Moisture-dependent physical properties of paddy grains

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Abstract: In order to design of harvesting, conveying and processing equipments, it is necessary to determination of physical properties of grains and agricultural commodities. This study was carried out to evaluate the effect of moisture content on some physical properties of paddy grains. Six levels of moisture content ranging from 8 to 24% (d.b.) were used. The average length, width, thickness, equivalent diameter, surface area, sphericity, thousand grain mass, angle of repose and aspect ratio increased from 10.20 to 10.28 mm, 2.31 to 2.42 mm, 1.85 to 1.94 mm, 3.53 to 3.66 mm, 36.87 to 39.16 mm^2, 34.53 to 35.46 %, 24.43 to 28.27 g, 38.27° to 46.13° and 0.226 to 0.236, respectively, as the moisture content increased from 8 to 24 % (d.b.). As the moisture content of paddy grains increased from 8 to 24% (d.b.), the bulk density and true density were found to increase from 381.77 to 428.5 kg/m^3, and 1328.65 to 1372.41 kg/m^3 respectively, while the porosity was found to decrease from 71.27 to 68.78%. The static coefficient of friction of paddy increased linearly against various surfaces, namely, glass (0.3577-0.4973), galvanized iron sheet (0.4629-0.5295), and plywood (0.4856-0.5830) as the moisture content increased from 8 to 24% (d.b.).

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1. Introduction

Rice (*Oryza sativa* L.) is the staple food for more than three billion people, over half the world's population. It provides 27% of dietary energy and 20% of dietary protein in the developing world. Rice is cultivated in at least 114, mostly developing, countries and is the primary source of income and employment for more than 100 million households in Asia and Africa. In Iran, rice is widely cultivated as a cereal crop for a long time and is grown on an area of about 615000 ha with an annual paddy production of about 3.5 million ton and its yield 5.56 t/ha (FAOSTAT, 2007). Main areas of rice cultivation of Iran are located in the north provinces, namely, Guilan and Mazandaran, producing 75 percent of Iran's rice product. Both high yielding and local varieties are grown in the rice cultivated areas in the country. In Guilan province however, the most popular varieties grown are local and aromatic varieties such as Hashemi and Binam. These varieties are characterized by long kernels having awns (Alizadeh *et al.,* 2006). In the case of Hashemi variety, the presence of long awns affects the physical and morphological characteristics of the product.

During various steps of rice production, paddy arrives into the each part with definite moisture content. The moisture content of paddy decreases from 22 to 8% during harvesting to milling projects. Variation the moisture content of paddy changes the physical properties of paddy grains. If the adjustment of various parts of the equipment was not proportional with the specific properties of the grain, it may lead to more excessive cracked and broken rice grains. Hence, in order to optimization of various stages of rice processing projects, determination of physical properties of paddy grains is essential. This information can help out the design of equipment used in harvesting, transportation, milling, processing and storage of rice. The size, shape and structural characteristics of paddy are important in designing of separating, sizing and grinding machines. Bulk density, true density and porosity (the ratio of inter granular space to the total space occupied by the grain) are used in design of storage bins and silos, separation of desirable materials from impurities. The angle of repose is used in the design of equipment for the processing of particulate solids. For example, it may be used to design an appropriate hopper or silo to store the material. It can also be used to size a conveyor belt for transporting the material. The static coefficient of friction of the grain against the various surfaces is also necessary in designing of handling and storing structures.

In recent years, physical properties have been studied for various crops such as sorrel seeds (Omobuwajo *et al.,* 2000); millet (Baryeh, 2002); groundnut kernel (Olajide and Igbeka, 2003); lentil seed (Amin *et al.,* 2004); sweet corn seed (Coşkun *et al.,* 2005); linseed (Selvi *et al.,* 2006); peanut (Aydin, 2007) and jatropha seed (Garnayak *et al.,* 2008). It seems that there is not much published work about moisture-dependent physical properties of paddy grains.

The objective of this study was to determination some physical properties of paddy grains such as axial dimensions, size, surface area, sphericity, thousand grain mass, bulk density, true density, porosity, angle of repose and static coefficient of friction on various surfaces in the moisture content range from 8 to 24% (d.b.).

2. Material and Methods

The paddy variety, Hashemi, used for this study was obtained from the Rice Research Institute, Rasht, Iran. The variety (Hashemi) used in the current study is one of the popular rice varieties in the north of Iran that characterized by long kernels having long owns (Fig. 1). Before starting experiments, the samples were cleaned manually to remove all foreign materials and broken grains. The initial moisture content of the samples was determined by oven drying method at 103 ˚C for 48 h (Sacilik *et al.*, 2003). The initial moisture content of the grains was 14.8% (d.b.).

Fig. 1. Paddy variety of Hashemi.

In order to increase the level of moisture content above the initial level, the samples were moistened with a computed quantity of water by using the following Eq. (1) and conditioned to raise their moisture content to the desired three different levels (Coşkun *et al.*, 2005):

$$Q = \frac{W_i\left(M_f - M_i\right)}{100 - M_f} \qquad (1)$$

where Q is the mass of water added (kg), W_i is the initial mass of the sample (kg), M_i is the initial moisture content of the sample (%, d.b.) and M_f is the final moisture content of the sample (%, d.b.).

To obtain three desired moisture levels below the initial moisture content, the samples were kept in an oven at a constant temperature of 43 ˚C until the desired moisture content of the samples were obtained (Yang *et al.*, 2003).

After making six levels of moisture contents, the samples were spilled in polyethylene bags and the bags were closed tightly. The samples were kept in a refrigerator at 5 ˚C for a week to enable the moisture to distribute uniformly throughout the sample. Before starting each test, the required quantities of the samples were taken out of the refrigerator and allowed to warm up to the room temperature for about 2 h. The rewetting technique to attain the desired moisture content in kernel and grain has frequently been used (Nimkar and Chattopadhyay, 2001; Sacilik *et al.*, 2003; Coşkun *et al.*, 2005; Garnayak *et al.*, 2008). All the physical properties of the grains were determined at moisture levels of 8, 11, 14, 18, 21 and 24% (d.b.).

The shape of the paddy grain was found to be prolate elliptical with three major principal dimensions, length (L), width (W) and thickness (T). The physical dimensions were determined randomly measuring the length, width and thickness of 100 grains using dial type vernier caliper (Mitutoyo Corporation, Japan) having least count of 0.01mm.

In order to determination of the thousand grain mass, 100 randomly selected grains from the bulk sample were averaged. The thousand grain mass was measured by means of a digital electronic balance having an accuracy of 0.001 g.

Considering a prolate spheroid shape for a paddy grain, the equivalent diameter (D_p) was calculated using (Mohsenin, 1986):

$$D_P = \left(L\frac{(W+T)^2}{4} \right)^{\frac{1}{3}} \qquad (2)$$

The criteria used to describe the shape of the seed are the sphericity and aspect ratio. Thus, the sphericity (ϕ) was accordingly computed as (Mohsenin, 1986):

$$\phi = \frac{(LWT)^{\frac{1}{3}}}{L} \qquad (3)$$

The aspect ratio (R_a) was calculated by (Maduako and Faborode, 1990):

$$R_a = \frac{W}{L} \qquad (4)$$

The surface area of the grain (S) was calculated using (Jain and Bal, 1997):

$$S = \frac{\pi B L^2}{(2L - B)} \qquad (5)$$

where:

$$B=\sqrt{WT} \qquad (6)$$

where L is the length, W is the width and T is the thickness of grain, all in mm.

The bulk density was determined using the mass/volume relationship by filling a cylindrical container of 500 ml volume and tare weight with the grains by pouring from a constant height, striking off the top level and weighing (Garnayak *et al.*, 2008). The true density is defined as the ratio of mass of grain to the solid volume occupied. The grain volume and its true density were determined using liquid displacement technique (Shepherd and Bhardwaj, 1986). Toluene was used instead of water so as to prevent the absorption during measurement and also to get the benefit of low surface tension of selected solvent (Sitkei, 1986; Ogut, 1998).

The porosity defined as the fraction of the space in the bulk grain which is not occupied by the grain (Thompson and Isaacs, 1967). The porosity was calculated from bulk and true densities using the relationship (Jain and Bal, 1997) as follows:

$$\varepsilon=\left(1-\frac{\rho_b}{\rho_t}\right)\times 100 \qquad (7)$$

where ε is the porosity (%), ρ_b is the bulk density (kg/m^3) and ρ_t is the true density (kg/m^3).

The angle of repose is the maximum angle of a stable slope determined by friction, cohesion and the shapes of the particles. When bulk granular materials are poured onto a horizontal surface, a conical pile will form. The internal angle between the surface of the pile and the horizontal surface is known as the angle of repose and is related to the density, surface area, and coefficient of friction of the material. In order to determine the angle of repose, an apparatus was specially made for this research which was consisted of an adjustable plywood box of 140×160×35 mm and an electrical motor to lifting the box (Fig. 2). The adjustable box was filled with the sample, and then was inclined gently by the electrical motor allowing the grains to follow and assume a natural slope; this was measured as emptying angle of repose. A similar trend has been done by Tabatabaeefar (2003).

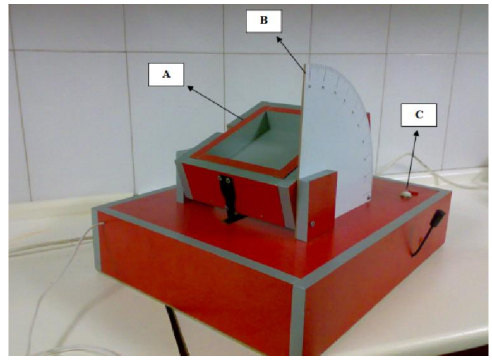

Fig. 2. Apparatus for measuring emptying angle of repose; A: Adjustable box, B: Angle gauge, C: Electrical key.

The static coefficient of friction of the grain was determined with respect to three structural materials, namely, plywood, glass and galvanized iron sheet using a cylinder of diameter 75mm and depth 50mm filled with grains (Fig. 3). With the cylinder resting on the surface, the surface was gradually raised so as not to touch the cylinder and the angle of inclination to the horizontal at which the sample started sliding was read off the protractor attached to the apparatus (Razavi and Milani, 2006). The coefficient of friction was calculated from the following relationship:

$$\mu=\tan\alpha \qquad (8)$$

where μ is the coefficient of friction and α is the angle of tilt in degrees.

Fig. 3. Apparatus for measuring static coefficient of friction.

The physical properties of paddy grain were investigated as a function of moisture content. At each level of moisture content, the experiments were replicated ten times and the average values were reported. The mean, standard deviation and correlation coefficient of dimensions and other characteristics of paddy grain were determined using Microsoft Excel 2003 software program. The effect of moisture content on the different physical properties of paddy grains was determined using the analysis of variance method, and significant differences of means were compared using the least significant difference test at 5% significant level using SPSS 13 software.

3. Resaults

3.1 Grain Dimensions

The effect of moisture content on the three axial dimensions of paddy grain, namely, length, width and thickness is shown in Fig. 4. As it can be seen, upon moisture absorption, the paddy grain expands in length, width and thickness within the moisture range of 8 to 24% (d.b.). The average length, width and thickness of the 100 grains increased from 10.20 to 10.28 mm, 2.31 to 2.42 mm and 1.85 to 1.94 mm, respectively, as the moisture content increased from 8 to 24% (d.b.). Based on the statistical analysis, the effect of moisture content on the grain length was not significant, while the effect on the grain width and thickness was significant at the 1% level of probability. The relationship between length (L), width (W), thickness (T) and moisture content (M) for the paddy grain can be expressed by the regressions:

$$L = 0.004M + 10.15 \qquad R^2 = 0.928 \qquad (9)$$

$$W = 0.007M + 2.251 \qquad R^2 = 0.980 \qquad (10)$$

$$T = 0.005M + 1.797 \qquad R^2 = 0.961 \qquad (11)$$

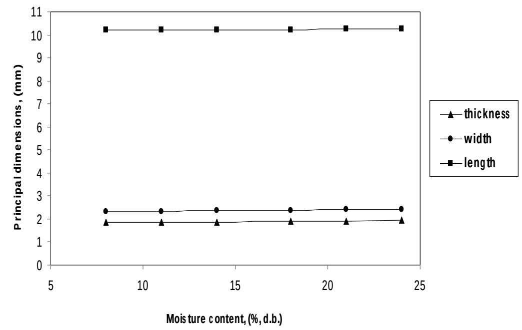

Fig. 4. Variation of principal dimensions of paddy grain with moisture content.

3.2 Thousand Grain Mass

Mean values of the thousand grain mass of paddy at different moisture contents are shown in Table 1. As the moisture content increased from 8 to 24% (d.b.), the thousand grain mass of paddy increased significantly ($p<0.01$) from 24.43 to 28.27g. The relationship between thousand grain mass (m_{tg}) and moisture content (M) can be represented by the regression:

$$m_{tg} = 0.247M + 22.37 \qquad R^2 = 0.991 \qquad (12)$$

A similar increasing trend has been reported by Sacilik *et al.* (2003) for hemp seed and Garnayak *et al.* (2008) for jatropha seed.

Table 1. Physical properties of paddy grain at different moisture contents

Moisture content, (%, d.b.)	Equivalent diameter, (mm)	Sphericity, decimal	Surface area, (mm^2)	Bulk density, (kg/m^3)	True density, (kg/m^3)	Porosity (%)	Angle of repose (°)	Thousand grain mass (g)	Aspect ratio
8	3.53 (0.06) a	34.53 (0.97) a	36.87 (1.59) a	381.77 (5.05) a	1328.65 (8.87) a	71.27 (0.35) a	38.27 (0.90) a	24.43 (0.65) a	0.226 (0.01) a
11	3.55 (0.06) ab	34.65 (1.04) ab	37.14 (1.56) a	390.03 (2.81) ab	1339.29 (2.07) ab	70.87 (0.25) ab	39.87 (0.83) b	25.11 (0.99) a	0.227 (0.01) ab
14	3.56 (0.07) bc	34.83 (0.82) bc	37.59 (1.59) ab	397.14 (4.40) b	1348.96 (9.17) bc	70.56 (0.52) bc	40.53 (0.93) b	25.73 (0.95) ab	0.231 (0.01) bc
0.233 (0.02) bc	26.67 (0.66) bc	42.73 (0.90) c	69.99 (0.41) c	1353.83 (9.21) bc	406.23 (6.39) c	38.12 (2.04) bc	35.07 (1.16) cd	3.60 (0.11) cd	18
0.234 (0.02) c	27.80 (0.70) cd	44.37 (0.96) d	69.24 (0.38) d	1364.96 (13.07) cd	419.81 (2.48) d	38.61 (2.01) cd	35.27 (1.24) cd	3.63 (0.10) de	21
0.236 (0.01) c	28.27 (0.41) d	46.13 (0.30) e	68.78 (0.21) d	1372.41 (9.47) d	428.5 (5.73) e	39.16 (1.94) d	35.46 (1.11) d	3.66 (0.09) e	24

Values in the same columns followed by different letters (a–e) are significant ($P < 0.05$). Figures in parenthesis are standard deviation.

3.3 Equivalent Diameter

The experimental results of the equivalent diameter of the paddy grain at different moisture contents are given in Table 1. Analysis of variance showed that increasing moisture content had a significant effect on the grain equivalent diameter at the 1% level of probability. As shown in Table 1, the equivalent diameter of paddy grain increased from 3.53 to 3.66 mm, as the moisture content increased from 8 to 24% (d.b.). The relationship existing between moisture content (M) and equivalent diameter (D_P) appears linear for the paddy grain, which can be represented by the regression

$$D_P = 0.008M + 3.457 \qquad R^2 = 0.979 \quad (13)$$

3.4 Sphericity

The average values of the grain sphericity at different moisture contents are presented in Table 1. As shown, the sphericity of the paddy grain increased significantly (P <0.01) from 34.53 to 35.46% as the moisture content increased from 8 to 24% (d.b.). Duta et al. (1988) and Bal and Mishra (1988) considered the grain as spherical when the sphericity value was more than 0.70 and 0.80, respectively. In the current study, Paddy grain should not be treated as an equivalent sphere for calculation of the surface area. Equation (14) shows the relationship between sphericity of the paddy grain ($ø$) and moisture content (M):

$$\phi = 0.059M + 34.02 \qquad R^2 = 0.996 \quad (14)$$

Reddy and Chakraverty (2004) for raw and parboiled paddy, Altuntaş *et al.* (2005) for fenugreek seeds, Karababa (2006) for papcorn kernels and Yalçın *et al.* (2007) for pea seed reported similar trends of increase in sphericity with increase in moisture content.

3.5 Aspect Ratio

Table 1 shows the aspect ratio of the paddy grain determined at different levels of moisture content. As seen, with increasing the moisture content from 8 to 24% (d.b.), the aspect ratio of paddy grain increases significantly (P <0.01) from 0.226 to 0.236.

3.6 Surface Area

The variation of surface area for the paddy grain with moisture content is shown in Table 1. It can be seen that the surface area of paddy grain increases linearly from 36.87 to 39.16 mm^2 when the moisture content increases from 8 to 24% (d.b.). Statistical analysis of the data showed that the grain surface area has significantly affected by the moisture content. The effect of moisture content was significant at the 1% level of probability. The variation of moisture content (M) and surface area (S) can be expressed mathematically as follows:

$$S = 0.143M + 35.61 \qquad R^2 = 0.991 \quad (15)$$

Similar results have been reported by Altuntaş *et al.* (2005) for fenugreek seeds and Selvi *et al.* (2006) for linseed.

3.7 Bulk Density

The effect of moisture content on the bulk density of paddy grains (was significant at the probability level of 1%) is presented in Fig. 5. The mean values of the bulk density with respect to the moisture content are also given in Table 1. The results showed that the grains bulk density increases linearly from 381.77 to 428.5 kg/m^3 with an increase in moisture content from 8 to 24% (d.b.). This was due to the fact that an increase in mass owing to moisture gain in the sample was higher than accompanying volumetric expansion of the bulk. The relationship between bulk density (ρ_b) of the grains and moisture content (M) can be expressed by the following equation:

$$\rho_b = 2.908M + 357.3 \qquad R^2 = 0.988 \quad (16)$$

Baryeh and Mangope (2002) for QP-38 variety pigeon pea and Kingsly *et al.* (2006) for dried pomegranate seeds have reported similar increasing trend in bulk density.

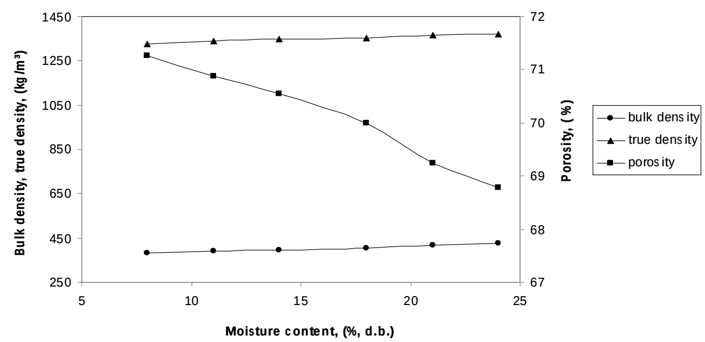

Fig. 5. Variation of bulk density, true density and porosity of paddy grain with moisture content.

3.8 True Density

Variation of the true density of paddy grains at different moisture contents is given in Fig. 5. The true density of paddy grains found to be increased from 1328.65 to 1372.41 kg/m^3 as the moisture content increased from 8 to 24% (d.b.). Based on the statistical analysis, the effect of moisture content on true density of the grains was significant at 1% level of probability. The moisture (M) dependence of the true density (ρ_t) was described by a linear equation as follows:

$$\rho_t = 2.624M + 1309 \qquad R^2 = 0.984 \quad (17)$$

Although the results were comparable to those reported by Bart-Plange and Baryeh (2003) for Category B cocoa beans, Coşkun *et al.* (2005) for sweet corn seed and Selvi *et al.* (2006) for linseed, different trends were reported by Sacilik *et al.* (2003) for hemp seed, Yalçin *et al.* (2007) for pea seed and Cetin (2007) for barbunia bean seed.

3.9 Porosity

The variation of porosity in accordance with the moisture content is shown in Fig. 5. The results indicated that as the moisture content of paddy grains increases from 8 to 24% (d.b.), the porosity decreases linearly from 71.27 to 68.78%. The effect of moisture content on the porosity was significant at the 1% level of probability. As described at the previous sections, porosity is a function of bulk density and true density. It can be seen from Fig. 5 that both the bulk and true densities of paddy grains increases with increase in moisture content, while the porosity decreases. This was due to the fact that an increase in the true density has a lower effect on the porosity than that of the bulk density. The relationship between the porosity (ε) and moisture content (M) of the grains can be represented by:

$$\varepsilon = -0.156M + 72.62 \qquad R^2 = 0.983 \qquad (18)$$

Sacilik *et al.* (2003) and Kingsly *et al.* (2006) reported similar trends in the case of hemp seed and dried pomegranate seeds, respectively. While Yalçin and Özarslan (2004), Altuntaş and Yildiz (2007) and Garnayak *et al.* (2008) reported different trends in the case of vetch seeds, faba bean grains and jatropha seed, respectively.

3.10 Angle of Repose

The average values of the angle of repose relative to the moisture content are presented in Table 1. As shown in Table 1, the angle of repose of paddy grains increases significantly (at 1% level of probability) from 38.27° to 46.13° in the moisture range of 8–24% (d.b.). This is due to the fact that increasing in moisture absorption leads to create a larger surface layer of moisture surrounding the particles, holding the aggregate of grains together by producing higher surface tension. Equation (19) can be used to express the relationship existing between the angle of repose (θ) and moisture content (M):

$$\theta = 0.482M + 34.26 \qquad R^2 = 0.989 \qquad (19)$$

The results were comparable to those reported by Altuntaş and Yildiz (2007), Garnayak *et al.*, (2008) for faba bean grains and jatropha seed, respectively.

3.11 Static Coefficient of Friction

The variation of static coefficient of friction of paddy grains against three surfaces, namely, glass, galvanized iron sheet and plywood with respect to their moisture content are presented in Fig. 6. As it can be seen, the static coefficient of friction of paddy grains increases linearly with increase in moisture content, for all the evaluated surfaces. Based on the statistical analysis, the effect of moisture content on the static coefficient of friction was significant at the 1% probability level, for all the investigated surfaces. Increase in static coefficient of friction at higher levels of moisture content may be due to the fact that the water present in the grain offering a higher cohesive force on the surface of contact (Garnayak *et al.*, 2008). The results also showed that at all levels of moisture contents, the maximum static coefficient of friction was offered by plywood, followed by galvanized iron sheet and glass surfaces. The least static coefficient of friction may be owing to smoother and more polished surface in the case of glass comparing with the other surfaces evaluated. Similar trends have been reported by Dutta *et al.*, (1988) and Garnayak *et al.* (2008) in the case of gram and Jatropha seed, respectively. The relationships between the moisture content (M) and static coefficient of friction on glass (μ_{gl}), galvanized iron sheet (μ_{gi}) and plywood (μ_{pw}) surfaces can be expressed by the following equations:

$$\mu_{gl} = 0.008M + 0.298 \qquad R^2 = 0.968 \qquad (20)$$

$$\mu_{gi} = 0.003M + 0.432 \qquad R^2 = 0.975 \qquad (21)$$

$$\mu_{pw} = 0.005M + 0.447 \qquad R^2 = 0.940 \qquad (22)$$

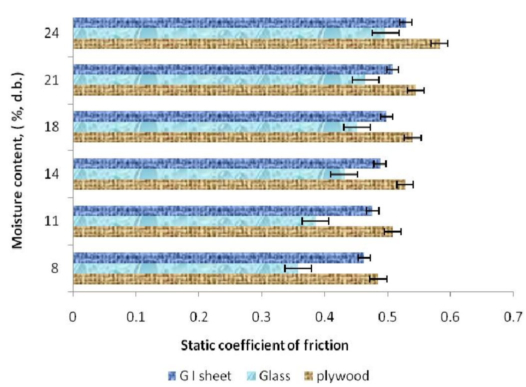

Fig. 6. Effect of moisture content on static coefficient of friction of paddy grain against various surfaces.

1. CONCLUSIONS

(1) As the moisture content of paddy grain increased from 8 to 24% (d.b.), the average length, width, thickness and equivalent diameter increased from 10.20 to 10.28 mm, 2.31 to 2.42 mm, 1.85 to 1.94 mm and 3.53 to 3.66 mm, respectively. Except the length of the grain, the effect of moisture content was significant on all the mentioned characteristics.

(2) The sphericity, surface area, thousand grain mass, angle of repose and aspect ratio increased significantly (p < 0.01) from 34.53 to 35.46%, 36.87 to 39.16 mm^2, 24.43 to 28.27 g, 38.27° to 46.13° and 0.226 to 0.236, respectively, in the moisture range of 8 to 24% (d.b.).

(3) The bulk density and true density of paddy grains were found to increase (both significantly at 1% of probability level) from 381.77 to 428.5 kg/m^3, and 1328.65 to 1372.41 kg/m^3 respectively, with increase in moisture content from 8 to 24% (d.b.), while the porosity decreased from 71.27 to 68.78% (P < 0.01).

(4) The static coefficient of friction increased significantly (p < 0.01) for all the evaluated surfaces, namely, glass (0.3577-0.4973), galvanized iron sheet (0.4629-0.5295), and plywood (0.4856-0.5830) as the moisture content increased from 8 to 24% (d.b.).

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