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Moisture-dependent properties of barnyard millet grain and kernel

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ABSTRACT

The geometric mean diameter, sphericity, grain surface area, 1000 grain mass, true density (toluene displacement method), terminal velocity, dynamic angle of repose, coefficient of internal friction, coefficient of static friction at different surfaces (sun mica, canvas and mild steel surfaces), specific deformation and rupture energy of the grain were found to increase 12.21%, 4.79%, 30.47%, 30.75%, 6.74%, 32.99%, 127.05%, 60%, 18.57%, 34–67%, 69.2% and 88.87% respectively at increase of moisture content from 0.065 to 0.265 kg kg^{-1} dry matter. However, true density (proximate composition method), bulk density, interstices and rupture force of grain was found to be decrease 8.64%, 20.1%, 86.49% and 21.17% respectively at increase of moisture content. Similar trend was observed for barnyard kernel also. True density (toluene displacement method) was found lower as compared to true density (proximate composition method) at all experimental moisture range indicated that the presence of void space inside the grain and kernel.

1. Introduction

Barnyard millet (*Echinochloa frumentacea* L.) is commonly grown millet crop in the arid and semiarid region of the world. It is commonly grown millet in Uttaranchal, Tamil Nadu, Andhra Pradesh, Karnataka and Chhattisgarh state of India. Under favorable moisture and temperature condition the grain could ripen within 45 days of sowing (Hulse et al., 1980). This crop is harvested at 0.24–0.26 kg kg^{-1} dry matter moisture content in month of October–November and kept under the sun until moisture content reduce to 0.12–0.14 kg kg^{-1} dry matter. The inflorescence produces one fertile and one infertile floret subtended by two unequal glumes. The glumes totally enclose the kernel. The mature pericarp consists of two epidermal layers. The cells of inner epidermis are closely compressed against those of the outer part. Barnyard millet has an aleuronic layer thought to contain strongly cutinized cell walls (Narayanaswami, 1955; Zee and O'brain, 1971). It contains protein 5–8.5%, fat 3.5–4.6%, carbohydrate 57–66%, ash 2.5–4.0%, fiber 6.4–12.2 at moisture content 0.25–0.05 kg kg^{-1} dry matter.

The presence of all the required nutrients in millet make them suitable for large scale utilization in the manufacture of baby food, snack foods, dietary food etc. from grain, kernel and flour (Subramanium and Viswanathan, 2007). Barnyard millet is low in phytic acid and rich in iron and calcium. Magnesium and niacin (B_3) in it can help to reduce the effects of migraines pain and level of cholesterol respectively. The presence of phosphorous in barnyard millet helps in fat metabolism, body tissue repair and converting food into energy. Almost all type of essential amino acids is present in barnyard millet. The study of physical, aerodynamic and mechanical properties of food grain is important and essential in the design of processing machines, storage structures and processes. The shape and size are important in the separation from foreign material and in the design and development of grading and sorting machineries. Rupture force, specific deformation, rupture energy, internal friction, static coefficient of friction and terminal velocity can be used in design and development of dehuller of barnyard millet. Bulk density, true density and porosity, are important factors in designing of storage structures. The dynamic angle of repose of the grains and kernels can be used for designing the bins, silos, hoppers and storage structures. Many researchers have been determined the properties of different agricultural produces like millet (Baryeh, 2002; Subramanium and Viswanathan, 2007), fenugreek seeds (Altuntas et al., 2005), sainfoin, grasspea and bitter vetch seeds (Altuntas and Karadag, 2006), arecanut, lentil (Amin et al., 2004), cowpea (Yalcin, 2007), moth gram (Nimkar et al., 2005), kidney bean (Isik and Ünal, 2007), okra seed (Sahoo and Srivastava, 2002), faba bean (Altuntas and Yildiz, 2007), caper seed (Dursun and Dursun, 2005), sesame seed (Akintunde and Akintunde, 2004), caper fruit (Sessiz et al., 2007), sunflower seed (Gupta et al., 2007) and tef grain (Zewdu, 2007). Jain and Bal (1997) and Baryeh (2002) studied about the properties of pearl millet, Subramanium and Viswanathan (2007) studied some physical properties like bulk density and friction coefficient of barnyard millet grain. However they did not consider other physical, aerodynamic and mechanical properties of barnyard millet grain and kernel. It is

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Nomenclature

D_{ge}	geometric diameter, mm	Θ	dynamic angle of repose, °
L	length, mm	μ_i	coefficient of internal friction
W	width, mm	μ_s	coefficient of static friction
T	thickness, mm	F_r	rupture force, N
φ	sphericity	Σ	specific deformation, %
S	surface area, mm^2	L_f	deformed grain and kernel dimension in direction of compression, mm
δ	density, kg m^{-3}	L_u	unreformed grain and kernel dimensions in direction of compression, mm
T	temperature, °C	D_r	deformation at rupture point, mm
δ_{td}	true density (kg m^{-3}) assessed by toluene displacement	α	tilt angle, °
δ_{pc}	true density (kg m^{-3}) assessed by proximate composition method	F_e	load on pan required to slide the empty cylinder
δ_{bd}	bulk density, kg m^{-3}	F_g	the incremental load applied on the loading pan to slide the top cylinder
I	interstice, %	N	mass of the grain or kernel sample contained in the top cylinder
ε	porosity, %	*BYMWGMSS*	barnyard millet whole grain at mild steel surface
E_r	rupture energy, N mm	*BYMKSS*	barnyard millet kernel at sun mica surface
BYMWG	barnyard millet whole grain	*BYMKCS*	barnyard millet kernel at canvas surface
BYMK	barnyard millet kernel	*BYMKMSS*	barnyard millet kernel at mild steel surface
BYMWGSS	barnyard millet whole grain at sun mica surface	*TDM*	toluene displacement method
BYMWGCS	barnyard millet whole grain at canvas surface		
PCM	proximate composition method		
V	terminal velocity, ms^{-1}		

evident from literature reviewed that there is not much published work relating to moisture-dependent physical, aerodynamic and mechanical properties of the barnyard millet (*E. frumentacea* L.) grain and kernel (Fig. 1). Hence this study was conducted to find out some properties of barnyard millet grain and kernel namely the mean diameter, sphericity, bulk density, true density (toluene displacement and proximate composition methods), coefficient of internal friction, coefficient static friction at different surfaces, dynamic angle of repose, 1000 grain weight, surface area, porosity, terminal velocity, rupture force, specific deformation and rupture energy of barnyard millet grain and kernel at moisture range 0.065–0.265 kg kg^{-1} dry matter, respectively.

2. Materials and methods

The samples of the desired moisture contents were prepared by adding the calculated amount of distilled water. The samples were then transferred to separate tightly sealed polyethylene bags. The samples were kept at 5 °C in a refrigerator for a week to enable the moisture to be distributed uniformly throughout the sample (Nimkar and Chattopadhyay, 2001 and Garnayak et al., 2008). Before starting a test, the required quantities of samples were taken out of the refrigerator and allowed to warm to the room temperature for about 2 h (Tavakoli et al., 2009). All physical, aerodynamic, engineering and mechanical properties were assessed at all five selected moisture content range. Five replications of each test were carried out at each moisture level.

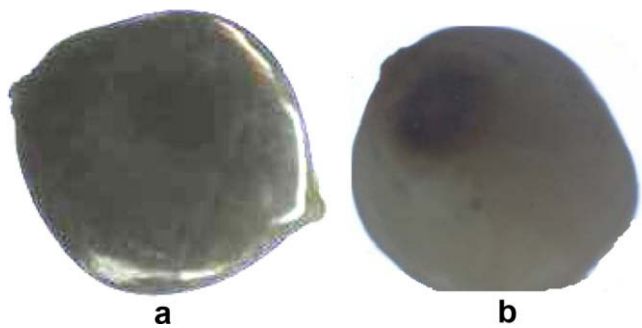

Fig. 1. Barnyard millet (a) grain and (b) kernel.

The mean geometrical diameter (D_{ge}) of the grain and kernels were assessed by measuring their three linear dimensions of 100 randomly selected grains and kernels, using vernier caliper with least count 0.001 mm. D_{ge} of grain and kernels was obtained using the following equations (Mohsenin, 1970):

$$D_{ge} = (\mathrm{LWT})^{1/3} \tag{1}$$

The sphericity (ϕ) of the grain and kernels was calculated using equation:

$$\phi = \frac{(\mathrm{LWT})^{1/3}}{L} \tag{2}$$

The surface area '*S*' of the barnyard millet grain and kernel was assessed by analogy with a sphere of same $D_{ge,}$ using Eq. (3) (McCabe et al., 1986; Dursun and Dursun, 2005; Baryeh, 2002; Al-Mahasneh and Rababah, 2007; Deshpande et al., 1993; Sessiz et al., 2007).

$$S = \pi D_{ge}^2 \tag{3}$$

Thousand grain and kernel mass were determined using electronic balance with least count 0.001 g. Bulk densities of barnyard millet grain and kernels at five moisture levels were found by filling a circular container of 500 ml capacity with grains and kernels without manual compaction (Singh and Goswami, 1996) and then the weight (W) of 500 ml grains of all samples were recorded. The bulk density was assessed using Eq. (4):

$$\delta_{bd} = \frac{W}{500} \times 10^6 \tag{4}$$

Toluene displacement method was used to determining the true density. It is evident from the literature (Dursun and Dursun, 2005) that the absorption of toluene (C_7H_8) by the grain and kernel is lesser as compared to water. The actual volume of grain will be equal to toluene displaced (Singh and Goswami, 1996; Ogut, 1998; Konak et al., 2002).

Apart from true density assessed by toluene displacement method the true density of any material can be assessed with the help of proximate composition of the material using following Eq. (5) (Choi and Okas, 1986):

$$\delta_T = \frac{1}{\left\{\left(\frac{C_{fat}}{\delta_{fat}}\right)+\left(\frac{C_{carb}}{\delta_{carb}}\right)+\left(\frac{C_{fib}}{\delta_{fib}}\right)+\left(\frac{C_{protein}}{\delta_{protein}}\right)+\left(\frac{C_{ash}}{\delta_{ash}}\right)+\left(\frac{C_{water}}{\delta_{water}}\right)\right\}} \quad (5)$$

where

$$\delta_{fat} = 9.26 \times 10^2 - 4.18 \times 10^{-1} T$$

$$\delta_{carb} = 1.60 \times 10^3 - 3.10 \times 10^{-1} T$$

$$\delta_{fib} = 1.31 \times 10^3 - 3.66 \times 10^{-1} T$$

$$\delta_{protein} = 1.33 \times 10^3 - 5.18 \times 10^{-1} T$$

$$\delta_{ash} = 2.42 \times 10^3 - 2.81 \times 10^{-1} T$$

$$\delta_{water} = 9.97 \times 10^2 + 3.14 \times 10^{-3} T - 3.38 \times 10^{-3} T^2$$

C_{fat}, C_{carb}, C_{fib}, $C_{protein}$, C_{ash} and C_{water} are fraction of fat, carbohydrate, fiber, protein, ash and water in barnyard millet grain and kernel at experimented moisture content.

Interstices are the void space due to intermolecular space among the molecules of the protein, fat, fiber, carbohydrate, ash and water. Interstice was calculated using Eq. (6):

$$I = \frac{\text{thousand grain mass}}{1000} \times \left(\frac{\delta_{pc} - \delta_{td}}{\delta_{pc} \times \delta_{td}}\right) \quad (6)$$

The porosity of barnyard millet grain and kernels at five selected moisture content was calculated using Eq. (7):

$$P = \left(1 - \frac{\delta_{bd}}{\delta_{td}}\right) \times 100 \quad (7)$$

Since the shape of the barnyard millet grain and kernel are not spherical so the terminal velocities of these grains were measured experimentally instead of using mathematical relationship. Air column experimental device was used to measure the terminal velocity of barnyard millet grain and kernels (Gupta et al., 2007; Zewdu, 2007; Sacilik et al., 2003). A transparent plastic made hollow cylindrical air column was used for this purpose. For each test run sample of 100 g was fed into the hopper. The vibrator in the feeder dropped the materials into air stream from the top of the vertical column. The airflow rate was gradually increased to suspend the material in the air stream for 30 s. The air velocity was measured using vane anemometer.

A plywood box of size 300 mm × 300 mm × 300 mm, having one side sliding and removable was taken to determine the dynamic angle of repose 'θ'. The box was filled with grain at desired moisture content and the sliding side of the box was quickly removed, allowing the grains to flow to their natural slope. The angle of repose was calculated from measurement of grain free surface depth at the end of the box and midway along the slope surface and horizontal distance from the end of the box to this mid point (Singh and Goswami, 1996; Dutta et al., 1988; Baryeh, 2002).

The internal coefficient of friction μ_i at five different moisture levels was determined with the help of experimental setup suggested by Subramanium and Viswanathan (2007). In this setup two identical hollow plastic cylinders, of 50 mm diameter and 55 mm height were used. Lower cylinder was fixed on the horizontal surface where as top cylinder kept free. The provision of pulley-rope with loading pan was made that the top cylinder can slide over stationary cylinder by increasing weight on the loading pan. The coefficient of internal friction was measured using Eq. (8):

$$\mu_i = \frac{F_g - F_e}{N} \quad (8)$$

The static coefficient of friction of barnyard millet grain and kernel against three different surfaces namely sun mica, mild steel and canvas surfaces were determined using a plastic cylinder of 100 mm, diameter and 50 mm height. The cylinder filled with grain was placed on an adjustable inclined surface. The plastic cylinder was raised slightly so that its bottom edge cannot touch the inclined surface. The all three surfaces were raised slowly with help of screw device until the cylinder filled with grain started to slide down. The angle of tilt was recorded. The coefficient of friction was calculated using Eq. (9):

$$\mu_s = \tan\alpha \quad (9)$$

where μ_s is the coefficient of static friction and α is tilt angle in degree.

Mechanical properties like rupture force, specific deformation and rupture energy of barnyard millet gain and kernel were also assessed at selected five moisture content.

Rupture force of the grain and kernel was determined using "Stable micro system texture analyzer" of 50 kg compression load cell. The individual grain and kernel were loaded between horizontal plate and load cell of the texture analyzer and compressed along with the thickness until rupture occurred. The rupture point is point at which the grain gets break or crack.The specific deformation force and rupture energy were determined using Eqs. (10) and (11), respectively (Altuntas and Yildiz, 2007):

$$\sigma = \left[\frac{L_u - L_f}{L_u}\right] \times 100 \quad (10)$$

$$E_r = \left[\frac{F_r \times D_r}{2}\right] \quad (11)$$

3. Results and discussion

3.1. Geometric mean diameter

The variation of mean geometrical diameter of the grain and kernels upon exposure of moisture is shown in Fig. 2. It is evident from the figure that mean diameter of grain and kernel increases with increase of moisture content followed second order polynomial equation shown in Eqs. (12) and (13):

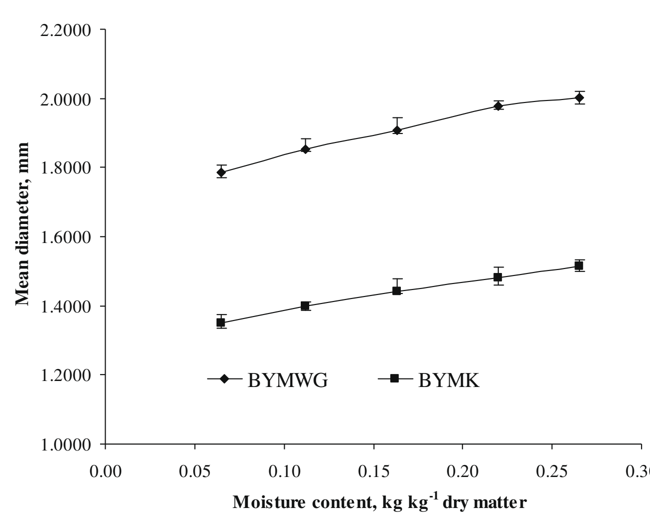

Fig. 2. Effect of moisture content on mean diameter.

$$D_{geg} = 1.68 + 1.78\,M - 2.03\,M^2, \quad (R^2 = 0.99) \tag{12}$$

$$D_{gek} = 1.28 + 1.14\,M - 1.03\,M^2, \quad (R^2 = 0.99) \tag{13}$$

High coefficient of determination ($R^2 > 0.99$) shows that on moisture gain of barnyard millet grain and kernel increase the mean diameter within the experimented moisture range. The increase in moisture from 0.065 to 0.265 kg kg^{-1} dry matter, 12.21% and 11.91% increase in mean diameter was observed for grain and kernel, respectively. However, the geometric mean diameter is lower than those reported for millet (Baryeh, 2002) and sunflower seed (Gupta and Das, 1997).

3.2. Sphericity

The sphericity of barnyard millet grain and kernel were calculated using Eqs. (12) and (13). The value of sphericity of grain and kernel increased with increase in moisture content. The value of sphericity of barnyard millet grain varied from 0.89 to 0.96 and for kernel from 0.91 to 97 with variation of moisture content from 0.065 to 0.265 kg kg^{-1} dry matter (Fig 3). The increase in sphericity upon addition of moisture have been reported for moth gram (Nimkar et al., 2005), vetch seed (Yalçin and Özarslan, 2004), pea seed (Yalcin et al., 2007) and cotton seed (Ozarslan, 2002). These studies reported that initial rate of increase in sphericity was higher and it becomes comparatively lower at latter stage. The variation of sphericity of grain and kernel with moisture content could be represented by the Eqs. (14) and (15) respectively:

$$\phi_g = 0.86 + 0.5\,M - 0.56\,M^2, \quad (R^2 = 0.99) \tag{14}$$

$$\phi_k = 0.91 + 0.19\,M + 0.17\,M^2, \quad (R^2 = 0.99) \tag{15}$$

3.3. Surface area

The value of surface area obtained for barnyard millet grain and kernel are graphically represented in Fig 4. The values of grain and kernel surface area increases linearly from 9.32 to 12.16 mm^2 and 5.58 to 7.13 mm^2 respectively with increase of moisture content from 0.065 to 0.265 kg kg^{-1} dry matter (Eqs. (16) and (17)):

$$S_g = 8.01 + 21.64\,M - 22.29\,M^2, \quad (R^2 = 0.99) \tag{16}$$

$$S_k = 4.79 + 10.02\,M - 7.10\,M^2 \quad (R^2 = 0.99) \tag{17}$$

This increase in surface area was happened due to increase of dimensions with increase of moisture content of grains and kernels. Similar trend of increase have been reported by Altuntas and Yildiz (2007) for faba bean and Isik and Ünal (2007) for kidney bean grain. However, Al-Mahasneh & Rababah (2007) and Coskuner and Korababa (2007) observed the polynomial increase of surface area with increase of moisture content in green wheat and coriander seed, respectively.

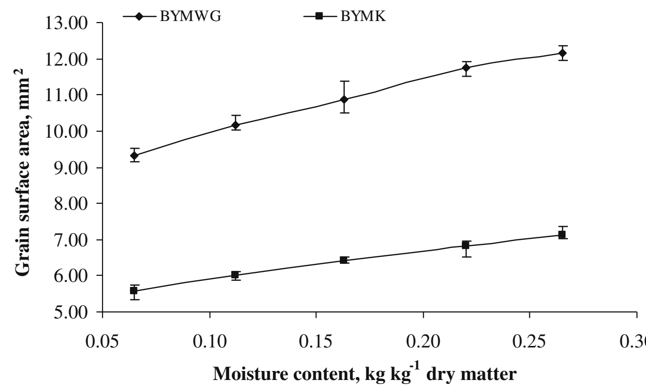

Fig. 4. Effect of moisture content on grain surface area.

3.4. Mass of 1000 grains and kernels

The mass of 1000 grain and kernel was found to increase linearly from 4.17–5.45 and 1.70–2.16 g, respectively with increase in moisture content, as shown in Fig 5 and Eqs. (18) and (19):

$$W_g = 3.85 + 4.00\,M + 7.59\,M^2, \quad (R^2 = 0.99) \tag{18}$$

$$W_k = 1.55 + 1.87\,M + 1.60\,M^2, \quad (R^2 = 0.98) \tag{19}$$

Similar results of the effect of grain moisture content on thousand grains mass have been reported for moth gram (Nimkar et al., 2005), green wheat (Al-Mahasneh and Rababah, 2007), and lentil seed (Amin et al., 2004). However, Sahoo and Srivastava (2002) found logarithmic relationship between the 1000 seed mass and moisture content.

3.5. Bulk density

The bulk density of barnyard millet grain and kernel decreases with increase of moisture content from 0.065 to 0.265 kg kg^{-1} dry matter and showed polynomial trend (Eqs. (20) and (21)) as shown in Fig 6 as follows:

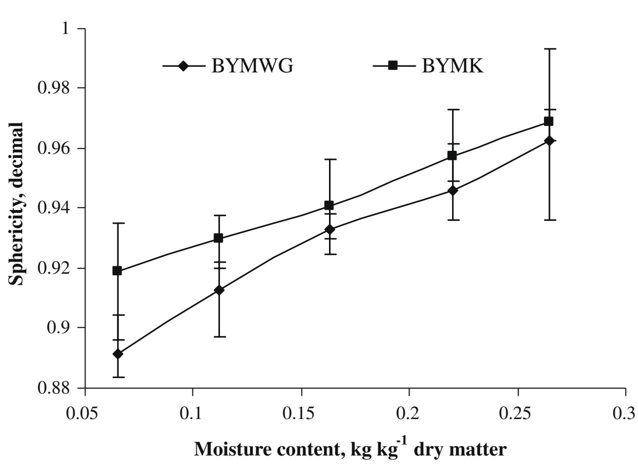

Fig. 3. Effect of moisture content on sphericity.

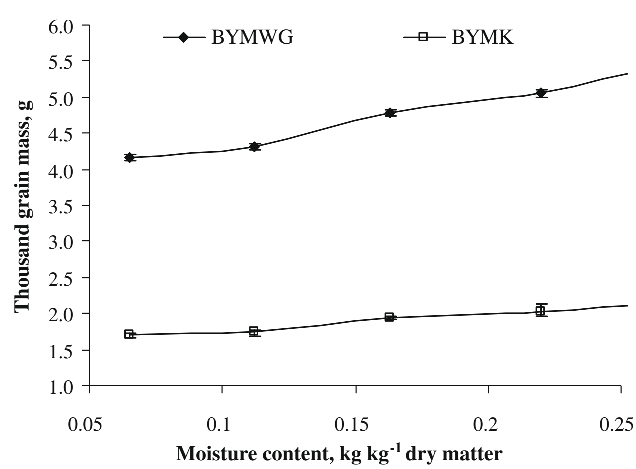

Fig. 5. Effect of moisture content on thousand grain weight.

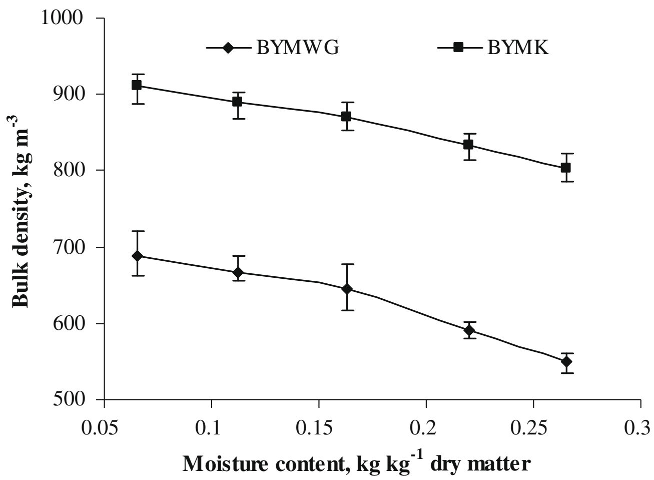

Fig. 6. Effect of moisture content on bulk density.

$$\delta_{bd\,g} = 696.02 - 2.29\ \mathrm{M} - 2091.9\ \mathrm{M}^2, \quad (R^2 = 0.99) \tag{20}$$

$$\delta_{bd\,k} = 929.23 - 228.24\ \mathrm{M} - 930.14\ \mathrm{M}^2 \quad (R^2 = 0.99) \tag{21}$$

The decrease in bulk density may be due to increase in intergranular space with increase of moisture content. Similar trend was found by Baryeh (2002) for millet, Singh and Goswami (1996) for cumin seed. However, Altuntas and Yildiz (2007); Nimkar et al. (2005); Isik and Ünal (2007); Sessiz et al. (2007) and Sahoo and Srivastava (2002) were found linear decrease in faba bean, moth grain, kidney bean grain, caper fruit and okra seed respectively, with increase of moisture content.

3.6. True density (toluene displacement method)

With the increase of moisture content from 0.065 to 0.265 kg kg^{-1} dry matter, the true density of grain increased in linear fashion from 1225.5 to 1308.1 kg m^{-3} and kernel from 1388.9 to 1491.5 kg m^{-3}. The variation of true density of grain and kernel with moisture content is depicted in Fig 7. The relationship may be shown as Eqs. (22) and (23) for grain and kernel, respectively.

$$\delta_{td\,g} = 1204.7 + 382.21\ \mathrm{M} + 12.51\ \mathrm{M}^2, \quad (R^2 = 0.96) \tag{22}$$

$$\delta_{td\,k} = 1331.6 + 920.42\ \mathrm{M} - 1134.7\ \mathrm{M}^2 \quad (R^2 = 0.98) \tag{23}$$

Similar trend was observed to be found by Baryeh (2002) for millet and Isik and Ünal (2007) for kidney bean. However, Sahoo and Srivastava (2002), Al-Mahasneh and Rababah (2007), and Dursun and Dursun (2005) were found decrease in true density, in okra seed, green wheat and caper seed, with increase of moisture content. The increase in true density was mainly due to the larger increase in grain and kernel volume as compared to their masses.

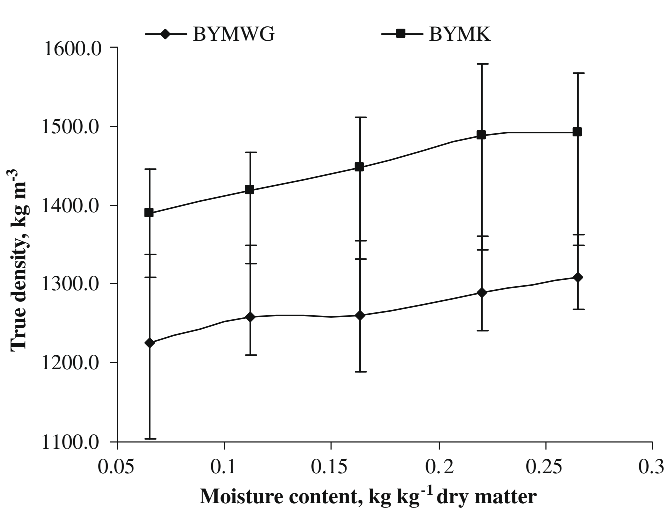

Fig. 7. Effect of moisture content on true density (toluene displacement method).

3.7. True density (proximate composition method)

True density calculated with the help of proximate composition of barnyard millet grain and kernel decrease with the increase of moisture content, as shown in Fig 8 and Eqs. (22) and (23). The results indicated that the percentage decrease in true density value for barnyard millet grain and kernel were 8.64% and 9.80% respectively for corresponding change in moisture content from 0.065 to 0.265 kg kg^{-1} dry matter.

The decrease in true density values for grain and kernel with increase with moisture content might be attributed due to increase of fraction of water in proximate composition. Since the density of other constituents like, fiber, ash, carbohydrate, protein and fat are less as compared to water.

$$\delta_{pc\,g} = 1499.2 - 797.42\ \mathrm{M} + 552.02\ \mathrm{M}^2, \quad (R^2 = 0.99) \tag{24}$$

$$\delta_{pc\,k} = 1554 - 890.51\ \mathrm{M} + 511.84\ \mathrm{M}^2, \quad (R^2 = 0.99) \tag{25}$$

3.8. Interstice

The volume of the grain and kernels can be calculated by two methods. First, with the help of mass of single grain divided by true density obtained from toluene displacement method. Here the volume of grain is included the intermolecular space inside the grain. The second method for calculating the volume of the grain is by adding the volume of each constituent of proximate composition of grain and kernel. The volumes of individual grain and kernel obtained from proximate composition were found lesser as compared to volume obtained from toluene displacement method. The difference of two volumes can be known as interstice.Interstice was found to decrease with increase in moisture content as shown in Fig 9, as follows:

$$I_g = 0.52 - 2.88\ \mathrm{M} - 4.30\ \mathrm{M}^2, \quad (R^2 = 0.97) \tag{26}$$

$$I_k = 0.23 - 0.79\ \mathrm{M} - 0.29\ \mathrm{M}^2, \quad (R^2 = 1) \tag{27}$$

The interstices of grain and kernel decrease from 0.37 to 0.05 and 0.18 to 0 respectively with moisture content increase from 0.065 to 0.265 kg kg^{-1} dry matter. The water absorption potential of any grain may be affected by the interstices inside the grain.

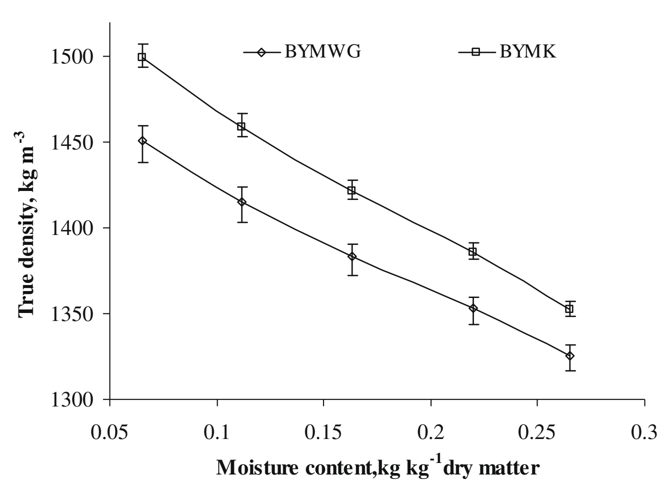

Fig. 8. Effect of moisture content on true density (proximate composition method).

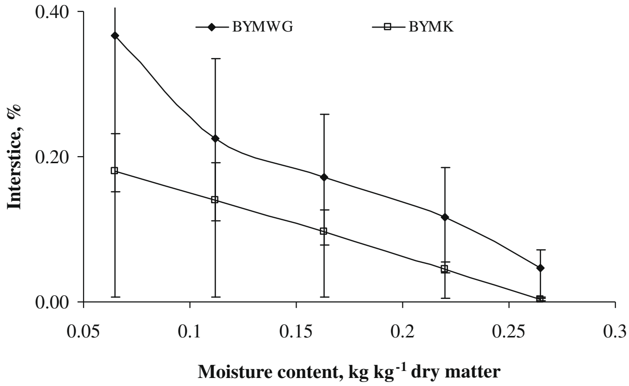

Fig. 9. Effect of moisture content on interstices.

3.9. Porosity

The porosity of barnyard millet grain and kernel was calculated from their bulk density and true density using Eq. (6). Porosity of both grain and kernel were found to be increase from 43.0% to 57.47% and 34.2% to 45.8%, respectively with the moisture content increase from 0.065 to 0.265 kg kg^{-1} dry matter shown in Fig 10. The grain and kernel follows linear polynomial relationship with moisture content which is shown in Eqs. (28) and (29):

$$E_g = 41.73 + 22.93\ M + 145.3\ M^2, \quad (R^2 = 0.99) \tag{28}$$

$$E_k = 30.42 + 58.64\ M - 0.97\ M^2, \quad (R^2 = 0.99) \tag{29}$$

Similar trend was found by Singh and Goswami (1996), for cumin seeds, Baryeh (2002) for millet, Calisir et al. (2005) for rapeseed, Deshpande et al. (1993) for soybean and Kaleemullah and Gunasekar (2002) for arecanut. However, porosity was reported to be decreased with the increase moisture content for green wheat (Al-Mahasneh and Rababah, 2007), caper seed (Dursun and Dursun, 2005) and popcorn (Karababa, 2006). The increase and decrease of porosity with increase of moisture content may be happened due to difference in shape and size of different grains.

3.10. Terminal velocity

The terminal velocity of grain and kernel of barnyard millet increased from 4.22 to 6.59 and 3.82 to 5.96 ms^{-1} respectively when moisture level increases from 0.065 to 0.265 kg kg^{-1}. The variation in terminal velocity of barnyard millet grain and kernel follows second-order polynomial relationship with moisture content which is represented by:

$$V_g = 3.99 + 2.36\ M + 27.60\ M^2, \quad (R^2 = 0.99) \tag{30}$$

$$V_k = 3.62 + 2.37\ M + 23.31\ M^2 \quad (R^2 = 0.98) \tag{31}$$

The terminal velocity of barnyard millet grain was found to be more as compared to kernel in the moisture content range from 0.065 to 0.265 kg kg^{-1} dry matter (Fig. 11). This difference of terminal velocity may be due to difference in grain mass, shape and size of grain and kernel. Similar trend was observed by Zewdu (2007) for tef grain and straw material and Baryeh (2002) for millet grains.

3.11. Dynamic angle of repose

The dynamic angle of repose of barnyard millet grain and kernel were observed to increase from 24.47 to 39.13° and 33.35 to 48.80° (Fig 12). The increase of dynamic angle of repose was may be due to increase of internal friction with increase of contact surface area among the grain and kernels. It is fact that if internal friction among the grain increases the angle of repose will also be increased. Similar trend was observed by Baryeh (2002) in millet, Dursun and Dursun (2005) in caper seed, Nimkar et al. (2005) in moth grain and Sahoo and Srivastava (2002) in okra seeds. The values of dynamic angle of repose for barnyard millet grain and kernel can be shows as linear Eqs. (32) and (33):

$$\theta_g = 21.05 + 47.37\ M + 81.84\ M^2, \quad (R^2 = 0.99) \tag{32}$$

$$\theta_k = 26.86 + 106.05\ M - 91.45\ M^2, \quad (R^2 = 0.99) \tag{33}$$

3.12. Coefficient of internal friction

Coefficient of internal friction of barnyard millet grain and kernel was found to be increased from 0.56 to 0.84 and 0.66 to 0.91, respectively when moisture level increased from 0.065 to 0.265 kg kg^{-1} dry matter. Coefficient of internal friction of kernel was found to be more as compared to grains at all experimented moisture range (Fig 13). The variation in coefficient of internal friction of barnyard millet grain and kernel follows second order polynomial Eqs. (34) and (35), respectively:

$$\mu_{ig} = 0.45 + 1.70\ M - 0.70\ M^2, \quad (R^2 = 0.99) \tag{34}$$

$$\mu_{ik} = 0.63 + 0.36\ M + 2.71\ M^2, \quad (R^2 = 0.99) \tag{35}$$

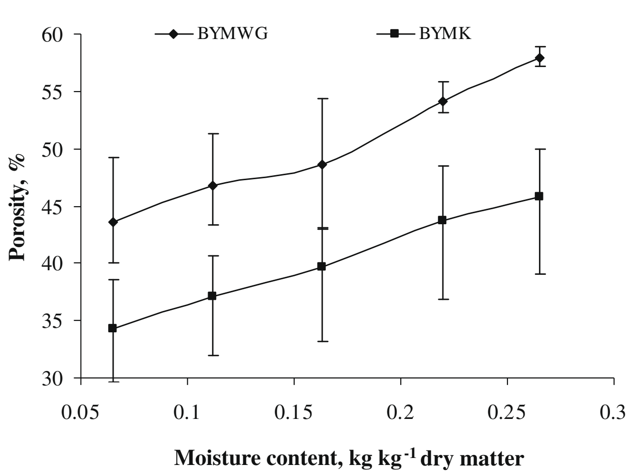

Fig. 10. Effect of moisture content on porosity.

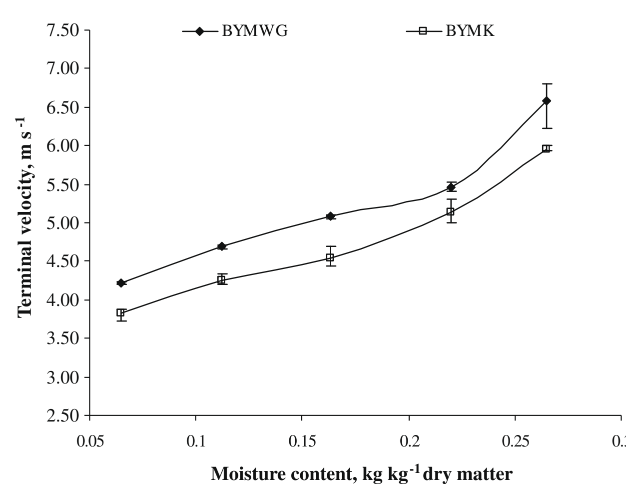

Fig. 11. Effect of moisture content on terminal velocity.

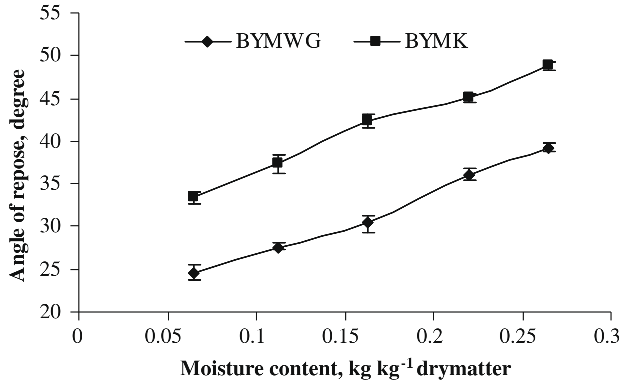

Fig. 12. Effect of moisture content on dynamic angle of repose.

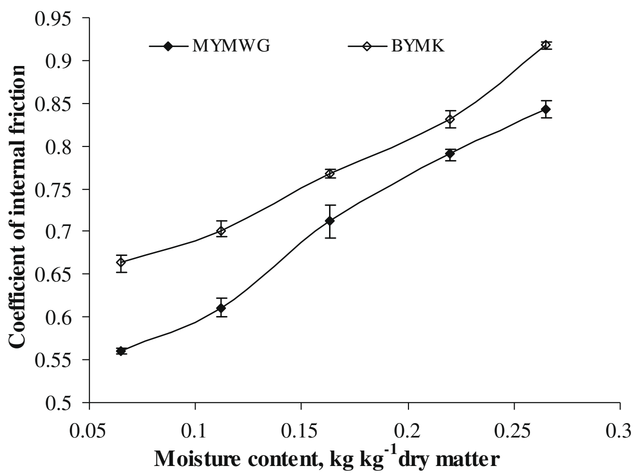

Fig. 13. Effect of moisture content on coefficient of internal friction.

Similar trend was observed by Subramanium and Viswanathan (2007) for millets grain and flours.

3.13. Static coefficient of friction

Static coefficient of barnyard millet grain and kernels on sun mica, iron and canvas surfaces shows a linear increase with increase of the moisture content from 0.065 to 0.265 kg kg^{-1} dry matter (Fig 14), were followed the second order polynomial equation shown below:

$$\text{Sun mica}: \mu_{sg} = 0.20 + 0.17\ \text{M} + 0.59\ \text{M}^2, \quad (R^2 = 0.99) \tag{36}$$

$$\mu_{sk} = 0.19 + 0.29\ \text{M} + 0.39\ \text{M}^2, \quad (R^2 = 0.99) \tag{37}$$

$$\text{Canvas}: \mu_s g = 0.27 + 0.87\ \text{M} + 0.48\ \text{M}^2, \quad (R^2 = 0.97) \tag{38}$$

$$\mu_s k = 0.38 + 1.22\ \text{M} + 0.21\ \text{M}^2, \quad (R^2 = 0.99) \tag{39}$$

$$\text{Mild steel}: \mu_s g = 0.21 + 1.00\ \text{M} + 0.24\ \text{M}^2, \quad (R^2 = 0.96) \tag{40}$$

$$\mu_{sk} = 0.22 + 2.35\ \text{M} + 3.72\ \text{M}^2, \quad (R^2 = 0.99) \tag{41}$$

Similar trend was observed by Kaleemullah and Gunasekar (2002) for areca nut kernel. However, linear increase of static friction coefficient with moisture content was observed by Isik and Ünal for kidney bean grain, Dursun and Dursun (2005) for caper seeds, Nimkar et al. (2005) for moth grain and Al-Mahasneh and Rababah (2007) for green wheat.

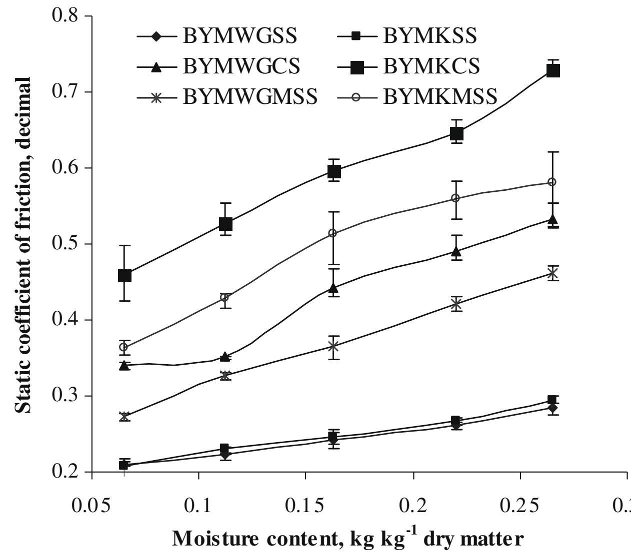

Fig. 14. Effect of moisture content on static coefficient of friction.

3.14. Rupture force

The rupture force of barnyard millet grain and kernel decreased from 45.67 and 36 N and 25.20 to 17.87 N respectively with increase in moisture content from 0.065 to 0.265 kg kg^{-1} dry matter respectively, as shown in Fig 15. The variation in rupture force of grain and kernel follows second order polynomial equation shown below:

$$F_g = 51.37 - 101.97\ \text{M} + 167.37\ \text{M}^2, \quad (R^2 = 0.99) \tag{42}$$

$$F_k = 29.21 - 29.21\ \text{M} + 97.84\ \text{M}^2, \quad (R^2 = 0.99) \tag{43}$$

Similar trend was observed by Altuntas and Yildiz (2007) for faba bean grain and Tavakoli et al. (2009) for soybean grains.

3.15. Specific deformation

The experimental values of specific deformation of barnyard millet grain and kernel increased from 26.09% to 44.13% and 30.09% to 48.80%, respectively with the increase of moisture content from 0.065 to 0.265 kg kg^{-1} dry matter, as shown in Fig 16. The specific deformation of kernel was found to be higher at all

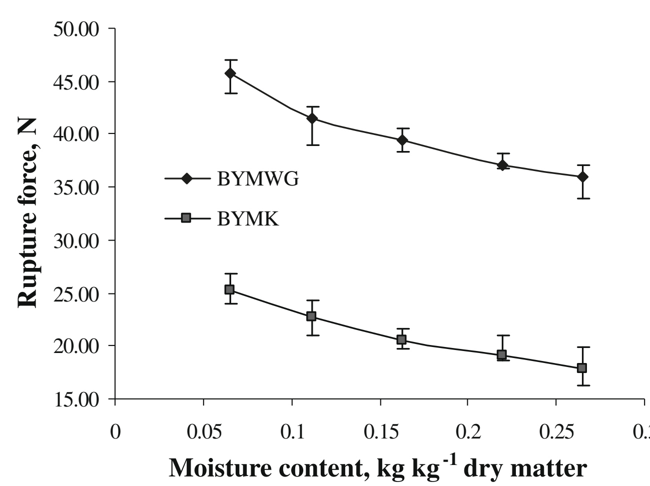

Fig. 15. Effect of moisture content on rupture force.

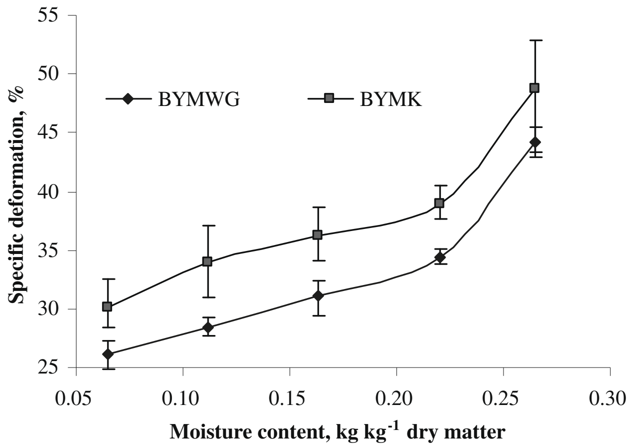

Fig. 16. Effect of moisture content on specific deformation.

range of experimental moisture content. The following regression equation was developed for specific deformation with moisture content:

$$\sigma_g = 31.59 - 31.56\ \mathrm{M} + 346.6\ \mathrm{M}^2, \quad (R^2 = 0.95) \tag{44}$$

$$\sigma_k = 28.94 - 62.85\ \mathrm{M} + 439.78\ \mathrm{M}^2, \quad (R^2 = 0.97) \tag{45}$$

Similar results were reported for faba bean grain (Altuntas and Yildiz, 2007) and soybean grain (Tavakoli et al., 2009).

3.16. Rupture energy

Rupture energy was found to increase with the increase in moisture content as shown in Fig 17, as follows:

$$E_{rg} = 2.96 + 40.69\ \mathrm{M} - 64.84\ \mathrm{M}^2, \quad (R^2 = 0.92) \tag{46}$$

$$E_{rk} = 2.03 + 6.68\ \mathrm{M} + 19.32\ \mathrm{M}^2, \quad (R^2 = 0.97) \tag{47}$$

Rupture energy of whole grain was found to greater than that of kernel at all experimental moisture range. The rupture energy of barnyard millet grain and kernel increased from 5.03 to 9.50 N mm and 2.43 to 5.31 N mm respectively with increase of moisture content from 0.065 to 0.265 kg kg^{-1} dry matter. These results were found much lower as compared to soybean grain (Tavakoli et al., 2009) and faba bean grain (Altuntas and Yildiz, 2007).

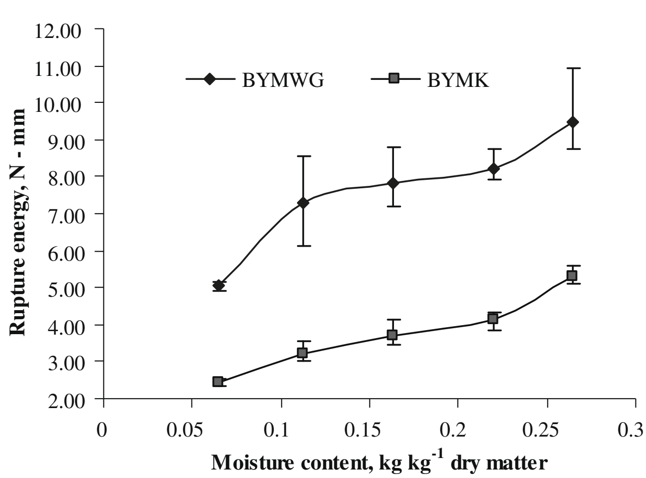

Fig. 17. Effect of moisture content on rupture energy.

4. Conclusions

The following conclusions were drawn from the experiment on properties of barnyard millet grain and kernel for moisture content range from 0.065 to 0.265 kg kg^{-1} dry matter. The geometric mean diameter, sphericity, grain surface area, 1000 grain mass, true density (toluene displacement), terminal velocity, dynamic angle of repose, coefficient of internal friction, coefficient of static friction at different surfaces (sun mica, canvas and mild steel surfaces), specific deformation and rupture energy of the grain increase with increase of moisture content. However, true density (proximate composition method), bulk density, interstices and rupture force of grain decrease at increase of moisture content. Lower true density (TDM) as compared to true density (PCM) at all moisture range indicates the presence of void space inside the grain and kernel.

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