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Mechanical Engineering

Elixir Mech. Engg. 52 (2012) 11609-11613

ISSN: 2229-712X

Moisture-dependent physical properties of rough rice grain

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ARTICLE INFO

Article history:

Received: 13 September 2012;

Received in revised form:

19 November 2012;

Accepted: 20 November 2012;

Keywords

Rough rice,

Physical properties,

Moisture content.

ABSTRACT

Some physical properties of the rough rice were studied at 10.29, 15.37, 20.5, 25.4, and 30.6% d.b. moisture contents. The length, width, thickness, equivalent diameter, and sphericity increased linearly from 10.63 to 10.82 mm, 1.96 to 2.14 mm, 1.82 to 1.99 mm, 3.34 to 3.55 mm, and 31.52 to 33.24%, respectively, as moisture content increased from 10.29 to 30.6% d.b. In the same moisture range, the one-thousand grain mass, grain volume, surface area, and angle of repose increased linearly from 21.34 to 25.04 g, 20.62 to 24.16 mm^3, 34.45 to 38.36 mm^2, and 28.54º to 39.41 º, respectively. Results showed that the bulk density, true density, and porosity increased linearly from 480.32 to 499.12 kg/m^3, 945.71 to 1131.02 kg/m^3, and 49.21 to 55.87%, respectively, with increasing moisture content. The static coefficient of friction varied from 0.479 to 0.732 over different structural surfaces in the specified moisture content range. The specific heat capacity varied from 1654 to 2517 J/kg K in 50, 60, 70, and 100 ºC particles temperatures and for the specified moisture content levels.

Introduction

The knowledge of various physical properties is essential to facilitate and improve the design of equipment for handling, harvesting, processing, and storing the agricultural material such as grains. Some physical properties of the grain particles are principal dimensions, equivalent diameter, sphericity, surface area, volume, bulk density, true density, porosity, angle of repose, friction coefficient, and specific heat capacity.

Principal dimensions namely, length, width, and thickness are important in sizing, sorting, and other processes. They can also be used to calculate equivalent diameter, sphericity, surface area, and volume of the grain particles. Bulk density and true density are useful in storing, handling, separating, and processing operations. Porosity data is required in modeling of the heat and mass transfer process operations. The angle of repose has practical applications in the design of processing, storage, and conveying systems of the grain material. The static coefficient of friction plays an important role in transport and storage of the grains. The specific heat capacity is necessary for the design of a new unit operation or analysis of the present process e.g. drying, cooling, and storage (Mohsenin, 1986; Sahay and Singh, 1996).

Several studies have been conducted to investigate the physical properties or the influence of moisture content on physical properties of different agricultural material such as sunflower seed (Gupta and Das, 1997), millet (Baryehe, 2002), almond nuts and kernels (Aydin, 2003), jatropha seed (Garnayak et al., 2008), niger seed (Solomon and Zewdu, 2009) shelled and kernel walnuts (Altuntas and Erkol, 2010), and tung seed (Sharma et al., 2011). Some physical properties of some specific varieties of the rough rice have been determined and reported by various research workers (Morita and Singh, 1979; Iguaz et al., 2003; Reddy and Chakraverty, 2004; Ghasemi Varnamkhasti et al., 2008; Kibar et al., 2010). However, there is a dearth of information on some physical properties of rough rice for a wide range of moisture content.

The aim of this study was to determine the moisture dependent physical properties of the rough rice, namely: length, width, thickness, equivalent diameter, sphericity, thousand grain mass, grain volume, surface area, bulk density, true density, porosity, angle of repose, static coefficient of friction, and specific heat capacity.

Materials and Methods

Dried long grain rough rice of the Fajr variety was used in this study. The moisture content of the cleaned grain was determined using the ASAE standard method (ASAE, 1984). Samples of the grains were conditioned to moisture content levels of 10.29, 15.37, 20.5, 25.4, and 30.6% d.b. (dry basis, kilograms of water per kilogram of dry solid). Samples of the rough rice with desired moisture content levels prepared as reported by Selvi et al. (2006). The length, width, and thickness of the grain were measured by a digital caliper with an accuracy of 0.01 mm.

The equivalent diameter considering a prolate spheroid shape for the grain particle was determined using the following equation (Mohsenin, 1986):

$$D_{eq} = \left(a \frac{(b+c)^2}{4} \right)^{\frac{1}{3}} \quad (1)$$

where D_{eq} is the equivalent diameter (mm), a is the length (mm), b is the width (mm), and c is the thickness (mm) of the grain particle.

The sphericity of the grain particle was calculated by following equation (Mohsenin 1986):

$$\emptyset = \frac{(abc)^{\frac{1}{3}}}{a} \times 100 \quad (2)$$

where $\emptyset$ is the sphericity (%).

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The volume and surface area of the grain particle were calculated using the following equations (Jain and Bal, 1997):

$$V_p = 0.25\left[\left(\frac{\pi}{6}\right)a(b+c)^2\right] \quad (3)$$

$$S_p = \frac{\pi a\sqrt{bc}}{\left(2a-\sqrt{bc}\right)} \quad (4)$$

where V_p is the particle volume (mm^3) and S_p is the particle surface area (mm^2).

To determine the bulk density of the rough rice, a container of volume 1000 ml was filled with grain from a height of 150 mm at a constant rate and the contents were weighted to a precision of 0.01 g (Gupta and Das, 1997). The true density was determined by the toluene displacement method (Mohsenin, 1986). The porosity was calculated using the following equation (Mohsenin, 1986):

$$\varepsilon = \frac{(\rho_t - \rho_b)}{\rho_t} \times 100 \quad (5)$$

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 was determined by using an open-ended cylinder of 15 cm diameter and 50 cm height. The cylinder was placed on the plate and was filled with the grain particles. The cylinder was raised slowly until it formed a cone on the plate (Karababa, 2006; Garnayak et al., 2008). The angle of repose was calculated using the formula:

$$\theta = tan^{-1}\left(\frac{2H}{D}\right) \quad (6)$$

where θ is the angle of repose (°), H is the height of the cone (mm), and D is the diameter of the cone (mm).

The static coefficient of friction was determined on four common surfaces: rubber, plywood, galvanized steel, and stainless steel. A cylinder of diameter 75 mm and height 50 mm was filled with the grain particles. With the cylinder resting on the adjustable tilting surface, the surface was raised gradually until the filled cylinder just started to slide down. The static coefficient of friction was taken as the tangent of the angle of the tilting surface with the horizontal (Singh and Goswami, 1996).

The specific heat capacity of the grain was determined using the method of mixtures (Mohsenin, 1980; Singh and Goswami, 2000). After maintaining the higher uniform desired temperature, a cylindrical copper test capsule containing rough rice was dropped into distilled water contained in a flask calorimeter at room temperature. Considering the heat balance during the process, the specific heat capacity of the grain was calculated using the following heat balance equation (Mohsenin, 1980):

$$C_p = \frac{(H_f + m_w C_w)(T_e - T_w) - H_c(T_p - T_e)}{m_p(T_p - T_e)} \quad (7)$$

where C_p is the specific heat capacity of the grain (J/kgK), C_w is the specific heat capacity of the distilled water (J/kgK), H_f is the heat capacity of the flask calorimeter (J/K), H_c is the heat capacity of the test capsule (J/K), m_w is the mass of the distilled water (kg), m_p is the mass of the grain (kg), T_e is the equilibrium temperature (K), T_w is the water temperature (K), and T_p is the grain temperature (K).

One hundred rough rice grain particles were randomly selected to determine the average values of the principal dimensions at each moisture content level. Five replications at each moisture content were taken to measure the bulk density, true density, one-thousand grain mass, angle of repose, and static coefficient of friction. The experiments for measuring the specific heat capacity of the rough rice were repeated three times at the specified levels of particles moisture content (10.29, 15.37, 20.5, 25.4, and 30.6% d.b.) and particles temperatures of 50, 60, 70, and 100 ºC. Then the average values were reported. All the results obtained in this study were subjected to analysis of variance (ANOVA) using SPSS software. The regression analyses were conducted using MATLAB (version 7.8) statistical toolbox.

Results and Discussion

The average values of the principal dimensions of the rough rice grain at different moisture contents are presented in Table 1. The grain particle expands along the three principal axes within the moisture range of 10.29 to 30.6% d.b. The average values of the principal dimensions show an increase of 1.88%, 9.18%, and 9.34% along length, width, and thickness, respectively. Differences between these values were statistically significant at $P < 0.05$. A greater expansion was found along the thickness and width than along the length of the grain particle. This could be due to the different cell arrangements in the grains and seeds. Similar results were reported by Aviara et al. (1999) for guna seeds and by Baryehe (2002) for millet.

The following equations were developed for length (a), width (b), and thickness (c) of the rough rice grain with moisture content (M):

$$a = 0.009M + 10.52 \quad (R^2=0.960) \quad (8)$$

$$b = 0.009M + 1.848 \quad (R^2=0.946) \quad (9)$$

$$c = 0.008M + 1.734 \quad (R^2=0.996) \quad (10)$$

As shown in Table 1, the equivalent diameter increased linearly with the increase in moisture content ($P < 0.05$). The equivalent diameter (D_{eq}) is found to have the following relationship with moisture content (M):

$$D_{eq} = 0.01M + 3.230 \quad (R^2=0.995) \quad (11)$$

Similar results were also reported for dimensional properties of the rough rice (Reddy and Chakraverty, 2004), and niger seed (Solomon and Zewdu, 2009). The sphericity increased with increasing moisture content ($P < 0.05$) (Table 1). Similar results were also presented by Kaleemullah and Gunasekar (2002) and Reddy and Chakraverty (2004). The following relationships were developed for sphericity ($\emptyset$) with moisture content (M):

$$\emptyset = 0.084M + 30.59 \quad (R^2=0.992) \quad (12)$$

The one-thousand grain mass increased linearly as moisture content increased (Table 2) ($P < 0.05$). The results were similar to those reported by Aviara et al. (1999) for guna seeds and Dursun and Dursun (2005) for caper seed. The relationship between the one-thousand grain mass (m_{1000}) and moisture content (M) was expressed as follows:

$$m_{1000} = 0.185M + 19.45 \quad (R^2=0.995) \quad (13)$$

The rough rice grain volume was found to increase linearly with increase in moisture content ($P < 0.05$) (Table 2). Similar results were reported for soybean (Deshpande et al., 1993), popcorn kernels (Karababa, 2006), and jatropha seeds (Garnayak et al., 2008). The relationship between the grain volume (V_p)

and moisture content (M) can be represented by following equation:

$V_p = 0.213M + 17.33$ (R^2=0.982) (14)

As shown in Table 2, the surface area of the rough rice grain was not significantly affected by the change in moisture content. However, increase in the surface area with increase in moisture content was observed for cotton seed (Özarslan, 2002) and linseed (Selvi et al., 2006). The surface area (S_p) of the grain and moisture content (M) can be correlated as follows:

$S_p = 0.205M + 32.23$ (R^2=0.983) (15)

The bulk density of the rough rice varied linearly from 480.32 to 499.12 kg/m^3 with increasing moisture content and the change was significant at 5% level of significance (Table 2). A similar result in true density was reported for rough rice (Iguaz et al., 2003; Reddy and Chakraverty, 2004) and for moth gram (Nimkar et al., 2005). The relationship between the bulk density (ρ_b) and moisture content (M) was expressed by following equation:

$\rho_b = 0.948M + 471.2$ (R^2=0.986) (16)

As shown in Table 2, the true density was found to increase linearly from 945.71 to 1131.02 kg/m^3 in the specified moisture content range ($P < 0.05$). A similar increasing trend in true density has been reported by Deshpande et al. (1993) for soybean, Gupta and Das (1997) for sunflower, and Kibar et al. (2010) for rough rice. The relationship between true density (ρ_t) and moisture content (M) of the rough rice was obtained as follows:

$\rho_t = 9.158M + 842.4$ (R^2=0.987) (17)

The porosity of the rough rice increased linearly as moisture content increased ($P < 0.05$) (Table 2). Similar results were reported by Aviara et al. (1999) for guna seeds and Selvi et al. (2006) for linseed. The relationship between porosity (ε) and moisture content (M) was found to be as follows:

$\varepsilon = 0.329M + 45.47$ (R^2=0.985) (18)

As shown in Table 2, the angle of repose was found to increase linearly in the specified range of moisture content ($P < 0.05$). Similar trends were reported for sunflower (Gupta and Das, 1997) and chick pea Seeds (Konak et al., 2002). The following equation was developed for angle of repose (θ) of the grain based on moisture content (M):

$\theta = 0.534M + 23.72$ (R^2=0.978) (19)

The values of the static coefficient of friction of the rough rice on four surfaces at different moisture content levels are shown in Table 3. The static coefficient of friction was found to increase linearly with increase in moisture content for all surfaces ($P < 0.05$). For the same moisture content, the highest static coefficient of friction was observed on rubber, followed by plywood, galvanized steel, and stainless steel surfaces. These results were in good agreement with the findings of previous researches for chick pea seeds (Konak et al., 2002), sesame seeds (Tunde-Akintunde and Akintunde, 2004), and moth gram seeds (Nimkar et al., 2005). The relationships between static coefficient of friction and moisture content on rubber (μ_r), plywood (μ_{wd}), galvanized steel (μ_{gs}), and stainless steel (μ_{ss}) were presented by following equations:

$\mu_r = 0.005M + 0.576$ (R^2=0.995) (20)

$\mu_{wd} = 0.005M + 0.532$ (R^2=0.981) (21)

$\mu_{gs} = 0.004M + 0.442$ (R^2=0.999) (22)

$\mu_{ss} = 0.004M + 0.427$ (R^2=0.963) (23)

The variation of the specific heat capacity of the rough rice with particles moisture content and temperature are shown in Table 4. It was observed that the specific heat capacity of rough rice increased with increase in particles moisture content and temperature ($P < 0.05$). Specific heat capacity of the rough rice ranged from 1654 to 2517 J/kg K in this study. This range of specific heat capacity was in good agreement with the results presented by Morita and Singh (1979) and Iguaz et al. (2003) for rough rice at same particles moisture content and temperature levels. It can be seen that specific heat capacity increased greatly with increase in particles moisture content but increased slightly with increasing temperature. The relationship between rough rice specific heat capacity (C_p) and its moisture content (M) and temperature (T_p) was expressed as following equation:

$C_p = 0.085\,M^2 + 29.693\,M + 3.819\,T_p - 0.008\,T_p M + 1163.54$
(R^2=0.996) (24)

Conclusions

Some of moisture-dependent physical properties of the rough rice with moisture contents ranging from 10.29 to 30.6% d.b. were investigated. The length, width, thickness, equivalent diameter, sphericity, one-thousand grain mass, grain volume, surface area, bulk density, true density, porosity, angle of repose, and static coefficient of friction on different surfaces increased linearly with increase in moisture content. The specific heat capacity of the rough rice increased with particles moisture content and temperature. The results showed that the effect of particles moisture content variation on the specific heat capacity was more significant than particles temperature. Mathematical expressions to predict all the studied physical properties of the rough rice based on moisture content were developed.

Nomenclature

a	length (mm)
b	width (mm)
c	Thickness (mm)
C_p	Particle specific heat capacity (J/kgK)
C_w	distilled water specific heat capacity (J/kgK)
D	Cone diameter (mm)
D_{eq}	Equivalent diameter (mm)
H	Cone height (mm)
H_c	heat capacity of the test capsule (J/K)
H_f	heat capacity of the flask calorimeter (J/K)
m_p	Mass of grain (kg)
m_w	mass of distilled water (kg)
m_{1000}	one-thousand grain mass (g)
M	Moisture content % (d.b.)
S_p	particle surface area (mm^2)
T_e	equilibrium temperature (K)
T_p	grain temperature (K)
T_w	water temperature (K)
V_p	particle volume (mm^3)
ε	porosity (%)
θ	angle of repose (°)
μ	Static coefficient of friction
ρ_b	bulk density (kg/m^3)
ρ_t	true density (kg/m^3).
$\emptyset$	Sphericity (%)

Table 1. Values of mean and standard error of the rough rice grain dimensional properties at different moisture contents

Moisture content % (d.b.)	Length (mm)	Width (mm)	Thickness (mm)	Equivalent diameter (mm)	Sphericity (%)
10.29	10.63^{a} (0.12)	1.96^{a} (0.07)	1.82^{a} (0.11)	3.34^{a} (0.09)	31.52^{a} (1.26)
15.37	10.66^{ab} (0.09)	1.98^{ab} (0.06)	1.86^{ab} (0.09)	3.39^{a} (0.08)	31.83^{ab} (1.12)
20.5	10.69^{bc} (0.10)	2.01^{b} (0.09)	1.91^{b} (0.07)	3.45^{ab} (0.09)	32.37b (0.98)
25.4	10.75^{d} (0.09)	2.08^{c} (0.09)	1.94^{bc} (0.08)	3.51^{b} (0.08)	32.69^{bc} (1.03)
30.6	10.82^{e} (0.11)	2.14^{d} (0.06)	1.99^{c} (0.09)	3.55^{c} (0.10)	33.24^{c} (1.34)

Different letters in the same columns indicate significant difference (P < 0.05)

Table 2. Values of mean and standard error of the rough rice thousand grain mass, volume, surface area, bulk density, true density, porosity, and angle of repose at different moisture contents

Moisture content % (d.b.)	One-thousand grain mass (g)	Volume (mm^3)	Surface area (mm^2)	Bulk density (kg/m^3)	True density (kg/m^3)	Porosity (%)	Angle of repose (°)
10.29	21.34^{a} (0.23)	19.69^{a} (1.01)	34.45^{a} (0.65)	480.32^{a} (2.14)	945.71^{a} (6.43)	49.21^{a} (1.65)	28.54^{a} (2.23)
15.37	22.32^{ab} (0 .35)	20.62^{ab} (0.87)	35.18^{a} (0.45)	485.89^{b} (1.98)	978.04^{ab} (2.11)	50.32^{ab} (1.87)	32.31^{b} (1.43)
20.5	23.19^{b} (0.22)	21.54^{b} (0.89)	36.38^{a} (0.34)	491.27^{c} (1.87)	1021.56^{c} (1.98)	51.91^{c} (2.01)	35.34^{c} (1.89)
25.4	24.32^{c} (0.25)	22.49^{c} (0.76)	37.76^{ab} (0.56)	496.34^{d} (1.65)	1071.31^{d} (2.11)	53.67cd (2.23)	37.64^{d} (2.11)
30.6	25.04^{c} (0.29)	24.16^{cd} (0.83)	38.36^{b} (0.61)	499.12e (1.71)	1131.02^{e} (4.31)	55.87^{e} (2.13)	39.41^{e} (1.43)

Different letters in the same columns indicate significant difference (P < 0.05)

Table 3. Values of mean and standard error of the rough rice static coefficient of friction on various surfaces at different moisture contents

Moisture content % (d.b.)	Static coefficient of friction on different surfaces			
	Rubber	Plywood	Galvanized steel	Stainless steel
10.29	0.631^{a} (0.011)	0.592^{a} (0.013)	0.488^{a} (0.015)	0.479^{a} (0.015)
15.37	0.652^{ab} (0.011)	0.621^{b} (0.021)	0.509^{ab} (0.012)	0.485^{a} (0.011)
20.5	0.683^{c} (0.019)	0.642^{bc} (0.018)	0.532^{c} (0.014)	0.524^{b} (0.008)
25.4	0.711^{cd} (0.016)	0.687cd (0.009)	0.554^{cd} (0.013)	0.545^{c} (0.013)
30.6	0.732^{d} (0.015)	0.704^{d} (0.014)	0.577^{d} (0.018)	0.563^{d} (0.011)

Different letters in the same columns indicate significant difference (P < 0.05)

Table 4. Values of mean and standard error of the specific heat capacity of rough rice at different particles moisture contents and temperatures

Moisture content % (d.b.)	Specific heat capacity (J/kg K)			
	T_p = 50 ºC	T_p = 60 ºC	T_p = 70 ºC	T_p = 100 ºC
10.29	1654^{a} (10)	1711^{a} (14)	1748^{a} (18)	1822^{a} (28)
15.37	1820^{b} (9)	1865^{b} (21)	1906^{b} (16)	2054^{b} (32)
20.5	1985^{c} (12)	2020^{c} (19)	2065^{c} (17)	2162^{b} (12)
25.4	2150^{d} (20)	2191^{d} (15)	2232^{d} (21)	2303^{c} (13)
30.6	2322^{e} (21)	2371^{e} (9)	2409^{e} (17)	2517^{d} (29)

Different letters in the same columns indicate significant difference (P < 0.05)

Acknowledgement

The authors acknowledge the experimental and financial support has been provided by Department of Agricultural Machinery Engineering, Faculty of Agricultural Engineering and Technology, University of Tehran, Karaj, Iran.

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