Note: Physical Properties of High Oleic Sunflower Seeds

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High oleic sunflower seeds evaluated at 5.6% moisture content (dry basis) showed a surface area of approximately 102.41 mm^2 with an average length, width, thickness and unit mass of 11.526, 5.008 and 2.809 mm and 0.055 g, respectively. Corresponding values for the kernel were 8.802, 3.897 and 1.907 mm and 0.036 g. The mean equivalent diameter and sphericity of the seeds were 5.49 mm and 0.46, respectively, while corresponding values for the kernels were 4.01 mm and 0.44. True density increased, within a moisture range of 4–26% d.b., between 652 and 708 kg/m^3 for the seed, between 1015 and 1057 kg/m^3 for the kernel and between 636 and 760 kg/m^3 for the hull. The bulk density decreased from 386 to 373 kg/m^3 for seeds and from 260 to 220 kg/m^3 for hulls and increased from 535 to 553 kg/m^3 for the kernels. Porosity increased from 41.2 to 47.1% in seeds, from 47.2 to 47.7% in kernels and from 59.2 to 70.1% in hull. Terminal velocity of seeds increased with moisture content between 2.8 and 5.5 m/s for seed, between 1.8 and 3.8 m/s for kernel and between 1.1 and 1.9 m/s for hull. Drag coefficient decreased when moisture content increased and varied between 4.7 and 1.4 in seed and between 12.5 and 3.1 in kernel. Angle of repose increased with moisture content between 25 and 46° in seeds, between 35 and 55° in kernels and between 49 and 66° in hull on different surfaces and resulted higher for hull and kernel than for seed. The coefficient of static friction was higher for kernel than that for seed and hull and also was higher on wood (with grain perpendicular to the direction of the motion) and lower on acrylic and galvanised iron. This coefficient increased with moisture content from 0.23 to 0.50 for seed, from 0.37 to 0.69 for kernel and from 0.31 to 0.60 for hull. All engineering properties evaluated showed a linear dependence with moisture content, leading to simple and accurate formulae, adequate to predict their variation in the range of moisture considered.

Key Words: sunflower seeds, physical properties, engineering

INTRODUCTION

Sunflower (*Helianthus annuus* L.) hybrid varieties are almost exclusively used for commercial oilseed production. Native sunflower oil is mainly used for human consumption since it contains a large amount of essential linoleic acid (w6 C18:2) which gives the sunflower seed oil a high nutritional value. In addition, 'high oleic' varieties have been obtained by chemical mutagenesis (Garcés et al., 1989) accumulating oleic acid (w 9.C18:1) up to 85% in the seed oil. This oil is nutritionally desired to increase the mono-unsaturated level in the diet. The use of this oil from a modified grain is so widespread that the researchers consider that this differential oil from high oleic sunflower will dominate the type of sunflower to be cultured (Fitch Haumann, 1998). The current problem is the relatively low volume of this grain produced, while it is considered as a special oilseed. By all means, the knowledge of the behaviour of these modified grains, specially during post-harvest processing, is not yet available and the proper design or selection of handling, drying, dehulling and extraction equipment is not possible without specific properties.

The knowledge of the morphology and size distribution of high oleic sunflower seeds is essential for the adequate design of the equipment for cleaning, grading and separation. Gravimetric properties are useful for the design of equipment related to aeration, drying, storage and transport (Kachru et al., 1994). Bulk density determines the capacity of storage and transport systems while true density is useful for separation equipment; porosity of the mass of grains determines the resistance to airflow during aeration and drying of grains.

Aerodynamic properties such as terminal velocity and drag coefficient are useful for air conveying or pneumatic separation of materials in such a way that when air velocity is higher then terminal velocity lifts the particles.

The frictional properties as the angle of repose and the coefficient of external friction are recognised by engineers as important properties concerned with rational design of grain bins and other storage structures

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whose operation is influenced by the compressibility and flow behaviour of materials (Kachru et al., 1994).

The objective of this study was to contribute to the knowledge of high oleic sunflower seeds, to improve and adequate the post-harvest operations and equipment through the investigation of some moisture-dependent physical properties as size distribution, morphology, gravimetric, aerodynamic and frictional properties of seeds, kernels and hulls. This knowledge is important to minimise the effect of an inadequate use of equipment that could affect the quality of the seed and its oil, and/or originates higher operation costs.

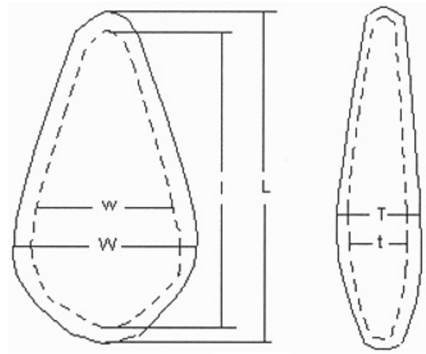

Figure 1. Characteristic dimensions of high oleic sunflower seed and kernel. The dotted lines represent the inner kernel. *L*, *l* – length; *W*,*w* – width; *T*, *t* – thickness.

MATERIAL AND METHODS

Samples

Trisum 568 (Mycoyen-Morgan), a striated high oleic genotype of sunflower (*Helianthus annuus* L.) was selected to carry out this study. Ten bulk samples, each consisting of 5 kg of seed, were procured from 1998/99 harvest season from Oriente, Coronel Dorrego, Argentina, after 80 days of physiological maturity stage. The seeds were manually cleaned for foreign matter, broken and immature seeds. The initial moisture content of the seeds was about 13% d.b. Whole kernels and hull were both obtained from manual dehulling of the seeds. Seeds, kernels and hulls were packed separately in double-layered low-density polyethylene bags sealed and stored at low temperature (5 °C). For each test, the required amount of seed and kernel was taken out and allowed to warm up for approximately 2 h (Joshi et al., 1993). To evaluate the effect of moisture content of the sample on some of its physical properties, samples of seeds, kernels and hulls at the desired moisture levels were prepared by adding calculated amounts of distilled water and sealing in separate polyethylene bags. The samples were kept at low temperature in a refrigerator to avoid the growth of microorganisms. Before starting a test, the required quantity of the sample was taken out of the refrigerator and was allowed to warm up to room temperature (Shepherd and Bhardwaj, 1986).

Methods

The physical properties of the seeds were determined at the following moisture contents: 4.2, 8.6, 14.3, 21.1 and 26.4% d.b. in seeds; 5.0, 8.1, 13.2, 19.3 and 23.8% d.b. in kernels and 7.5, 14.4, 18.2 and 23.2% d.b. in hulls. Moisture content was determined by oven drying method (ASAE Standard, 1999).

Spatial Dimensions, Size, Sphericity, Surface Area

In order to determine the size and shape of the seed and its components, three sub-samples, each weighing 0.5 kg were randomly taken from the bulk sample. From each of three 0.5 kg sub-samples, 200 seeds were picked out and the 600 seeds thus obtained were mixed thoroughly. Finally, 100 seeds were randomly selected and labelled for easy identification (Dutta et al., 1988, Joshi et al., 1993). For each individual seed and its kernel, three principal dimensions (Gupta and Das, 1997), namely length, width and thickness were measured using a micrometer (least count 0.01 mm). Because of the irregular shape of the sunflower seed and kernel, only the greatest values of both, width and thickness were taken (Figure 1). Each seed and kernel were weighed on a precision electronic balance reading to 0.001 g. The equivalent diameter (D_e) and sphericity (ϕ) for both seed and kernel were determined using the following expressions according to Mohsenin (1978):

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

$$\phi = (\mathrm{LWT})^{1/3}/L \quad (2)$$

where L, W and T are length, width and thickness respectively.

Seeds were classified into three categories, namely, large, medium and small, using ASTM sorting sieves. This classification simplifies the operation conditions (storage, drying, dehulling). The distribution of seeds by number as well as by mass for each category of size was determined. Relationships between seed and kernel dimensions were also established using regression analysis.

High oleic sunflower seeds tend to have the shape of a cone-elliptical cylinder with a major axis significantly greater than the intermediate axis. The seeds may therefore be described as being oval in shape. The surface area (S) was determined according to two different empirical relationships developed in terms of the principal dimensions (Kachru et al., 1994):

$$S = \frac{3}{4}L\pi[3(W' + T') - \sqrt{(3W' + T')(W' + 3T')}] \quad (3)$$

$$S = \frac{13}{11}(W + T)L \quad (4)$$

where W' and T' represent the half values of the width and thickness of seed, respectively.

Gravimetric Properties

Bulk and true densities for seed, kernel and hull at different moisture levels were determined. The bulk density (ρ_b), defined as the ratio of the mass sample of the grain to its total volume, was determined using a standard equipment of 250 mL of total volume with a piston for air displacement. The true density (ρ) defined as the ratio of mass of the sample to its true volume, was determined using an electronic balance and a pycnometer (water displacement method). The seeds and kernels were coated with a very thin layer of epoxy resin adhesive (Araldite) in order to avoid absorption of water during the experiment. The adhesive was found to be insoluble in water, resistant to heat and humidity and the increase in weight of the material due to the adhesive coating was negligible (less than 0.5%). The porosity value (ε) defined as the fraction of space in the bulk grain which is not occupied by the grain (Thompson and Isaac, 1967) was calculated from the following relationship:

$$\varepsilon = (1 - \rho_b/\rho) \times 100 \quad (5)$$

Aerodynamic Properties

Terminal velocity (V_t) of high oleic sunflower seeds and kernels were measured using a vertical air tunnel. The air velocities were varied through a computer controller that enables to regulate the opening of the air entrance into the blower (Kachru et al., 1994). Air velocity was measured with a calibrated orifice plate connected to an inclined micro-manometer (least count of 0.5 mm of water, Dwyer Instruments Inc., USA) that determines the differential pressure. The air velocity at which the grain remains in suspension is considered the terminal velocity. The tests were carried out with five replications for each moisture content of seed, kernel and hull. Once the terminal velocity of grain in air was determined, the following relationship (Mc Cabe et al., 1991) could be used for the calculation of drag coefficient C_D:

$$3\rho_a C_D Vt^2 = 4gD_e(\rho - \rho_a) \quad (6)$$

Frictional Properties

The emptying or dynamic angle of repose (θ) was determined for seed, kernel and hull and its variation with moisture content for each sample was also measured. A plywood box with a section of $0.30 \times 0.30\,m^2$ and a removable front panel was filled with grains. The front panel was quickly removed, allowing the seeds to flow and assume a natural slope. The angle of repose was calculated from the measurements of the vertical depth and radius of spread of sample on plywood (with grains in parallel and perpendicular with respect to the direction of the motion) and galvanised iron.

The static coefficient of friction (μ) for seed and kernel was measured against three structural materials, namely plywood (with grains perpendicular to the direction of the motion), acrylic and galvanised iron. A galvanised iron cylinder of 100-mm diameter and 50-mm height was placed on an adjustable tilting plate, faced with the test surface, and filled with the sample. The cylinder was raised slightly so as not to touch the surface. The structural surface with the cylinder resting on it was inclined gradually with a screw device until the box just started to slide down and the angle of tilt was read from a graduated scale.

Values reported for each property were the average of triplicate measurements.

RESULTS AND DISCUSSION

Physical and Chemical Characteristics of Trisum 568

High oleic (HO) sunflower seed studied, Trisum 568 resulted heavier than those of the traditional hybrid selected for comparison, lower in oil content and with higher hull/kernel ratio (Table 1). The ratio oleic/linoleic was the principal difference in the chemical oil composition.

Spatial Dimensions, Size Distribution, Sphericity and Surface Area

Approximately 48% of the seed sample (5.6%, d.b moisture content) had a length between 11 and 12 mm, while a large fraction (31%) is over 12 mm and the small one (21%) is less than 11 mm long. The mean values of the length, width, thickness and unit mass were found to be 11.526, 5.008 and 2.809 mm and 0.055 g, respectively (Table 2). The corresponding values for the kernel were 8.802, 3.897 and 1.907 mm and 0.036 g, respectively. Some differences due to variety with respect to other oil sunflowers have been detected. In particular this high oleic resulted longer, thinner and heavier than one traditional variety (Gupta and Das, 1997).

Table 1. Some physical and chemical characteristics of sunflower seed according to previous works.

Sunflower Seeds	1000 Seed Weight (g)	Oil Content (% d.b.)	Hull/Kernel Ratio	Oleic/Linoleic Ratio
Trisum 568 (HO) (Gely and Santalla, 2000)	50–52	43–45	0.53–0.55	8.2
Trisum 80 (Fernández San Juan, 1993)	–	–	–	7.5
Others HO (Fernández San Juan, 1993)	–	–	–	7.0–8.8
CF9 Argentinian genotype (Gely and Santalla, 2000)	42–48	49–51	0.32–0.34	0.25–0.29
Worldwide collection (Fernández Martínez and Domínguez Giménez, 1985)	27–71	41–56	0.20–0.43	0.60
Traditional (Salunkhe et al., 1992)	–	38–54	0.10–0.60	0.20–0.70

Table 2. Size distribution of seeds and kernels at 5.6 % moisture content (d.b.).

	Size Category			
Properties	Ungraded	Large	Medium	Small
Length of seed (mm)	10.12–13.04	>12	11–12	<11
Percent of Sample (by number)	100	31	48	21
Seed				
Length (mm)	11.585 ± 0.632	12.282 ± 0.243	11.526 ± 0.272	10.672 ± 0.281
Width (mm)	5.125 ± 0.387	5.395 ± 0.307	5.008 ± 0.346	5.002 ± 0.397
Thickness (mm)	2.797 ± 0.312	2.978 ± 0.305	2.809 ± 0.247	2.676 ± 0.290
Mass (g)	0.055 ± 0.010	0.063 ± 0.009	0.055 ± 0.009	0.053 ± 0.007
Kernel				
Length (mm)	8.787 ± 0.435	8.963 ± 0.422	8.802 ± 0.389	8.490 ± 0.412
Width (mm)	3.914 ± 0.448	4.059 ± 0.265	3.897 ± 0.332	3.826 ± 0.556
Thickness (mm)	1.887 ± 0.197	1.985 ± 0.179	1.907 ± 0.177	1.815 ± 0.191
Mass (g)	0.036 ± 0.006	0.039 ± 0.006	0.035 ± 0.006	0.034 ± 0.005

Table 3. Correlation of seed and kernel dimensions at 5.6 moisture content (d.b.).

Ratios	Value	Degrees of Freedom	Correlation Coefficient
L/W	2.26	98	0.453*
L/T	4.18	98	0.226**
L/M	209.44	98	0.427*
l/w	2.25	98	0.298*
l/t	4.66	98	0.194
l/m	247.10	98	0.392*
L/l	1.32	98	0.482*
W/w	1.31	98	0.592*
T/t	1.48	98	0.672*
M/m	1.55	98	0.857*
W/M	92.68	98	0.798*
T/M	50.59	98	0.765*
w/m	110.05	98	0.565*
t/m	53.06	98	0.764*

*Significant at 1% level. **Significant at 5% level.

The coefficients of correlation obtained for the ratio between the main dimensions and mass (Table 3) showed that length of seed is mostly related to width (less in kernel) than to thickness but the mass is more related with thickness and width than with length. Higher values for correlation coefficients showed that width of seed and kernel were more strongly correlated to their length than to their thickness, but also the mass of seed and kernel are correlated to their length. The higher correlation coefficients for the relations L/l, W/w, T/t and W/w also indicated that, in general, greater seeds give greater kernels when dehulled and that kernel size is directly proportional to seed size.

The highest correlation between linear dimensions and moisture content was found for the mass ($R^2 = 0.85$) followed by the thickness ($R^2 = 0.42$) and the width ($R^2 = 0.32$) of the seed (Table 4). It can also be seen that grains expand relatively more along their thickness than along the main axes. Other correlations were not significant.

The mean equivalent diameter for high oleic sunflower seed in the range of 4.22–26.44% moisture content (d.b.) was 5.34 mm (± 0.07) and for kernel it was 3.88 mm (± 0.12) (Table 4). Sphericity of high oleic sunflower varied between 0.449 and 0.479 for seed and between 0.434 and 0.464 for kernel with the maximum standard deviation for seed and kernel of 0.030 and 0.035, respectively.

Surface area increased with moisture content between 101.85 and 105.14 mm^2 (according to Equation (3)) and 104.24 and 107.28 mm^2 (according to Equation (4)) for seed and between 55.22 and 58.26 mm^2 (according to Equation (3)) and 56.92 and 59.77 mm^2 (according to Equation (4)) for kernel.

Table 4. Size, mass and morphology of high oleic sunflower seeds and kernels (Trisum 568) at different moisture contents ($n = 100$).

	Moisture (% d.b.)	Mass (kg)	Length (mm)	Width (mm)	Thickness (mm)	Equivalent Diameter (mm)	Sphericity
Seed	4.22	0.049	11.623	4.926	2.489	5.224	0.449
	8.60	0.056	11.207	5.095	2.716	5.373	0.479
	14.33	0.057	11.386	4.998	2.676	5.340	0.469
	21.13	0.058	11.465	5.049	2.677	5.371	0.468
	26.44	0.063	11.412	5.079	2.717	5.400	0.473
R^2		0.85	0.01	0.32	0.42	0.59	0.444
Kernel	5.04	0.031	8.567	3.737	1.717	3.802	0.456
	8.14	0.034	8.717	4.001	1.895	4.044	0.464
	13.19	0.035	8.511	3.818	1.801	3.883	0.464
	19.30	0.032	8.578	3.596	1.669	3.720	0.434
	23.75	0.035	8.768	3.777	1.845	3.938	0.449
R^2		0.12	0.14	0.16	0.00	0.01	0.11

One Thousand Seed Weight

In the range of 4.22–26.44% moisture (d.b.) the thousand grains mass increased from 49 to 63 g in seed and from 31 to 37 g in kernel. A close linear relationship was found between this property and the moisture content in seed (1000 grain mass $= 47.3 + 0.59\ M_c\ R^2 = 0.979$) but no relationship was found for the kernel.

Gravimetric Properties

Bulk Density

The bulk densities of seed, kernel and hull were determined in the range of moisture content of 4–26% d.b., 5–24% d.b. and 7–24% d.b., respectively. The bulk density of seeds (374–386 kg/m^3) resulted lower than that of kernels (535–552 kg/m^3) and higher than that of hulls (220–260 kg/m^3) at the same moisture level and varied with moisture content as indicated by the following expressions:

$$\rho_{bs} = 387.4 - 0.53 M_c \quad (R^2 = 0.799)$$
$$\rho_{bk} = 533.7 + 0.85 M_c \quad (R^2 = 0.899)$$
$$\rho_{bh} = 275.34 - 2.36 M_c \quad (R^2 = 0.786)$$

These results were in agreement with those obtained for traditional sunflower. Besides, for the same level of moisture content, bulk density of high oleic sunflower was lower than those for corn (Nelson, 1980) and safflower (Gupta and Prakash, 1992) and higher than for pumpkinseed (Joshi et al., 1993).

True Density

The true densities of the seed, kernel and hull were determined in the same range of moisture content than bulk density and were found to vary between 652 and 708 kg/m^3, 1015 and 1057 kg/m^3 and 636 and 760 kg/m^3 respectively.

The variations with moisture content were represented by the following correlations:

$$\rho_s = 651.1 + 2.14\ M_c \quad (R^2 = 0.871)$$
$$\rho_k = 1012.4 + 2.04\ M_c \quad (R^2 = 0.849)$$
$$\rho_h = 572.2 + 7.90\ M_c \quad (R^2 = 0.989)$$

These fittings showed that for the three components of high oleic sunflower genotype, their densities are linearly related with the moisture content. Similar trends were obtained for seeds of traditional oilseed type sunflower (Gupta and Das, 1997), pumpkin (Joshi et al., 1993) and safflower (Gupta and Prakash, 1992).

It was also observed that the bulk density of hull was much lower than that of seed and kernel but the true density of hull of high oleic hybrid was close to the seed value (636–760 kg/m^3) for the moisture range evaluated.

Porosity

The porosities of seed, kernel and hull were found to vary between 41.0 and 47.0%, 47.2 and 47.7% and 59.0 and 70.0%, respectively. This physical property increased linearly with the increase of moisture content according to the following expressions:

$$\varepsilon_s = 40.62 + 0.25 M_c \quad (R^2 = 0.975)$$
$$\varepsilon_k = 47.30 + 0.022 M_c \quad (R^2 = 0.585)$$
$$\varepsilon_h = 53.88 + 0.74 M_c \quad (R^2 = 0.939)$$

The highest variation with moisture content was observed for hull. These results showed lower variation with moisture content than those of traditional sunflower (Gupta and Das, 1997). Similar trends were reported for traditional sunflower (Gupta and Das, 1997) and gram (Dutta et al., 1988) however this tendency was opposed to the results reported for safflower (Gupta and Prakash, 1992) and pumpkin seed (Joshi et al., 1993).

Aerodynamic Properties

Terminal velocity increased linearly in seed, kernel and hull with moisture as follows:

$$Vt_s = 2.227 + 0.1176M_c \quad (R^2 = 0.976)$$
$$Vt_k = 1.254 + 0.1024M_c \quad (R^2 = 0.975)$$
$$Vt_h = 0.7681 + 00454M_c \quad (R^2 = 0.959)$$

As the moisture content increased from 4 to 26% terminal velocity of seed and kernel approximately doubled their values. Terminal velocity of high oleic sunflower resulted lower than that of Turkish mahaleb seeds (Aydin et al., 2002) and pumpkin seeds (Joshi et al., 1993).

Drag coefficient decreased in exponential form with moisture content between 4.69 and 1.36 in seed and between 12.46 and 3.11 in kernel (Figure 2(a)). Morphology of hull was not determined due to its irregular shape therefore no values of drag coefficient of hull were reported. Figure 2(b) represents a typical curve of drag coefficient versus Reynolds number (defined as $D_e V_t \cdot \rho_a/\mu_a$) for high oleic sunflower seed and kernel. As it is expected, as terminal velocity increases, drag coefficient decreased until values around 1 for $Re_{,p}$ higher than 2000.

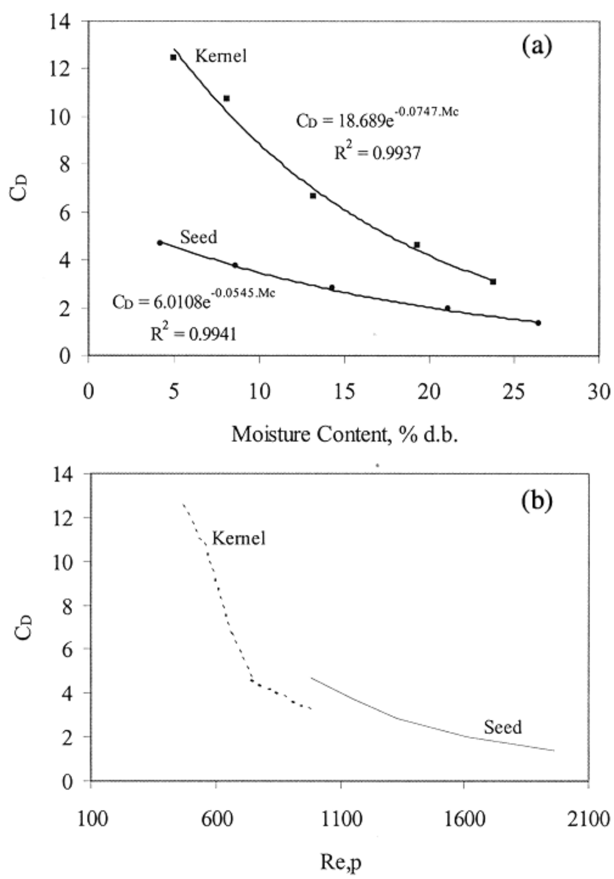

Figure 2. Variation of drag coefficient for high oleic seed and kernel: (a) With moisture content; (b) with the Reynolds number $Re_{,p}$ (defined as $Re_{,p} = D_e Vt \rho_a/\mu_a$).

Frictional Properties

Angle of Repose

The angle of repose of high oleic sunflower seed, kernel and hulls was evaluated over three different surfaces: wood with grain parallel and perpendicular to the direction of the motion and galvanised iron. The higher values were obtained on wood with grains perpendicular and the lower ones on galvanised iron. This may be due to the rough surface of wood with respect to metal and also to the shape of sunflower seed that provokes resistance in the seeds from sliding with respect to each other. The angle of repose of hull resulted higher than that for kernel and both these were higher than that found for seed. The higher angle of kernel with respect to that of seed did not agree with the results reported by Gupta and Das (1997) for traditional sunflower, in which kernel had lower angle of repose. In our work, the seeds presented lower resistance for sliding than kernel. This might be due to the lower roughness of its hull with respect to the kernel that is covered by its oily tegument. Joshi et al. (1993) had found a similar relation between seed and kernel of pumpkinseeds at low values of moisture content.

The experimental results showed a clear linear increase of the angle of repose with moisture content. The angle of repose varied from 23 to 46° for seed, from 35 to 55° for kernel and from 49 to 66° for hull. These values resulted in a higher level of variation than those found for traditional sunflower (maximum difference in similar range of moisture content). The slopes of the linear regressions were similar for the three cases. The following relationships represent the variation of the angle of repose with moisture content:

Wood with perpendicular grains:

$$\theta_s = 24.95 + 0.79M_c \quad (R^2 = 0.994)$$
$$\theta_k = 34.80 + 0.87M_c \quad (R^2 = 0.999)$$
$$\theta_h = 50.80 + 0.64M_c \quad (R^2 = 0.999)$$

Wood with parallel grains:

$$\theta_s = 21.56 + 0.71M_c \quad (R^2 = 0.996)$$
$$\theta_k = 32.83 + 0.78M_c \quad (R^2 = 0.998)$$
$$\theta_h = 47.05 + 0.70M_c \quad (R^2 = 0.993)$$

Galvanised iron:

$$\theta_s = 20.69 + 0.56M_c \quad (R^2 = 0.990)$$
$$\theta_k = 31.51 + 0.75M_c \quad (R^2 = 0.994)$$
$$\theta_h = 41.90 + 0.96M_c \quad (R^2 = 0.996)$$

Static Coefficient of Friction

The experimental values of static coefficient of friction of high oleic sunflower seeds and its fractions varied between 0.23 and 0.47 (maximum standard deviation 0.012), between 0.37 and 0.69 (maximum standard deviation 0.016) and between 0.31 and 0.60 (maximum standard deviation 0.020) for seed, kernel and hull, respectively. The higher values were found for the kernel and the difference between seed and hull was lower as compared to seed and kernel. This may be due to the oily surface of the kernel that makes their sliding more difficult than that of whole seeds or hulls.

The experimental results showed the effect of the structural surfaces and the moisture content on the static coefficient of friction. The higher values were found on plywood with the grains perpendicular to the direction of motion followed by acrylic surface and the lower values on galvanised iron. For all evaluated structural surfaces the coefficient of static friction increased with moisture content according to the following relationships:

$$\mu_{\text{swood}} = 0.34 + 0.0067M_c \quad (R^2 = 0.946)$$
$$\mu_{\text{kwood}} = 0.55 + 0.0057M_c \quad (R^2 = 0.985)$$
$$\mu_{\text{hwood}} = 0.49 + 0.0045M_c \quad (R^2 = 0.968)$$
$$\mu_{\text{sacryl}} = 0.25 + 0.0092M_c \quad (R^2 = 0.957)$$
$$\mu_{\text{kacryl}} = 0.48 + 0.0057M_c \quad (R^2 = 0.940)$$
$$\mu_{\text{hacryl}} = 0.34 + 0.0059M_c \quad (R^2 = 0.950)$$
$$\mu_{\text{sgalv}} = 0.19 + 0.0109M_c \quad (R^2 = 0.964)$$
$$\mu_{\text{kgalv}} = 0.35 + 0.0069M_c \quad (R^2 = 0.956)$$
$$\mu_{\text{hgalv}} = 0.23 + 0.0090M_c \quad (R^2 = 0.942)$$

It appears that the static coefficient of friction for high oleic sunflower on galvanised iron surface is similar to that for traditional sunflower but results higher than those of gram (Dutta et al., 1988), pigeon pea (Sheperd and Bhardwaj, 1986) and oilbean seed (Oje and Ugbor, 1991), except for pumpkin seed (Joshi et al., 1993) and resulted lower than that reported for gram (Dutta et al., 1988) on wood with grains perpendicular to flow.

NOMENCLATURE

C_D = drag coefficient, dimensionless
D_e = equivalent diameter of seed (mm)
d.b. = dry basis
d_e = equivalent diameter of kernel (mm)
g = gravitational acceleration
L = length of seed (mm)
l = length of kernel (mm)
M = unit mass of seed (g)
M_c = moisture content (% d.b.)
m = unit mass of kernel (g)
S = surface area (mm^2)
T = thickness of seed (mm)
T' = half of thickness (mm)
t = thickness of kernel (mm)
V_t = terminal velocity (m/s)
W = width of seed (mm)
W' = half of width (mm)
w = width of kernel (mm)
ε = porosity, dimensionless
ϕ = sphericity, dimensionless
μ = coefficient of friction, dimensionless
μ_a = air viscosity (kg/ms)
θ = angle of repose (°)
ρ = true density (kg/m^3)
ρ_a = air density (kg/m^3)
ρ_b = bulk density (kg/m^3)

Subscripts

h = hull
k = kernel
s = seed

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