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The effect of moisture content on physical and mechanical properties of rice (*Oryza sativa* L.)

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Abstract

The objective of this study was to investigate some physical and mechanical properties of Osmancık-97 rice variety widespread cultivated in Turkey in order to determine needed designing parameters for handling and storage facilities. In this study, some physical and mechanical properties were evaluated as a function of moisture content in the range of 10-14% d.b. Length, width, thickness, arithmetic and geometric mean diameter ranged from 8.27 to 9.01 mm, 3.10 to 3.48 mm, 2.05 to 2.26 mm, 4.47 to 4.92 mm, 3.75 to 4.13 mm, respectively as the moisture content increased; sphericity, grain volume, surface area, true density and porosity increased from 43 to 45%, 130.97 to 160.32 mm^3, 38.68 to 46.91 mm^2, 939.0 to 962.1 kg m^{-3}, and 36.61 to 41.97%; bulk density decreased from 595.5 to 560.5 kg m^{-3}; the angle of internal friction increased linearly from 29.70° to 32.53° with the increase of moisture content; the static coefficient of friction increased from 0.764 to 0.972, 0.524 to 0.702 and 0.576 to 0.764 for concrete, galvanized steel and wood surfaces, respectively; the poisson ratio and pressure ratio decreased linearly with the increase of moisture content. The data obtained from the study will be useful in the structural design of rice bin to calculate loads on bins from the stored material.

Additional key words: angle of internal friction, bulk density, porosity, pressure ratio.

Resumen

Efecto del contenido en humedad sobre las propiedades físicas y mecánicas del arroz (*Oryza sativa* L.)

El objetivo de este estudio fue investigar algunas propiedades físicas y mecánicas de la variedad de arroz Osmancık-97, ampliamente cultivada en Turquía, con el fin de determinar el diseño de los parámetros necesarios para la manipulación y almacenamiento. En este estudio se evaluaron algunas propiedades físicas y mecánicas en función del contenido de humedad en el rango de 10-14% (base seca). Según aumentaba el contenido de humedad, la longitud, anchura, grosor, media aritmética y media geométrica del diámetro variaron de 8,27 a 9,01 mm, 3,10 a 3,48 mm, 2,05 a 2,26 mm, 4,47 a 4,92 mm, 3,75 a 4,13 mm, respectivamente; la esfericidad, volumen del grano, superficie, densidad real y porosidad aumentaron de 43 a 45%, de 130,97 a 160,32 mm^3, 38,68 a 46,91 mm^2, 939,0 a 962,1 kg m^{-3}, y 36,61 a 41,97%; la densidad aparente disminuyó de 595,5 a 560,5 kg m^{-3}; el ángulo de fricción interna aumentó linealmente de 29,70° a 32,530°; el coeficiente de fricción estática aumentó de 0,764 a 0,972, 0,524 a 0,702 y 0,576 a 0,764 para el hormigón, el acero galvanizado y superficies de madera, respectivamente; el coeficiente de Poisson y la relación de la presión disminuyeron linealmente con el aumento del contenido de humedad. Los datos obtenidos en este estudio serán útiles en el diseño estructural de los contenedores de arroz para calcular las cargas en los contenedores a partir del material almacenado.

Palabras clave adicionales: ángulo de fricción interna, densidad aparente, porosidad, ratio de presión.

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Abbreviations used: A (cellular area, cm^2), B (diameter of the spherical part of the grain, mm), c (coefficient of cohesion, D_a (arithmetic average diameter, mm), D_g (geometric average diameter, mm), F_s (force starting movement at surface interface, kg m^{-2}), G_1 (free weight of bulk density bucket, kg), G_2 (weight of bulk density bucket with rice, kg), k_E (pressure ratio according to Eurocode-1), k_L (pressure ratio according to Lohnes), k_S (pressure ratio according to Schulze), L (length, mm), M_c (moisture content, %), M_f (final moisture content of sample, %), M_i (initial moisture content of sample, %), m_s (weight of liquid, kg), m_w (weight of air dry sample, kg), N (load applied on the sample, kg), Q (amount of added water, g), S (surface area, mm^2), T (thickness, mm), T_s (shear force, load on cutting edge, kg), V (grain volume, mm^3), V_b (volume of bulk density bucket, m^3), V_s (volume of liquid, m^3), V_w (volume of sample, m^3), W (width, mm), W_i (dry sample weight, g), W_s (force applied to surface interface, kg m^{-2}), ϕ (sphericty, %), φ (angle of internal friction, degrees), γ (bulk density, kg m^{-3}), ε (porosity, %), μ_s (static coefficient of friction, ρ (true density, kg m^{-3}), σ (normal stress, kPa), τ (shear stress, pressure on cutting edge, kPa), ν (Poisson rate).

Introduction

Rice (*Oryza sativa* L.) is the second most important cereal after wheat. The world's major rice producing countries are China, India, Indonesia, Bangladesh and Vietnam. In the year 2007, world rice production was 422 million tonnes and Turkey's rice production was 388,800 tons (Faostat, 2009).

The marketing value of rice as an agricultural product depends on its physical qualities after processing. The percentage of whole grain is the most important parameter for the rice processing industry (Marchezan, 1991).

The main features of agro and food materials that make them different from mineral materials are strong influence of moisture content on mechanical behaviour and high deformability of granules. These differences bring about certain peculiar behaviours and necessity of adjustments of models of material, experimental techniques and technological solutions (Molenda and Horabik, 2005).

Engineering properties of granular agro-materials are important in terms of the machines and storage facilities designing. Bulk density, true density, porosity and the static coefficient of friction can be useful in sizing grain hoppers and storage facilities (Varnamkhastia *et al.,* 2007). These properties are important in the construction of bulk storage facilities and the calculation of the dimensions of intermediate holding bins of a given capacity. Problems associated with design should not be attributed to disagreement among design philosophies, but rather to a serious lack of understanding of certain grain properties and how they relate to bin design (Thompson and Ross, 1983).

Knowledge of the physical and mechanical properties of the agricultural products is of fundamental importance for the appropriate storage procedure and for design, dimensioning, manufacturing and operating different equipments used in post harvest processing operations of these products (Corrêa *et al.*, 2007). Kongkiattikajorn *et al.* (2004) reported that peak viscosity of rice stored at 25°C increased throughout storage but the value of the rice stored at 37°C caused the value to increase in the first month but later this value decreased. The changes in rice properties, including viscosity, colour, flavor, and composition affect rice quality (Suzuki *et al.,* 1999).

To design equipments for application in plantation, harvesting, transportation, storage and processing operations of rice, the knowledge of various physical and mechanical properties as a function of moisture content is important. Both structural properties and features of the stored material are important in the design of storage equipment and facilities (Molenda *et al.,* 2004).

For rice grains and other commodities it can be seen that increased moisture content causes notable increases of pressure on silo walls. Because the increase of pressure requires an increase in the thickness of silo construction materials, costs of construction increase. Also, flow problems in silos such as arching, ratholing, irregular flow and segregation occur with increased moisture content. When arching or rat-holing occurs, much of the stored product flows at the center only, leaving some remaining behind in dead zones of the silo for long periods.

The aim of this study was to investigate some physical and mechanical properties of Osmancık-97 rice variety cultivated in Turkey.

Material and methods

Material

The variety of rice used in the present study was obtained from the crop grown, as a representative of commercial processing, during 2009 in the zone of Bafra lowland (41° 35' N, 35° 56' E) of Samsun city, Turkey, which is at an altitude of 20 m. The broken, fragmented and distorted grains were removed from the samples before the experiment. The moisture content of rice after harvesting was 24% (dry basis). The moisture content of the samples was measured by drying them at 140 ± 5°C in a drying oven for 3 h (Yağcıoğlu, 1999).

Physical properties of rice

The dry basis moisture content under laboratory conditions was taken as the reference for the desired moisture content in rice. Equation [1] developed by Balasubramanian (2001) was used for calculating the amount of moisture to be added over the level of equilibrium moisture.

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

Calculated amount of distillate water was added to the samples and were packed in polyethylene bags. The samples were then stored in a refrigerator (4°C) for attaining equilibrium. The samples were removed from the refrigerator (duration of storage was one week) and kept at room temperature (23 ± 2°C) before the experiment was started. The physical and mechanical properties of grain were investigated at three moisture levels (10, 12, 14% d.b.). At each moisture content levels, the length, width, and thickness were measured for 100 grains sampled randomly. Length, width and thickness of the samples were measured using a digital caliper with 0.01 mm accuracy.

The average diameter of the grains was calculated from the arithmetic mean and geometric mean of the three axial dimensions. The arithmetic mean diameter D_a (Eqn. [2]) and geometric mean diameter D_g (Eqn. [3]) of the grains were calculated by using the following relationships (Mohsenin, 1980):

$$D_a = \frac{L + W + T}{3} \qquad [2]$$

$$D_g = (LWT)^{0.333} \qquad [3]$$

The sphericity (ϕ), grain volume (V) and surface area (S) of the samples, depending on the shape of grain, were determined using Equations [4], [5] and [6] as described by Mohsenin (1980) and Jain and Bal (1997):

$$\phi = \left(\frac{D_g}{L}\right) x100 \qquad [4]$$

$$V = \frac{\pi BL^2}{6\left(2L - B\right)} \qquad [5]$$

$$S = \frac{\pi BL^2}{2L - B} \qquad [6]$$

where $B = (WT)^{0.5}$.

To determine the bulk density of the experimental samples at different moisture levels, the method defined by Mohsenin (1980) and Singh and Goswami (1996) was used. A container of 1,000 mL volume was used to determine bulk density. The bulk density container was filled to 5 cm above the top. The rice grains were then allowed to settle into the container and the excess grains in container was removed with the help of spatula before bulk density determination, using Eqn. [7].

$$\gamma = \frac{G_2 - G_1}{V_b} \qquad [7]$$

The water displacement method, as described by Abalone *et al.* (2004), was used to determine the true density of rice samples. In this method, toluene (C_7H_8) was used in place of water because it is absorbed to a lesser extent by rice and its surface tension is low. To calculate true density, the air dried weight of samples was first determined. The samples were then submerged in toluene and the displacement volume was determined. In the second stage, the true density of samples was calculated by using Eqn. [8] as follows:

$$\rho = \frac{m_s + m_w}{V_s + V_w} \qquad [8]$$

The porosity of the rice was calculated from bulk and true densities using Eqn. [9] the relationship given by Mohsenin (1980) as follows:

$$\varepsilon = \left(1 - \frac{\gamma}{\rho}\right) x100 \qquad [9]$$

Mechanical properties of rice

To determine the angle of internal friction of rice samples the direct shear method was used according to Uzuner (1996), Zou and Brusewitz (2001), Molenda *et al.* (2002) and Mani *et al.* (2004). The velocity used during the experiment was 0.7 mm min^{-1} (Molenda *et al.,* 2002) and the angle of internal friction of samples was calculated by using Equations [10] to [12].

$$\sigma = \frac{N}{A} * 100 \qquad [10]$$

$$\tau = \frac{T_s}{A} * 100 \qquad [11]$$

$$\tau = (c + \sigma\ x \tan\varphi) \qquad [12]$$

The static coefficients of friction of samples were determined according to the method given by Beyhan *et al.* (1994). Wood, concrete (C30) and galvanized steel surfaces were used as friction surfaces. During the experiment, the test surface moved at a low velocity (1,400 mm min^{-1}). The surfaces were driven by a 12 V, adjustable direct current motor and strength of friction was measured by using a digital dynamometer. Static coefficient of friction was calculated from the constant strength of friction read in the digital dynamometer after movement occurred at the interface. The static coefficients of friction of rice samples were calculated by using Eqn. [13].

$$\mu_s = \frac{F_s}{W_s} \qquad [13]$$

The poisson ratio was calculated using Eqn. [14] developed by Qu *et al.* (2001).

$$\nu = \frac{1 - \sin\varphi}{2 - \sin\varphi} \qquad [14]$$

In this study, to determine the pressure ratios of rice grains the equalities developed by Lohnes (1993), Eurocode-1 (2003) and Schulze (2005), given at Equations [15], [16] and [17], respectively, were evaluated.

$$k_L = \frac{(1 - \sin\varphi)x(1 + \frac{2}{3}x\sin\varphi)}{1 + \sin\varphi} \qquad [15]$$

$$k_E = 1.1x(1 - \sin\varphi) \qquad [16]$$

$$k_S = 1 - \sin\varphi \qquad [17]$$

The average size of the grain was measured from 100 randomly selected grains and the other physical properties of the rice grains were determined with three replications at three moisture (from 10 to 14% d.b.) content level. The results obtained were subjected to analysis of variance (ANOVA) using SPSS 10.0 software and analysis of regression using Microsoft Excel.

Results and discussion

Dimensional properties

Table 1 shows the dimensions of rice at different moisture contents in the range of 10-14% (d.b.). The dimensions increased with increase of moisture content. Differences between the values were statistically significant at $P < 0.01$. The increase in the dimensions are attributed to expansion or swelling as a result of moisture uptake in the intracellular spaces within the seeds. Varnamkhasti *et al.* (2007) have reported the value of length, width and thickness as 8.54 mm, 2.47 mm and 1.83 mm respectively, which is lower than the result obtained in this investigation. The observations in this study are in agreement with previous related studies. The relationships between the axial dimensions (L, W, T, D_a and D_g) and moisture content of grain were given by following equations:

$$L = 6.453 + 0.185M_c \quad (R^2 = 0.97) \qquad [18]$$

$$W = 2.157 + 0.095M_c \quad (R^2 = 0.99) \qquad [19]$$

$$T = 1.523 + 0.053M_c \quad (R^2 = 0.98) \qquad [20]$$

$$D_a = 3.378 + 0.110M_c \quad (R^2 = 0.99) \qquad [21]$$

$$D_g = 2.807 + 0.095M_c \quad (R^2 = 0.98) \qquad [22]$$

This results show that there is an important and positive relationship between moisture content and axial dimensions of grain. Similar results for different granular agro-materials have been reported by Çalışır *et al.* (2005) for rapeseed, Karababa (2006) for popcorn kernels and Özgöz *et al.* (2005) for yarma bulgur.

Sphericity

The sphericity of rice grains increased with increasing moisture content (Fig. 1a). The sphericity of rice grains calculated at different moisture contents exhibited a change from 43 to 46%, indicating that sphericity of rice was statistically significant ($P < 0.05$) as the moisture content increased from 10% to 12% d.b. This indicates that relatively proportional changes occurred in the dimensions of rice grains . Similar trends have been reported by Olajide and Ade-Omowaye (1999) for locust bean seed and Asoegwu *et al.* (2006) for African oil bean seed. The relationship between sphericity and moisture content can be represented by following the regression equation:

$$\phi = 0.35 + 0.0075M_c \quad (R^2 = 0.96) \qquad [23]$$

Table 1. Axial dimensions of rice grain as influenced by moisture content

Moisture content, % db	Length (L) (mm)	Width (W) (mm)	Thickness (T) (mm)	Arithmetic average diameter (D_a) (mm)	Geometric average diameter (D_g) (mm)	L/T	L/W	L/Dg
10	8.27 ± 0.50	3.10 ± 0.27	2.05 ± 0.12	4.47	3.75	4.03	2.67	2.21
12	8.74 ± 0.37	3.31 ± 0.20	2.15 ± 0.16	4.73	3.96	4.07	2.64	2.21
14	9.01 ± 0.44	3.48 ± 0.12	2.26 ± 0.14	4.92	4.13	3.99	2.59	2.18

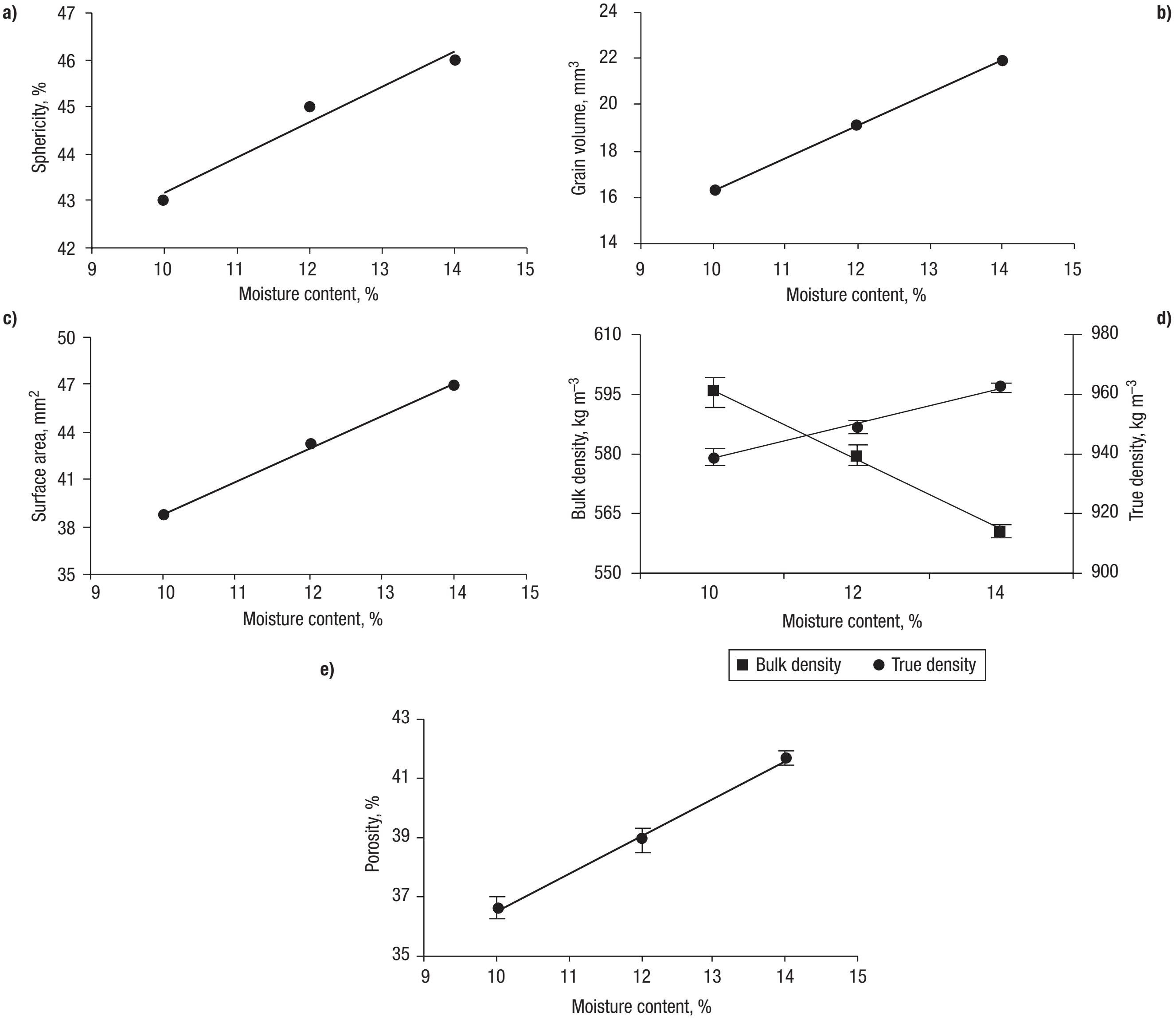

Figure 1. Effect of moisture content on physical properties of rice grains: a) sphericity, b) grain volume, c) surface area, d) bulk density and true density, and e) porosity.

Grain volume

The grain volume of samples increased linearly with the increase of moisture content (Fig. 1b). The grain volume increased from 130.97 to 160.32 mm^3 (statistically significant at $P<0.01$) when moisture content increased from 10% to 14% (d.b). This volumetric expansion may be attributed to the expansion in the dimensions which contributed to weight increase of rice thereby resulting to the displacement of more liquid. Similar results have been reported by Baümler *et al.* (2000) for safflower seed, and Karababa (2006) for popcorn kernels. The relationship between moisture content and grain volume can be expressed by following regression equation:

$$V = 2.19 + 1.41M_c \quad (R = 0.98) \qquad [24]$$

Surface area

As seen from the Figure 1c, the surface area of rice grain increased linearly from 38.68 to 46.91 mm^2 ($P<0.01$) when the moisture content increased from 10 to 14% d.b. The increase in the values might be attributed to its dependence on the three principal dimensions of rice grain. Similar results have been reported by Saçılık *et al.* (2003) for hemp seed, Paksoy and Aydın (2004) for squash seed, and Yalçın (2006) for cowpea seed. The variation of moisture content and surface area can be expressed mathematically as follows:

$$S = 18.27 + 2.05M_c \quad (R^2 = 0.98) \qquad [25]$$

Bulk density and true density

The bulk density of rice varied from 595.5 to 560.5 kg m^{-3} ($P < 0.01$) (Fig. 1d) and indicated a decrease in bulk density with an increase in moisture content from 10 to 14% d.b. This was due to the fact that an increase in mass owing to moisture gain in the sample was lower than accompanying volumetric expansion of the bulk (Pradhan *et al.,* 2008; Solomon and Zewdu, 2009). Similar results have been reported by Özarslan (2002) for cotton seed and Mwithiga and Sifuna (2006) for sorghum seeds. The linear relationship between the bulk density and moisture content in rice grain was found to be the following:

$$\gamma = 683.63 - 8.75M_c \quad (R^2 = 0.97) \qquad [26]$$

The variation of true density with moisture content for rice grain is shown Figure 1d. The true density of rice grain was found to increase from 939.0 to 962.1 kg m^{-3} ($P < 0.01$) with the moisture content. The increase in true density with increase in moisture content might be attributed to the relatively lower true volume as compared to the corresponding mass of rice grains attained due to adsorption of water. The density values of rice was used in design of storage bins and silos, separation of desirable materials from impurities, cleaning and grading and quality evaluation of the products (Solomon and Zewdu, 2009). A similar result was reported by Ghadge *et al.* (2008). The variation in true density with moisture content of rice grain was described by the following equation:

$$\rho = 880.87 + 5.76M_c \quad (R^2 = 0.98) \qquad [27]$$

Porosity

The porosity of the grain varied linearly and increased with the moisture content from 36.61 to 41.97% (Fig. 1e). Differences between the values were statistically significant at $P < 0.01$. This could be attributed to the expansion and swelling of rice grains that might have resulted in more void space between the grains and increase in the bulk volume. This was also exhibited in the reduction of bulk density with increase in moisture content. Similar results have been reported by Baryeh (2002) for millet and Kabas *et al.* (2005) for cactus pear. The relationship between porosity and moisture content appears linear and can be represented by the following regression equation:

$$\varepsilon = 23.87 + 1.26M_c \quad (R^2 = 0.97) \qquad [28]$$

Angle of internal friction

The angle of internal friction of test samples are presented in Figure 2a. The angle of internal friction increased with the increase of moisture content in the test samples ($P < 0.01$). A positive linear relationship between the moisture content and angle of internal friction was determined. The highest value for the angle of internal friction at 14% moisture content, the lowest value was recorded at 10% moisture content. Molenda *et al.* (1998) also found in their study (for wheat) that the angle of internal friction increased linearly with increase of moisture content. As the moisture content increased, the angle of internal friction of rice grain was found to increase linearly and below equqtions give these relationships:

$$\varphi = 22.59 + 0.71M_c \quad (R^2 = 0.98) \qquad [29]$$

Static coefficient of friction

Figure 2b shows the static coefficients of friction for rice grain on galvanized steel, wood and concrete (C30) surfaces at different moisture contents. It was observed that the static coefficient of friction increased linearly with the increase of the moisture content of grain on test surfaces. While the highest value (0.972) for the static coefficient of friction was recorded for concrete surface at 14% moisture content, the lowest value (0.524) was recorded for galvanized steel surface at 10% moisture content. The relation between moisture content with each of surface were found to be statistically significant ($P < 0.05$). Beyhan *et al.* (1994), expressed that the relationship between friction surface and moisture content for granular agro-materials are important in terms of the static coefficient of friction. Similar results on effect of grain moisture on static

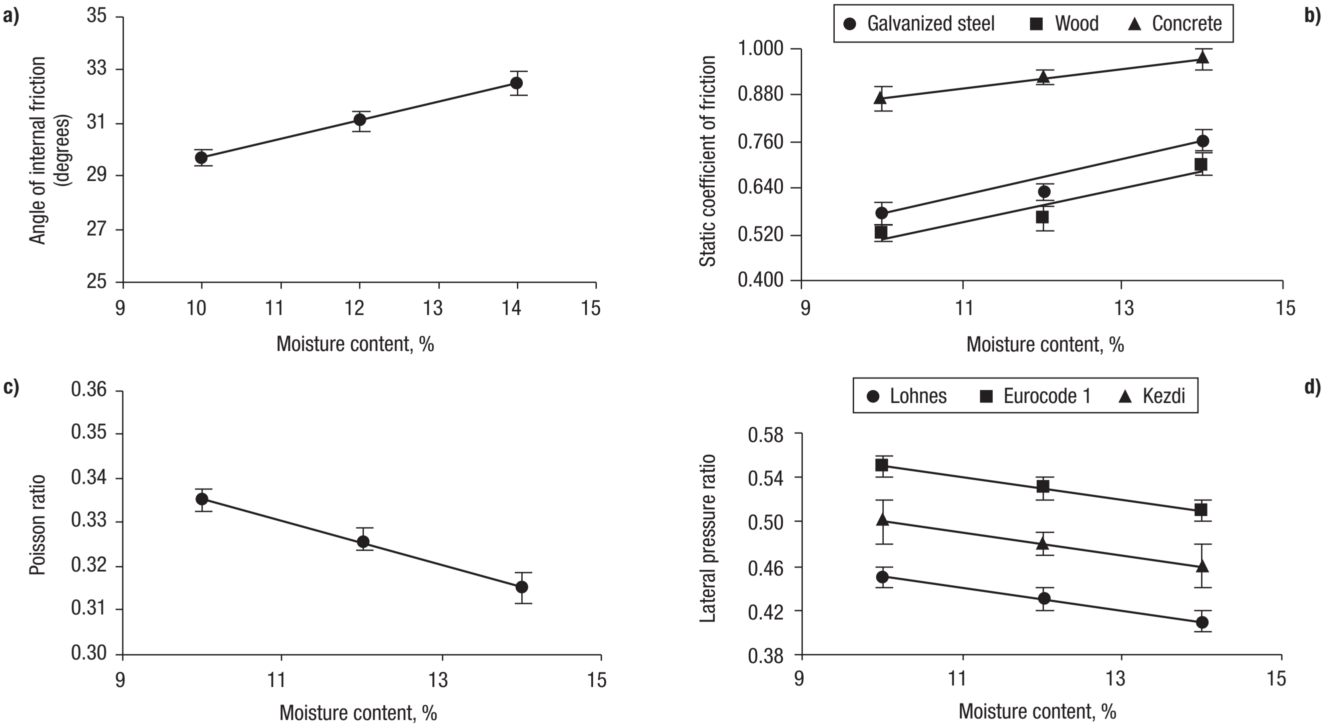

Figure 2. Effect of moisture content on mechanical properties of rice grains: a) angle of internal friction, b) static coefficient friction, c) poisson ratio, and d) lateral pressure ratio.

coefficient of friction have been reported by Gupta and Das (1997) for sunflower seed and Çalışır *et al.* (2005) for rapeseed. The regression equations related to the static coefficient of friction in samples and R^2 values are given in Table 2.

Poisson ratio

The poisson ratio of test samples decreased linearly with the increase of moisture content (Fig. 2c). The highest value (0.34) for poisson ratio at 10% moisture content, the lowest value (0.32) was recorded at 14% moisture content. The relation between moisture content with poisson ratio were found to be statistically significant according to $P < 0.01$ Poisson's ratio of African nutmeg in the moisture range of 8.0-28.7% decreased linearly with increase of moisture content (Brubai *et al.,* 2008). The relationship between the poisson ratio and moisture content for rice can be represented by the following regression equation:

$$V_p = 0.385 \pm 0.005M_c \quad (R^2 = 0.98) \qquad [30]$$

Table 2. Regression equations relating to static coefficient of friction of rice grain

Surfaces	Equations	R^2	*P* values
Galvanized steel	$\mu_{gs} = 0.043 + 0.0142M_c$	0.93	0.03*
Wood	$\mu_w = 0.044 + 0.0617M_c$	0.92	0.02*
Concrete (C30)	$\mu_c = 0.026 + 0.6133M_c$	0.95	0.03*

* Significant at 0.05 level.

Lateral pressure ratio

The lateral pressure ratio and standard errors for rice grain depending on moisture content and methods (Lohnes, Eurocode-1, Schulze) are presented in Figure 2d. It was observed that the lateral pressure ratio decreased linearly with the increase in moisture content of rice grain as calculated by all three methods. While the highest value (0.55) for the lateral pressure ratio was recorded for Eurocode-1 – at 10% moisture content, the lowest value (0.41) for lateral pressure ratio was recorded for Lohnes at 14% moisture content. Differences between the moisture content with each of methods (k_L, k_E, and k_S) were statistically significant ($P < 0.01$). Horabik and Rusinek (2002) have reported similar results for some cereal grains (Barley, corn, oat, wheat,

Table 3. Regression equations relating to lateral pressure ratio of rice grain

Methods	Equations	R^2	*P* values
Lohnes	$k_L = 0.55 - 0.01M_c$	0.98	0.006**
Eurocode-1	$k_E = 0.65 - 0.01M_c$	0.99	0.008**
Schulze	$k_S = 0.60 + 0.01M_c$	0.97	0.004**

** Significant at 0.01 level.

rape seed). The regression equations related to the lateral pressure ratio in samples and R^2 values are given in Table 3.

Conclusions

In this study, some physical and mechanical properties of Osmancık-97 rice variety widespread cultivated in Turkey were investigated in the range of moisture contents from 10 to 14% (d.b). The following conclusions are drawn from this investigation:

1. Physical and mechanical properties of rice grain depended on its moisture content.
2. The axial dimensions of rice grain increased with moisture content. This situation is due to water absorption by rice.
3. Arithmetic and geometric mean diameter, sphericity, grain volume, surface area, true density and porosity of rice grain also increased with increasing moisture content.
4. Bulk density of rice grain decreased with increase in moisture content.
5. The static coefficient of friction for rice grain was higher on concrete surface, followed by galvanized steel and wood.
6. Poisson ratio of rice grain decreased with increase in moisture content.
7. The lateral pressure ratio of rice grain decreased linearly with increase in moisture content. The pressure ratio for rice grain was greatest on Eurocode-1, followed by Schulze, and Lohnes.

In brief, this study dealt with physical and mechanical properties of rice, enlarging the knowledge about this grains and providing useful data for its industrial processing and estimating loads in storage structures for crops. Further studies should be conducted to investigate the moisture content-dependent physical and mechanical properties of different varieties of rice.

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