Physical properties of Pearl Millet Grain

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ABSTRACT : Physical properties of grains are essential requirement for design of structures, machineries and equipment. Physical properties of pearl millet grain varieties ('Pusa composite 383', 'Pusa composite 701', 'Pusa composite 1201' and 'Pro agro 9444') were evaluated at varying moisture content (range: 10-30% db). The mean value of properties were recorded for length (2.997-3.172 mm), width (2.433-2.609 mm), thickness (2.036-2.209 mm), geometric mean diameter (2.453-2.629 mm), sphericity (0.821-0.833), projected area (5.745-6.509 mm^2), thousand grain mass (9.114-10.123 g), grain volume (6.324-7.833 mm^3), bulk density (711.9-827.5 kg/m^3), true density (1216.97-1314.17 kg/m^3), porosity (37.02-41.47 %). Moreover, static friction coefficients against wood (0.220-0.397), mild steel (0.237-0.403), galvanised iron (0.231-0.408) and aluminium (0.245-0.423), emptying angle of repose (28.83-33.57 degree), filling angle of repose (24.34-29.38 degree) and rupture strength (22.36-49.47 N) were also determined. Mean values of properties like size, sphericity, projected area, thousand grain mass, grain volume, coefficient of friction at different surfaces and angle of repose increased with increase in grain moisture content; bulk density, true density and rupture strength decreased. Varietal differences were significant ($p \leq 0.05$) for some of the properties under investigation. Regression yielded high R^2 values for linearly varying properties with moisture content except sphericity representing shape of the grain.

Key words: Moisture effect, Pearl millet, physical properties, varietal effect

Some abbreviations			
L	Length	BD	Bulk density
W	Width	TD	True density
T	Thickness	P	Porosity
GMD	Geometric mean diameter	SFC	Static friction coefficient
Θ	Sphericity	Θ (e)	Angle of repose (emptying)
A (P)	Projected area	Θ (f)	Angle of repose (filling)
TGM	Thousand grain mass	RS	Rupture strength
V	Grain volume	PC	Pusa composite
PA	Pro agro		

Pearl millet (*Pennisetum glaucum*) is a gluten-free grain (Leder, 2004 and Zhu, 2014) with excellent drought and heat tolerance. Having versatile uses as food, feed and fuel (Florence-Suma and Urooj, 2014), it covers around 27 million ha of Asia and sub-Saharan Africa (Reddy *et al*., 2013). Shadang and Jaganathan (2014) mentioned it as an extensive crop, feeding approximately 400 million of teeming population. India holds first position in production (9.18 million tonnes) and area (7.32 million ha) with productivity of 1255 kg/ ha in 2014-15 (Agricultural statistics at a glance 2016, Department of Agriculture Cooperation and Farmers Welfare, Ministry of Agriculture and Farmers Welfare, GOI).

Pearl millet contains 62.8-70.5 g/ 100g of starch in Indian genotypes (Suma and Urooj, 2015) with 14.0% crude protein, 5.7% fat, 2.1% ash, 2.0% crude fibre and 76.3% carbohydrate (Sade, 2009). Amadou *et al*. (2014) identified it for phytochemicals, phenolic compounds, minerals, nutraceuticals, essential micronutrients and vitamins. It contains 8-19% of protein content with better balance of amino acids as compared to most of the cereals.

The grain passes through various pre and post harvest operations viz. planting, harvesting, threshing, handling, conveying, storage and processing. Efficient unit operations are possible through optimizing the design of concerned equipment, machineries or structures. These design features are functions of properties of grains, seeds and kernels, which are moisture dependent. The shape, size and density are important while developing the machineries for dry cleaning, sorting and grading. Teye and Abano (2012) emphasised on physical properties of grains for design of such equipment. While rupture strength, static friction coefficient and internal friction are needed for design of dehullers; dynamic repose angle, porosity, bulk density and true density are required for designing of storage structures. Besides, the drying and aeration systems design require porosity and bulk density. Equipments for mass flow and storage structures use the angle of repose data. The friction coefficient between grain and surfaces is helpful for separation on oscillating sieve, movement on oscillating conveyor, loading and unloading. The physical properties are also important for developing sensors for automation of machineries and processes. Esref and Halil (2007) acknowledged the importance of physical properties for storage structures and processing operations. The irregular shapes and composition for most of the biological materials further signifies the utility of these characteristics.

The engineering properties have been reported for various millets such as HMT 1001 variety of foxtail millet (Sunil *et al*., 2016), finger millet of sub-Saharan Africa (Ramashia *et al*., 2017), finger millet (Swami and Swami, 2010), finger millet and little millet (Nazni and Bhuvaneswari, 2015), minor millets (Balasubramanian and Vishwanathan, 2010), grains and kernels of baryard millet (Singh *et al*., 2010) and *Pennisetum gambiense* (Baryeh, 2002). Badau *et al*. (2002) and Chhabra and Kaur (2017) evaluated pearl millet cultivars, while Thilagavathi *et al*. (2015) compared pearl millet (COC9 variety) with proso millet, kodo millet and little millet for physico-chemical characteristics at fixed moisture content. It is thus evident that varietal differences in physical properties of pearl millet grains as affected by moisture content have not yet been evaluated systematically. Therefore, the objective of the current research work was to evaluate the properties of popular varieties of pearl millet grown in India and to establish their relationship with moisture content.

MATERIALS AND METHODS

Pearl millet varieties ('Pusa Composite 383', 'Pusa Composite 701', 'Pusa Composite 1201' and 'Pro agro 9444') were obtained from the farm of ICAR-Indian Agricultural Research Institute, New Delhi. The grains of each variety were cleaned thoroughly for removing extraneous materials as well as broken and immature kernels before storing it for further analysis.

Sample Preparation

The moisture content (X) of the grain was measured using the method described by Zewdu and Solomon (2007). To achieve particular moisture content of the grain, calculated quantity of water was sprayed on the grain in a polyethylene bag. The bag was sealed and kept in a refrigerator (5°C) for 7 days (Singh *et al*., 2010). Shaking of sample in bag was done daily to equilibrate the moisture throughout the sample. To measure the properties of the sample, it was kept at ambient condition for about 2 h to equilibrate the grain temperature with the room temperature (Singh *et al*., 2010 and Tavakoli *et al*., 2009). The properties of kernels were determined at varying moisture contents (10-30 %).

Size

The vernier calliper (least count of 0.001 mm) was used for measuring all linear dimensions namely length (L), width (W) and thickness (T) of hundred randomly selected grains at each moisture levels for all the varieties. The geometric mean diameter (Mohsenin, 1970 and Singh *et al*., 2010) was determined using relationship mentioned below.

$$Dg = (L*W*T)^{1/3} \quad \text{... (1)}$$

Sphericity

Sphericity is defined as the ratio of geometric mean diameter to the length of grain (Zewdu and Solomon, 2007 and Singh *et al*., 2010) and was determined using relationship

$$\Phi = \frac{(L*W*T)^{1/3}}{L} = \frac{Dg}{L} \quad \text{... (2)}$$

Projected area

Projected area (A_P) is the area subtended by projection of the grain on a plane surface. It was determined as the equation (3).

$$A_P = (\pi/4)*L*W \quad \text{... (3)}$$

Thousand grain mass

The thousand grain mass was determined for ten replications using digital electronic balance with an accuracy of 0.001g as suggested by Singh *et al.* (2010) and Zewdu and Solomon (2007).

Grain volume

Volume of single grain was calculated through the equation suggested by Jain and Bal (1997) and Karababa and Coskuner (2013) as

$$V = \frac{(\pi B^2 L^2)}{6(2L-B)} \text{ ; where } B = (WT)1/2 \quad \text{... (4)}$$

Bulk density

Bulk density is defined as the mass per unit volume of the grain including the pore space. It was calculated as the ratio of sample mass and its total volume (Singh *et al.*, 2010).

True density

True density, the ratio of grain sample mass and its volume excluding the pore space, was determined using the toluene displacement method as reported by Singh *et al*. (2010).

Porosity

The porosity (ε) is the percentage of pore space in the bulk grain and was calculated by the following relationship as mentioned by Mohsenin (1970).

$$\varepsilon = 100^* \left[1- \frac{\rho^{(b)}}{\rho^{(t)}}\right] \quad \text{... (5)}$$

Static friction coefficient

Static friction coefficient was determined as the tangent of the inclination angle of a plane gently raised from horizontal position until the grain containing plastic cylinder started to slide down. It was determined against four different surfaces namely wood, mild steel, galvanised iron and aluminium (Singh *et al*., 2010 and Subramanian and Viswanathan, 2007).

$$\mu = \tan(\alpha) \quad \text{... (6)}$$

Where, α is the inclination angle and μ is the friction coefficient. The average of ten readings was noted for each moisture level.

Emptying and filing angle of repose

The emptying, draining, funnelling or dynamic angle of repose (Θ_e, degree) was determined using a cubical box of 200mm x 200mm x 200mm, one front of which was removable (Karababa and Coskuner, 2007 and Jain and Bal, 1997).

$$\Theta_e = \tan^{-1}(\text{slope}) \quad \text{... (7)}$$

Filling or piling angle of repose was also determined using a cylindrical container open at both ends and placed on the centre of a circular wooden plate. The grain filled cylinder was raised slowly till the grains forming a cone shape on the plate. The average of ten replications was calculated at each moisture level using the following relationship as applied by Sessiz *et al*. (2007) and Balasubramanian and Viswanathan (2010).

$$\Theta_e = \tan^{-1} 2 \frac{H}{D} \quad \text{... (8)}$$

Where H is the height (cm) of the cone and D is the diameter (cm) of the cone.

Rupture strength

The rupture strength of the grains was measured using the Texture analyzer (Model: *TA+HDi*, Stable Micro Systems, UK) equipped with a stainless steel probe (P75) and load cell of 500 kg having accuracy of ±0.001mm in deformation and ±0.001N in force. The test was objective evaluation for the force-deformation characteristics of the grain. The pre-test, test and post-test speeds during the analysis were 1, 0.2 and 2 mm/s respectively with 60% strain. The compression of individual grain along its thickness resulted in to a force-deformation diagram. The failure (visible or invisible) in the form of breaks or cracks during grain rupture was indicated as the rupture point (Tavakoli *et al*., 2009). The rupture point was detected when subsequent points in the diagram were found with continuously decreasing load. The average of 20 replications is reported (Altuntaş and Yıldız, 2007).

Statistical Analysis

The properties of pearl millet grains were determined as a function of moisture content for four varieties using Completely Randomized Design (CRD). Data was analysed using MS Excel 2007. Relationships between properties and moisture contents were developed through regression analysis, while pooling the data of all the varieties. Statistical analyses were conducted to observe the difference for 5% level of significance in properties with varieties and moisture contents.

RESULTS AND DISCUSSION

Size

Size of the pearl millet grain was determined in terms of linear dimensions (L, B and T) and geometric mean diameter (GMD). The average values of length, width, thickness and geometric mean diameter varied from 2.997-3.172, 2.433-2.609, 2.036-2.209 and 2.453-2.629 mm respectively (Fig 1). Jain and Bal (1997) reported respective values as 2.98-3.36, 1.86-2.24, 1.70-2.00 and 1.81-2.12, mm. Ramashia *et al.* (2017) reported a higher value of average length (3.85 mm) and GMD (2.81 mm) of pearl millet with at par values of average width (2.40 mm) and thickness (2.31mm). However, lower values were obtained for linear dimensions (1.41-1.67, 1.28-1.47 and 1.22-1.35) and GMD (1.35-1.49 mm) of finger millet. Lower values of average length (2.17 mm), width (1.59 mm), thickness (1.45 mm) and GMD (1.70 mm) were reported for foxtail millet (Sunil *et al.*, 2016). The length, width, thickness and GMD of pearl millet grains were increasing with increase in moisture content as:

$$L = 0.008X + 2.91 \ (R^2 = 0.94) \quad ... (1)$$

$$W = 0.008X + 2.36 \ (R^2 = 0.93) \quad ... (2)$$

$$T = 0.008X + 1.97 \ (R^2 = 0.95) \quad ... (3)$$

$$GMD = 0.008X + 2.38 \ (R^2 = 0.97) \quad ... (4)$$

Table 1 and 2 showed the significance of moisture content and varietal difference respectively on size of grains. In general, moisture content had significant ($p \le 0.05$) effect on size of grains (Table 1). Table 2 revealed insignificant ($p > 0.05$) difference of PC-383 with 'PA-9444' and 'PC-701' with 'PC-1201' for length. Width and thickness were significantly ($p \le 0.05$) different for all the varieties. However, GMD was insignificantly ($p > 0.05$) different only for 'PC-701' with 'PA-9444'. Established relations depicted very high values of R^2 for linear and positive correlation of length, width, thickness and geometric mean diameter with moisture content. Singh *et al.* (2010) found GMD following second order polynomial for grain and kernel of barnyard millet.

Sphericity

The sphericity value approaching unity exhibits the uniformity of grain shape. The mean sphericity ranged from 0.821-0.833. Sphericity of pearl millet was reported as 0.937-0.942 (Jain and Bal, 1997), 0.667-0.744 (Ojediran *et al*., 2010) and 0.58 (Chhabra and Kaur, 2017). Thus, wide variation in sphericity of pearl millet varieties is amply clear. Variation in sphericity with moisture content could be presented with the help of equation below:

$$\Phi = 0.0004X + 0.82 \ (R^2 = 0.236) \quad ... (5)$$

Table 1: Moisture effect on Properties of pearl millet grain

MC	10	15	20	25	30	LSD
L	2.997^c	3.024^c	3.103^b	3.102^b	3.172^a	0.035
W	2.433^d	2.498^c	2.502^c	2.538^b	2.609^a	0.029
T	2.036^d	2.111^c	2.122^c	2.164^b	2.209^a	0.030
GMD	2.453^e	2.512^d	2.539^c	2.568^b	2.629^a	0.023
ϴ	0.821^b	0.833^a	0.821^b	0.831^a	0.831^a	0.008
A (P)	5.745^d	5.945^c	6.110^b	6.195^b	6.509^a	0.111
TGM	9.114^e	9.361^d	9.597^c	9.851^b	10.123^a	0.082
V	6.324^d	6.858^c	7.011^c	7.330^b	7.833^a	0.222
BD	827.50^a	807.47^b	762.50^c	725.72^d	711.90^e	5.374
TD	1314.17^a	1293.95^b	1268.60^c	1242.20^d	1216.97^e	7.300
P	37.02^c	37.58^c	39.85^b	41.56^a	41.47^a	0.557
SFC (W)	0.220^e	0.246^d	0.319^c	0.366^b	0.397^a	0.009
SFC (MS)	0.237^d	0.286^c	0.352^b	0.403^a	0.403^a	0.010
SFC (GI)	0.231^e	0.249^d	0.348^c	0.394^b	0.408^a	0.008
SFC (Al)	0.245^e	0.266^d	0.366^c	0.410^b	0.423^a	0.008
Θ (e)	28.83^e	29.45^d	31.303^c	33.02^b	33.57^a	0.235
Θ (f)	24.34^e	25.48^d	26.783^c	29.05^b	29.38^a	0.256
RF	49.47^a	37.00^b	28.91^c	22.72^d	22.36^d	2.838

Table 2: Varietal effect on properties of pearl millet grain

Property	PC-383	PC-701	PC-1201	PA-9444	LSD
L	3.101[a]	3.063[b]	3.053[b]	3.102[a]	0.031
W	2.407[d]	2.516[b]	2.661[a]	2.481[c]	0.026
T	2.043[d]	2.134[b]	2.242[a]	2.096[c]	0.027
GMD	2.474[c]	2.538[b]	2.627[a]	2.522[b]	0.021
AR	78.088[d]	82.65[9b]	87.484[a]	80.273[c]	1.018
Θ	0.801[d]	0.832[b]	0.863[a]	0.815[c]	0.007
A (P)	5.873[c]	6.073[b]	6.398[a]	6.062[b]	0.100
TGM	8.804[d]	9.206[b]	11.072[a]	9.355[b]	0.074
V	6.304[d]	7.096[b]	8.083[a]	6.806[c]	0.199
BD	779.00[a]	766.92[b]	755.460[c]	766.70[b]	4.807
TD	1285.32[a]	1250.88[b]	1240.920[c]	1291.60[a]	6.530
P	39.42[b]	38.72[c]	39.16[bc]	40.70[a]	0.498
SFC (W)	0.297[c]	0.302[bc]	0.306[b]	0.335[a]	0.008
SFC (MS)	0.341[ab]	0.331[bc]	0.325[c]	0.350[a]	0.009
SFC (GI)	0.320[b]	0.318[b]	0.320[b]	0.347[a]	0.007
SFC (Al)	0.336[b]	0.336[b]	0.340[b]	0.358[a]	0.008
Θ (e)	31.33[b]	30.84[d]	31.077[c]	31.710[a]	0.210
Θ (f)	27.04[b]	26.76[c]	26.40[d]	27.83[a]	0.229
RF	30.17[b]	32.76[a]	32.57[ab]	32.89[a]	2.539

Note: Means with the same letter are not significantly (p>0.05) different

Its decrease can be referred to greater increase in length relative to the width and/ or thickness and vice-versa. Table 1 exhibited acute differences of sphericity with the moisture levels. However, varietal differences were significant for all the cultivars under investigation (Table 2). Very low R^2 value was obtained for sphericity with moisture content. Lower value was meant for its irregular variation with moisture content (Fig. 2).

Projected area

The mean projected area varied in the range of 5.745-6.509 mm^2 respectively (Fig 3). All the cultivars were significantly ($p \leq 0.05$) different except 'PC-701' with 'PA-9444' (Table 2). Regression equation (6) revealed linearly increasing projected area with moisture content as:

$$A (P) = 0.036X + 5.39 \ (R^2 = 0.968) \quad ... (6)$$

Thousand grain mass (TGM)

TGM (9.114-10.123 g) was comparable for pearl millet as reported by Ojediran *et al*. (2010), Thilagavathi *et al*. (2015) and Chhabra and Kaur (2017). The value was quite lower for proso millet, kodo millet and little millet (Thilagavathi *et al*., 2015).

It had relation (Fig 4) with moisture content in agreement with the millet (Baryeh, 2002). Table 1 showed its significant ($p \leq 0.05$) increase throughout the moisture range (10-30 %db). Insignificant ($p>0.05$) difference was observed only for 'PC-701' with 'PA-9444' (Table 2). Pooled data of all the varieties yielded linear relation with moisture content having very high coeffient of determination as:

$$TGM = 0.050X + 8.61 \ (R^2 = 0.999) \quad ... (7)$$

Grain volume

Mean grain volume was lying in the range of 6.324-7.833 mm^3. Pearl millet was reported with quite low (3.59±1.12 mm^3) values (Ramashia *et al.*, 2017) and comparable (5.794 mm^3) values (Jain and Bal, 1997) for grain volume. Volume increase (Fig. 5) with moisture content can be attributed to the moisture-absorption behaviour of grain. Baryeh (2002) found thoroughly increasing trend (linear) for millet (*Pennisetum gambience*). It was higher than the reported values for pearl millet and finger millet (Ramashia *et al*., 2017) and pearl millet, kodo millet, proso millet and little millet (Thilagavathi *et al*., 2015).

Grain volume was increasing significantly ($p \leq 0.05$) throughout the moisture range except insignificant ($p>0.05$) increase from 15 to 20 % moisture level (Table 1). The cultivars were also significantly ($p \leq 0.05$) different (Table 2). Linear relationship was found for grain volume with the moisture content as:

$$V = 0.070X + 5.67 \ (R^2 = 0.971) \quad ... (8)$$

Bulk density

The mean BD was varying from 827.5-711.9 kg/m^3 in the moisture range of 10 to 30 % (db). Pearl millet was reported with quite lower (354.6±3.85 kg/ m^3) range (Ramashia *et al*., 2017), lower (646.4-817.64 kg/ m^3) range (Ojediran *et al*., 2010) and at par (720-790 kg/ m^3) range (Chhabra nd Kaur, 2017) of bulk density. It was at par (737.127 kg/ m^3) with foxtail millet (Sunil *et al*., 2016) and higher (993.6-1158 kg/ m^3) for finger millet (Ramashia *et al*., 2017).

It is evident from figure 6 and table 1 that the bulk density decreased significantly (p≤0.05) in the moisture range of 10-30 % db. The decrease in bulk density with increase in moisture content may be attributed to higher increase in volume as compared to increase in grain mass in the moisture range. Decreasing trend of BD was also reported for millet (Baryeh, 2002) as well as grain and kernel of barnyard millet (Singh *et al*., 2010). Table 2 exhibited significant (p≤ 0.05) difference among the cultivars except for 'PC-701' with 'PA-9444'. Very high R^2 value was obtained for relation with moisture content explained highly proportionate variation among the varieties despite their differences (Fig 6).

$$BD = -6.26X + 892.2 \ (R^2 = 0.974) \quad ... (9)$$

True density

True density of pearl millet ranged from 1314.17-1216.97 kg/m^3. It was reported with quite low (953.26-995.24) value (Ojediran *et al*., 2010), comparable (1220±200) value (Chhabra and Kaur, 2017) and quite high (1531.2±42.72) value (Ramashia *et al*., 2017). However, similar (1260.132 kg/ m^3) value for foxtail millet (Sunil *et al*., 2016) and high (1515.6-1613.4 kg/ m^3) value for finger millet (Ramashia *et al*., 2017) was also reported.

True density decreased significantly (p≤ 0.05) with increase in grain moisture content (Fig 6 and Table 1) similar as millet (Baryeh, 2002) and contrary to the Nigerian varieties of pearl millet (Ojediran *et al*., 2010). Decreasing true density was because of reduced grain matter for certain volume despite increase in TGM with moisture content. Table 2 revealed significant (p≤0.05) difference among the cultivars except for 'PC-383' with 'PA-9444'. Regression yielded linearly decreasing true density with moisture content as the equation given below:

$$TD = -4.92X + 1365.6 \ (R^2 = 0.998) \quad ... (10)$$

Porosity

The mean porosity ranged from 37.02 to 41.56 % in 10-30% (db) moisture range. It was quite low to comparable (15.17-32.64 %), comparable (36.2%) and quite high (76.83%) as reported by Ojediran *et al.* (2010), Chhabra and Kaur (2017) and Ramashia *et al*. (2017) respectively for pearl millet. Sunil *et al*. (2016) found similar values for foxtail millet (41.47%), but finger millet (Ramashia *et al*., 2017) had lower value (24.31-32.41 %) for the same. Fig 7 and Table 1 revealed generally increasing trend of porosity with moisture content. Decreased porosity was attributed to greater increase in BD as compared to TD. Ojediran *et al.* (2010) also found increasing porosity for Nigerian varieties of pearl millet in the range of 10-20 %wb moisture. Its increase was polynomial (2nd order) for millet (Baryeh, 2002) and grain and kernel of barnyard (Singh *et al.*, 2010). Table 2 revealed significant (p≤0.05) difference among the cultivars except for 'PC-1201' with 'PC-383' and 'PC-701'. Linearly increasing trend was obtained with moisture content as the equation given below:

$$P = 0.26X + 34.35 \ (R^2 = 0.917) \quad ... (11)$$

Static friction coefficients (SFC)

The static friction coefficient was determined against wood (0.220-0.397), mild steel (0.237-0.403), galvanized iron (0.231-0.408) and aluminium (0.245-0.423). Its increase was generally significant (p≤ 0.05) throughout the moisture range for all the surfaces (wood, mild steel, galvanised iron and aluminium) as shown in Fig 8 and Table 1. But, the same was decreasing with steel, glass and aluminium as reported for pearl millet by Ojediran *et al*. (2010). Increasing trend with polynomial of 2nd order relations were reported for grains and kernels of barnyard millet (Singh *et al*., 2010). Table 2 revealed significant (p≤ 0.05) difference among the cultivars except for 'PC-701' with 'PC-383' and 'PC-1201' (wood). Significant (p≤0.05) differences were also for 'PC-383' with 'PC-1201' and 'PA-9444' with 'PC-701' and 'PC-1201' (MS). However, differences were insignificant (p>0.05) among 'PC-383', 'PC-701' and 'PC-1201' cultivars for galvanised iron and aluminium. Regression equations 12, 13, 14 and 15 for SFC at surfaces of wood, mild steel, galvanised iron and aluminium respectively with moisture content were:

SFC (W) = 0.01X + 0.12 (R^2 = 0.978) ... (12)
SFC (MS) = 0.01X + 0.16 (R^2 = 0.937) ... (13)
SFC (GI) = 0.01X + 0.13 (R^2 = 0.930) ... (14)
SFC (Al) = 0.01X + 0.14 (R^2 = 0.928) ... (15)

Such relations depicted increasing static friction coefficients with moisture content, while establishing relations with variety and moisture.

Angle of repose

Emptying angle of repose varied from 28.83 to 33.57 (degree), whereas filling angle of repose ranged from 24.34 to 29.38 (degree). It was confirmed through the study that repose angle was greater for emptying as compared to the same for filling. Ojediran *et al*. (2010) reported higher values for emptying angle of repose (29.33-40.00 degree) of pearl millet.

Fig 9 depicted significantly ($p \leq 0.05$) increasing trends (Table 1) for angle of repose (Emptying and filling) throughout the moisture range (10-30 % db). Table 2 also exhibited significant ($p \leq 0.05$) difference among the cultivars under investigation. Regression with moisture content yielded linearly varying equations for emptying and filling repose angles as:

$\Theta_e = 0.26X + 26.02$ (R^2 = 0.967) ... (16)
$\Theta_f = 0.27X + 21.56$ (R^2 = 0.965) ... (17)

Rupture strength

Rupture strength of pearl millet grains varied between 49.47 and 22.36 N in the moisture range (10-30 %db) under investigation. Fig 10 depicted generally decreasing trend as obvious because of the softness of grain at higher moisture. Balasubramanian and Viswanathan (2010) also reported thoroughly decreasing rupture strength with increasing moisture content. But, increased rupture strength at higher moisture could be attributed to harder layer inside after removal of outer grain layer. Fig 10 and Table 1 exhibited its significant ($p \leq 0.05$) decrease throughout the moisture range except insignificant ($p>0.05$) decrease from 25 to 30 % moisture content. Difference was significant ($p \leq 0.05$) for 'PC-383' with 'PC-701' and 'PA-9444' only. Linear decrease of rupture strength was observed with moisture content as the regression equations given beow:

RS = -1.36X + 59.35 (R^2 = 0.895) ... (18)

CONCLUSION

The mean grain size, projected area, thousand grain mass, grain volume, porosity, static friction coefficients (wood, mild steel, galvanized iron and aluminium), emptying repose angle, filling repose angle and yielded linear and positive relations with moisture content (10-30 %db) as obvious. Shape of the grain represented by the sphericity had uncertain trend throughout the moisture range. Consequently, the regression analysis yielded very low R^2 value for linear and positive relation with moisture content. On the other hand, bulk density, true density and rupture strength were linearly decreasing with increase in moisture content. Safe design of structure or machinery must consider extreme value of properties for moisture range to work with. Moreover, selection of lower or upper extreme value is done based on the specific requirement with some factor of safety. All these parameters could be presented as linear equations of regression with moisture content as independent variable.

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