Jun. 2010, Volume 4, No.3 (Serial No.28)
Journal of Agricultural Science and Technology, ISSN 1939-1250, USA

Frictional Behavior of Sunflower Seed and its Kernel as a Function of Moisture Content, Variety and Size

R. Khodabakhshian, B. Emadi and M. H. Abbaspour Fard

Agricultural Machinery Department, Ferdowsi University of Mashhad, Mashhad 91775-1163, Iran

Received: September 26, 2009 / Accepted: December 04, 2010 / Published: June 15, 2010.

Abstract: The object of this study was to investigate the frictional properties (repose angles and friction coefficient) of Iranian sunflower seed and its kernel (Fandoghi, Azargol and Shahroodi) as a function of moisture content, size and variety. The static coefficient of friction were determined on five structural surfaces including aluminium, plywood, galvanized iron, polyethylene and rubber when moisture content varied between 3 and 14 % d.b. The obtained results showed that static coefficient of friction on five studied surfaces increase linearly as moisture content increase from 3 to 14% for both seed and kernel. Among the applied surfaces, rubber showed the highest value of friction coefficient for both sunflower seed and kernel followed by plywood, polyethylene, galvanized iron and aluminium. The obtained values of emptying and filling angles of repose increase linearly with an increase in moisture content. Furthermore, the values of empting and filling angles of repose for small sizes were higher than big sizes in all levels of moisture content for both seed and kernel. Also, the emptying angle of repose assumed higher values than the filling angle of repose for all varieties and categories.

Key words: Frictional properties, sunflower seed and kernel, moisture content, variety, size.

1. Introduction

Sunflower seed (*Helianthus annuus* L.) is one of the most important crops in the world's oilseeds industry [1]. The need for knowledge of friction coefficients of agricultural materials on various surfaces has long been recognized by engineers concerned with rational design of grain bins, silos and other storage structures [2]. The frictional properties (angles of repose and coefficients of friction) of sunflower seed, like other seeds and grains, are necessary for the design of various equipment for handling, harvesting, conveying, separating, grading, dehulling, and storing. For example, the design of hoppers, storage and handling systems for grains requires data on friction coefficients of commonly used materials (aluminium, plywood, galvanized iron, polyethylene and rubber) and angles of repose. Furthermore, if the conveying or handling of the seed and its kernel is required, knowledge of their coefficient of friction on common surfaces is essential for selecting material of surface for related equipment.

The static and dynamic coefficients of friction for different varieties of grains and seeds as a function of moisture content have been reported by several researchers [3, 4]. They have reported an increase in coefficients of static and dynamic frictions with increase in moisture content for cereal grains and peanuts, respectively. Many researchers have also reported a linear increase in static coefficient of friction for various food and agricultural produce on concrete, plywood, rubber, mild steel, aluminium, stainless steel and glass as a function of moisture content [1, 5-12]. Also, many researchers have revealed an increase in the value of empting angle of repose with increase in moisture content [13-18].

Gupta and Das (1997) have reported static and dynamic friction coefficients of sunflower seed and its kernel on six different surfaces (plywood, mild steel,

Corresponding author: R. Khodabakhshian, Master, research fields: postharvest technology, design of farm machinery and maintenance. E-mail: ra_kh544@stu-mail.um.ac.ir.

galvanized iron, aluminium, stainless steel and rubber) between 4 and 20% d.b.. Also, the empting angle of repose of sunflower seed and its kernel as a function of moisture content have been previously disclosed [1]. They studied only the effect of moisture content and didn't consider size and variety as a function for their research. Although the study of filling angles of repose for seed and kernel of sunflower seed is also important, no work has published yet. Isik and Izil (2007) investigated some moisture dependent properties of only sunflower seed for a Turkish cultivar. They have showed that the static coefficient of friction of sunflower seeds increase linearly on surfaces of six structural materials, namely rubber, aluminium, stainless steel, galvanized iron, glass and MDF (average density fiberboard) as the moisture content increase from 10.06-27.06 % (d.b.).

As it can be found from literature review, despite an extensive research on frictional properties of grains, very limited published results on the frictional properties of sunflower seeds and their kernel are available. Hence, the aim of this research was to investigate the frictional properties (repose angles and friction coefficient) of sunflower seed and its kernel as a function of moisture content, size and variety. The emptying (dynamic) and filling (static) angle of repose and static coefficient of friction on five structural surfaces (aluminium, plywood, galvanized iron, polyethylene and rubber) evaluated for three varieties of Iranian sunflower seed and its kernel (Shahroodi, Fandoghi and Azargol) in the range of moisture content from 3% to 14% (d.b.).

2. Materials and Methods

2.1 Sample Preparation

Three different varieties of sunflower seeds, namely Fandoghi, Azargol and Shahroodi were obtained from three regions of Khorasan Razavi province (Iran) during autumn season in 2008 (Fig. 1). A mass of twenty kilograms from each variety of sunflower seed

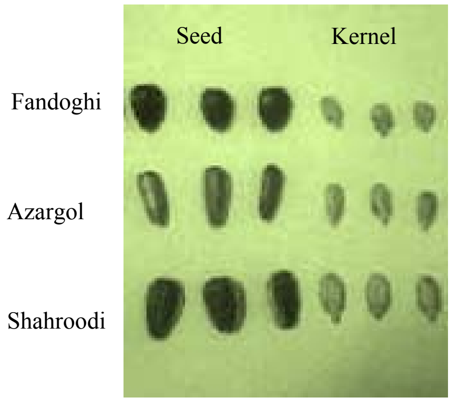

Fig. 1 The illustrated view of seed and kernel of three varieties of Iranian sunflower.

were collected. At first, the sunflower seeds were manually cleaned to get rid of foreign materials, broken and immature seeds. To prepare the samples of whole kernels, a part of the seeds were randomly separated and manually dehulled. The initial moisture content of seed and kernel samples were determined using the standard hot air oven method with a temperature setting of 105±1 ℃ for 24 h [1, 19-20]. To study the effect of sample's sizes in frictional properties, the samples of each variety were graded into three size categories (small, medium and large) using 5.5, 6.5 and 8 mesh sieves. To provide the seeds and kernels with the desired moisture content, sub-samples of both seeds and kernels of each variety and category of size, each weighing 0.5 kg, were randomly drawn from the bulk sample and dried (oven method at 75 ℃ for 2 h) or adding calculated quantity of water to the seeds.

2.2 Frictional Properties Determination

The static coefficient of friction, μ, for seed and its kernel was measured on five structural surfaces: aluminium, plywood, galvanized iron, polyethylene and rubber, which are common useable materials for handling and processing of grains, construction of storage and drying bins [9]. An open-ended galvanized iron cylinder, 100 mm diameter and 50 mm height, was filled with the sample of the desired moisture content and was placed on the adjustable tilting surface so that the cylinder dose not touch the surface (Fig. 2). The

Fig. 2 The illustrated view of open-ended galvanized iron cylinder that was used.

tilting surface with the cylinder resting on it was raised gradually with a screw device until the cylinder just started to slide down. Then the angle of tilt (α) was read from a scale [1, 11, 21-22]. The coefficient of friction (μ) was calculated from the following relationship [2]:

$$\mu = \tan \alpha \quad (1)$$

Both static and dynamic angles of repose were also investigated. The static angle of repose is the angle of produce with the horizontal plane at which the produce will stand when they are pilled. The dynamic angle of repose is more important than the static one as it arises in all cases where the bulk of the material is in the motion such as the movement of solids discharging from bins and hoppers. To determine the dynamic angle of repose, θ, a plywood box of 30×30×30 cm with a removable front panel was used. The box was filled with the samples at the desired moisture content, and the front panel was quickly removed, allowing the samples to flow and assume a natural slope [1, 23]. The empting angle of repose was calculated from the measurements of the vertical depth and radius of spread of the sample [1].

The static or filling angle of repose, β, was determined by using an open-ended cylinder of 15 cm diameter and 25 cm height. The cylinder was placed at the center of a circular plate with diameter of 35 cm. It was filled with the samples and was raised slowly until a cone formed on the circular plate [11]. The diameter (D) and height (H) of the cone were recorded. The filling angle of repose was calculated using the following formula [24]:

$$\beta = \mathrm{Arc}\tan(2H/D) \quad (2)$$

Some other researchers have also used this method [6, 22].

The experiments were conducted at least in five replications for each level of moisture content, variety, and category, and then the average values were calculated and reported. Average, minimum, maximum, standard deviations, correlation coefficients of dimensions and regression equations were computed using Microsoft Excel Software (2003).

3. Results and Discussion

3.1 Static Coefficients of Friction

The static coefficients of friction for studied varieties of sunflower seed and its kernel in three size categories on five structural surfaces including aluminium, plywood, galvanized iron, polyethylene and rubber against moisture content in the range of 3-14 % d.b are presented in Figs. 3-17, respectively.

3.1.1 Aluminium

Figs. 3-5 show the variation of static coefficient of friction for both seed and kernel of Fandoghi, Azargol and Shahroodi varieties on aluminium surface in all categories at studied moisture content (3% to 14% d.b.). As it can be found from these Figs, static coefficient of

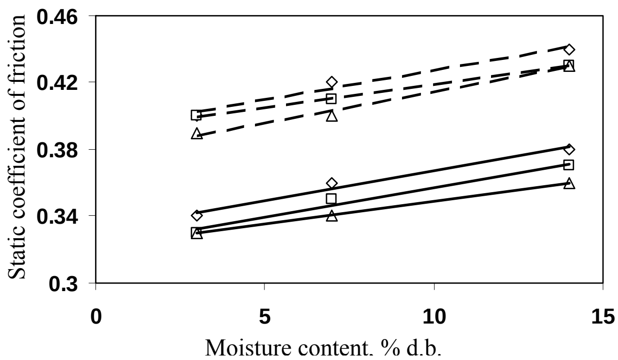

Fig. 3 The static coefficient of friction of Fandoghi sunflower seed and its kernel on aluminium surface as a function of moisture content and size (◊, large; □, medium; △, small; —, seed; - - -, kernel.).

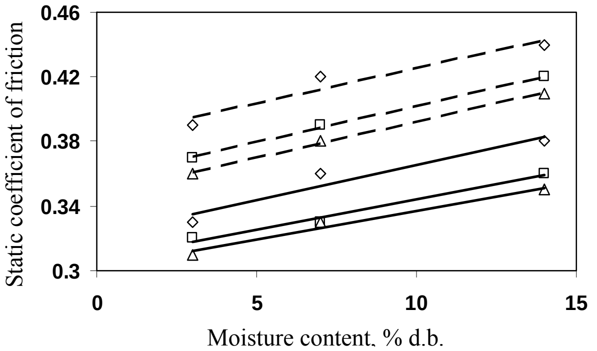

Fig. 4 The static coefficient of friction of Azar gol sunflower seed and its kernel on aluminium surface as a function of moisture content and size (◊, large; □, medium; △, small; —, seed; - - -, kernel.).

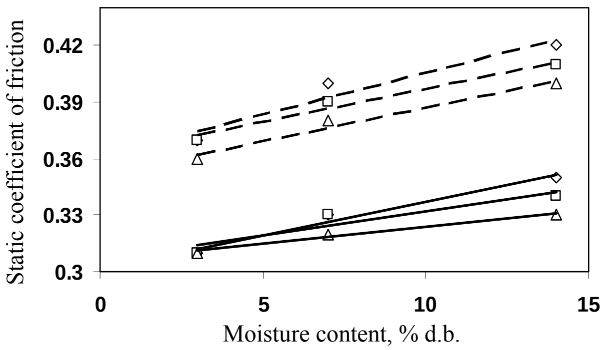

Fig. 5 The static coefficient of friction of Shahroodi sunflower seed and its kernel on aluminium Surface as a function of moisture content and size (◊, large; □, medium; △, small; —, seed; - - -, kernel.).

friction for each variety and category of sunflower seed and kernel increased linearly as the moisture content increased. For the studied varieties of sunflower seed, Fandoghi had maximum values of static coefficient of friction, 0.33-0.38, then Azargol in the range of 0.31-0.38 and the lowest values belonged to Shahroodi, 0.31-0.35. The similar order was also found among kernels, Fandoghi (0.39-0.44), Azargol (0.36-0.44) and Shahroodi (0.36-0.42). In addition, the values of static coefficients of friction of seed and its kernel increased with an increase in size. The values of the static coefficients of friction of seeds were less than those kernels in each variety, size and moisture level. Gupta and Das (1998) observed static coefficients of friction of sunflower seed and its kernel in the range of 0.38-0.49 and 0.40-0.66 on aluminium surface, respectively. Isik and Izil (2007) revealed that static coefficient of friction for sunflower seed increased linearly from 0.50 to 0.57 on aluminium surface when the moisture content increased from 10.06 to 27.06% d.b.

3.1.2 Plywood

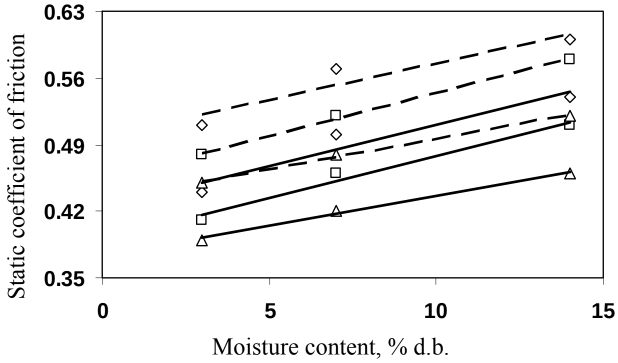

Fig. 6 The static coefficient of friction of Fandoghi sunflower seed and its kernel on plywood surface as a function of moisture content and size (◊, large; □, medium; △, small; —, seed; - - -, kernel.).

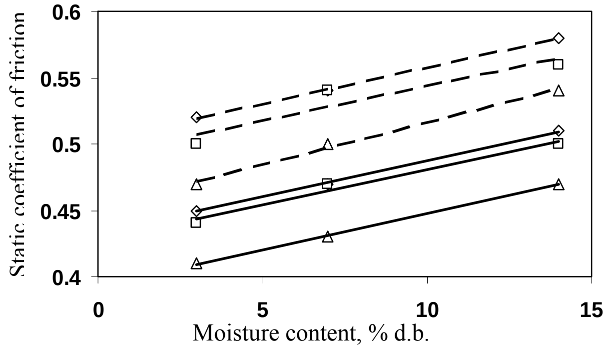

Fig. 7 The static coefficient of friction of Azar gol sunflower seed and its kernel on plywood surface as a function of moisture content and size (◊, large; □, medium; △, small; —, seed; - - -, kernel.).

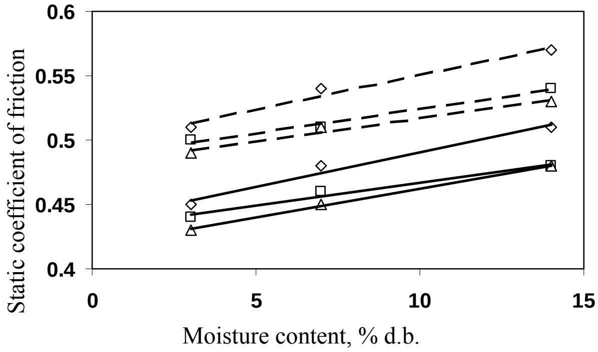

Fig. 8 The static coefficient of friction of Shahroodi sunflower seed and its kernel on plywood surface as a function of moisture content and size (◊, large; □, medium; △, small; —, seed; - - -, kernel.).

Experimental data of static coefficient of friction for the studied varieties of sunflower seed and its kernel on plywood surface in all categories at the investigated moisture levels are shown in Figs. 6-8. As it can be seen, the static coefficient of friction of sunflower seed and kernel on plywood surface increased linearly when the moisture content increased from 3 to 14% d.b, in all varieties and categories. Also, it can be found that the values of kernel are higher than seed for all runs. Furthermore, an increase in size revealed an increase in static coefficient of friction for both seed and kernel in all moisture contents and varieties. As shown in these Figs, the highest friction for sunflower seed was obtained for Fandoghi (0.39-0.54), then Shahroodi (0.43-0.51) and the lowest for Azargol (0.41-0.51). The results for kernels showed the maximum value of static coefficient in Fndoghi (0.45-0.6), then Azargol (0.47-0.58) and the minimum in Shahroodi (0.49-0.57). The static coefficient of friction for sunflower seed and its kernel on plywood surface were reported in the range of 0.48-0.60 and 0.49-0.74, respectively [1]. In comparison with obtained values of static coefficient of friction on aluminium surface, the values of friction on plywood surface were greater for both seed and kernel. The reason may attributes to rough surface of plywood compared with aluminum.

3.1.3 Galvanized Iron

The variation of static coefficient of friction for sunflower seed and its kernel on galvanized iron sheet at different levels of moisture content for all varieties and categories are shown in Figs. 9-11. The highest friction for seed was obtained for Fandoghi variety (0.37-0.45), followed by Azargol (0.35-0.42) and Shahroodi (0.35-0.42). The order for kernel was different as Fandoghi (0.43-0.52), Shahroodi (0.4-0.49) and Azargol (0.41-0.48). The results on galvanized iron sheet showed an increase in static coefficient of friction with increase of moisture content and size for both seed and kernel. Also, the values for kernel were higher than those for seed like results for previous surfaces (aluminium and plywood). Gupta and Das (1998) ranged the variation of static coefficient of friction for sunflower seed and kernel on galvanized iron sheet as

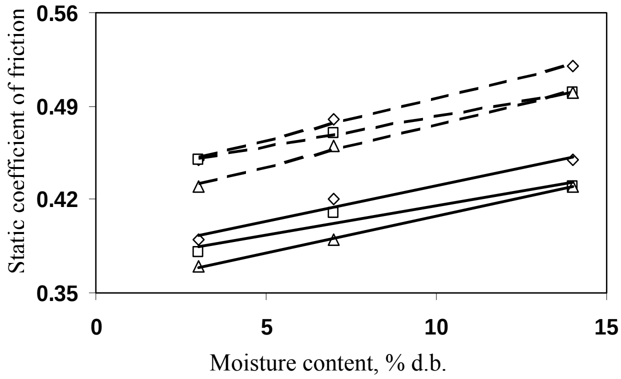

Fig. 9 The static coefficient of friction of Fandoghi sunflower seed and its kernel on galvanized iron sheet as a function of moisture content and size (◊, large; □, medium; △, small; —, seed; - - -, kernel.).

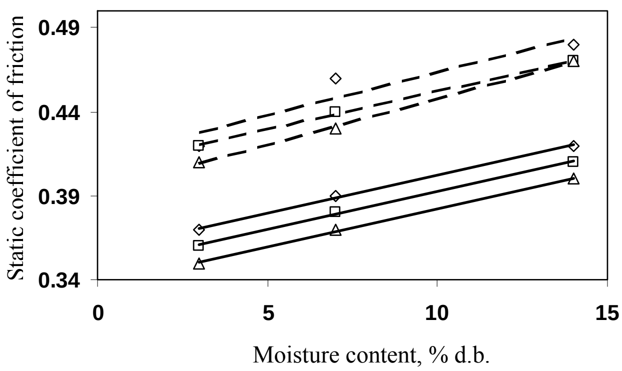

Fig. 10 The static coefficient of friction of Azar gol sunflower seed and its kernel on galvanized iron sheet as a function of moisture content and size (◊, large; □, medium; △, small; —, seed; - - -, kernel.).

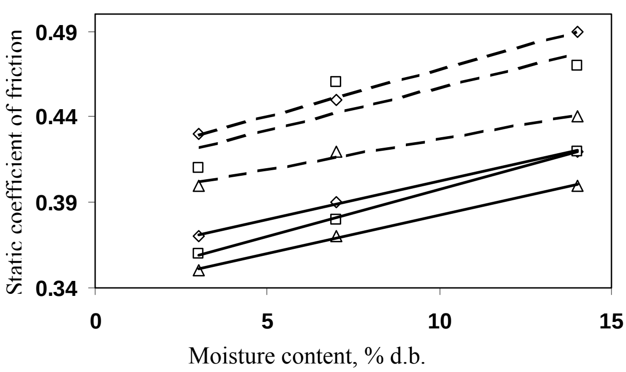

Fig. 11 The static coefficient of friction of Shahroodi sunflower seed and its kernel on galvanized iron sheet as a function of moisture content and size (◊, large; □, medium; △, small; —, seed; - - -, kernel.).

0.40-0.52 and 0.41-0.70, respectively. In addition, the range of variation of static coefficient of friction for sunflower seed on galvanized iron was reported from 0.53 to 0.59 [10]. As it can be found in Figs. 3-11, the values of static coefficient of friction on galvanized iron sheet were higher than those on aluminium surface but were lower than the values on plywood surface for both seed and kernel. The reason may be attributed to different roughness degree of applied surfaces. This agrees with the results for sunflower seed [1] and pistachio [11].

3.1.4 Polyethylene

Figs. 12-14 show the variation of static coefficient of friction with moisture content for all studied varieties and sizes of seed and kernel on polyethylene surface. As it can be seen in these Figs, static coefficient of friction increases linearly with an increase in moisture content and size for both seed and kernel. Also, the values of static coefficient of friction for kernel were higher than that seed in each category, variety and moisture level like results on previous surfaces. Among the studied varieties, the maximum range of static coefficient of friction for sunflower seed belonged to Azargol (0.37-0.50), then for Shahroodi (0.37-0.48), and the lowest value was obtained for Fandoghi (0.37-0.47). The greatest range of static coefficient of friction for kernel on polyethylene surface belonged to Azargol (0.43-0.56), then for Shahroodi variety (0.43-0.55) and the lowest one was found for Fandoghi (0.43-0.54). Despite an extensive use of polyethylene in various equipment and machines, no published literature was found on the detail of static coefficient of friction for seeds or grains on it. In comparison with pervious surfaces, the resulted values on the polyethylene surface were greater than the ones values for aluminium and galvanized iron, but they were lower than the values for plywood.

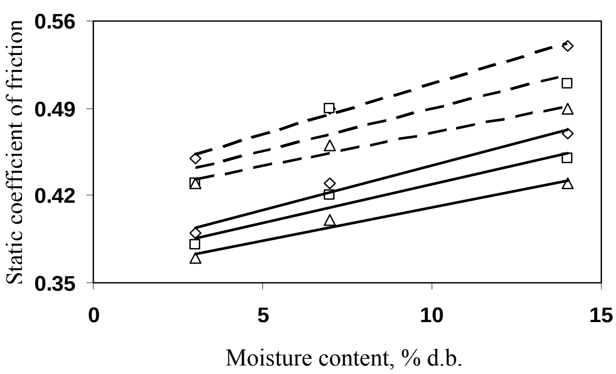

Fig. 12 The static coefficient of friction of Fandoghi sunflower seed and its kernel on polyethylene surface as a function of moisture content and size (◊, large; □, medium; △, small; —, seed; - - -, kernel.).

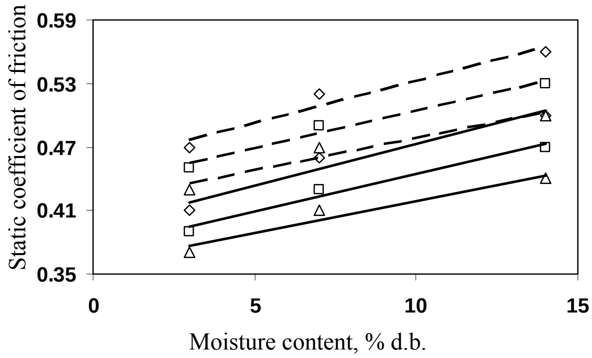

Fig. 13 The static coefficient of friction of Azar gol sunflower seed and its kernel on polyethylene surface as a function of moisture content and size (◊, large; □, medium; △, small; —, seed; - - -, kernel.).

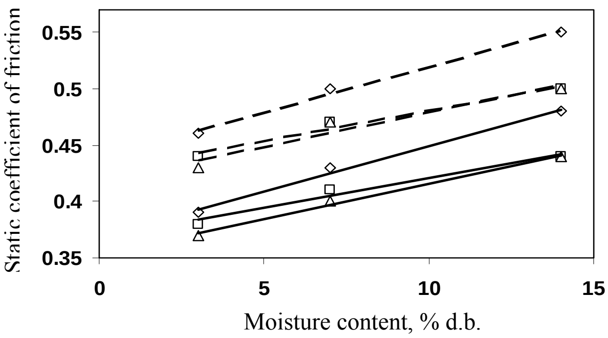

Fig. 14 The static coefficient of friction of Shahroodi sunflower seed and its kernel on polyethylene surface as a function of moisture content and size (◊, large; □, medium; △, small; —, seed; - - -, kernel.).

3.1.5 Rubber

The results of static coefficient of friction for studied varieties of sunflower seed and its kernel in all categories at different moisture levels are shown in Figs. 15-17. The values of static coefficient of friction increased as moisture content and size increased, like results of the pervious mentioned surfaces. Also, kernels revealed higher values in comparison with the seeds. The comparison of resulted values in the case of seed showed that Fandoghi (0.48-0.59) was the greatest, and after Azargol (0.45-0.56), the lowest values belonged to Shahroodi (0.45-0.54). The resulted values of kernels for Fanoghi, Azargol and Shahroodi were ranged as 0.55-0.66, 0.5-0.64 and 0.5-0.59, respectively. Gupta and Das (1998) revealed static coefficients of friction for sunflower seed and kernel in the range of 0.51-0.65 and 0.53-0.78 on rubber surface, respectively. Isik and Izil (2007) found that static coefficient of friction for sunflower seed increased linearly from 0.55 to 0.65 on rubber surface as the moisture content increased from 10.06 to 27.06%.

As it can be found in Figs. 3-17, static coefficient of friction for both seed and kernel on five studied surfaces increased linearly as moisture content increased from 3 to 14% in all varieties and sizes. This 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 [9], almond nut [25], pistachio nut and kernel [11], caper fruit [26] and barbunia bean [27]. Also, the results showed that the highest value of static coefficient of friction for both seed and kernel was on the rubber surface, followed by plywood, polyethylene, galvanized iron, and finally aluminium surfaces. In addition, the static coefficients of friction for sunflower seed were lower than that of sunflower kernel at similar moisture content of the samples and on the same surfaces. The higher coefficients for sunflower kernel might be attributed to its lower sphericity of shape compared with that of sunflower seed.

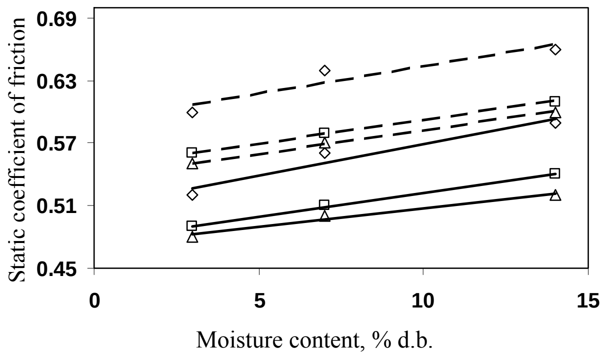

Fig. 15 The static coefficient of friction of Fandoghi sunflower seed and its kernel on rubber surface as a function of moisture content and size (◊, large; □, medium; △, small; —, seed; - - -, kernel.).

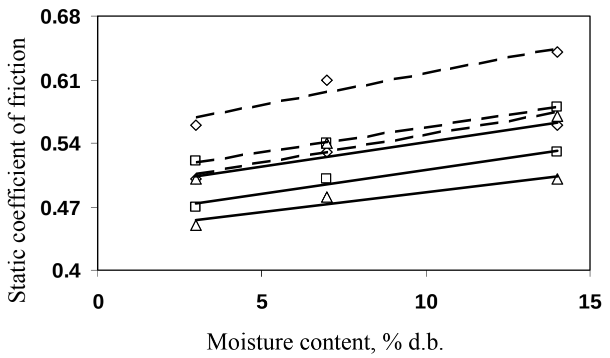

Fig. 16 The static coefficient of friction of Azar gol sunflower seed and its kernel on rubber surface as a function of moisture content and size (◊, large; □, medium; △, small; —, seed; - - -, kernel.).

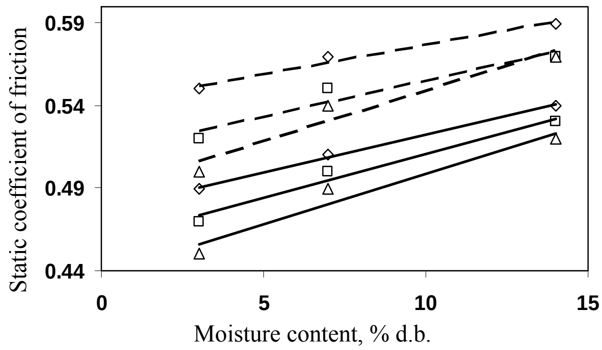

Fig. 17 The static coefficient of friction of Shahroodi sunflower seed and its kernel on rubber surface as a function of moisture content and size (◊, large; □, medium; △, small; —, seed; - - -, kernel.).

Tables 1 and 2 show the regression models and coefficients of determination (R^2) achieved by fitting the experimental data of static coefficient of friction for each sunflower seed and kernel variety as a function of moisture content and size. The relationship between static coefficient of friction and moisture content for studied varieties (seed and its kernel) was a positive linear relation. Similar trends have been reported for cumin seed [7], sunflower seed [1], gram [21], cotton seed [24], millet [9], and Jatropha seed [22]. However, several researchers observed a nonlinearly relationship [27-29].

Table 1 Regression models and coefficients of determination achieved for static coefficient of friction of studied varieties of sunflower seed as a function of moisture content (3-14% d.b.) and size.

Variety	Size						
	Surface	Large	R^2	Medium	R^2	Small	R^2
Fandoghi	Aluminium	μ = 0.0035Mc+ 0.3316	0.98	μ = 0.0035Mc + 0.3216	0.98	μ = 0.0027Mc+ 0.3214	0.99
	Plywood	μ = 0.0087Mc + 0.4237	0.93	μ = 0.0089Mc + 0.3890	0.98	μ = 0.0063Mc + 0.3730	0.99
	Galvanized iron	μ = 0.0053Mc + 0.3774	0.98	μ = 0.0044Mc + 0.3718	0.93	μ = 0.0055Mc + 0.3528	0.99
	Polyethylene	μ = 0.0071Mc + 0.3732	0.98	μ = 0.0061Mc + 0.3676	0.94	μ = 0.0053Mc + 0.3574	0.98
	Rubber	μ = 0.0061Mc + 0.5076	0.94	μ = 0.0045Mc + 0.4772	0.99	μ = 0.0035Mc + 0.4716	0.98
Azargol	Aluminium	μ = 0.0044Mc + 0.3218	0.93	μ = 0.0037Mc + 0.3070	0.98	μ = 0.0035Mc + 0.3016	0.98
	Plywood	μ = 0.0055Mc + 0.4328	0.99	μ = 0.0053Mc + 0.4274	0.98	μ = 0.0055Mc + 0.3928	0.99
	Galvanized iron	μ = 0.0045Mc + 0.3572	0.99	μ = 0.0045Mc + 0.3472	0.99	μ = 0.0045Mc + 0.3372	0.99
	Polyethylene	μ = 0.0079Mc + 0.3934	0.95	μ = 0.0071Mc + 0.3732	0.98	μ = 0.0061Mc + 0.3576	0.94
	Rubber	μ = 0.0053Mc + 0.4874	0.98	μ = 0.0053Mc + 0.4574	0.98	μ = 0.0044Mc + 0.4418	0.93
Shahroodi	Aluminium	μ = 0.0035Mc + 0.3016	0.98	μ = 0.0026Mc + 0.3060	0.88	μ = 0.0018Mc + 0.3058	0.98
	Plywood	μ = 0.0053Mc + 0.4374	0.98	μ = 0.0035Mc + 0.4316	0.98	μ = 0.0045Mc + 0.4172	0.99
	Galvanized iron	μ = 0.0045Mc + 0.3572	0.99	μ = 0.0055Mc + 0.3428	0.99	μ = 0.0045Mc + 0.3372	0.99
	Polyethylene	μ = 0.0081Mc + 0.3688	0.99	μ = 0.0053Mc + 0.3674	0.98	μ = 0.0063Mc + 0.3530	0.99
	Rubber	μ = 0.0045Mc + 0.4772	0.99	μ = 0.0053Mc + 0.4574	0.98	μ = 0.0061Mc + 0.4376	0.94

Table 2 Regression models and coefficients of determination achieved for static coefficient of friction of studied varieties of sunflower kernel as a function of moisture content (3 – 14% d.b.) and size.

Variety	Size						
	Surface	Large	R^2	Medium	R^2	Small	R^2
Fandoghi	Aluminium	μ = 0.00354Mc + 0.3916	0.98	μ = 0.0027Mc + 0.3914	0.99	μ = 0.0037Mc + 0.377	0.98
	Plywood	μ = 0.0077Mc + 0.4981	0.89	μ = 0.009Mc + 0.4544	0.99	μ = 0.0063Mc + 0.433	0.99
	Galvanized iron	μ = 0.0063Mc + 0.433	0.99	μ = 0.0045Mc + 0.4372	0.99	μ = 0.0063Mc + 0.413	0.99
	Polyethylene	μ = 0.0081Mc + 0.4288	0.99	μ = 0.0068Mc + 0.4225	0.82	μ = 0.0053Mc + 0.4174	0.98
	Rubber	μ = 0.0052Mc + 0.592	0.89	μ = 0.0045Mc + 0.5472	0.99	μ = 0.0045Mc + 0.5372	0.99
Azargol	Aluminium	μ = 0.0044Mc + 0.3818	0.93	μ = 0.0045Mc + 0.3572	0.99	μ = 0.0045Mc + 0.3472	0.99
	Plywood	μ = 0.0055Mc + 0.5028	0.99	μ = 0.0052Mc + 0.492	0.89	μ = 0.0063Mc + 0.453	0.99
	Galvanized iron	μ = 0.0052Mc + 0.412	0.89	μ = 0.0045Mc + 0.4072	0.99	μ = 0.0055Mc + 0.3928	0.99
	Polyethylene	μ = 0.0079Mc + 0.4534	0.95	μ = 0.0071Mc + 0.4332	0.98	μ = 0.0061Mc + 0.4176	0.94
	Rubber	μ = 0.0069Mc + 0.5478	0.92	μ = 0.0055Mc + 0.5028	0.99	μ = 0.0061Mc + 0.4876	0.94
Shahroodi	Aluminium	μ = 0.0044Mc + 0.3618	0.93	μ = 0.0035Mc + 0.3616	0.98	μ = 0.0035Mc + 0.3516	0.98
	Plywood	μ = 0.0053Mc + 0.4974	0.98	μ = 0.0037Mc + 0.487	0.98	μ = 0.0035Mc + 0.4816	0.98
	Galvanized iron	μ = 0.0055Mc + 0.4128	0.99	μ = 0.005Mc + 0.4067	0.75	μ = 0.0035Mc + 0.3916	0.98
	Polyethylene	μ = 0.0081Mc + 0.4388	0.99	μ = 0.0053Mc + 0.4274	0.98	μ = 0.0061Mc + 0.4176	0.94
	Rubber	μ = 0.0035Mc + 0.5416	0.98	μ = 0.0044Mc + 0.5118	0.93	μ = 0.0061Mc + 0.4876	0.94

3.2 Emptying Angle of Repose

The experimental results of empting angle of repose for studied varieties of sunflower seed and its kernel at different moisture levels and size categories (3-14 % d.b) are shown in Figs. 18-20, respectively. The emptying angle of repose increased linearly with an increase in moisture content. It attributes to the higher moisture content which cause higher stickness of seeds surfaces and then lowers easiness of rolling seeds on each other [11]. Among the studied varieties of seed, Shahroodi had maximum value for empting angle of repose (28.55-33.8°) then Azargol in the range of 25.64-31.74° and the lowest values belonged to Fandoghi (26.65 -29.76°). In addition, this order was seen among kernels: Shahroodi (20.58-23.21°), Azargol (19.35-22.16°) and Fandoghi (19.42-21.49°). Empting angle of repose values of small sizes were higher than the values for big sizes in all varieties and moisture levels for both seed and kernel. This can be due to the higher moisture content and higher sphericity of the shape for the samples of big size (seed and kernel) in comparison with small size of them that permits the easiness of sliding of seeds on each other and causes a higher value for radius of spread of the sample (seed or kernel). Gupta and Das (1997) reported the range of emptying angle of repose for sunflower seed and its kernel 33-41° and 26-38°, respectively when moisture content increased from 4 to 20% d.b. A linear increase in empting angle of repose when the seed moisture content increases has also been noted for karingda seeds, cumin seed, chick pea seeds, quinoa seeds, edible squash, fenugreek, sorghum seeds, and Coskuner and Karababa (2007) for flaxseed [7, 15, 16, 19, 27, 30, 31]. Aviara *et al.* (1999) and Bart-Plange and Baryeh (2003), however, found that the emptying angle of repose increase non-linearly with increase in moisture content for guna seeds and cocoa beans, respectively. These behaviors could be due to existing differences in surface roughness of grains or seeds.

The equations representing relationship between emptying angle of repose of sunflower seeds and their kernels with moisture content for each sunflower variety and category are presented in Table 3. There was a linear relationship with very high correlation (R^2) between emptying angle of repose and moisture content for all sunflower varieties.

3.3 Filling Angle of Repose

Figs. 21-23 show the variation of filling angle of repose against moisture content for all varieties and sizes of sunflower seed and kernel. Filling angle of repose increased linearly with an increase in moisture content for both seed and kernel. It could be attributed

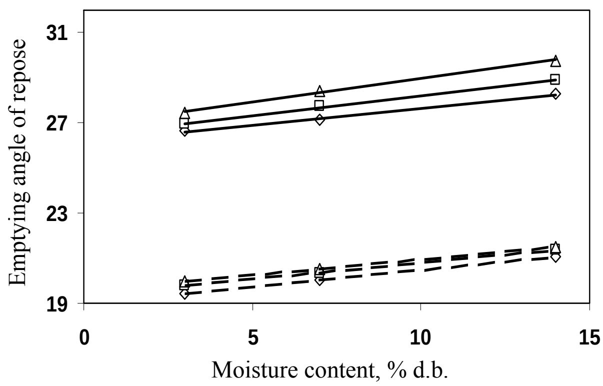

Fig. 18 The emptying angle of repose of Fandoghi sunflower seed and its kernel as a function of moisture content and size (◊, large; □, medium; △, small; —, seed; - - -, kernel.).

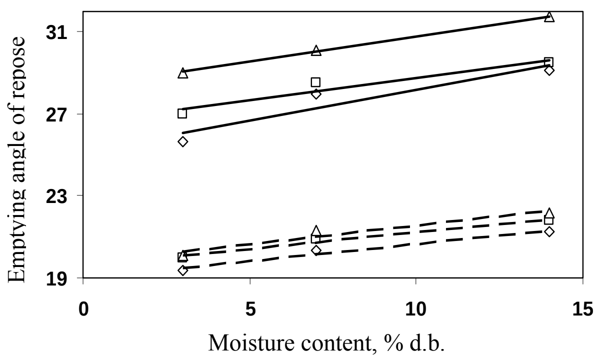

Fig. 19 The emptying angle of repose of Azar gol sunflower seed and its kernel as a function of moisture content and size (◊, large; □, medium; △, small; —, seed; - - -, kernel.).

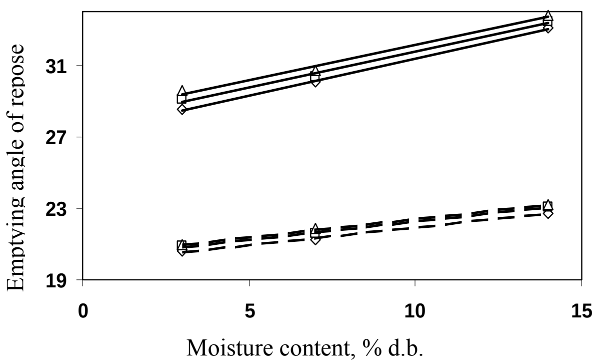

Fig. 20 The emptying angle of repose of Shahroodi sunflower seed and its kernel as a function of moisture content and size (◊, large; □, medium; △, small; —, seed; - - -, kernel.).

Table 3 Regression models and coefficients of determination achieved for emptying angle of repose of studied varieties of sunflower seed and its kernel as a function of moisture content (3-14% d.b.) and size.

Variety	Size	seed	R^2	kernel	R^2
Fandoghi	Large	θ = 0.1494Mc + 26.172	0.99	θ = 0.1473Mc + 18.979	1
	Medium	θ = 0.1776Mc + 26.436	0.99	θ = 0.1397Mc + 19.386	0.99
	Small	θ = 0.2061Mc + 26.904	0.99	θ = 0.1365Mc + 19.578	1
Azargol	Large	θ = 0.299Mc + 25.188	0.88	θ = 0.1684Mc + 18.98	0.96
	Medium	θ = 0.2132Mc + 26.624	0.93	θ = 0.1592Mc + 19.626	0.97
	Small	θ = 0.24614Mc + 28.324	0.99	θ = 0.1795Mc + 19.761	0.93
Shahroodi	Large	θ = 0.4139Mc + 27.256	0.99	θ = 0.1976Mc + 19.933	0.99
	Medium	θ = 0.4019Mc + 27.745	0.99	θ = 0.2029Mc + 20.243	0.99
	Small	θ = 0.3905Mc + 28.233	0.99	θ = 0.205Mc + 20.36	0.99

Table 4 Regression models and coefficients of determination achieved for filling angle of repose of studied varieties of sunflower seed and its kernel as a function of moisture content (3-14% d.b.) and size.

Variety	Size	seed	R^2	kernel	R^2
Fandoghi	Large	θ = 0.2027Mc + 13.175	0.99	θ = 0.2105Mc + 11.679	0.94
	Medium	θ = 0.279Mc + 13.731	0.93	θ = 0.2427Mc + 12.881	0.98
	Small	θ = 0.2732Mc + 14.774	0.95	θ = 0.2339Mc + 14.219	0.99
Azargol	Large	θ = 0.2444Mc + 13.845	0.91	θ = 0.2892Mc + 11.823	0.91
	Medium	θ = 0.276Mc + 14.146	0.89	θ = 0.2792Mc + 13.25	0.84
	Small	θ = 0.2971Mc + 15.047	0.91	θ = 0.256Mc + 14.429	0.87
Shahroodi	Large	θ = 0.2156Mc + 16.546	0.96	θ = 0.2063c + 15.236	0.93
	Medium	θ = 0.2239Mc + 17.389	0.93	θ = 0.0.161Mc + 16.672	0.80
	Small	θ = 0.2029Mc + 18.583	0.91	θ = 0.2166Mc + 17.394	0.87

to the increase of the sphericity of shape with increasing moisture, allowing them to slide and roll over on each other easily. As shown in these Figs, the highest filling angle of repose for sunflower seed was obtained for Shahroodi (17.01-21.28°), then Azargol (14.27-18.99°) and the lowest for Fandoghi (13.69-18.46°). The results for kernels showed the maximum range of values in Shahroodi (15.62-20.38°), then Azargol (12.32-17.79°) and the minimum in Fandoghi (12.09-17.45°). Similar to the values of empting angle of repose, filling angle of repose values of small sizes were higher than the values of big sizes in all varieties and moisture levels for both seed and kernel. This can be due to higher moisture content and higher sphericity of shape for category of big sizes (seed and kernel) in comparison with small sizes of them that allows the easiness of sliding of seeds on each other and causes a higher value for diameter of spread of the sample (seed or kernel). Despite extensive researches on the properties of sunflower seed and its kernel, no published literature was found on the detail of their filling angle of repose. However, several researches carried out on measuring of filling angle of repose for other produce such as cocoa beans [32], caper seed [33]and pistachio nut and its kernel [11].

The obtained equations of linear regression are also presented in Table 4, together with the coefficient of determination for all three varieties. There were positive linear relationships with very high correlation (R^2) between filling angle of repose and moisture content for all varieties and categories.

4. Conclusions

In this paper, frictional properties of sunflower seed and its kernel including emptying (dynamic) and filling

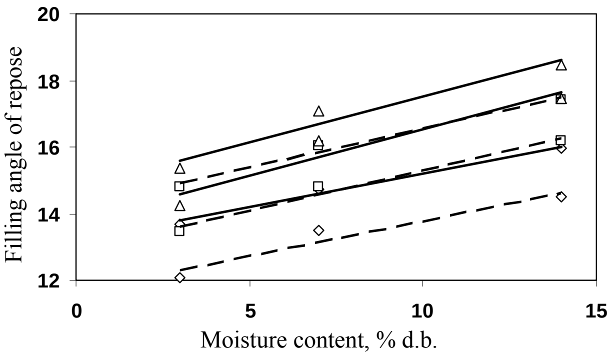

Fig. 21 The filling angle of repose of Fandoghi sunflower seed and its kernel as a function of moisture content and size (◊, large; □, medium; △, small; —, seed; - - -, kernel.).

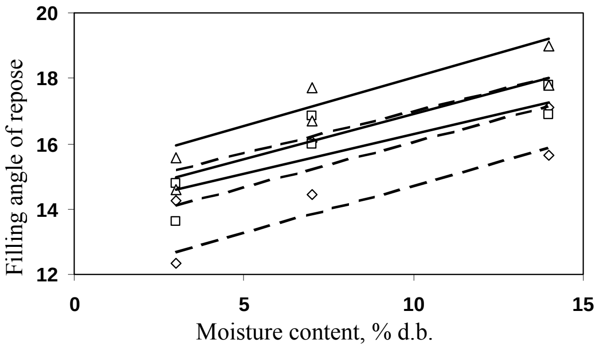

Fig. 22 The filling angle of repose of Azar gol sunflower seed and its kernel as a function of moisture content and size (◊, large; □, medium; △, small; —, seed; - - -, kernel.).

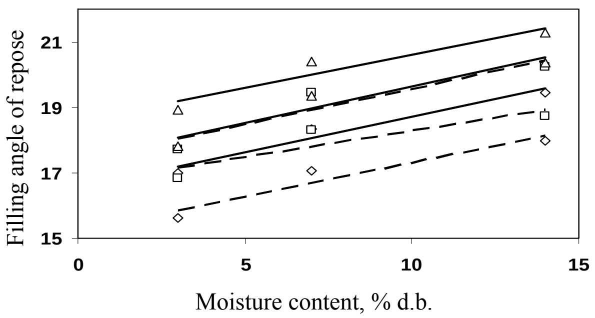

Fig. 23 The filling angle of repose of Shahroodi sunflower seed and its kernel as a function of moisture content and size (◊, large; □, medium; △, small; —, seed; - - -, kernel.).

(static) angle of repose and static coefficient of friction on five structural surfaces (aluminium, plywood, galvanized iron, polyethylene and rubber) were investigated as a function of moisture content, size and variety. The following are concluded:

(1) Static coefficient of friction for both seed and kernel on five studied surfaces increased linearly as moisture content increased from 3 to 14% in all varieties and sizes.

(2) The highest static coefficient of friction for both seed and kernel was obtained on the rubber surface, followed by plywood, polyethylene, galvanized iron, and finally aluminium surfaces. In addition, the static coefficients of friction for sunflower seed were lower than that of sunflower kernel at similar moisture contents of the samples and the same surfaces.

(3) The emptying angle of repose increased linearly with an increase in moisture content. In addition, empting angle of repose values of small size were higher than the values for big sizes in all varieties and moisture levels for both seed and kernel.

(4) The filling angle of repose increased linearly with an increase in moisture content for both seed and kernel. Also, filling angle of repose values of small sizes was higher than the values for big sizes in all varieties and moisture levels for both seed and kernel. Among all varieties, the highest filling angle of repose for sunflower seed and its kernel was obtained for Shahroodi then Azar gol and the lowest for Fandoghi.

(5) The emptying angle of repose assumed higher values than the filling angle of repose for all varieties and categories at all moisture contents.

Acknowledgments

The authors would like to thank Ferdowsi University of Mashhad for providing the laboratory facilities and financial support.

References

[1] R.K. Gupta, S.K. Das, Physical properties of sunflower seeds, Journal of Food Engineering Research 66 (1997) 1-8.

[2] N.N. Mohsenin, Physical Properties of Plant and Animal Materials, 2nd Revised and Updated Edition, Gordon and Breach Science Publishers, New York, 1986.

[3] P.J. Lawton, Coefficients of friction between cereal grain and various silo wall materials, Journal of Agricultural Engineering Research 25 (1980) 75-86.

[4] J.H. Chung, L.R. Verma, Determination of friction coefficients of beans and peanuts, Trans. ASAE 32 (1989) 745-750.

[5] K. Oje, E.C. Ugbor, Some physical properties of oil bean seed, Journal of Agricultural Engineering Research 50 (1991) 305-313.
[6] D.C. Joshi, S.K. Das, R.K. Mukherjee, Physical properties of pumpkin seeds, Journal of Agricultural Engineering Research 54 (1993) 219-229.
[7] K.K. Singh, T.K. Goswami, Physical properties of cumin seed, Journal of Agricultural Engineering Research 64 (1996) 93-98.
[8] V. Chandrasekar, R. Visvanathan, Physical and thermal properties of coffee, Journal of Agricultural Engineering Research 73 (1999) 227-234.
[9] E.A. Baryeh, Physical properties of millet, Journal of Food Engineering Research 51 (2002) 39-46.
[10] E. Isik, N. Izli, Physical properties of sunflower seeds, Journal of Agricultural Engineering Research 8 (2007) 677-686.
[11] M.A. Razavi, A. Rafe, T. Mohammadi moghaddam, A. Mohammad Amini, Physical properties of pistachio nut and its kernel as a function of moisture content and variety, Journal of Food Engineering Research 56 (2007) 89-98.
[12] R.C. Pradhan, S.N. Naik, N. Bhatnagar, S.K. Swain, Some physical properties of Karanja Kernel, Journal of Indian Crops and Products 28 (2008) 155-161.
[13] L.A.O. Ogunjimi, N.A. Aviara, O.A. Aregbesola, Some physical properties of Locust bean seed, Journal of Food Engineering Research 55 (2002) 95-99.
[14] K. Sacilik, R. Ozturk, R. Keskin, Some physical properties of Hemp seed, Biosystem Engineering 86 (2003) 191-198.
[15] C. Vilche, M. Gely, E. Santall, Physical properties of quinoa seeds, Biosystem Engineering 86 (2003) 59-65.
[16] M. Paksoy, C. Aydin, Some physical properties of Edible squash seeds, Journal of Food Engineering Research 65 (2004) 225-231.
[17] F. Ozdemir, I. Akinci, Physical and nutritional properties of four major commercial Turkish hazelnut varieties, Journal of Food Engineering Research 63 (2004) 341-347.
[18] O.J. Oyelade, P.O. Odugbenro, A.O. Abioye, N.L. Raji, Some physical properties of African star apple (*Chrysophyllum alibidum*) seeds, Journal of Food Engineering Research 67 (2005) 435-440.
[19] E. Altuntas, M. Yildiz, Effect of moisture content on some physical and mechanical properties of faba bean (*Vicia faba* L.) grains, Journal of Food Engineering Research 78 (2007) 174-183.
[20] Y. Coskuner, E. Karababa, Some physical properties of flaxseed (*Linum usitatissimum* L.), Journal of Food Engineering Research 78 (2007) 1067-1073.
[21] S.K. Dutta, V.K. Nema, R.K. Bhardwaj, Physical properties of gram, Journal of Agricultural Engineering Research 39 (1988) 259-268.
[22] D.K. Garnayak, R.C. Pradhan, S.N. Naik, N. Bhatnagar, Moisture-dependent physical properties of Jatropha seed (*Jatropha curcas* L.), Indian Crops Products 27 (2008) 123-129.
[23] E.A. Baryeh, B.K. Mangope, Some physical properties of QP-38 variety pigeon pea, Journal of Food Engineering Research 56 (2001) 59-65.
[24] C. Ozarslan, Physical properties of cotton seed, Biosystem Engineering 83 (2002) 169-174.
[25] N.A. Aviara, M.I. Geandzang, M.A. Hague, Physical properties of guna seeds, Journal of Agricultural Engineering Research 73 (1999) 105-111.
[26] A. Sessiz, R. Esgici, S. Kizil, Moisture-dependent physical properties of caper (*Capparis* ssp.) fruit, Journal of Food Engineering Research 79 (2007) 1426-1431.
[27] M. Konak, K. Carman, C. Aydin, Physical properties of Chick pea seeds, Biosystem Engineering 82 (2002) 73-78.
[28] S. Kalimullah, J.J. Gunasekar, Moisture-dependent physical properties of Arecanut kernels, Biosystem Engineering 82 (2002) 331-338.
[29] C. Aydin, Physical properties of Almond nut and kernel, Journal of Food Engineering Research 60 (2003) 315-320.
[30] S.H. Suthar, S.K. Das, Some physical properties of karingda (*Citrullus lanatus* (Thumb) Mansf) seeds, Journal of Agricultural Engineering Research 65 (1996) 15-22.
[31] G. Mwithiga, M. MasikaSifuna, Effect of moisture content on the physical properties of three varieties of sorghum seeds, Journal of Food Engineering Research 75 (2006) 480-486.
[32] A. Bart-Plange, E.A. Baryeh, The physical properties of Category B cocoa beans, Journal of Food Engineering Research 60 (2003) 219-227.
[33] F. Ozguven, V. Kubilay, Some physical, mechanical and aerodynamic properties of pine (*Pinus pinea*) nuts, Journal of Food Engineering Research 68 (2004) 191-196.
[34] M. Cetin, Physical properties of barbunia bean (*Phaseolus vulgaris* L. cv. 'Barbunia') seed, Journal of Food Engineering Research 80 (2007) 353-358.