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Some engineering properties of white kidney beans (*Phaseolus vulgaris* L.)

Esref Işik* and Halil Unal

Department of Biosystem Engineering, Faculty of Agriculture, Uludag University,16059 Bursa, Turkey.

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Some engineering (physical and mechanical) properties of white kidney bean grains (*Phaseolus vulgaris* L.) were determined as a function of moisture content in the range of 10.01 to 25.00% dry basis (d.b.). The average length, width and thickness were 8.638, 16.747 and 4.958 mm, at a moisture content of 10.01% d.b., respectively. Nonetheless, the thousand grain mass increased from 472.5 to 696.2 g, the projected area from 128.13 to 198.83 mm^2, the true density from 1128.05 to 1290.85 kgm^{-3}, the porosity from 39.79 to 56.38% and the terminal velocity from 5.51 to 8.50 ms^{-1} in the moisture range from 10.01 to 25.01% d.b. The static coefficient of friction of white kidney bean grains increased linearly against surfaces of six structural materials, namely, rubber (0.501 to 0.727), stainless steel (0.384 to 0.468), aluminium (0.345 to 0.499), galvanized iron (0.346 to 0.489), medium density fibreboard (MDF) (0.325 to 0.426) and glass (0.287 to 0.345) as the moisture content increased from 10.01 to 25.00% d.b. The shelling resistance of white kidney bean grains decreased as the moisture content increased from 105.18 to 71.44 N.

Key words: Engineering (physical and mechanical) properties, white kidney beans, moisture content, thousand grain mass, static coefficient of friction.

INTRODUCTION

White kidney beans (*Phaseolus vulgaris* L.) are a cultivated plant grown for fresh and dry consumption and a common raw material in the canned food industry. On average, the bean contains 21.7 g protein, 0.75 g oil, 55.2 g total carbohydrates, 131.6 mg calcium, 7.6 mg iron and 1293.5 mg potassium per 250 ml (dry) (Nutritional Values, 2006). Turkey has about 155.000 ha of dry bean harvesting area, and 250.000 tons of dry bean production per annual with a yield of 1616 kg/ha of bean (FAO, 2004).

The knowledge of engineering (physical and mechanical) properties constitutes important and essential data in the design of machines, storage structures, and processes. The value of this basic information is not only important to engineers but also to food scientists, processors, and other scientists who may exploit these properties and find new uses. The size and shape are, for instance, important in their electrostatic separation from undesirable materials and in the development of sizing and grading machinery (Mohsenin, 1970). The shape of the material is important for an analytical prediction of its drying behaviour. Bulk density and porosity are major considerations in designing near-ambient drying and aeration systems, as these properties affect the resistance to airflow of the stored mass. The theories used to predict the structural loads for storage structures have bulk density as a basic parameter. The angle of repose is important in designing the equipment for

*Corresponding author. E-mail: dresref@gmail.com or dresref@uludag.edu.tr. Tel: +90 224 2941603. Fax: +90 224 2941603.

Nomenclatures: A_p, Projected area (mm²); A_s, surface are (mm²); C_1, C_2, regression coefficients; D_a, arithmetic mean diameter of grain (mm); D_g, geometric mean diameter of grain (mm); L, length of grain (mm); M_c, moisture content (% d.b.); M_{1000}, thousand grain mass (g); M_f, final moisture content of sample (% d.b.); M_i, initial moisture content of sample (% d.b.); P_f, porosity (%); Q, mass of water added (g); R_s, shelling resistance (N); R^2, coefficient of determination (dimensionless); T, thickness of grain (mm); V_t, terminal velocity (m/s); W, width of grain (mm); W_i, initial mass of sample (g); ρ_b, bulk density (kg/m³); ρ_t, true density (kg/m³); ϕ, sphericity of grain (dimensionless); μ, coefficient of friction (dimensionless).

mass flow and structures for storage. The frictional characteristics are important for the proper design of agricultural product handling equipment (Kaleemullah and Kailappan, 2003).

The major moisture-dependent physical properties of biological materials are shape and size, densities, porosity, mass of grains and friction against various surfaces. These properties have been studied for various crops such as soybean (Deshpande et al.,1993), pumpkin grains (Joshi et al., 1993), lentil (Tang and Sokhansanj, 1993), sunflower grain (Gupta and Das, 1997), white lupine (Öğüt, 1998), green gram (Nimkar and Chattopadhyay, 2001), pigeon pea (Baryeh and Mangope, 2002), chick pea grain (Konak et al., 2002), cotton (Özarslan, 2002), okra grain (Sahoo and Srivastava, 2002), hemp (Saçılık et al., 2003), quinoa seeds (Vilche et al., 2003), vetch (Yalçın and Özarslan, 2004), caper seed (Dursun and Dursun, 2005), sweet corn seed (Coşkun et al., 2006), black-eyed pea (Unal et al., 2006), Turkish Göynük Bombay beans (Tekin et al., 2006), some grain legume seeds (Altuntaş and Demirtola, 2007) and Faba bean (Altuntaş and Yıldız, 2007).

Despite an extensive search, no published literature was available on the detailed physical properties of white kidney beans and their dependency on operation parameters that would be useful for the design of processing machineries. In order to design equipment and facilities for the handling, conveying, separation, drying, aeration, storing and processing of white kidney beans, it is necessary to know their physical properties as a function of moisture content. Therefore, an investigation was carried out to determine moisture-dependent physical properties of white kidney beans in the different moisture contents. The purpose of this study was to investigate some moisture-dependent physical properties, namely, axial dimensions, arithmetic and geometric mean diameters, sphericity, thousand grain mass, surface and projected areas, bulk and true densities, porosity, terminal velocity, static coefficient of friction and shelling resistance of white kidney beans.

MATERIALS AND METHODS

The white kidney bean grains used in the study were obtained from a local market (Marmara Region, Bursa, Turkey). The grains were cleaned manually to remove all foreign matter such as dust, dirt, stones and chaff as well as immature, broken grains. The initial moisture content of the grains in dry basis was determined using a digital moisture meter (Pfeuffer HE 50, Germany).

The samples of each one 1500 grains of the 10.01, 15.74, 16.69, 20.77 and 25.00% moisture contents were prepared by adding the amount of distilled water calculated (Sacilik et al., 2003; Coşkun et al., 2006):

$$Q = \frac{W_i(M_f - M_i)}{(100 - M_f)} \quad (1)$$

The samples were then placed inside polyethylene bags and sealed tightly. The samples were kept at 5°C in a common refrigerator for a week to enable the moisture to distribute uniformly throughout the sample. Before starting a test, 1000 grains from each one polyethylene bags was taken out of the refrigerator and allowed to equilibrate to the room temperature for about 2 h (Singh and Goswami, 1996).

All the physical properties of the grains were determined at five moisture content levels ranging from 10.01 to 25.00% d.b. with ten replications at each moisture content level. These values are within the range of moisture contents for white kidney bean grains recommended for safe module storage as 12.35% d.b. on 5°C (Isik and Yüksel, 1997).

To determine the average size of the grain, 100 grains were randomly chosen from the polyethylene bags and their three axial dimensions namely, length (L), width (W) and thickness (T) were measured using a digital compass (Minolta, JAPAN) with an accuracy of 0.01 mm. (Mohsenin, 1970).

The average diameter of the grain was calculated using the arithmetic mean and geometric mean of the three axial dimensions. The arithmetic mean diameter D_a and geometric mean diameter D_g of the grain were calculated by using the following relationships (Mohsenin, 1970):

$$D_a = (L + W + T)/3 \quad (2)$$

$$D_g = (LWT)^{1/3} \quad (3)$$

The sphericity of grains ϕ was calculated by using the following relationship (Mohsenin, 1970):

$$\phi = \frac{(LWT)^{1/3}}{L} \quad (4)$$

The one thousand grain mass was determined by means of an electronic balance (Baster, Germany) reading to 0.001 g (Unal et al., 2006).

The surface area A_s in mm^2 of the grains was found by analogy with a sphere of same geometric mean diameter, using the following relationship (Tunde-Akintunde and Akintunde, 2004).

$$A_s = \pi D_g^2 \quad (5)$$

The projected area A_p was determined from the pictures of the grains taken by a digital camera (Creative DV CAM 316; 6.6 Mpixels, China), in comparison with the reference area to the sample area by using the Global Lab Image 2-Streamline (trial version) program (Isik and Güler, 2003).

The average bulk density of the grain was determined using the standard test weight procedure (Gupta and Das, 1997) by filling a container of 500 ml with the grain from a height of 150 mm at a constant rate and then weighing the content.

The average true density was determined using the toluene displacement method. The volume of toluene (C_7H_8) displaced was found by immersing 50 g of white kidney bean grains in the toluene (Coşkun et al., 2006). The porosity was calculated from the following relationship (Mohsenin 1970):

$$P_f = (1 - \frac{\rho_b}{\rho_t})100 \quad (6)$$

The terminal velocities of the grains at different moisture contents were measured using a cylindrical air column in which the material

Table 1. Means and standard errors of the grain at different moisture content*.

Moisture content (% d.b.)	Axial dimension (mm)			Average diameter (mm)	
	Length (L)	Width (W)	Thickness (T)	Arithmetic mean (D_a)	Geometric mean (D_g)
10.01	16.747± 0.154[a]	8.638±0.059[a]	4.958± 0.056[a]	10.114[a]	8.926[a]
15.74	16.826±0.117[a]	8.871± 0.064[a]	5.154± 0.073[b]	10.284[a]	9.137[b]
16.69	16.871±0.107[a]	9.487± 0.069[b]	5.408± 0.054[b]	10.589[b]	9.511[c]
20.77	16.878±0.145[a]	9.534± 0.075[c]	5.700± 0.081[c]	10.704[c]	9.684[d]
25.00	17.369±0.122[b]	9.739± 0.065[c]	7.358± 0.081[d]	11.489[d]	10.741[e]

*Values in the same columns followed by different letters are significant (P<0.05).

was suspended in the air stream (Nimkar and Chattopadhyay, 2001). The air column was 28 mm in diameter. Relative opening of a regulating valve provided at blower output end was used to control the airflow rate. In the beginning, the blower output was set at minimum. For each experiment, a sample was dropped into the air stream from the top of the air column. Then, airflow rate (range from 0 to 17 m/s) was gradually increased till the grain mass was suspended in the air stream. The air velocity which kept the grain in suspension was recorded by a digital anemometer (Thies clima, Germany) having a least count of 0.1 m/s (Ozdemir and Akıncı, 2004).

The static coefficient of friction of white kidney bean grains against six different structural materials, namely rubber, galvanized iron, aluminium, stainless steel, glass and medium density fibreboard (MDF) was determined. A polyvinylchloride (PVC) cylindrical pipe of 50 mm diameter and 100 mm height was placed on an adjustable tilting plate, faced with the test surface and filled with the grain sample. The cylinder was raised slightly so as not to touch the surface. The structural surface with the cylinder resting on it was raised gradually with a screw device until the cylinder just started to slide down and the angle of tilt was read from a graduated scale (Singh and Goswami, 1996). The coefficient of friction was calculated as:

$$\mu = \tan \alpha \qquad (7)$$

Shelling resistance R_s was determined by forces applied to one axial dimension (thickness). The shelling resistance of grain was determined under the point load by using a penetrometer (Bosch BS45 tester, Germany) (Unal et al., 2006).

Statistical design

The average size of the grain (100 grains) was randomly chosen and the other physical and mechanical properties of the grains were determined at six moisture (from 11.31% to 25.03% d.b.) content with ten replications at each moisture content level, and the results obtained were subjected to analysis of variance (ANOVA) and DUNCAN test using SPSS 14.0 software and analysis of regression using Microsoft Excel.

RESULTS AND DISCUSSION

Grain dimensions

The mean values of the axial dimensions of the white kidney bean grains at different moisture contents are presented in Table 1. All three axial dimensions increased with an increase in moisture content. The mean dimensions and standard errors of 100 grains measured at a moisture content of 10% d.b. are: length (16.747 ± 0.154 mm), width (8.638 ± 0.059 mm), and thickness (4.958 ± 0.056 mm).

The average diameters also increased with increasing moisture content as axial dimensions. The arithmetic and geometric mean diameter ranged from 10.114 to 11.489 mm and 8.926 to 10.741 mm as the moisture content increased from 10 to 25% d.b., respectively. The values of dimensions of a single white kidney bean were higher than those for lentils, cotton seeds, sweet corn and pea, respectively (Joshi et al., 1993; Özarslan, 2002; Coşkun et al., 2005; Paksoy and Aydin, 2006).

One thousand grain mass

It can be seen from Figure 1 that thousand grain mass M_{1000} increased linearly from 472.5 to 696.2 g (P<0.05) when the moisture content was increased from 10.01 to 25.00% d.b Increase of 47.3% in the one thousand grain mass was recorded within the above moisture range. The relationship between the thousand grain mass and moisture content can be represented as:

$$M_{1000} = 337.25 + 15.085 M_c \qquad (R^2 = 0.9669) \qquad (8)$$

White kidney bean has a relatively big grain size, compared with other commonly grown legume crops; for example at moisture content of 10.01% d.b., the thousand grain mass for green gram was 472.5 g while it was 245.4 g for black-eyed pea (Unal et al., 2006), 111.0 g for soybean (Deshpande et al., 1993), 173 g for gram (Dutta et al., 1988) and 28.2 g for green gram (Nimkar and Chattopadhyay, 2001). On the other hand, it has small grain size, compared with Turkish Göynük bombay beans; about 1700 g (Tekin et al., 2006).

Surface area of grain

The variation of the surface area with the white kidney

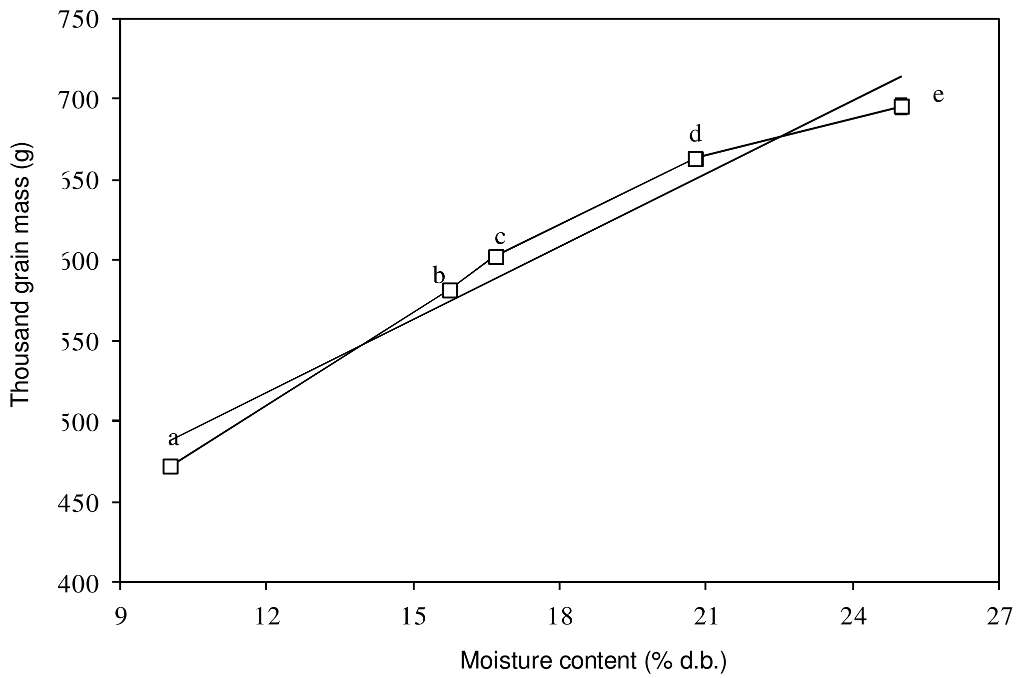

Figure 1. Effect of moisture content on the one thousand grains mass of white kidney beans. [a-e]Values followed by different letters are significant at P<0.05.

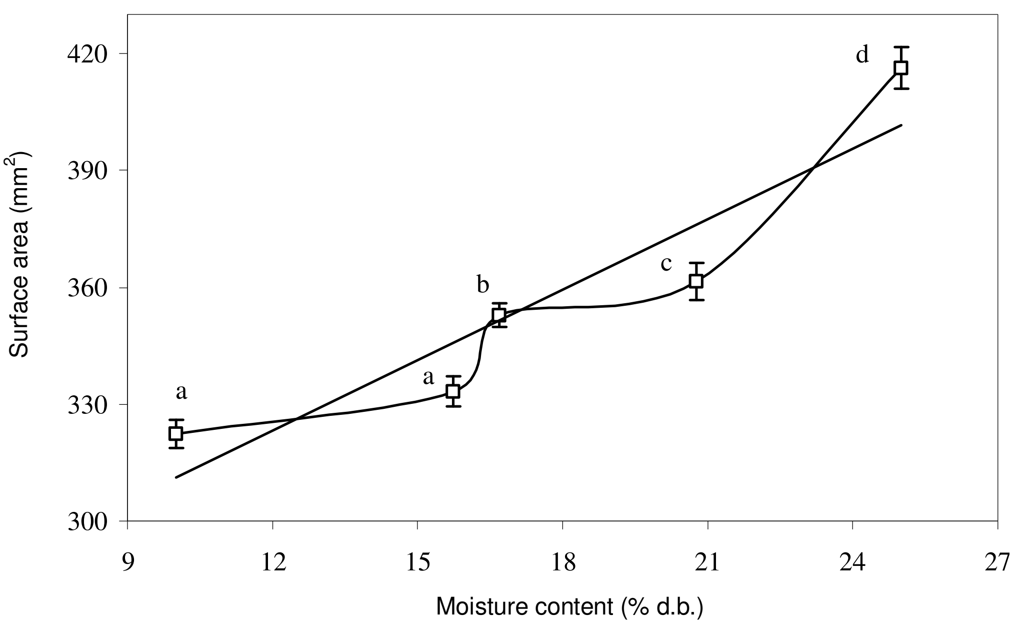

Figure 2. Effect of moisture content on surface area of white kidney beans. [a-d]Values followed by different letters are significant at P<0.05.

bean grains moisture content is shown in Figure 2. The surface area of white kidney bean grains increased linearly from 322.36 to 416.32 mm² when the moisture content increased from 10.01 to 25.00% d.b.

The variation of moisture content and surface area can be expressed mathematically as follows:

$$A_s = 250.91 + 6.0298M_c \tag{9}$$

with a value for the coefficient of determination R^2 of 0.8663.

Linear increase in surface area with increase in grain

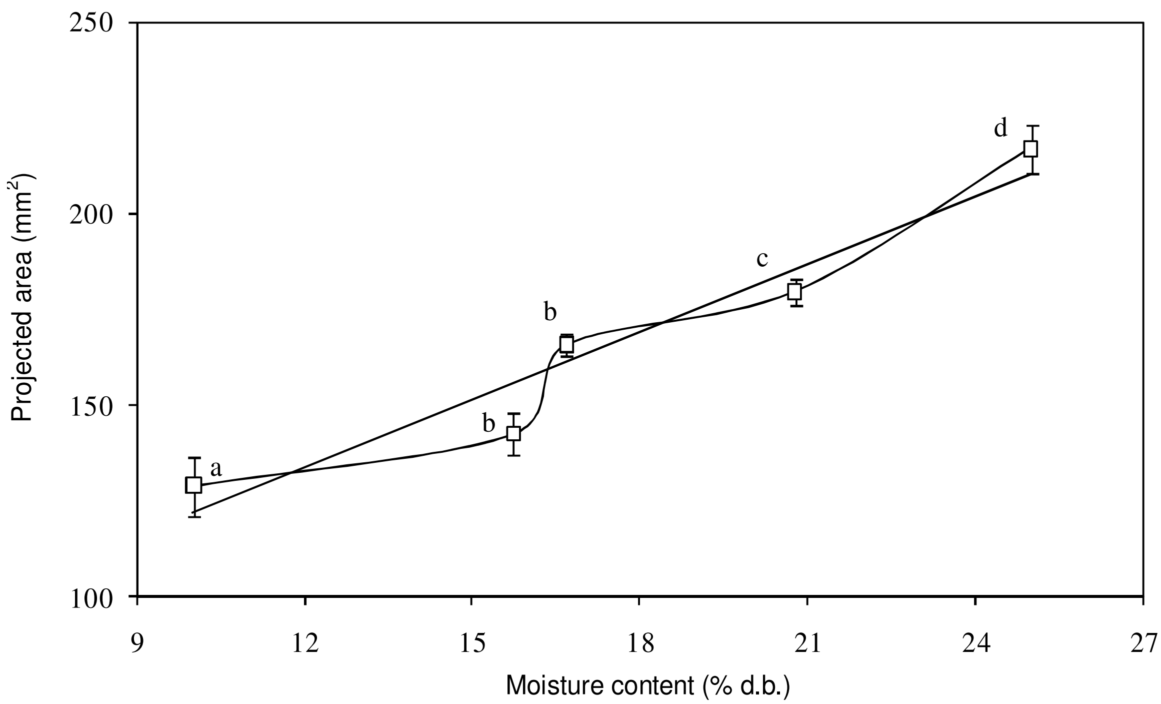

Figure 3. Effect of moisture content on projected area of white kidney beans. [a-d]Values followed by different letters are significant at P<0.05.

moisture content was observed by Dursun and Dursun (2005) for caper seed, Deshpande et al. (1993) for soybean and Saçılık et al. (2003) for hemp seed.

Projected area of grain

The projected area of white kidney bean grains increased from 128.13 to 198.83 mm² with increasing moisture content (Figure 3). The variation in projected area with moisture content of white kidney bean grains can be represented by:

$$A_p = 72.63 + 4.8139M_c \qquad (R^2 = 0.9484) \quad (10)$$

Linear increase in projected area with increase in grain moisture content was observed by Unal et al. (2006) for black-eyed pea, Tekin et al. (2006) for Turkish Göynük Bombay bean, Dursun and Dursun (2005) for caper seed, Deshpande et al. (1993) for soybean and Saçılık et al. (2003) for hemp seed.

Sphericity

The values of sphericity were calculated individually with Equation (4) using the data on geometric mean diameter and the major axis of the grain and the results obtained are presented in Figure 4. The results indicate that the sphericity of the grain was found increased from 0.536 to 0.619 in the specified moisture levels. This relationship can be represented by:

$$\phi = 0.4586 + 0.00061M_c \qquad (R^2 = 0.9165) \quad (11)$$

The sphericity of white kidney bean was compared with those of other grains and it was observed that the sphericity of grain at a given moisture level was lower than those of black-eyed pea (Unal et al., 2006), Türkish Göynük bombay bean (Tekin et al., 2006) and green gram (Nimkar and Chattopadhyay, 2001).

Bulk density

The bulk density decreased from 679.14 to 563.04 kg/m³ when the moisture content decreased from 10.01 to 25.00% d.b., respectively (Figure 5). The decrease in bulk densities with increase in moisture contents indicates that the decrease in weight owing to moisture gain in the sample is greater than the accompanying volumetric contraction of the bulk. Similar trends have been reported for black-eyed pea (Unal et. al., 2006), Turkish Göynük bombay beans (Tekin et al., 2006) and green gram (Nimkar and Chattopadhyay, 2001). The variation in bulk density (ρ_b) was found to be linear with the moisture content (M_c) and can be represented by the following regression equation:

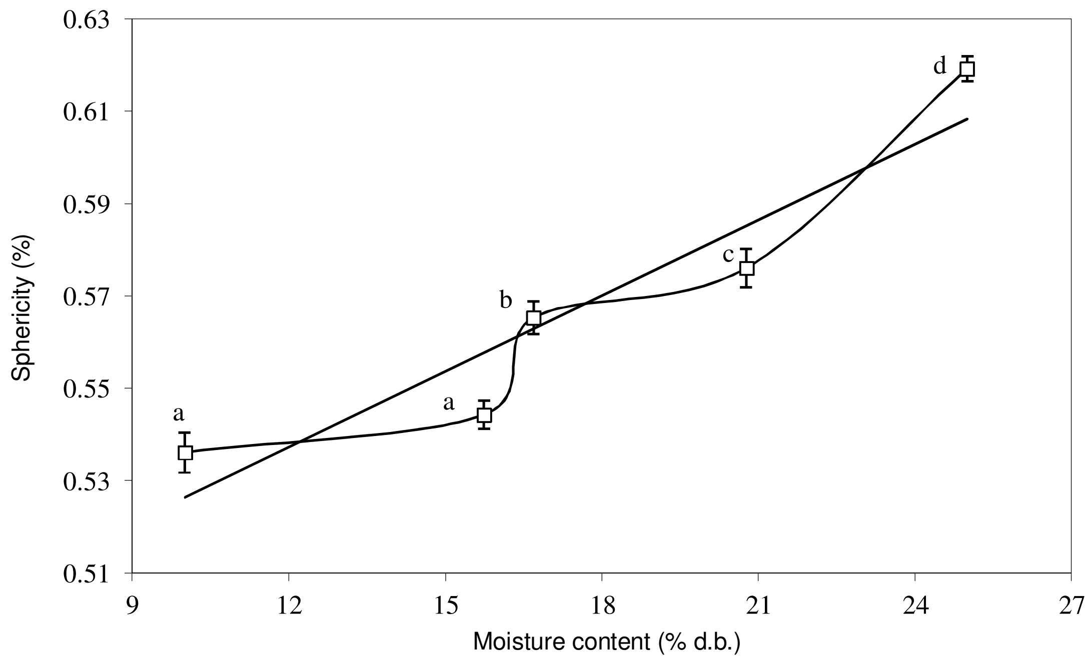

Figure 4. Effect of moisture content on sphericity of white kidney beans. [a-d]Values followed by different letters are significant at P<0.05.

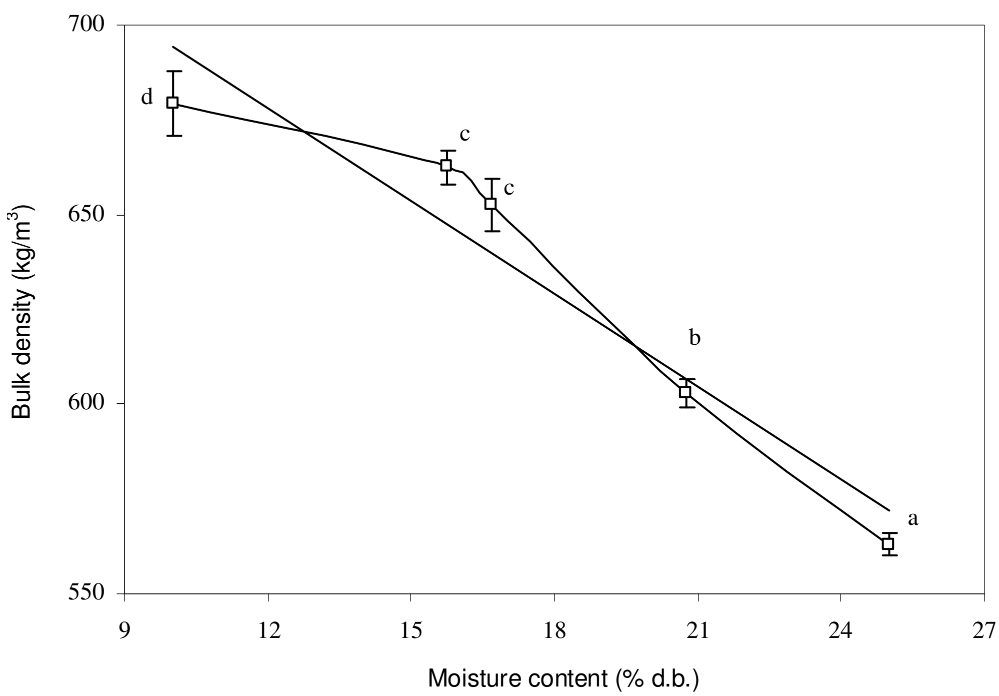

Figure 5. Effect of moisture content on bulk density of white kidney beans. [a-d]Values followed by different letters are significant at P<0.05.

$$\rho_b = 776.22 - 8.1757M_c \quad (12)$$

with a R^2 value of 0.9231.

True density

The true density varied from 1128.05 to 1290.85 kg/m^3 when the moisture level increased from 10 to 25% d.b.

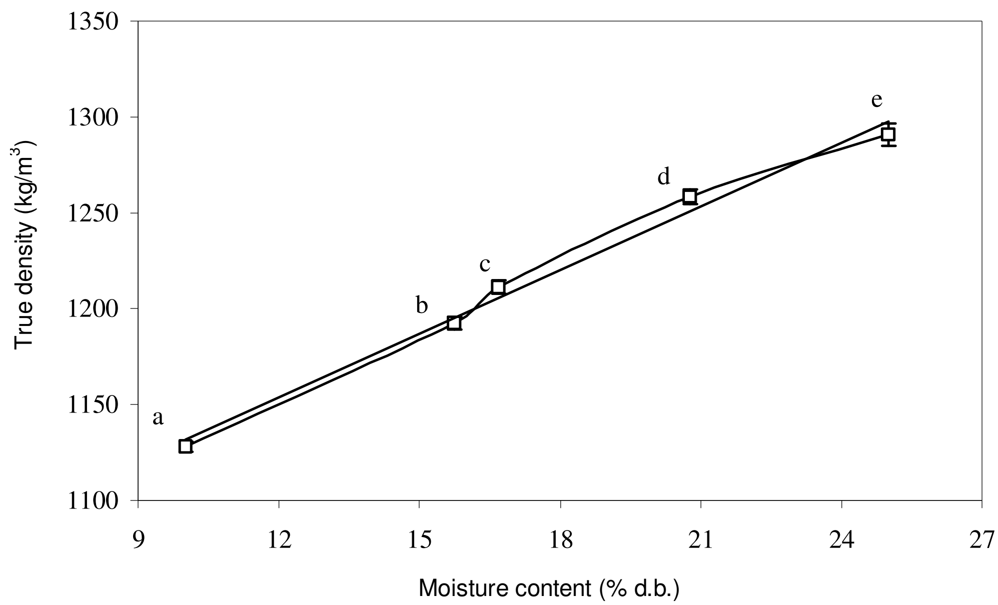

Figure 6. Effect of moisture content on true density of white kidney beans. [a-e]Values followed by different letters are significant at P<0.05.

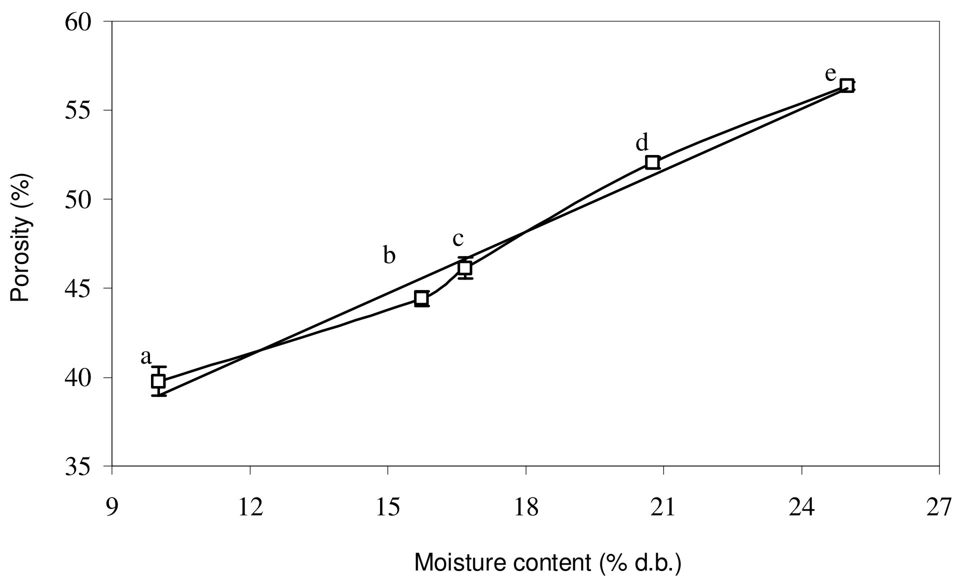

Figure 7. Effect of moisture content on porosity of white kidney beans. [a-e]Values followed by different letters are significant at P<0.05.

(Figure 6). True density and the moisture content of grain can be correlated as follows:

$$\rho_t = 1020.6 + 11.08 M_c \quad (13)$$

with a value for R^2 of 0.9903.

A similar increasing trend in true densities was observed by Baryeh (2002) for millet, Unal et al. (2006) for black-eyed pea and Tekin et al. (2006) for Turkish Göynük bombay bean.

Porosity

Porosity was evaluated using mean values of bulk density and true density in Equation (6). As shown in Figure 7, the porosity was found to increase linearly from 39.79 to 56.38 % in the specified moisture levels. A

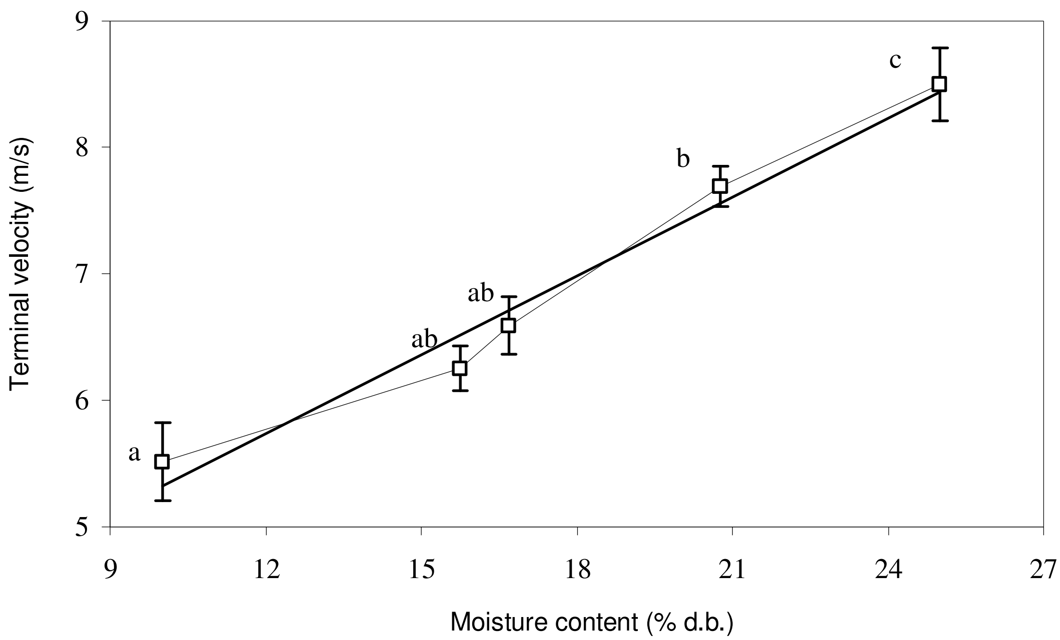

Figure 8. Effect of moisture content on terminal velocity of white kidney beans. [a-c]Values followed by different letters are significant at P<0.05.

comparison of porosity of white kidney bean with that of other grains (Gupta and Das, 1997; Öğüt, 1998; Nimkar and Chattopadhyay, 2001; Konak et al., 2002; Unal et al., 2006; Aviara et al., 2005; Çalışır et al., 2005; Coşkun et al., 2006) revealed that it increased with moisture content in the same way as other grains. The white kidney bean have been found with close porosity values to sunflower seed, white lupine, green gram, chick pea, black-eyed pea, *Balanites aegyptiaca* nuts, okra seed and sweet corn seed, respectively. The relationship between bulk porosity and the moisture content of the grain was obtained as:

$$P_f = 27.475 + 1.1499 M_c \quad (14)$$

with a value for R^2 of 0.9836.

Terminal velocity

Experimental results for the terminal velocity of white kidney bean grains at various moisture levels are plotted in Figure 8. As moisture content increased, the terminal velocity V_t was found to increase linearly from 5.51 to 8.50 m/s in the specified moisture range.

The relationship between terminal velocity and moisture content can be represented with the following relationship:

$$V_t = 3.2395 + 0.208 M_c \qquad (R^2 = 0.9749) \quad (15)$$

The results were similar to those reported by Çarman (1996), Nimkar and Chattopadhyay (2001), Suthar and Das (1996), Unal et al. (2006) and Singh and Goswami (1996) but the values were lower than those for lentil and green gram, and higher than those for karingda seed, black-eyed pea and cumin seed, respectively. The increase in terminal velocity with increase in moisture content within the study range can be attributed to the increase in mass of an individual grain per unit frontal area presented to the air stream.

Static coefficient of friction

The effects of moisture content and surface nature of materials on the static and kinetic coefficients of friction of white kidney bean grains are shown in Figure 9. The static coefficient of friction on the rubber surface varied from 0.501 to 0.727, on the stainless steel from 0.384 to 0.468, on the aluminium from 0.345 to 0.499, on the galvanised iron from 0.346 to 0.489, on the MDF sheet from 0.325 to 0.426 and on the glass from 0.287 to 0.345 for moisture contents between 10.01 and 25.00% d.b., respectively. The maximum static coefficients of friction were noticed on rubber surface, followed by stainless steel, aluminium, galvanised iron, MDF and glass surfaces.

All the static coefficients of friction increased linearly in the moisture range of 10.01 to 25.00% d.b. Similar trends was reported for soybeans, red kidney beans, unshelled peanuts, (Chung and Verma, 1989), black-eyed pea,

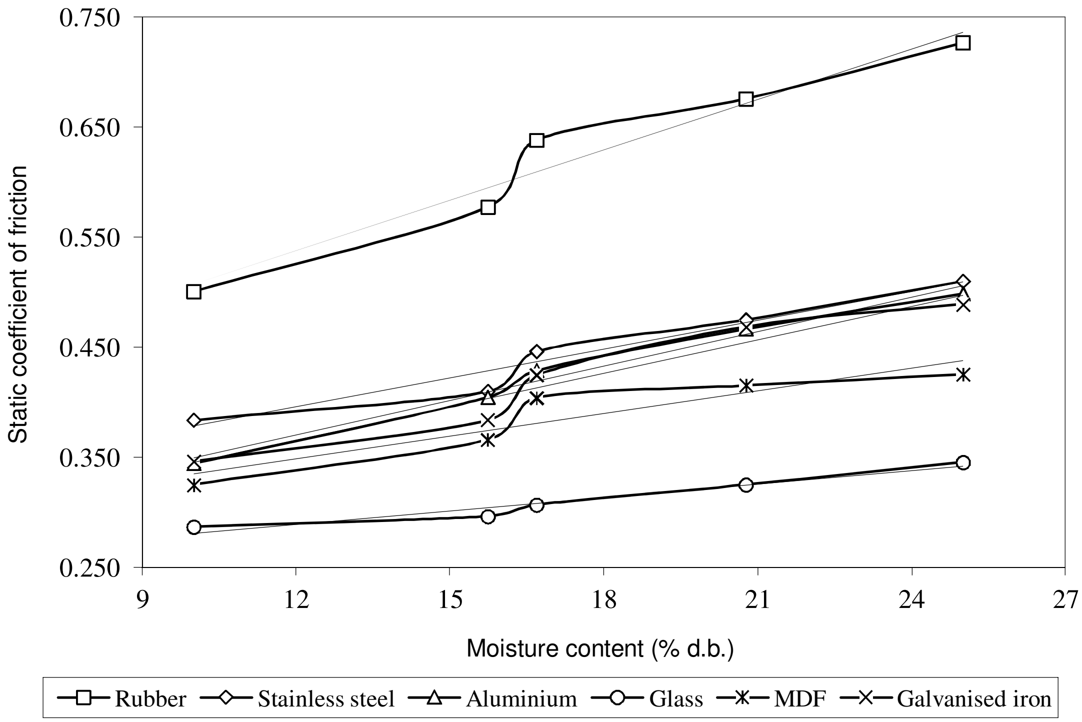

Figure 9. Effect of moisture content on static coefficient of friction of white kidney beans against various surface.

Table 2. Regression coefficients for static coefficient of friction of white kidney bean on different surfaces.

Surface	Regression coefficient		Coefficient of determination (R^2)
	C_1	C_2	
Rubber	0.3546	0.0153	0.9582
Stainless steel	0.2913	0.0087	0.9536
Aluminium	0.2447	0.0104	0.9843
Galvanized iron	0.2435	0.0101	0.9430
Medium density fibreboard (MDF)	0.266	0.0069	0.8682
Glass	0.2405	0.0041	0.9490

(Unal et al., 2006), Turkish Göynük bombay beans (Tekin et al., 2006), cumin seed (Singh and Goswami, 1996) and lentil seeds (Çarman, 1996). The regression equations for static coefficient of friction on different surfaces can be expressed as:

$$\mu = C_1 + C_2 M_c \quad (16)$$

The regression coefficients and coefficients of determination for static coefficient of friction on various surfaces are given in Table 2.

Shelling resistance

The shelling resistance of white kidney beans decreased with the increase in moisture content (Figure 10). The smaller shelling resistance at higher moisture content might have resulted from the fact that the grains became more sensitive to cracking at high moisture (Unal et al., 2006). The variation in shelling resistance of white kidney beans R_s in N with moisture content can be represented by:

$$R_s = 128.4 - 2.3262 M_c \quad (17)$$

with value for R^2 of 0.9891.

A similar increasing trend in shelling resistance was observed by Baryeh (2002) for millet, Unal et al. (2006) for black-eyed pea, Özarslan (2002) for cotton, Tekin et al. (2006) for Turkish Göynük Bombay bean and Konak

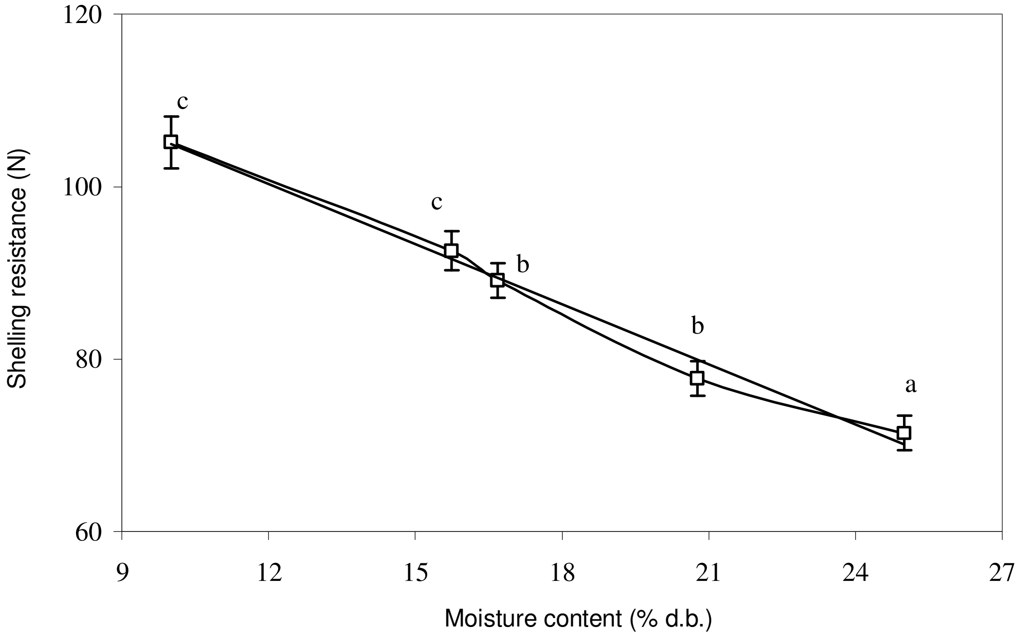

Figure 10. Effect of moisture content on shelling resistance of white kidney beans. [a-c]Values followed by different letters are significant at P<0.05.

et al. (2002) for chick pea grains.

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