EFFECT OF MOISTURE AND LOADING ORIENTATION ON THE MECHANICAL PROPERTIES OF SORGHUM AND MILLET

E.L. Lazaro§ , J.F. Favier[1] and S.M. Mpanduji
Department of Agricultural Engineering, Sokoine University of Agriculture, P.O.Box 3003,
Morogoro, Tanzania
[1] Department of Agriculture and Environmental Science, University of New Castle Upon Tyne,
NE1 7RU, United Kingdom

Uniaxial compression properties of sorghum and millet grain at different moisture contents (12- 25% dry basis) and at different kernel orientation were investigated. These included: modulus of deformability, maximum compressive force, deformation and toughness at grain break point. Individual grain kernels of two varieties of sorghum, (Dionje and Jumbo) and one variety of pearl millet, (IM) at 12, 15, 20, and 25% moisture content dry basis (mc.db), were quasi-statically loaded using a J.J.universal tensile testing machine to their breaking point. The modulus of deformability, maximum compresive force required to initiate grain rupture and the grain toughness (energy absorbed at break point per unit volume) decreased with increasing moisture content, while deformation at break point increased as moisture content of the grain increased from 12 to 25% for both sorghum and millet. Sorghum grain kernels loaded on the side loading orientation had lower modulus of deformability and required less compressive force and energy to rupture the grain kernel than those loaded in flat loading orientation. It was concluded that moisture content of the grain has a significant effect on the grain strength properties and sorghum grain kernel is anisotropic with respect to compressive strength.

Keywords: *Mechanical properties, moisture content, loading orientation, sorghum and millet*

INTRODUCTION

Sorghum and millet rank fifth and sixth respectively in importance among world cereals in terms of production and utilisation (Dogget, 1988). They are widely grown throughout the semi arid Tropics of Africa and Asia and constitute a major source of energy and proteins for millions of people living in these regions. Nutritionally sorghum and millet are comparable to other important cereals like wheat, maize and rice, however, these two grains carry among sophisticated people the stigma of being considered coarse grain intended for animal feeds and are hence consumed only by the economically poor section of the community (Munck, 1995). The main reason hindering wide acceptance of sorghum and millet as food grain, is the lack of improved processing technology for production of refined products from these grains as compared to other cereal grains such as wheat, rice, and maize, where specialised milling technologies have been developed to produce highly refined finished products of high acceptance. So far, the potential to industrially utilise sorghum and millet for food products especially in urban areas has been little developed. In order to make sorghum and millet competitive with other cereals, there is an urgent need to improve their processing technology especially the dehulling process which is prerequisite for the removal of the seed coat, which is high in fibre and other anti-

---

§ Author to whom correspondence should be directed. E-mail Address: lazaroel@suanet.ac.tz nutritional factors such as tannins. Currently, these grains are mostly processed by the age-old traditional methods, which although effective, are tedious and time consuming. The current mechanical dehulling systems for dehulling of sorghum and millet results in substantial breakage of the kernel, leading to high losses of the endosperm fraction in the bran and poor dehulling efficiency.

Mechanical properties of sorghum and millet such as hardness and compression characteristics are important in post-harvest unit operations, especially in the design of processing and handling equipment (Mohsenin, 1986). These properties vary widely with the moisture content of the grain and are therefore useful to the designer because post-harvest unit operations involve handling and processing of the grain at various moisture levels. This is especially important in the dehulling operation, which involve tempering or hydration of the grain before processing. It is therefore important to know how different mechanical properties will change under these processing conditions if we really need to improve the processing efficiency of these grains.

Mechanical dehulling of sorghum and millet mainly consists of subjecting the grain kernels to both compressive and abrasive forces to remove the seed coat from the endosperm. The grain kernel hardness or its ability to remain intact while its seed coat is being removed is one of the major factors, which determine the dehulling efficiency of the grain. Breakage of the grain before the seed coat is removed results in materials other than the seed coat being removed and lost with the bran, leading to high losses of endosperm and poor dehulling efficiency. A study of the relationship between the applied forces and the mechanical properties of the grain especially those related to fracture resistance of the grain kernels at different process conditions may lead to a better understanding of the dehulling process, and can provide valuable information for future design of improved mechanical dehulling machines for sorghum and millet. So far very little is known in this regard as far as sorghum and millet are concerned. This study was therefore, undertaken to study the effect of moisture content and Kernel orientation on uniaxial compression and failure characteristics of sorghum and millet.

MATERIALS AND METHODS

Materials

Two varieties of sorghum, *Dionje*, a vitreous, white branned sorghum from Tanzania and *Jumbo* a red branned, soft endosperm sorghum from Australia, and one pearl millet (*IM*) variety from India were used in this study.

Methods

Conditioning of the grain samples

The grain samples were conditioned to different moisture levels by adding calculated amounts of distilled water to the grain to obtain samples with four moisture levels i.e. 12, 15, 20 and 25 % (dry basis). The samples were then mixed thoroughly, sealed in moisture proof polythene bags and kept in a refrigerator at 5 °C for 7 days to allow the moisture to be distributed evenly within individual kernels. Final moisture content was determined by oven drying of three representative samples from each bag in accordance with ASAE recommendations (ASAE – S352.2, 1995) . Before starting an experiment, the grain samples were taken out of the refrigerator and allowed to warm up to the room temperature (25 °C) for 1 hour while still sealed in the polythene bags. The grain to be tested were taken from the bags just before measurement were made.

Compression tests

Quasi-static compression tests were performed on individual grain kernels using a tensile testing machine (model T20K, J.J Lloyd

Instruments Ltd.) equipped with a 500 N load cell. The data from the machine was fed directly into a personal computer from which force-deformation curves were obtained. A deformation rate of 1.25 mm/min was used for all compression tests (ASAE - S368.3, 1995) .Twenty Individual kernels of sorghum and millet were randomly selected at each moisture level and loaded between parallel plates at the pre-set speed. Prior to loading, the grain kernels were visually inspected using a magnifying glass to make sure only undamaged kernels were used in the tests, also the thickness of each kernel was measured with a micrometer screw gauge and then individual kernels were cemented on a flat plate using supper glue. This prevented the kernel from slipping or rolling during compression and also prevented kernel deformation on its bottom side. Each kernel was loaded up to its break point. The breakpoint was detected as the point on the force-deformation curve where force decreased or remained constant as deformation continues to increase.

To investigate the effect of loading orientation on the strength properties of the kernels it was necessary to simulate the types of loading orientation which could possibly be encountered in practice, this required consideration of the three different kernel configurations, which may be classified in decreasing order of stability as; lying flat (hilum facing down), lying on its side (with hilum on the side) or on end position. In this investigation the grains were loaded on their two most stable positions i.e. lying flat (flat loading orientation) and lying on its side (side loading orientation). Twenty grain kernels were tested at each moisture level, in each loading position for each sorghum variety.

Determination of mechanical properties

As far as processing of sorghum and millets is concerned, the most meaningful criteria of studying their mechanical properties is from their force-deformation relationship, i.e. how they behave under load. Therefore, data obtained at different moisture levels and loading orientation were used to produce force-deformation curves which were analysed to evaluate different mechanical properties of the grain which are important during the dehulling process. These included, modulus of deformability (modulus based on the first loading cycle), force and deformation at rupture or break point and toughness or modulus of toughness (energy per unit volume absorbed in deforming the kernel to its maximum strength or break point). The deformation and maximum load which the kernel could support before rupture were found directly from the force-deformation curve as the deformation and force at the break or rupture point, while modulus of toughness (G_t) was evaluated by computing the area under the force-deformation curve up to rupture point and divide by the kernel volume. Modulus of deformability was computed using the following equation (Mohsenin, 1986) .

$$E_{(t)} = 0.531\frac{(1-\mu)}{D^{\frac{3}{2}}}F_{(t)}\left(\frac{1}{R_1}+\frac{1}{R_1'}\right)^{\frac{1}{2}} \qquad (1)$$

where $E_{(t)}$ is the modulus of deformability (MPa), μ is the Poisson ratio (0.4 was used in this study), F is the force producing deformation midway between the origin and the linear limit (N), D is the deformation (mm), R_1, R_1' are radii of curvature of the grain kernel. The radii of curvature were determined according to ASAE recommendation S368.3 for compression of agricultural materials (ASAE - S368.3, 1995) .

Statistical analysis

The data was processed on Microsoft Excel software to plot the graphs. T-test was used to compare the treatment means at 5% level of probability (Mead, et al., 1993)

RESULTS AND DISCUSSION

Results

Quasi-static compression tests

Typical force-deformation curves obtained during compression of individual grain kernels are shown in Figures 1(a) and 1(b) for sorghum and millet respectively. Considerable variation was observed in the results of compression of individual kernels for both sorghum and millet.

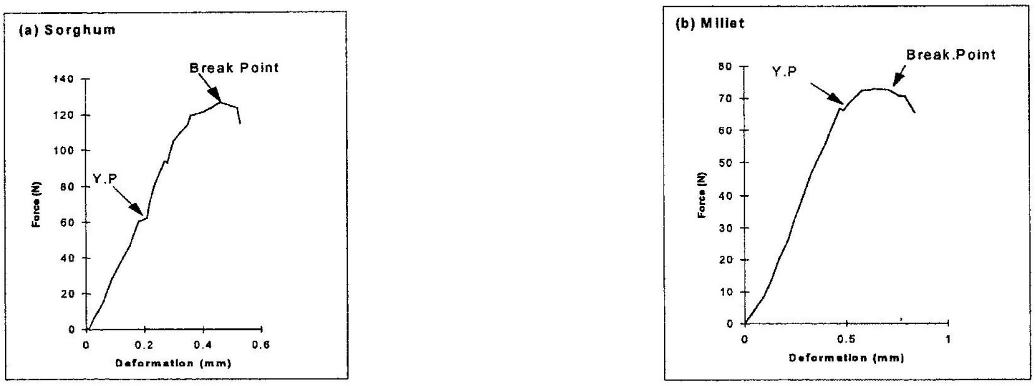

Figure 1: Typical F-D curves for (a) sorghum (*Dionje*) and (b) millet (*IM*) at 15% (mcdb) (Y.P. is the yield point)

This was probably due to the non-homogeneous nature of the grain kernels and stress concentrations set up by the irregular bearing surface of the grain kernels. However, from the force-deformation curves obtained, the elastic properties of the grain kernels during the initial period of deformation were apparent. In most cases the initial part of the curve was linear up to the elastic limit, beyond which it become non-linear until rupture occurred. Most force-deformation curves displayed clear yield and rupture points at low moisture content range (12-15% db), however, this became less and less obvious at higher moisture ranges (20-25% db).For sorghum the deformation at yield point was much lower compared to millet (ie 0.2 mm compared to 0.5) this was due to the fact that Sorghum (Dionje) is harder and less elastic than millet as evidenced from the slope of the two F-D curves and the force required to break the two grain types.

The effect of moisture content on the mechanical properties of sorghum and millet

Typical results for the effect of moisture content on the force-deformation characteristics of sorghum are shown in Figure 2 for sorghum (*Dionje*). The results showed that the force required to cause a similar amount of deformation in the grain kernel decreased with increase in moisture content of the grain, thus giving an indication that the grain kernels were becoming softer as moisture content increased. Similar behaviour has been observed in wheat and Maize (Zoerb and Hall, 1960) , in Maize endosperm (Shelef and Mohsenin, 1969) , in soybeans (Misra and Young, 1981) , in rice (Hoki and Tomita, 1976) , in wood (Meredith, 1956) and in wheat (Praveen et al., 1995). Observation of the force-deformation curves obtained at different moisture contents also indicated that the linear elastic range decreased with an increase in grain moisture content.

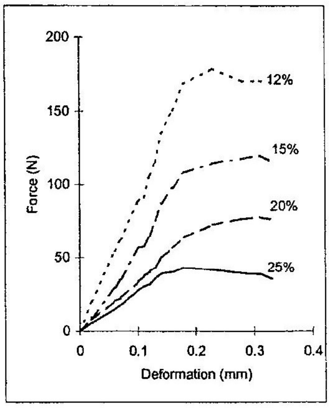

Figure 2: Effect of moisture content on force-deformation behaviour of sorghum (*Dionje*)

Tablel. Fitted constants for the relationship between grain mechanical properties and moisture content using equation (2)

Grain variety	Mechanical property	a	b	R^2
Dionje	E_{mod}	8.1	-0.10	0.97
	G_t	8.7	-0.10	0.98
	F	5.6	-0.05	0.96
	D	0.2	0.08	0.99
Jumbo	E_{mod}	8.8	-0.15	0.99
	G_t	7.6	-0.08	0.97
	F	5.3	-0.07	0.99
	D	0.3	0.01	0.98
Millet (*IM*)	E_{mod}	8.3	-0.11	0.99
	G_t	7.6	-0.06	0.96
	F	4.0	-0.04	0.97
	D	0.2	0.01	0.99

E_{mod} is the modulus of deformability, G_t is the modulus of toughness, F is the force at break point and D is the deformation at break point.

Effect of moisture content on modulus of deformability (E_{mod})

Modulus of deformability of both sorghum and millet grain decreased with increase in moisture content [Figure 3(a)]. The average modulus of deformability decreased from 1150 MPa to 274 MPa, 1016 MPa to 158 MPa and from 1225 MPa to 288 MPa for *Dionje*; *Jumbo* and *IM* millet respectively as the grain moisture content increased from 12% - 25% (db). The decrease in E_{mod} with increase in moisture content was found to be statistically significant in both grains ($P<0.05$). The relationship between kernel moisture content and E_{mod} is shown in Figure 3(b) for both sorghum and millet. The values of the constants and corresponding R^2 values for the fitted lines are given in Table 1. There was a high correlation between the log of E_{mod} and moisture content as indicated by the high R^2-values. Loading position also had significant effect on the values of E_{mod} obtained. The E_{mod} of *Dionje* obtained for side loading orientation was approximately 50% lower than that obtained for flat loading orientation (746 MPa vs. 1554 MPa) The same trend was observed for *Jumbo* variety where for flat loading E_{mod} was 1018 MPa and side loading was 519 MPa

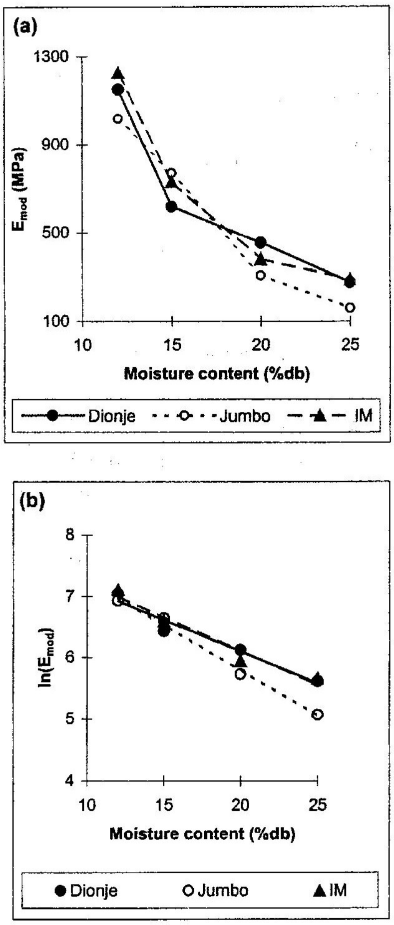

Figure 3: (a) Modulus of deformability of sorghum and millet as a function of moisture content and (b) a log-linear plot of E_{mod} against moisture content with fitted lines

The effect of moisture content on modulus of toughness (G_t)

Modulus of toughness of the grain decreased as moisture content increased from 12% to 25% (mcdb) for all varieties tested (Figure 4 (a)). The modulus of toughness decreased from 2018 MJ/m^3 at 12% (mcdb) to 590 MJ/m^3 at 25% (mcdb) for *Dionje*, from 797 to 271 MJ/m^3 for *Jumbo*, and from 921 MJ/m^3 to 413 MJ/m^3 for millet within the same moisture range. The relationship between moisture content and kernel toughness (G_t) is illustrated in Figure 4 (b) and the values for the constants for the fitted lines representing the relationship are given in Table 1.

The effect of moisture content on force required to break the grain kernel

The results of the effect of moisture content on the force required to break the grain kernel are given in Figure 5 (a). There was a significant ($P< 0.05$) decrease in the amount of force required to break the grain kernel as moisture content increased from 12% to 25% (db). *Dionje* required an average of 148 N at 12% (mcdb) and only 82 N at 25% (mcdb) to break the grain kernel, (a decrease of about 45%.) *Jumbo* required an average of 86.3 N at 12% mc and 35 N at 25% mc (a decrease of 59%), and millet required 37 N at 12% (mcdb) and only 23 N at 25% (mcdb) (a decrease of 38%).

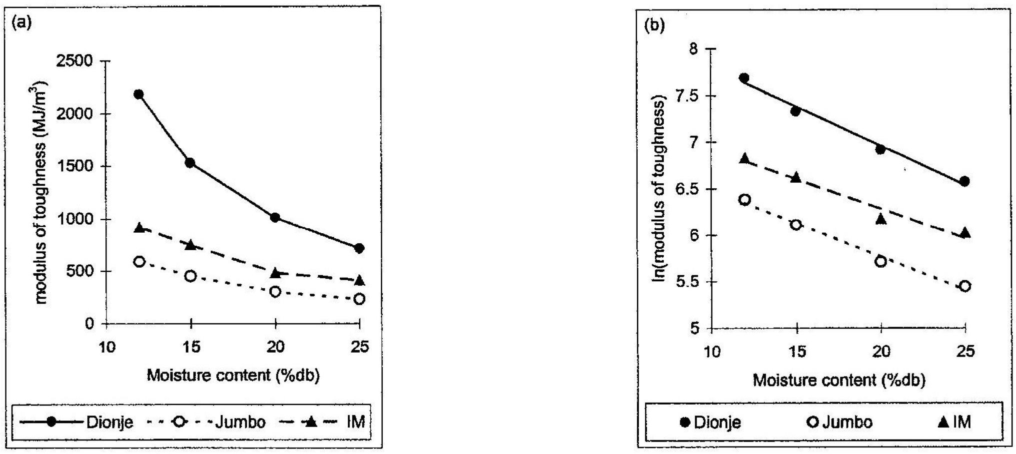

Figure 4: (a) Modulus of toughness of sorghum and millet as a function of moisture content and (b) a log-linear plot of modulus of toughness against moisture content with fitted lines

Loading position also had a significant effect on the grain toughness, with kernels loaded in flat position showing much higher toughness than those loaded on the side loading position (for extra data see Appendix 1). The modulus of toughness of *Dionje* for flat loading position was 3151 MJ/m^3 at 12% mc and 855 MJ/m^3 at 25% (mcdb), while for side loading position was only 1266 MJ /m^3 at 12 % mc. and 573 MJ/m^3 at 25 % (mcdb).

The decrease in force required to break the grain kernel could be attributed to a decrease in the strength of the grain kernel at high moisture content, a trend, which was also observed in soybeans (Paulsen, 1978) and in maize and wheat (Zoerb and Hall, 1960) . The relationship between force to break point and moisture content is shown in Figure 5(b) and the values of the constants for the log-linear model representing this relationship together with R^2 values are given in Table 1.

Grain loaded on flat position required 148 N and 86 N to break the grain at 12% mc for

Dionje and *Jumbo* respectively while in side loading position, *Dionje* required 106 N and *Jumbo* 46 N to break the grain at the same moisture content. Statistical evaluation of data on rupture force for flat and side loaded grain kernels (for extra data see Appendix I) showed that the difference in rupture force between flat and side loading was significant at ($P< 0.05$). These results are in good agreement with the results of other researchers who observed that substantially less force was required for cumin seed (Singh and Goswani, 1998) and soybeans (Paulsen, 1978) rupture in side loading orientation as compared to flat loading orientation.

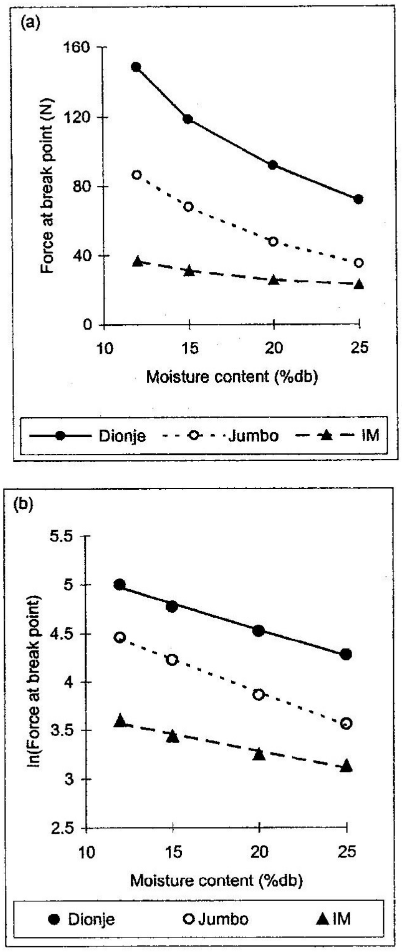

Figure 5: (a) Force at kernel break point for sorghum and millet as a function of moisture content and (b) a log-linear plot of force at break point against moisture content with fitted lines

Effect of moisture content on deformation at break point

Deformation at kernel break point increased as the moisture content of the grain increased for both sorghum and millet (Figure 6 (a)). On average, deformation at break point increased by 40% from 0.27 mm to 0.38 mm for *Dionje*, 30% from 0.43 mm to 0.56 mm for *Jumbo* and by 36% from 0.33 mm to 0.45 mm, for millet as the kernel moisture increased from 12% to 25% (db). This suggested that sorghum and millet grain kernels become softer at higher moisture content and therefore capable of higher deformation before breakage. The relationship between moisture content and deformation at break point is shown in Figure 6(b) and the values of constants for the fitted lines are given in Table 1.

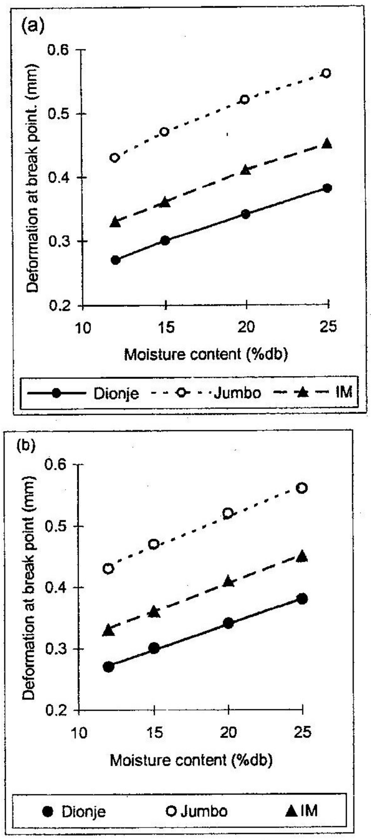

Figure 6: (a) Deformation at kernel break point in sorghum and millet as a function of moisture content and (b) a linear plot of deformation at kernel break point against moisture content with fitted lines

Discussion

The results obtained in this study showed that moisture content had a significant influence on the mechanical properties of sorghum and millet varieties used in this study. All strength properties of sorghum and millet grain investigated, with exception of kernel deformation, decreased in magnitude with increase in moisture content within the moisture range 12 to 25% mc.db.

These findings could be explained by considering the constituents of the grain kernel and how they are affected by moisture content. The endosperm comprises about 80 to 84% by weight of sorghum and millet kernel (Sullins and Rooney, 1975) , therefore the endosperm must had a substantial influence on the results obtained here. Microscopic study of sorghum endosperm (Sullins and Rooney, 1974) has shown that individual starch granules in both corneous and floury endosperm lay completely embedded in a matrix composed largely of protein, and majority of the molecules in the network are oriented in a particular way. It is recognised that powerful intermolecular binding forces exist in crystalline or oriented high polymeric substances, and this account for their toughness (Ferry, 1961).

From the above considerations, the mechanical properties of the sorghum and millet kernels are largely related to the whole protenetious matrix of the endosperm, as well as the compactness and orientation of the starch granules within the endosperm. At low moisture content the kernel is very stiff and hence its deformation in the elastic range is relatively small (as evidenced by the steep force-deformation curve at low moisture content). When water molecules enter the molecular chain units which are close to each other, they are forced to rearrange their relative positions, apparently such geometrical rearrangement of the chain units affect the orientation and hence mechanical strength of the grain causing the grain kernel to became soft as moisture content increase.

Another factor, which might have affected these properties as related to moisture content, is the friction coefficient of the starch granules within the endosperm. Behaviour of dry endosperm can be compared to an undiluted polymer with a relatively high friction coefficient. When the moisture level is increased, the friction coefficient becomes smaller, since some of the nearest neighbours of starch granules are water molecules which are much more mobile (Ferry, 1961) .Under such conditions the deformation under a given load gradually increase and the moduli together with other strength properties decrease with increase in the number of water molecules present.

Another factor, which might have contributed to the trend of events, observed in this study is the disruption of the endosperm matrix as moisture content increased. Sullins and Rooney (1975) working on reconstituted sorghum found that there was a disruption of endosperm matrix at high moisture content caused by the swelling of starch granules as they absorb moisture. This disruption could lead to the softening of the grain kernels and account for the decrease in compressive strength of the kernel with increase in moisture content.

Maximum compressive strength and modulus of deformability of sorghum grains at all moisture levels depended greatly on whether the kernel was loaded while on edge or flat loading position (see Table 2). Thus position had a strong influence on the value of the property under consideration. This difference in strength properties in two orthogonal directions is an important consideration to be taken into account in determination of kernel properties to be used in processing or in design of bulk handling containers and processing machines since any orientation is possible during such processes.

Table 2 Effect of moisture content and loading position on modulus of deformability, modulus of toughness and maximum compressive force

Grain variety	Moisture content (%db)	Modulus of deformability		Modulus of toughness		Maximum force	
		F/loading (MPa)	S/loading (MPa)	F/Loading (MJ/m^3)	S/Loading (MJ/m^3)	F/Loading (N)	S/Loading (N)
Dionje	12	1554.3	746.7	3151.0	1266.0	148.4	106.3
	15	737.1	499.5	2168.8	806.6	128.5	89.5
	20	659.4	248.5	1105.4	659.8	91.9	48.5
	25	427.1	121.8	855.3	573.0	81.8	30.5
Jumbo	12	1018.5	519.9	971.3	622.7	86.0	46.4
	15	550.4	324.7	596.6	387.2	51.1	30.9
	20	393.6	218.9	448.1	302.9	37.0	20.9
	25	213.7	103.9	360.5	181.4	35.2	17.9

F/loading = flat loading; S/loading = side loading,

CONCLUSIONS

Based upon the findings of this study, the following conclusions can be drawn:

Moisture content had a significant effect on the strength properties of sorghum and millet investigated under compressive loading. Modulus of deformability, kernel toughness and Compressive force required to cause grain rupture all decreased as the grain moisture content increased from 12% to 25% db

Deformation at grain rupture point increased as moisture increased from 12% to 25%, confirming that sorghum and millet kernels at higher moisture contents are softer and more susceptible to breakage than at lower moisture contents.

Sorghum grain is anisotropic with respect to compressive strength, it exhibit higher strength values when loaded in flat loading orientation than when loaded in side loading orientation. Thus orientation had a strong influence on grain resistance to breakage. This means that when designing a processing machine or bulk handling container for these grains the data for mechanical strength must consider all possible kernel orientation which might be encountered during the process.

ACKNOWLEDGEMENT

The authors wish to acknowledge their appreciation to the Association of Commonwealth Universities for providing financial assistance, which made the research reported in this article possible

NOMENCLATURE

A,b	Constants
D	Deformation (mm)
E(t)	Modulus of deformability (Mpa)
F	Force (N)
M	moisture content (%)
mcdb	Moisture content on dry basis (%)
R_1, R_1'	Radii of curvature of grain kernel (mm)
R^2	Regression coefficient

Greek Symbols

μ	Poisson's ratio

REFERENCES

1. ASAE Recommendation S352.2, *Moisture Measurement - Unground Grain and Seeds.* Agricultural Engineers Yearbook.ASAE , St. Joseph, MI, 1995
2. ASAE Recommendation S368.3, *Compression Tests of Food Materials of Convex Shape.* Agricultural Engineers Yearbook, ASAE , St. Joseph, MI, 1995
3. Dogget, H., *Sorghum.* 2nd ed, Longmans, UK. 512pp.,1988
4. Ferry, J.D., *Viscoelastic Properties of Polymers.* Wiley and Sons, New York, 415pp., 1961.
5. Hoki, M. and K. Tomita, *Moisture Effect on Mechanical Strength of Soybeans,* Bulletin of the Faculty of Agriculture, Mie University, TSU, Japan, No.5, pp. 103 – 110, 1976.
6. Mead, R., Curnow, R.N. and A.M. Hampstead, *Statistical Methods in Agriculture and Experimental Biology,* 2nd ed. Chapman and Hall, London 1993.
7. Meredith, R., *The Mechanical Properties of Textile Fibres.* Interscience, New York, 1956.
8. Misra, R. N. and J. H. Young, *A Model for Predicting the Effect of Moisture Content on the Modulus of Elasticity of Soybeans.* Transactions of the ASAE, Vol. 24, pp. 1338 – 1341, 1981.
9. Mohsenin, N.N., *Physical Properties of Plant and Animal Materials,* Gordon Breach Scientific Publishers, New York, 1986
10. Munck, L., *New Milling Technologies and Products: Whole Plant Utilisation of Botanical and Chemical Components*; in Sorghum and Millets: Chemistry and Technology, David A.V. Dendy, Ed., 1995
11. Paulsen M. R., *Fracture Resistance of Soybeans to Compression Loading.* Transactions of the ASAE, Vol. 21 pp. 1210 – 1216, 1978.
12. Praveen, C. B., J. Irudayaraj, and B. Marquis, *Studies on Rheological Behaviour of Canola and Wheat.* J. Agric. Eng. Res., Vol. 61, pp. 267 – 274, 1995.
13. Shelef, L. and N.N. Mohsenin, *Effect of Moisture Content on Mechanical Properties of Shelled Corn.* J. Agric. Eng. Res., Vol. 46, pp. 242 – 253, 1969.
14. Singh, K. K. and Goswani, T. K., *Mechanical Properties of Cumin Seed Under Compressive Loading.* Journal of Food Engineering, Vol. 36, pp. 311 – 321, 1998.
15. Sullins, R. D. and Rooney, L. W., *Light and Scanning Electron Microscopic Studies of Waxy and Non-Waxy Endosperm Sorghum Varieties.* Cereal Chem., Vol. 52, pp. 361 – 366, 1975.
16. Sullins, R.D. and Rooney, L. W., *Microscopic Evaluation of the Digestibility of Sorghum Grain that Differ in Endosperm Characteristics.* Cereal Chem., Vol. 51, pp. 134 – 142, 1974.
17. Zoerb, G. C. and C.W. Hall., *Some Mechanical and Rheological Properties of Grains.* J. Agric. Eng. Res., Vol. 5, pp. 83 – 93, 1960.