mm.
4. Compressive stress decreased exponentially with cocoa bean moisture content from 1.5 MPa to 0.3 MPa.
5. The compressive strain decreased linearly with increasing moisture content from 0.009 to 0.0045 mm/mm.
6. The crushing energy of the cocoa beans increased with moisture content from 0.013 J to 0.2 J
7. As a function of moisture content, the young's modulus values decreased linearly from 1300 to 205 MPa

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Table 1: Mean Dimensions of the Cocoa Beans used for the Compression Experiment

Moisture content (% w.b)	Mean Length mm	Mean width mm	Mean thickness mm	Mean effective diameter (mm)	Sphericity
7	21.47	12.01	7.27	12.26	0.57
10	21.69	12.09	7.19	12.28	0.57
14	22.04	12.49	7.21	12.49	0.57
18	22.05	12.62	7.31	12.59	0.58
22	22.08	12.65	7.32	12.61	0.58

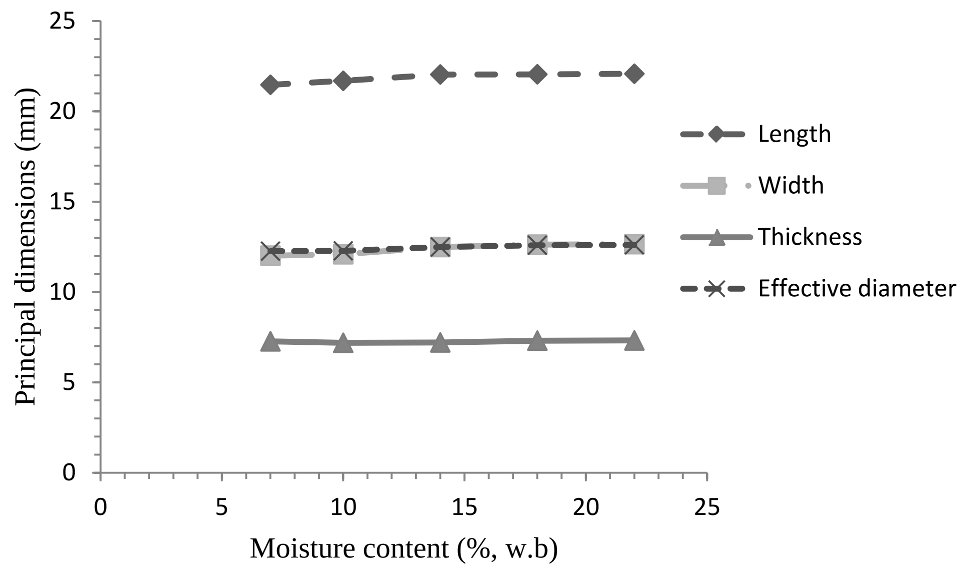

Fig. 1: Principal Dimensions of the Cocoa Bean as a Function of Moisture Content

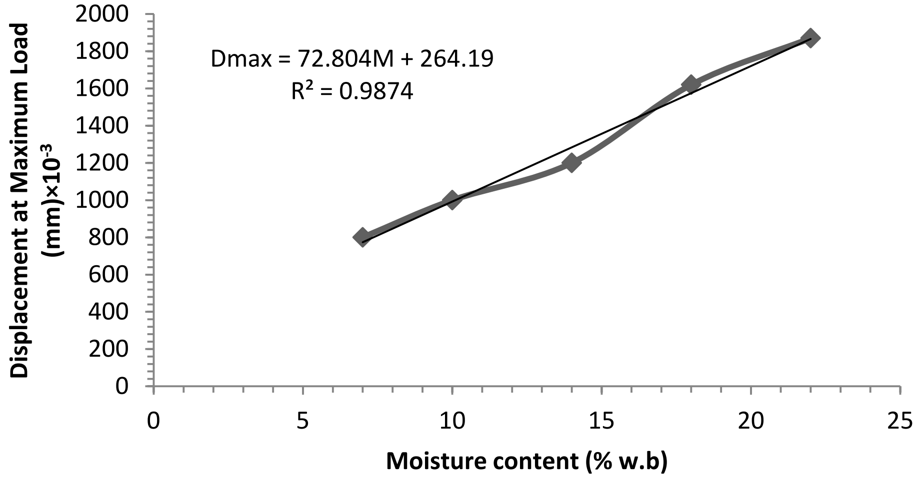

Fig. 2: Variation of Cocoa Bean Moisture Content Versus Displacement at Maximum Load

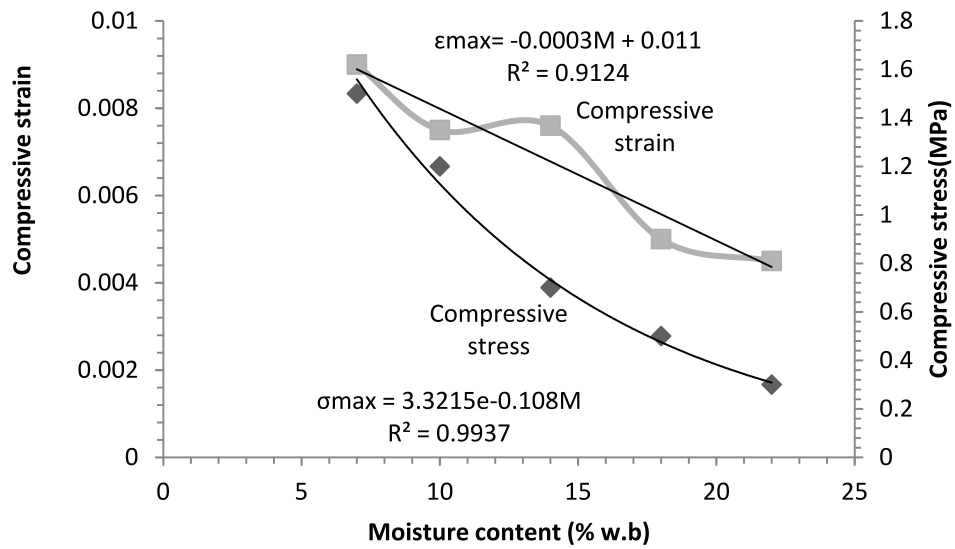

Fig. 3: Variation of Compressive Strain and Stress Versus Bean Moisture Content

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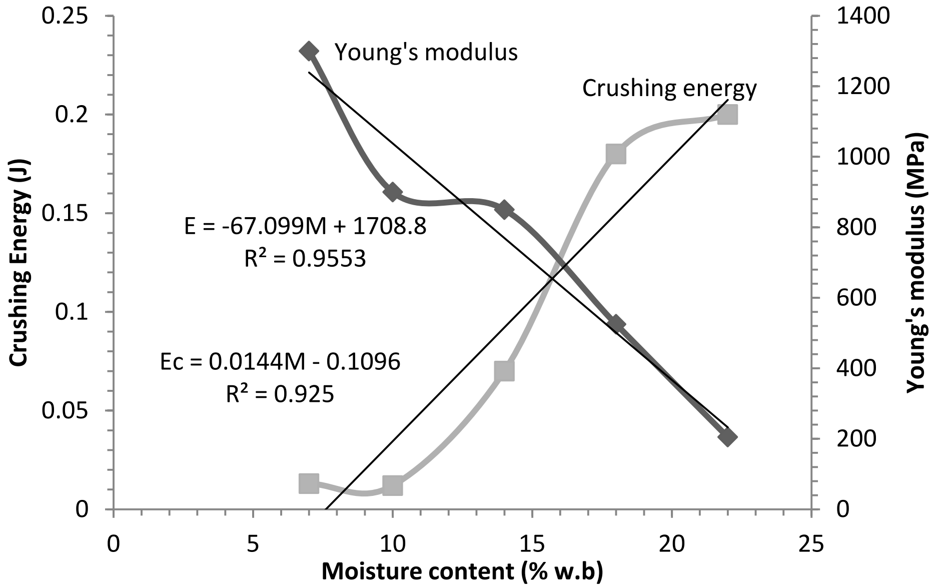

Fig. 4: Variation of Young's Modulus and Crushing Energy against Cocoa Bean Moisture Content