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Physical properties of watermelon seed as a function of moisture content and variety

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A b s t r a c t. The physical properties of three common Iranian varieties of melon seeds have been evaluated as a function of seed moisture content varying from 4.75 to 47.6, from 5.02 to 46.81, and from 4.55 to 45.22% (w.b.) for Ghermez, Kolaleh and Sarakhsi, respectively. Increasing moisture content was found to increase axial dimensions, surface area, emptying angle of repose, bulk and true density, sphericity, geometric and arithmetic mean diameters, and static friction coefficient on five structural surfaces, while decreasing porosity and filling angle of repose. Among the varieties, Ghermez had the highest values of geometrical properties, in all moisture contents studied. An increase of surface area with moisture content was observed. The maximum values of bulk density and true density among the varieties were obtained for Kolaleh seeds. Ghermez melon seed had the highest porosity which decreased with increase in moisture content. The filling angle of repose decreased as the moisture contents increased for all three varieties. The maximum and minimum values for emptying angle of repose were obtained for Sarakhsi and Kolaleh. At all moisture contents, plywood showed the highest friction coefficient, followed by galvanized iron sheet, then fibreglass, and finally glass. The increase in friction coefficient with moisture content was the largest for Ghermez melon seed on fibreglass surface, followed by Sarakhsi and Kolaleh on fibreglass and galvanized iron sheet surface, respectively. Ghermez variety had the highest friction on all frictional surfaces at all moisture levels.

K e y w o r d s: watermelon seed, physical properties, moisture content, variety

INTRODUCTION

Watermelon (*Cucumis melo*), from the family of cucumber (*Cucurbitacea*), is large, oval, round or oblong in shape. The skin is smooth, with dark green rind or sometimes pale green stripes that turn yellowish green when ripe. Watermelon is a very rich source of vitamins, can be served for breakfast, as an appetizer or snack, depending on how it is prepared (Kerje and Grum, 2003). It also serves as a good source of phytochemical and lycopene, a red carotenoid pigment which acts as antioxidant during normal metabolism and protects against cancer (Perkins-Veazie and Collins, 2004).

Watermelon is one of the major under-utilized fruits grown in the warmer part of the world. The juice or pulp from watermelon is used for human consumption, while rind and seeds are major solid wastes (Bawa and Bains, 1977; Hour *et al*., 1980; Ahmed, 1996). The rind is utilized for products such as pickles and preserves, as well as for extraction of pectin (Hasan, 1993; Godawa and Jalali, 1995).

Melon fruit contains large quantities of seeds. The kernels are sometimes used as dressing for bread, cake, confectionery, sweetmeats and snack foods, often in place of almonds and pistachio (Teotia and Ramakrishna, 1984). The seeds can be cooked and dried and served as snacks *eg* Egypt, Iran and might also be cooked, ground (West Africa) and fermented for use as a flavour enhancer in gravies and soups (Nwokolo and Sim, 1987).

Many researchers have determined the physical properties of other seeds and grains, viz. pigeon pea (Shepherd and Bhardwaj, 1986), gram (Dutta *et al., 1988),* soybean (Sreenarayanan *et al*., 1988; Deshpande, *et al*., 1993), oil bean seed (Oje and Ugbor, 1991), neem nuts (Visvanathan, *et al*., 1996), karingda seed (Suthar and Das, 1996), cumin seed (Singh and Goswami, 1996), lentil seeds (Carman, 1996), sunflower seeds (Gupta and Das, 1997), coffee (Chandrasekar and Viswanathan, 1999), green gram (Nimkar and Chattopadhyaya, 2001), chick pea seeds (Konak *et al*., 2002) quinoa seeds (Vilche *et al*., 2003), hemp seed (Sacilik *et al*., 2003) and faba bean (Haciseferogullaria *et al*., 2003). Reports on physical characteristics of various cucurbit seeds, such as melon and pumpkin seeds, are available. Milani *et al*., (2007) studied some physical properties of three Iranian varieties of cucurbit seeds such as

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geometric properties, gravimetric properties and frictional properties, and reported that the mean values of all geometric properties increased with increasing moisture content. Makanjuola (1972) determined the size and shape of the seeds of two melon varieties and correlated the dimensions of the seeds and kernels. He measured the bending properties of melon seed as a function of moisture content and orientation of loading. Razavi and Milani (2006) investigated several physical properties of three dried watermelon seed varieties. Their results showed that the Red variety had the maximum volume, length, width, arithmetic mean diameter, geometrical mean diameter, sphericity, surface area and funnelling angle of repose among the varieties, while the greatest thickness was obtained for Sarakhsi variety and the highest accounted bulk density and true density were belonged to Kolaleh variety. Paksoy and Aydin (2004) estimated some physical properties of squash seeds at different moisture content (6.4-52.9%). The bulk density, true density, porosity, pro- jected area and terminal velocity increased as the moisture content increased.

The physical properties of watermelon seeds are essential for the design of equipment for handling, processing, storing, sowing the seeds, and are the most important factors in determining the optimum vacuum pressure of the precision vacuum seeder (Karayel *et al*., 2004). Although some data are available on the physical properties of dried melon seeds (Razavi and Milani, 2006), there are no published data on the moisture dependency of the seeds. Knowing the moisture dependency is useful for further investigation on drying the seeds. Thus, the objective of this study was to investigate some moisture-dependent physical properties of three varieties of watermelon seeds, namely, axial dimensions, mean diameters, sphericity, surface area, volume, 1000 seed mass, bulk density, true density, porosity, angle of repose, the static coefficients of friction on various surfaces as a function of moisture content. These data will determine the behaviour of the watermelon seeds during processing.

MATERIALS AND METHODS

Sample preparation

Several varieties of watermelon are cultivated in different regions of Iran, but 3 of them are used for their seeds. Ghermez, Kolaleh and Sarakhsi are the main watermelon seeds variety which are cooked, dried and served as snacks (Fig. 1). Dried melon seeds used in this study were obtained from a local market in Mashhad, Iran. The seeds were cleaned manually by hand to remove all foreign matter such as dust, dirt, stone pieces and broken seed.

The initial moisture content of the seeds was determined by following a standard oven method (AOAC, 2002) and was found to be 4.55, 4.75 and 5.02 (w.b. %) for Sarakhsi, Ghermez and Kolaleh, respectively.

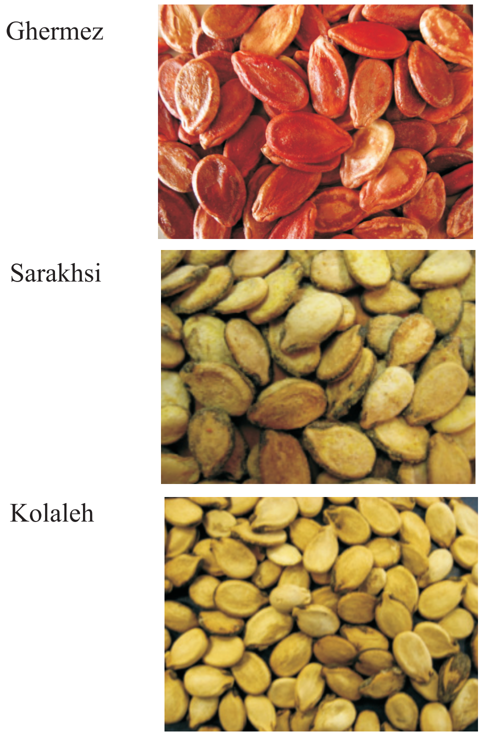

Fig. 1. Pictorial view of three common Iranian melon seed varieties.

The melon seed samples of the desired moisture levels were prepared by adding calculating amounts of distilled water, through mixing and then sealing in separate plastic bags. The samples were kept at 5°C in a refrigerator for at least a week to enable the moisture to distribute uniformly throughout the sample. Before starting a test, the required quantities of the seed were allowed to warm up to room temperature (Deshpande *et al*., 1993; Carman, 1996; Dursun and Dursun, 2005; Kashaninejad *et al*., 2005). The quantity of distilled water was estimated from the following equation:

$$W_2 = W_1 \frac{M_1 - M_2}{100 - M_1}, \qquad (1)$$

where: W_2 is the mass of distilled water added (kg), W_1 is initial sample mass (kg), M_1 is initial moisture content of sample (w.b. %), and M_2 is desired moisture content of sample (w.b. %). All the physical properties of melon seeds were measured at moisture levels of 4.75, 18.42, 32.00 and 47.6% (w.b.) for Ghermez; 5.02, 19.69, 34 and 46.81% for Kolaleh; 4.55, 16.65, 30.25 and 45.22% for Sarakhsi, with three replications at each level.

Dimensions, size, surface area and sphericity

In order to determine the average size of the seeds, ten sub-samples, each weighing 0.5 kg, were randomly drawn from the bulk sample. From each of the ten sub-samples, 10 seeds were picked and thus 100 seeds were obtained. For each individual seed, three principal dimensions, namely length (L), width (W) and thickness (T) were measured using an electronic micrometer (model QLR digit-IP54, China) with an accuracy of 0.001 mm. Because of the irregular shape of the melon seeds, only the greatest values of both width and thickness were taken.

The arithmetic mean diameter (D_a, mm) and the geometric mean diameter (D_g, mm) of the seeds were calculated using the following relationships, respectively (Mohsenin, 1978):

$$D_a = \frac{L+W+T}{3}, \quad (2)$$

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

According to Mohsenin (1978), the degree of sphericity, ϕ_M (%), can be expressed as follows:

$$\phi_M = \frac{(LWT)^{\frac{1}{3}}}{L}. \quad (4)$$

Jain and Ball (1997) have also stated that the sphericity, ϕ_J (%), and seed surface area, S_J (mm^2), may be given by:

$$\phi_J = \left[\frac{B(2L-B)}{L}\right]^{\frac{1}{3}}, \quad (5)$$

$$S_J = \frac{\pi BL^2}{2L-B}, \quad (6)$$

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

The surface area, S_M (mm^2), was also found by McCabe, Smith and Harriott (1986) to be given by the following equation:

$$S_M = \pi D_g^2. \quad (7)$$

True density, bulk density and porosity

True density is the ratio of the mass of the sample to the true volume of the particles *ie* excluding the volume of any internal pores. To obtain the mass, each melon seed was individually weighed on a precision electronic balance (Model GT 2100, Germany) that gave readings to the nearest 0.01 g. The seed volume was determined using the liquid displacement method (Mohsenin, 1978). Toluene (C_7H_8) was used in place of water, because it is absorbed by seeds to a lesser extent and its surface tension is low, so that it fills even shallow dips in a seed and its dissolution power is low (Ogut, 1998). A standard pycnometric method was used to determine the volume of weighed samples at different moisture contents. Five replicates were conducted for each melon seed variety. The volume (V, in m^3) was calculated by the following relationship (Mohsenin, 1978):

$$V = \frac{M_{td}}{\rho_{tol.}} = \frac{(M_{ps}-M_p)-(M_{pts}-M_t)}{\rho_{tol.}}. \quad (8)$$

where: M_{td} is unit mass of seed, M_t is mass of pycnometer filled with toluene; M_p, mass of pycnometer; M_{pts}, mass of pycnometer filled with toluene and sample; M_{ps}, mass of pycnometer and sample; and ρ_{tol}, density of toluene. The true density (ρ_t, kg m^{-3}) of melon seed was obtained by the following equation:

$$\rho_t = \frac{M_{ps}-M_p}{V}. \quad (9)$$

Bulk density, ρ_b, is based on the volume occupied by the bulk sample as poured into a container of known volume. In order to measure the bulk density, the melon seeds were poured into a calibrated container of known volume and weight, up to the top from a height of about 15 cm, and excess amount was removed by a strike-off stick. The seeds were not compacted in any way. The ratio of the mass and volume was expressed as bulk density. The bulk density was measured at all four moisture levels, with 10 replications at each level and for each variety.

The porosity was calculated from the measured values of bulk density (ρ_b) and true density using the relationship given by Mohsenin (1978). This relationship is presented in the form of equation :

$$\varepsilon = \left(1-\frac{\rho_b}{\rho_t}\right)100. \quad (10)$$

Angles of repose

The filling angle of repose is the angle with the horizontal at which the material will stand when piled. This was determined by using a topless and bottomless hollow cylindrical mould of 15 cm diameter and 50 cm height. The cylinder was placed at the centre of a raised circular plate having a diameter of 35 cm, filled with melon seeds and raised slowly until it formed a cone of seeds. The diameter (D) and height (H) of the cone were recorded. Average value of five replications for each variety was reported. The filling angle of repose (θ_f) was calculated by the formula as given by Razavi *et al*. (2007):

$$\theta_f = Arc\tan\left(\frac{2H}{D}\right). \quad (11)$$

To determine the emptying angle of repose, a fibreglass box of 20 x 20 x 20 cm, having a removable front panel was used. The box was filled with the seeds at the desired moisture content, and the front panel was quickly removed, allowing the seeds to flow to their natural slope (Joshi *et al*., 1993). The emptying angle of repose (θ_e) was calculated from the measurement of the depth of the free surface of the sample at the centre using the following equation (Paksoy and Aydin, 2004):

$$\theta_e Arc\tan(H / X) . \qquad (12)$$

X– is points (H_1 and H_2) in the sloping seed heap and X is the horizontal distance between two points (X_1 and X_2).

Static coefficient of friction

The coefficient of static friction was determined with respect to four surfaces: plywood, glass, fibreglass and galvanized iron sheet. A fibreglass box measuring 150 mm in length, 100 mm in width, 40 mm in height and open at both ends was filled with the seeds at the desired moisture content and placed on an adjustable tilting surface such that the box did not touch the surface. The tilting surface was raised gradually by means of a screw device until the cylinder with seeds just started to slide down. The angle of the incline (α) was read from a graduated scale and the static coefficient of friction (μ_s) was calculated from the following equation:

$$\mu_s = \tan\alpha . \qquad (13)$$

All the experiments on each test surface were carried out five times, and the average values reported.

RESULTS AND DISCUSSION

Linear dimensions

The axial dimensions, including length (L), width (W) and thickness (T) of the different varieties of melon seeds over the moisture content are shown in Fig. 2. It is clear that of the three varieties investigated, Ghermez seeds had the largest dimensions. As moisture content increased from 4.75 to 47.6% (w.b.), Ghermez seed length increased slightly from 18.72 to 18.91 mm (1.01% increase), seed width increased from 10.69 to 10.90 mm (1.2% increase) and seed thickness increased from 2.94 to 3.8 mm (29% increase). For the increase in moisture content of Kolaleh seed from 5.02 to 46.81% (w.b.), the increase of length, width and thickness was 3.80, 6.19 and 4.12%, respectively. Length and width of Sarakhsi seed increased with increase in moisture content (4.55-45.22) from 15.56 to 16.98 mm and 9.17 to 10.07 mm, respectively, but thickness had no significant change with moisture content. The estimated dimensions of Ghermez melon seed were greater than those of the squash seed (Paksoy and Aydin, 2004) and of seed of Morden variety sunflower (Gupta and Das, 1997), while these were smaller than the Pumpkin seed dimensions (Teotia *et al*., 1989).

Geometric mean diameter, sphericity and surface area

The average values of geometric and arithmetic mean diameter; sphericity (calculated by Eqs (4) and (5)), and surface area (obtained by Eqs (6) and (7)) of different varieties of melon seeds at different moisture contents are

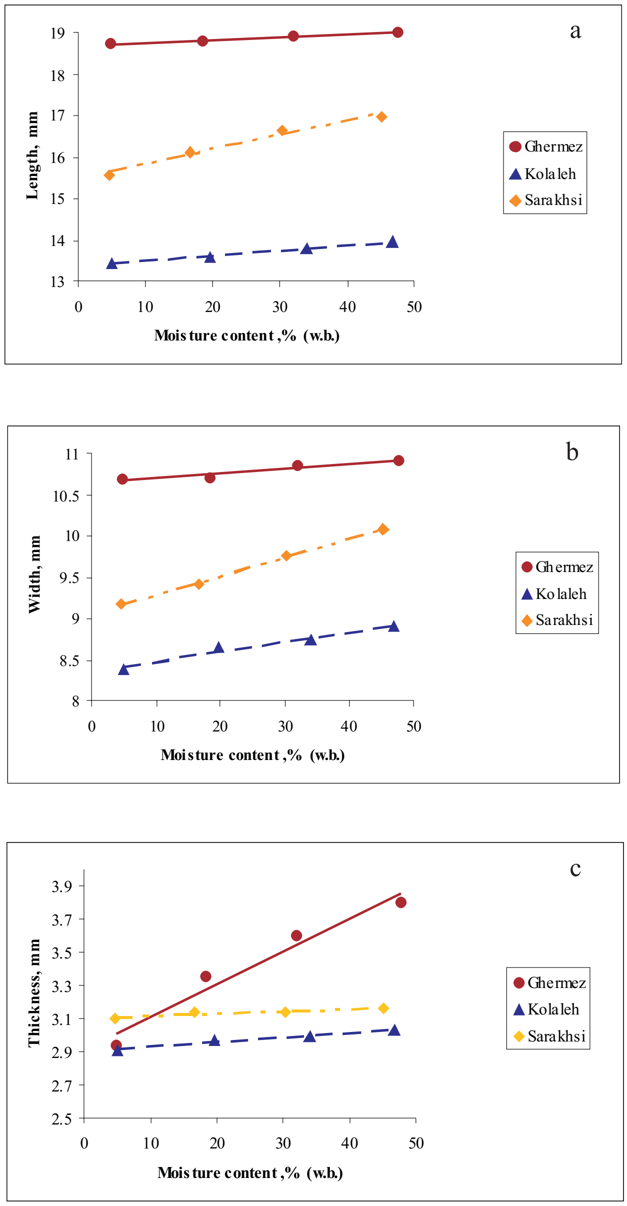

Fig. 2. Dimensional properties of melon seeds as a function of variety and moisture content; (a) length, (b) width, (c) thickness.

given in Table 1. It can be found that geometric and arithmetic mean diameter, sphericity and surface area of the three varieties increased with increase in moisture content.

The geometric and arithmetic mean diameters were 6.89 and 8.24 mm for Kolaleh, 8.37 and 10.79 mm for Ghermez, and 7.61 and 9.28 mm for Sarakhsi at moisture content of 5.02, 4.75, and 4.55% w.b., respectively. Both geometric and arithmetic diameters were significantly correlated to moisture content of seeds (Table 2). The relationship between sphericity (given by Eqs (4) and (5)) and moisture content of all the varieties are shown in Table 3. The sphericity increased gently and linearly with moisture

T a b l e 1. Mean and standard error for mean diameters (D), sphericity (ϕ) and surface area (S) of melon seeds as a function of moisture content (M_C)

Variety	M_C (%, w.b.)	D_a (mm)	D_g (mm)	ϕ_M	ϕ_J	S_M (mm^2)	S_J (mm^2)
Ghermez	4.75	10.79±0.35	8.37±0.34	0.447±0.021	2.118±0.033	220.45±17.88	193.84±14.62
	18.42	10.94±0.65	8.74±0.55	0.466±0.22	2.156±0.048	241.14±30.32	210.10±25.87
	32.00	11.14±0.52	9.09±0.43	0.481±0.023	2.188±0.037	259.81±24.98	224.92±21.21
	47.60	11.31±0.39	9.42±0.53	0.500±0.021	2.22±0.022	283.08±35.45	239.26±18.24
Kolaleh	5.02	8.24±0.47	6.89±0.39	0.513±0.022	2.003±0.039	149.37±17.04	127.80±14.31
	19.69	8.49±0.49	7.08±0.42	0.516±0.021	2.021±0.042	157.97±18.71	135.25±15.81
	34.00	8.51±0.44	7.11±0.38	0.517±0.254	2.025±0.38	159.08±16.99	136.03±14.15
	46.81	8.67±0.41	7.23±0.47	0.518±0.038	2.038±0.043	165.31±24.59	140.78±20.96
Sarakhsi	4.55	9.28±0.50	7.61±0.44	0.488±0.028	2.065±0.043	182.51±21.39	157.49±17.88
	16.65	9.56±0.58	7.79±0.53	0.488±0.027	2.079±0.051	191.68±26.54	165.73±22.17
	30.25	9.84±0.55	7.96±0.46	0.489±0.023	2.094±0.043	199.86±23.32	173.13±19.73
	45.22	10.12±0.42	8.14±0.55	0.489±0.021	2.109±0.052	208.46±20.54	182.48±18.45

T a b l e 2. Equations representing relationship between axial dimensions (L, W and T), geometric mean diameter (D_g), arithmetic mean diameter (D_a) and moisture content for different varieties of melon seed

Variety	M_C (%, w.b.)	Equation	R^2
Ghermez	4.47-47.60	$L = 0.0068\ M_C + 18.672$	0.977
		$W = 0.0057\ M_C + 10.631$	0.908
		$T = 0.0198\ M_C + 2.9138$	0.962
		$D_a = 0.0124\ M_C + 10.727$	0.996
		$D_g = 0.0246\ M_C + 8.274$	0.997
Kolaleh	5.02-46.81	$L = 0.0126\ M_C + 13.357$	0.991
		$W = 0.0119\ M_C + 8.356$	0.975
		$T = 0.0027\ M_C + 2.903$	0.966
		$D_a = 0.0094\ M_C + 8.229$	0.909
		$D_g = 0.0075\ M_C + 6.879$	0.931
Sarakhsi	4.55-45.22	$L = 0.0350\ M_C + 15.47$	0.979
		$W = 0.0224\ M_C + 9.058$	0.998
		$T = 0.0013\ M_C + 3.103$	0.830
		$D_a = 0.0206\ M_C + 9.202$	0.998
		$D_g = 0.0129\ M_C + 7.562$	0.998

content. The values given by Eq. (5) were higher than values obtained by the Eq. (4), due to the shape assumption of the two equations (Table 1). These linear behaviours are in accordance with similar reported results for Amaranth seeds (Abalone *et al*., 2004), sunflower seed (Gupta and Das, 1997), edible squash seed (Paksoy and Aydin, 2004) and cumin seed (Singh and Goswami, 1996).

The seeds surface area increased linearly with increasing seed moisture content for all three varieties (Tables 1 and 3). The increase of surface area was 10.67, 28.4% and 14.22 for Kolaleh, Ghermez and Sarakhsi, respectively. Shepherd and Bhardwaj (1986), Paksoy and Aydin (2004), and Baryeh (2002) found a similar behaviour with soybeans, edible squash seeds, and millet seeds, respectively. However, Hsu *et al*. (1991) showed the surface area of pistachios to decrease with increasing grain moisture content. Eq. (7) gave higher surface areas than Eq. (6). This is due to different seeds shapes assumed for these equations. Baryeh (2002) also found the surface of different varieties of millet to have higher values using Eq. (7).

Bulk density and true density

The variation of bulk density (ρ_b) of different varieties of melon seeds with moisture content is depicted in Fig. 3. It can be seen that the bulk density increased with increase in moisture content. The values of bulk density for different moisture contents varied from 299 to 440.35 kg m^{-3}, 470.54 to 541.56 kg m^{-3} and 337.27 to 540.09 kg m^{-3} for Ghermez, Kolaleh and Sarakhsi seeds, respectively. The same trends have also been reported by Paksoy and Aydin (2004), Aydin and Ozcan (2002), Aviara *et al*. (1999) and Sreenarayanan *et al*. (1988) for squash, terebinth fruits, guna seeds and soybean, respectively. Konak *et al*. (2002) and Masoumi and Tabil (2003) obtained values of bulk density for cheak pea from 800 to 741.4 kg m^{-3}, and from 806.31 to 778.54 kg m^{-3} at different moisture content, respectively. Carman (1996) reported that bulk density values of lentil seeds decreased linearly from 612.1 to 585.1 kg m^{-3} with increase in moisture

T a b l e 3. Equations representing relationship between sphericity, surface area and moisture content for different varieties of melon seed

Variety	M_C (%, w.b.)	Equation	R^2
Ghermez	4.47-47.60	Φ_M=0.0001 M_C + 0.513	0.927
		Φ_J=0.0024 M_C + 2.11 S	0.995
		$_M$=1.454 M_C + 213.77	0.999
		S_J=1.061 M_C + 189.77	0.997
Kolaleh	5.02-46.81	Φ_M=0.0001 M_C + 0.513	0.927
		Φ_J=0.0008 M_C + 2.001	0.949
		S_M= 0.350 M_C + 148.69	0.929
		S_J= 0.285 M_C + 127.45	0.917
Sarakhsi	4.55-45.22	Φ_M= 5E-05 M_C + 0.488	0.917
		Φ_J= 0.0011 M_C + 2.061	0.998
		S_M= 0.636 M_C + 180.34	0.996
		S_J= 0.607 M_C + 155.04	0.997

content. The negative relationship between bulk density and moisture content was also found by Al-Mahasneh and Rababah (2007) for green wheat, and by Dursun and Dursun (2005) for caper seeds. These discrepancies could be due to the cell structure and the volume and mass increase characteristics of the fruits and seeds as moisture content increases.

At the moisture content of 4.75% w.b. for Ghermez, 5.02% w.b. for Kolaleh and 4.55% w.b. for Sarakhsi, the true density of melon seeds was 862.07, 866.669 and 858.529 kg m^{-3}, respectively, and it increased linearly with increase in moisture content as can be seen in Fig. 3. The results were similar to those reported by Deshpande, Bal and Ojha (1993) for soybean, Gupta and Das (1997) for sunflower, Ogut (1998) for white lupin, and Chandrasekar and Viswanathan (1999) for coffee. It is, however, contrary to the results of Mwithiga and Masika Sifuna (2006), Al-Mahasneh and Rababah (2007), Sessiz *et al*. (2007) and Cetin (2007) who found the true density to decrease with moisture content for sorghum seeds, green wheat, caper fruit and barbunia bean, respectively. These seeds thus have lower weight increase in comparison to volume increase as their moisture content increases.

The regression equations of bulk and true density with moisture contents and R^2 of the present study are presented in Table 4. As the coefficient of determination (R^2) for all varieties was adequately high, it seems that the moisture content had remarkable influence on the density of melon seeds.

Porosity

As it is seen in Fig. 3, the porosity of the melon seeds decreased with increase in moisture content. The results also showed that porosity of melon seeds ranged from 63.32 to 49.83% for the Ghermez variety, 49.23 to 38.72% for the Kolaleh variety and 57.83 to 40.19% for the Sarakhsi variety. The magnitude of decrease in porosity may be attributed to the change in true and bulk density with increase in moisture content. The change in porosity with moisture content can be represented by the equations shown in Table 5. Similar trends were reported for pomegranate seeds (Kingsly *et al*., 2006), green wheat (Al-Mahasneh and Rababah, 2007), and caper fruit (Sessiz *et al*., 2007), but these are different from the behaviour reported for quinoa seeds (Vilche *et al*., 2003), sunflower (Gupta and Das, 1997), raw cashew nut (Balasubramanian, 2001), soybean (Deshpande *et al*., 1993), and pumpkin seeds (Joshi *et al*., 1993).

Filling and emptying angle of repose

The experimental data for filling angle of repose (θ_f) of melon seeds are presented in Fig. 4. The filling angle of repose decreased linearly as the seed moisture content increased for all three varieties, and it can be expressed by the relations shown in Table 6. The filling angle of repose for Ghermez, Kolaleh and Sarakhsi varieties ranged from 32.38 to 19.25°, 27.09 to 19.01° and 30.57 to 17.12° as the moisture contents ranged from 4.75 to 47.6% (w.b.), 5.02 to 46.81% (w.b.) and 4.55 to 45.22% (w.b.), respectively. The values for melon seeds at their initial moisture content (4.75, 5.02 and 4.55% w.b. for Ghermez, Kolaleh and Sarakhsi, respectively) were higher than those reported for millet (Baryeh,

T a b l e 4. Equation representing relationship between bulk density, true density and moisture content for different varieties of melon seed

Variety	M_C (%, w.b.)	Equation	R^2
Ghermez	4.47-47.60	ρ_t= 0.3456M_C + 861.31	0.966
		ρ_b= 3.510M_C + 278.32	0.965
Kolaleh	5.02-46.81	ρ_t= 0.549M_C + 863.94	0.998
		ρ_b=1.852M_C + 457.33	0.944
Sarakhsi	4.55-45.22	ρ_t= 0.583M_C + 856.67	0.989
		ρ_b=5.064M_C + 297.96	0.964

T a b l e 5. Equations representing relationship between porosity and moisture content for different varieties of melon seed

Variety	M_C (w.b. %)	Equation	R^2
Ghermez	4.47-47.60	ε = -0.3453M_C + 66.062	0.927
Kolaleh	5.02-46.81	ε = -0.2756M_C + 50.512	0.927
Sarakhsi	4.55-45.22	ε = -0.4074M_C + 59.793	0.949

2002), lentil seeds (Amin *et al*., 2004), arecanut kernels (Kaleemullaha and John Gunasekar, 2002) and edible squash (Paksoy and Aydin, 2004). The difference could be due to differences in surface roughness of seeds or grains.

The decrease in values for the angle of repose with increasing moisture content could be attributed to the increase of sphericity with increasing moisture, allowing them to slide and roll over on each other easily. This means that the forces of solid friction at the seed/material interface were generally decreased when the grain moisture content increased.

The variation of the emptying angle of repose (θ_e) of melon seeds with moisture content is plotted in Fig. 5. It can be found that the emptying angle of repose increased linearly with seed moisture content. It seems that this is due to the higher moisture contents and therefore higher stickiness of the surface of the seeds that confines the ease of sliding of seeds on each other. The emptying angle of repose of melon seeds at the moisture contents of 4.75, 5.02 and 4.55% (w.b.) was 28.15, 21.66 and 26.12° for Ghermez, Kolaleh and Sarakhsi, respectively. The regression constants for the linear regression are also presented in Table 6, together with the coefficient of determination for all three varieties. As it can be concluded, there were positive linear relationships with very high correlation (R^2) between emptying angle of repose and moisture content for all watermelon varieties.

A linear increase in angle of repose when the seed moisture content increases has also been noted by Suthar and Das (1996) for karingda seeds, Gupta and Das (1997) for sun-

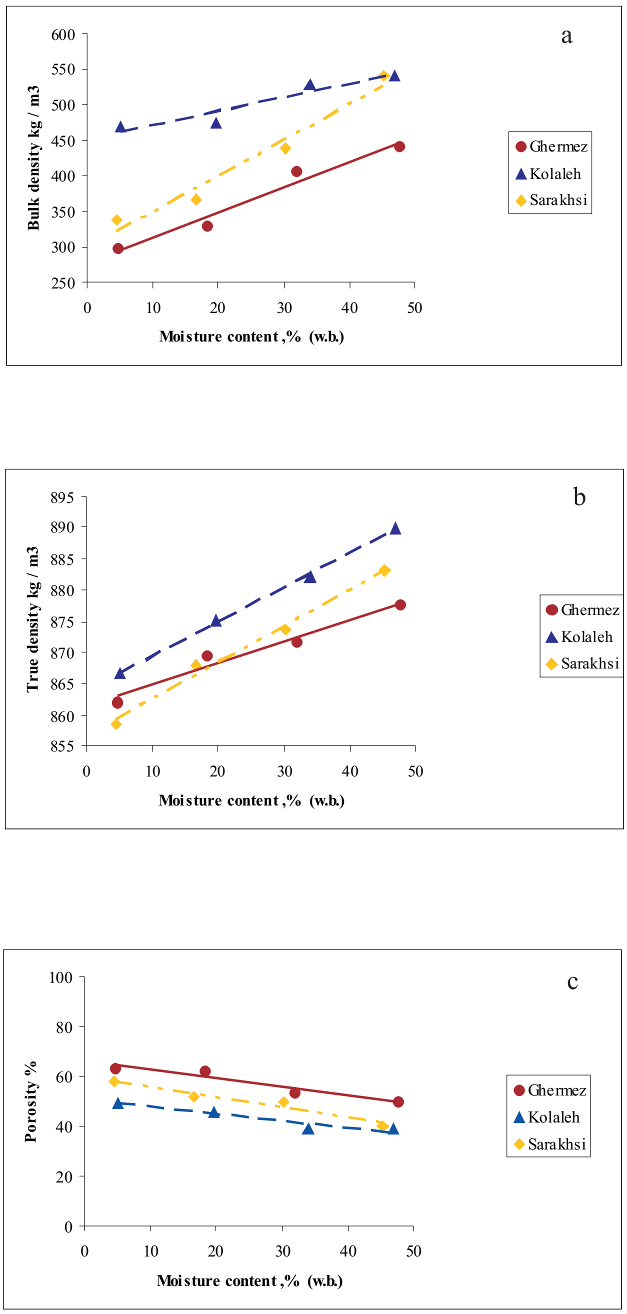

Fig. 3. Bulk density (a), true density (b), and porosity (c) of melon seeds as a function of variety and moisture content.

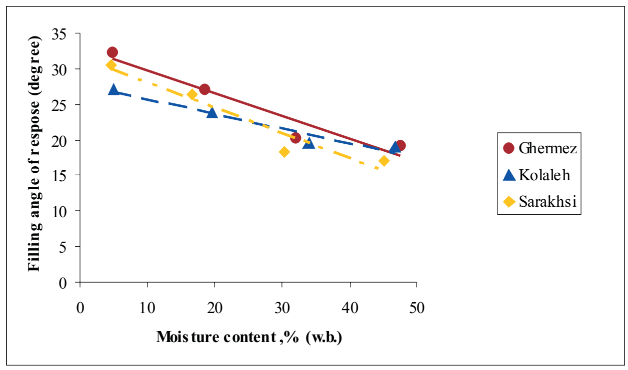

Fig. 4. Filling angle of repose of melon seeds as a function of variety and moisture content.

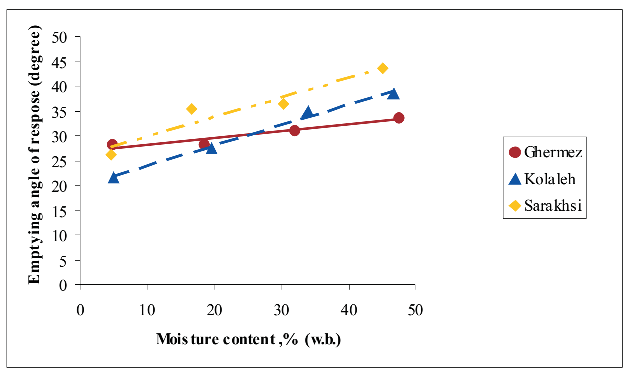

Fig. 5. Emptying angle of repose of melon seeds as a function of variety and moisture content.

flower, Konak, Arman and Aydin (2002) for chick pea seeds, Vilche *et al*. (2003) for quinoa seeds, Paksoy and Aydin (2004) for edible squash, Altuntas *et al*. (2005) for fenugreek, Mwithiga *et al.* (2006) for sorghum seeds, and Coskuner and Karababa (2007b) for flaxseed. Aviara *et al.* (1999) and Bart-Plange and Baryeh (2003), however, found the emptying angle of repose to increase non-linearly with increase in moisture content for guna seeds and cocoa beans, respectively.

At a moisture content of 13.67% (w.b.), the two angles of repose for Ghermez melon seeds were both equal to 28.62°. This moisture content is 13.16% w.b. for Kolaleh melon seed and both angles of repose were equal to 25.07°. For Srakhsi melon seed, the moisture content at which both angles were equal is 5.73% w.b. and the angles of repose were 28.17°.

Low angle of repose makes the seeds spread out wider on a plane surface compared to high angle of repose. Low angle of repose is often advisable during belt conveying, while high angle of repose is more desirable when unloading onto a horizontal surface. Hence, low moisture content is advisable for belt conveying, while high moisture content is suitable when unloading the seeds.

Static coefficient of friction

The static coefficients of friction for different varieties of melon seeds with respect to fibreglass (μ_{fg}), glass (μ_{gl}), galvanized iron sheet (μ_{gi}) and plywood (μ_{pl}) surfaces at different moisture levels are presented in Figs 6 and 7. It was observed that the static coefficient of friction increased with increase in moisture content for all the surfaces tested. Increase in friction coefficient with moisture content may be explained by increased cohesive force of wet seeds with the structural surface, since the surface becomes stickier as moisture content increases. Similar findings were reported for millet (Baryeh, 2002), almond nut (Aydin, 2003), pistachio nut and kernel (Razavi *et al*., 2007), caper fruit (Sessiz *et al*., 2007) and barbunia bean (Cetin, 2007).

The highest static coefficient of friction on fibreglass surface was observed for Ghermez (0.34-0.9), followed by Sarakhsi (0.3-0.81) and Kolaleh (0.36-0.76) (Fig. 6). The estimated coefficient of friction for melon seeds was grater than for pine nuts (Ozguven and Kubilay, 2004) and pistachio nuts (Razavi *et al*., 2007).

As it is seen in Fig. 7, the highest static coefficient of friction on glass surface was obtained for Ghermez seed

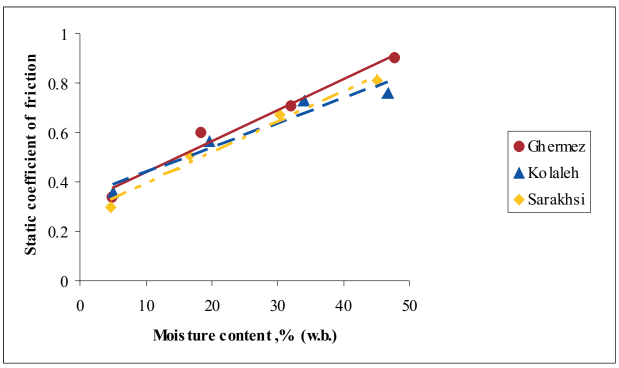

Fig. 6. Static coefficient of friction of melon seed on fibreglass surface (μ_{fg}) as a function of moisture content and variety.

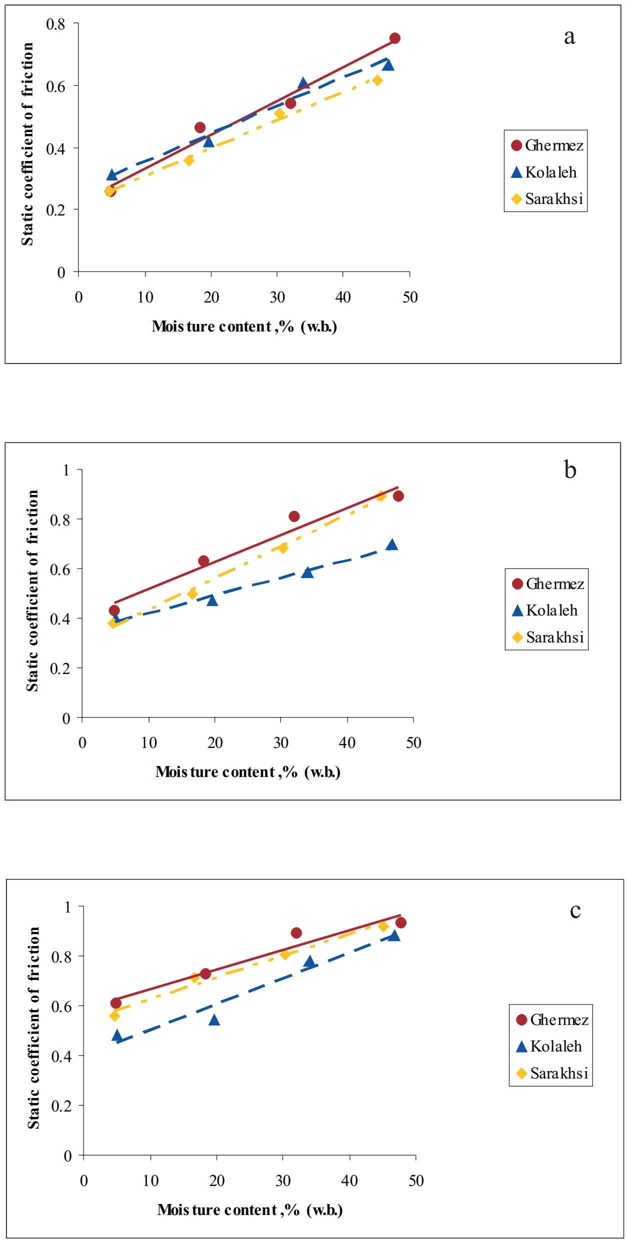

Fig. 7. Static coefficient of friction of melon seed on: a – glass (μ_{gl}), b – galvanized iron sheet (μ_{gi}), and c – plywood (μ_{pl}) surfaces as a function of moisture content and variety.

(0.26-0.75), then for Kolaleh seed (0.31-0.66), and the lowest for Sarakhsi seed (0.26-0.62). Overall, the measured values for melon seeds were greater than those for oil bean seed (Oje and Ugbor, 1991), locust bean seed (Olajide and Ade-Omowaye, 1999), lentil (Amin *et al*., 2004), pistachio nuts (Kashaninejad *et al*., 2005; Razavi *et al*., 2007) and white speckled red kidney bean grains (Isik and Unal, 2007).

The static coefficient of friction on galvanized iron sheet surface was 0.43-0.89 for Ghermez seed, 0.40-0.70 for Kolaleh seed and 0.38-0.90 for Sarakhsi seed (Fig. 7). The static coefficient of friction on galvanized iron sheet surface for melon seeds was greater than the reported values for faba beans (Fraser, *et al*., 1978), pearl millet (Jain and Bal, 1997), locust bean seed (Olajide and Ade-Omowaye, 1999), hackberry (Demir *et al*., 2002), caper buds (Ozcan *et al*., 2004), pine nuts (Ozguven and Kubilay, 2004), lentil (Amin *et al*., 2004), gumbo fruit (Akar and Aydin, 2005), pistachio nuts (Kashaninejad *et al*., 2005; Razavi *el al*., 2007), faba beans (Altuntas and Yildiz, 2007), barbunia bean (Cetin, 2007), white speckled red kidney bean grains (Isik and Unal, 2007) and lower than that for pomegranate seeds (Kingsly *et al*., 2006).

The results obtained for friction coefficient of watermelon seeds on plywood surface, as shown in Fig. 7, indicated that the highest value was for Germez seed (0.61-0.93), followed by Sarakhsi seed (0.56-0.92) and the lowest for Kolaleh seed (0.48-0.88). The static coefficient of friction with respect to plywood surface for melon seeds were greater than those reported value for hackberry (Demir *et al*., 2002), almond nut (Aydin, 2003), Turkish hazelnut (Ozdemir and Akinci, 2004), lentil (Amin *et al*., 2004), faba bean (Altuntas and Yildiz, 2007; Fraser *et al*., 1978), African star apple seed (Oyelade *et al*., 2005), pomegranate seeds (Kingsly *et al*., 2006), green wheat (Al-Mahasneh and Rababah, 2007) and cowpea seed (Kabas *et al*., 2007).

Plywood showed the highest friction coefficient followed by galvanized iron sheet, then fibreglass, and finally glass. This might be due to the surface roughness which is largest in the case of plywood and probably the least for glass. The increase in friction coefficient with moisture content was observed largest for Germez melon seed on fibreglass surface, followed by Sarakhsi and Kolaleh seeds on fibreglass and galvanized iron sheet surface, respectively. The highest friction on all frictional surfaces at all moisture levels were offered by Germez variety. It might be due to the higher moisture content of this variety. It means that at higher moisture contents the seeds became stickier and sliding characteristics are diminished, so that the static coefficient of friction increased.

The regression equations and their R^2 values obtained by fitting the experimental data of static coefficient of friction as a function of moisture content are listed in Table 6. It can be found that the relationship of static coefficient of friction of melon seeds with moisture content was linear for all friction surfaces and melon varieties. These linear behaviours are in accordance with similar reports for pomegranate seeds (Kingsly *et al*., 2006), green wheat (Al-Mahasneh and Rababah, 2007), pistachio nut (Razavi *et al*., 2007), caper fruit (Sessiz *et al*., 2007) and barbunia bean (Cetin, 2007), white speckled red kidney bean grains (Isik and Unal, 2007), faba beans (Altuntas and Yildiz, 2007) and cowpea seed (Kabas *et al*., 2007). It is, however, contrary to the result of Konak *et al*. (2002), Kaleemullah and Gunasekar (2002), Aydin, (2002), Baryeh and Mangope (2002) and Coskuner and Karababa (2007a) who found that the static coefficient of friction has non-linear relationship with moisture content for chick pea, Arecanut, hazelnut, QP- 38 pigeon pea and coriander seeds, respectively.

T a b l e 6. Equations representing relationship between angles of repose and moisture content for melon seed varieties

Variety	M_C (w.b. %)	Equation	R^2
Ghermez	4.47-47.60	$\theta_f = -0.322\ M_C + 33.023$ $\theta_e = 0.1366\ M_C + 26.753$	0.919 0.914
Kolaleh	5.02-46.81	$\theta_f = -0.206\ M_C + 27.779$ $\theta_e = 0.4157\ M_C + 19.60$	0.944 0.991
Sarakhsi	4.55-45.22	$\theta_f = -0.354\ M_C + 31.66$ $\theta_e = 0.392\ M_C + 25.926$	0.923 0.913

CONCLUSIONS

1. It is evidenced that the increase in moisture content of watermelon seeds linearly increased the axial dimensions, surface area, empting angle of repose, bulk and true density, sphericity, geometric and arithmetic mean diameters, and static friction coefficient on five structural surfaces, while it decreased the porosity and filling angle of repose.

2. The results also showed that these parameters vary from variety to variety. Among the varieties, Ghermez had the highest values of geometric properties. The maximum values of bulk density and true density among the varieties were obtained for Kolaleh seeds, and Ghermez melon seed had the highest porosity. The maximum and minimum values for emptying angle of repose were obtained for Sarakhsi and Kolaleh.

3. At all moisture contents, plywood showed the highest friction coefficient, followed by galvanized iron sheet, then fibreglass, and finally glass. Ghermez variety had the highest friction on all frictional surfaces at all moisture levels. The increase in friction coefficient with moisture content was the largest for Ghermez melon seed on fibreglass surface, followed by Sarakhsi and Kolaleh on fibreglass and galvanized iron sheet surface, respectively. Ghermez variety had the highest friction on all frictional surfaces at all moisture levels.

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