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Effect of moisture content on some physical properties of barley

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ABSTRACT

Physical properties of barley (*Hordeum vulgare* L.) seeds were determined as a function of moisture content. Several properties were studied in the moisture range from 13.15 to 45.82% dry basis, the length increased from 8.10 to 8.62 mm, the width from 3.42 to 3.74 mm, the thickness from 2.61 mm to 2.84 mm, the arithmetic and geometric diameter of seeds from 4.71 to 5.07 mm and from 4.16 to 4.50 mm, respectively. Besides, the 1000-seed mass increased from 39.46 to 51.13 g, the surface area increased from 54.60 to 63.79 mm^2, the porosity increased from 42.69% to 44.44%, the angle of repose increased from 18.18° to 27.31°, and the static coefficient of friction showed an increase of 60.17%, 38.41% and 59.35% for the surfaces of plywood, galvanized steel and aluminum, respectively. From the experimental determinations it could be observed that only the apparent and true density decreased from 699.38 to 647.04 kg m^{-3} and from 1220.30 to 1164.62 kg m^{-3} respectively. In the range of evaluated moisture, all these properties – except length – showed moisture dependence according to linear relationships; the length exhibited a behavior of second-order polynomial. Finally, the sphericity behaves differently presenting a maximum of 53.15% for a moisture content of 35.29%.

1. Introduction

Barley (*Hordeum vulgare* L.) is one of the oldest crops, the fourth in the line of cereal production all over the world, being Germany, France, Ukraine and Russia the leading producers and exporters. In Argentina, barley is cultivated in about 0.7 million hectares with an annual production of 2.9 million tons (FAO, 2012). The most common varieties are *Painé*, *Barke*, *Danuta*, *Shakira*, *Scarlett* and *Ayelén*, the last two covering about 15 and 60% of the area, respectively.

In recent times, about two-thirds of the barley crop has been used for feed, one-third for malting and about 2% for food directly (Baik and Ullrich, 2008). In Argentina, about 90% of the production of barley is used in the malting industry, accompanying a 54% increase in world production of beer in the period 1999–2009 (FAO, 2012).

Malting process of barley grains guarantees certain physical and chemical changes in the grains, which are stabilized by subsequent drying thereof. Three steps are necessary to ensure that these changes occur: (A) soaking, to ensure good water absorption by the grain (12% moisture content in dry basis (db) to about 40–42% (db)); (B) germination, to maintain the growth of the embryo, the synthesis of enzymes and a limited deterioration of the endosperm, and (C) roasting, to ensure the stability of the product (Guiga et al., 2008). Therefore, a thorough understanding of the physical properties of barley grains is helpful to improve the technology associated with the various operations and equipment related to post-harvest processes such as cleaning, sorting, transport, ventilation, drying, storage and malting.

Knowledge of the morphology and size distribution of barley seeds is essential for the proper design of equipment for cleaning, sorting and separation (Kachru et al., 1994). Furthermore, the characteristic dimensions allow a calculation of the surface area and volume of grains, important aspects for the modeling of drying and ventilation (Al-Mahasneh and Rababah, 2007).

Different researchers report the use of characteristic dimensions to determine the size of seeds and grains (Deshpande et al., 1993; Gupta and Das, 1997).

The bulk density is used to determine the capacity of storage and transport, while the true density is useful to design proper separation equipment. Moreover, the porosity of the grain mass determines the resistance to airflow during aeration and drying operation (Brooker et al., 1992; Kachru et al., 1994).

The frictional properties as the angle of repose and coefficient of friction are recognized by engineers as important properties for the design of seed containers and other storage structures (Vilche et al., 2003).

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In recent years, physical properties of various crops like rice (Zareiforoush et al., 2009), fruit of Jatropha (Pradhan et al., 2009), niger seed (Solomon and Zewdu, 2009), soybean (Tavakoli et al., 2009a), rice grains (Zareiforoush et al., 2009), have been studied.

Some researchers have determined some physical properties of barley grains. Öztürk and Esen (2008) analyzed the effect of moisture content (ranging from 10% to 14% db) on the apparent density, true density, angle of internal friction, porosity and the static coefficient of friction of barley grains of the *Fahrettinbey* variety. In turn, Tavakoli et al. (2009b) reported the dependence on moisture content (in the range of 7.34–21.58% db) of the characteristic dimensions, sphericity, surface area, thousand grain weight, bulk density, true density, porosity, angle of repose and static coefficient of friction for *Nosrat* barley variety.

A literature review showed that there is a lack of information on physical properties of barley grains for wide ranges of moisture concerning the levels commonly used in the malting process (soaking process). Then, there is a need for a comprehensive study of the physical properties of grains of barley in order to achieve an optimal design of the equipment involved in the malting process. Therefore, this study aims at determining the following physical properties of the barley malting grain, *Scarlett* variety, including the characteristic dimensions, sphericity, surface area, thousand grain weight, bulk density, true density, porosity, angle of repose and static coefficient of friction, moisture in the wide range of 13.15–45.82% db, for the period of soaking.

2. Materials and methods

The sample of *Scarlett* barley variety used in this study was produced in the southwest of the Buenos Aires province, in Argentina. The grains were cleaned manually to remove foreign matter like dust, dirt, twigs and immature seeds. The moisture content was determined according to ASAE Standard (Standard S352.2, DEC97, ASAE, 1999), 10 g barley drying in a forced air oven at 130 °C for 20 h. The weight of the samples was recorded on analytical balance (accuracy 0.0001 g) in quadruplicate and their average value was recorded.

The initial moisture content of grain was 13.15% db.

The sample was divided into lots that were conditioned for moisture content in the range of 13.15–45.82% db by adding predetermined amounts of distilled water calculated from the following relationship:

$$Q = \frac{B_i(M_f - M_i)}{M_i + 100} \tag{1}$$

where Q is the mass of water to add (kg); B_i is the initial mass of the sample (kg); M_i is the initial moisture content of the samples (% db) and M_f is the final content of the samples (% db).

Wetting was carried out by keeping the sample primed with the necessary amount of water in each case in an airtight container which was rotated periodically over a period of 48 h. The moist samples were stored in plastic bags in a refrigerator at 4 °C for a week to allow uniform moisture content within the seeds (Sun and Woods, 1994).

Prior to starting the trials, the necessary amounts of sample were removed from the refrigerator to allow them to reach equilibrium with the room temperature.

All the physical properties of the grains were measured for six moisture contents in the range of 13.15–45.82% db. The determinations were carried out with 10 repetitions for the six moisture contents. Unless otherwise noted, average values are reported.

In order to determine the size and shape of the seeds, three subsamples of 0.5 kg each were chosen at random from the overall sample. Two hundred seeds were collected from each of the three sub-samples and the 600 seeds thus obtained were mixed. Finally, 50 seeds were selected at random. This random sampling method was similar to the one used by Dutta et al. (1988).

For each grain, three-dimensional features were measured: length (L), width (W) and thickness (T) with a digital micrometer (Mitutoyo, Japan) with an accuracy of 0.001 mm.

The arithmetic mean diameter (D_a) and the geometric mean diameter (D_g) of the seeds were calculated from the following equations (Mohsenin, 1986):

$$D_a = \frac{L + W + T}{3} \tag{2}$$

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

The sphericity (Φ) of barley seeds was calculated using the following relationship (Mohsenin, 1986):

$$\Phi = \left[\frac{(LWT)^{1/3}}{L}\right] \times 100 \tag{4}$$

where L is the length, W is the width and T is the thickness, all in mm.

The thousand grain weight was determined randomly selecting 100 grains of the overall sample, measuring their weight on a digital electronic balance with an accuracy of 0.0001 g and multiplying by 10 to get the mass of 1000 grains (Coşkuner and Karababa, 2007).

The equivalent surface area of barley grains (S) was obtained with the geometric mean diameter by analogy of a sphere, using the following relationship (Deshpande et al., 1993; Nimkar et al., 2005).

$$S = \pi D_g^2 \tag{5}$$

where S is the surface area (mm^2).

Bulk density (ρ_b) was considered as the ratio between the mass of a sample of grain and the total volume it occupies. It was determined by a balance of test weight (250 mL total volume) (Deshpande et al., 1993; Vilche et al., 2003).

The true density (ρ), defined as the ratio between the mass of the sample seeds and the actual volume it occupies, was determined for eight moisture content (in the range of 13.15–42.82% db) using a digital electronic scales (accuracy 0.0001 g) and a Model 930 Beckman pycnometer of 25 mL at 20 °C (method of moving a liquid xylene), with five replications (Singh and Goswami, 1996).

The porosity (ε) of the grain bed was defined as the fraction of space in a bed of grains that is not occupied by grains. The percentage porosity was calculated by the following equation (Mohsenin, 1986):

$$\varepsilon = \frac{1 - \rho_b}{\rho_t} \times 100 \tag{6}$$

The static coefficient of friction (μ) of barley was determined for the displacement of grains on three different materials, plywood, aluminum and galvanized steel. A polyvinyl chloride cylindrical tube (50 mm diameter and 50 mm height) was placed on a plate with adjustable tilt, and was filled with the seed sample. The cylinder was slightly raised in order to avoid contact with the plate surface, and both the plate and the cylinder at rest were leaned slowly with a screw device until the cylinder started to slide down. At that moment, the angle of the plate was recorded on a scale. The coefficient of friction was calculated by the following relationship:

$$\mu = \tan\ \alpha \tag{7}$$

In order to determine the angle of repose, an acrylic box with a wooden bottom (100 mm × 100 mm) and a removable front panel (especially designed for the experiment), was used. The box full of barley seeds was placed on a horizontal surface. Eventually, the front panel was quickly removed, allowing the grains to slide down and take their natural slope. The angle of repose was calculated

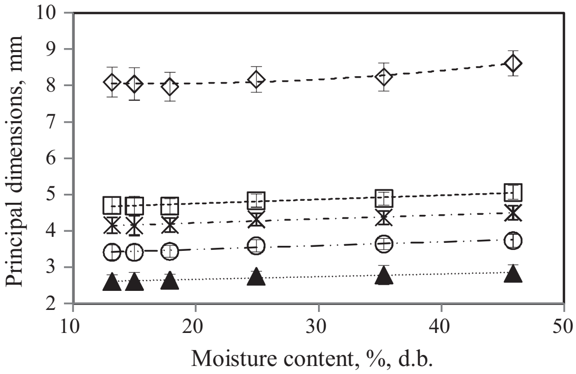

Fig. 1. Variation of the principal dimensions, arithmetic and geometric mean diameter of barley seeds with moisture content: (◊) length, *L*; (○) width, *W*; (▲) thickness, *T*; (□) arithmetic mean diameter D_a; (×) geometric mean diameter, D_g.

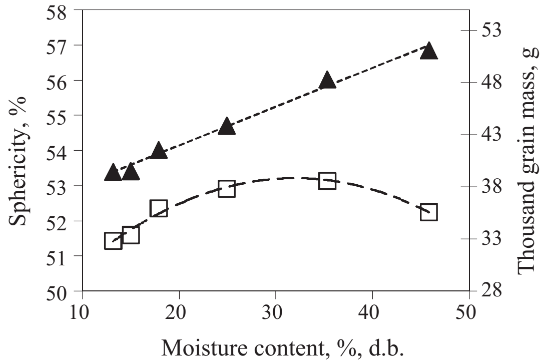

Fig. 2. Effect of moisture content on sphericity (□) and thousand grain mass (▲).

from measuring the grain bed depth (height of the natural slope) at two known distances. Other researchers have already used this method (Dutta et al., 1988; Gupta and Das, 1997; Mwithiga and Sifuna, 2006).

The characteristic dimensions and the other physical properties of barley were determined for six moisture contents (from 13.15 to 45.82% db), and the results obtained were subjected to analysis of variance (ANOVA) using Systat® 10.0 software and linear regression analysis, using Microsoft Excel®.

3. Results and discussion

3.1. Grain dimensions

With increasing moisture content from 13.15 to 45.82% db, the length (*L*), width (*W*), thickness (*T*), the arithmetic mean diameter (D_a) and the geometric mean diameter (D_g) of seeds increased significantly ($p < 0.01$) from 8.10 to 8.62 mm, 3.42 to 3.74 mm, 2.61 mm to 2.84 mm, 4.71 to 5.07 mm and 4.16 to 4.50 mm, respectively.

Fig. 1 shows the average ranges of the experimental results, together with their corresponding standard deviation values, which were lower than 0.44 mm (*L*), 0.22 mm (*W*) and 0.26 mm (*T*, D_a, D_g) in all the cases.

The increase in size could be attributed to the expansion of the grain as a result of moisture absorption in the intracellular spaces inside the seeds (Solomon and Zewdu, 2009). The dependence of these properties with moisture content (*Mc*) could be represented by the following equations (Fig. 1):

$$L = 0.0007Mc^2 - 0.0227Mc + 8.2453 \quad (8)$$

$$W = 0.0103Mc + 3.2795 \quad (9)$$

$$T = 0.0074Mc + 2.2522 \quad (10)$$

$$D_a = 0.0114Mc + 4.5275 \quad (11)$$

$$D_g = 0.0109Mc + 4.0061 \quad (12)$$

where *Mc* is the moisture content in % db, corresponding R^2 values of 0.94, 0.95, 0.93, 0.95 and 0.96, respectively, for each of the above equations.

Similar trends were reported for jatropha, guna, chickpea, barley grain and nut (Garnayak et al., 2008; Aviara et al., 1999; Dutta et al., 1988; Tavakoli et al., 2009b; Visvanathan et al., 1996).

3.2. Sphericity

The values of sphericity (Φ) were calculated individually (Eq. (4)), using data from the geometric mean diameter and the main axis of the grains of *Scarlett* barley (length, *L*). The results are presented in Fig. 2. The sphericity increased from 51.43 to 53.14% ($p < 0.01$) when the moisture content increased from 13.15% to 35.29% db, and then decreased to 52.26% when the moisture content was 45.82% db, thus showing the relevance of the variation of Φ in the full range of humidity ($p < 0.01$), with values of standard deviations of up to 1.64.

The initial increase in the sphericity may have been caused by a proportional increase in the length, width and thickness. However, higher moisture contents than 35.29% db could have produced a greater increase in grain length compared with the width and thickness, causing the reduction of Φ, before mentioned as decreasing tendency (Sahoo and Srivastava, 2002). The relationship between moisture content and the sphericity (Φ) of the grain could be represented by the following polynomial equation:

$$\Phi = -0.0055Mc^2 + 0.3465Mc + 47.877 \quad (13)$$

with R^2 value of 0.9812.

In accordance with the present work, Sahoo and Srivastava (2002) reported an initial increase followed by a decrease in the sphericity of the seeds of okra. Tavakoli et al. (2009b) determined a linear increase of Φ with moisture content for *Norstat* barley, in total accordance with the observations of the present work, when compared in the same ranges.

3.3. Weight of thousand grains

The variation of the weight of thousand grains (P_{1000}) is shown in Fig. 2. The P_{1000} increased ($p < 0.01$) linearly from 39.46 to 51.13 g as the moisture content increased from 13.15 to 45.86% db. Standard deviation values lower than 1.52 in all the cases. The relationship between moisture content and weight of thousand grains can be represented by the following regression:

$$P_{1000} = 0.3721Mc + 34.564 \quad (14)$$

with R^2 value of 0.9337.

Similar behaviors were reported for green wheat, soybeans, chickpeas and cumin seeds (Al-Mahasneh and Rababah, 2007; Deshpande et al., 1993; Dutta et al., 1988; Singh and Goswami, 1996).

3.4. Surface area

The surface area (*S*) of grains was calculated using Eq. (5), and a linear significant increase ($p < 0.01$) from 54.60 to 63.79 mm^2 was observed when the moisture content increases from 13.15% to 45.86% db. The relationship between the moisture content and the surface area could be expressed as the following equation:

$$S = 0.2929Mc + 50.348 \quad (15)$$

with R^2 value of 0.9672.

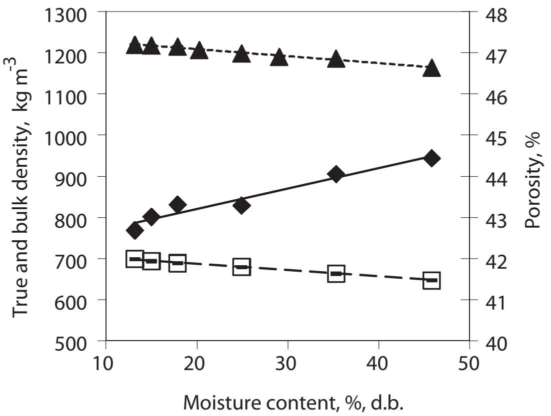

Fig. 3. Effect of moisture content on porosity (♦), true density (▲) and bulk density (□).

Similar trends have been reported for seeds of jatropha and rice (Garnayak et al., 2008; Zareiforoush et al., 2009). Tavakoli et al. (2009b) reported a linear increase on the surface area of *Nosrat* barley grains with respect to the moisture content, being this trend more remarkable than the observed in the present work for *Scarlett* barley. These differences may be attributed to a minor expansion occurring on the characteristic lengths of Scarlet grains compared with the variety previously mentioned.

3.5. Bulk density

Bulk density (ρ_b) of the bed of barley grains at different moisture levels varied significantly ($p < 0.01$) from 699.38 to 647.04 kg m^{-3} when moisture content increased from 13.15% to 45.86% db (Fig. 3). This behavior could be attributed to the fact that the increased mass of the sample associated with increased humidity resulted lower than the volume expansion experienced by grains, i.e. the volume of air entrained between the wetter grains was larger than the volume of the inter-grain air in drier grains.

This would cause the effect of having greater compaction (higher bulk density) in dry beans compared with wet grains. The relationship of bulk density (ρ_b) of barley seeds *cv. Scarlett* and moisture content can be expressed by the following equation:

$$\rho_b = -1.5473Mc + 718.03 \qquad (16)$$

with R^2 value of 0.9855.

A similar trend has been reported for various materials like guna seeds, chickpeas, soybeans, sunflower and barley (Aviara et al., 1999; Dutta et al., 1988; Deshpande et al., 1993; Gupta and Das, 1997; Öztürk and Esen, 2008; Tavakoli et al., 2009b).

3.6. True density

The true density (ρ_t) of barley grains *cv. Scarlett* showed a significant ($p < 0.01$) decrease from 1220.30 to 1164.62 kg m^{-3} when moisture content changed from 13.15 to 45.82% db (Fig. 3). In view of the fact that the true density relates to the grain mass contained in a grain volume, the observed reduction on ρ_t could be explained due to the fact that the increment of grain weight caused by the moisture grain resulted lower than the volume expansion experimented by grains.

$$\rho_t = -1.6986Mc + 1242.9 \qquad (17)$$

with R^2 value of 0.8035.

Similar results were reported for canola (Çalişir et al., 2005), soybeans (Deshpande et al., 1993) and sorghum (Mwithiga and Sifuna, 2006). The values of true density obtained for barley *cv. Scarlett* at different moisture contents were lower than those reported for barley *cv. Nosrat* (Tavakoli et al., 2009b) and higher than that reported for barley *var. Fahrettinbey* (Öztürk and Esen, 2008).

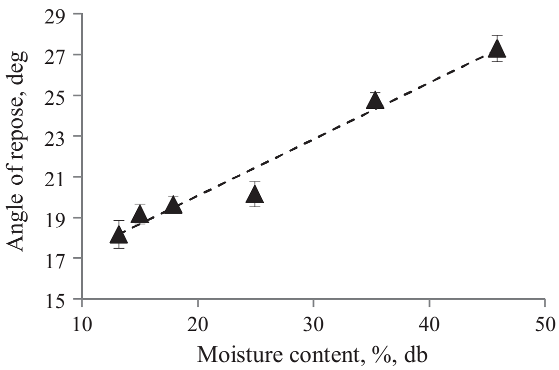

Fig. 4. Effect of moisture content on the angle of repose (▲) for barley grains.

3.7. Porosity

The porosity was calculated by means of Eq. (6), using the average values of bulk density and true density of each batch. It was observed that when moisture content increased from 13.15 to 45.82% db, porosity increased significantly ($p < 0.01$) from 42.69 to 44.44% as shown in Fig. 3. The reason of this increment can be explained as follows: while the grains absorb moisture, their individual volume increases, especially due to the increment of their length (which grows more rapidly than the width and thickness); consequently, the shape of the grain changes, and their bulk volume. This behavior causes the number of grains occupying a fixed volume to decrease, and then the bulk density decreases. In other words, for a given mass of grain, an increase in the moisture content leads to higher bulk volume. Similarly, the addition of water to the grain structure leads to an increase in its true density. But, as the volume change produced by wetting the grain differently affects their characteristic dimensions, altering mainly the length (and in second term, the width) it influences more on the resulting bulk density than on the true density of grain, increasing porosity (Solomon and Zewdu, 2009). The relationship between the value of porosity (ε) and the moisture content can be expressed as:

$$\varepsilon = 0.0496Mc + 42.212 \qquad (18)$$

with R^2 value 0.9462.

Similar behaviors were reported for three sorghum varieties (Mwithiga and Sifuna, 2006) and niger seed (Solomon and Zewdu, 2009). By comparing the porosity of barley *var. Scarlett* with other grains at different moisture contents, it was observed that it was less than that reported for green wheat and canola (Al-Mahasneh and Rababah, 2007; Çalişir et al., 2005).

3.8. Angle of repose

The experimental results of angle of repose with respect to moisture content are shown in Fig. 4, showing a significant increase of 18.18 degrees to 27.31 degrees ($p < 0.01$) when humidity increased from 13.15 to 45.82% db. This trend could be due to the fact that moisture in the surface layer of the grain keeps them bound together by surface tension effect (Pradhan et al., 2008). The angle of repose is of paramount importance in the design of openings of hoppers, pending side walls and storage structures in the bulk of seeds per ramp (Solomon and Zewdu, 2009). Therefore, the moisture content of the seeds should be taken into account when designing

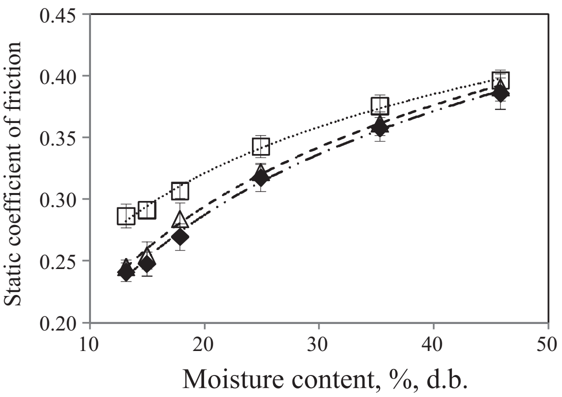

Fig. 5. Effect of moisture content on the static coefficient of friction for different surfaces: aluminum (△), plywood (♦) and galvanized steel (□).

such equipment and structures. The linear relationship between the angle of repose (θ) and the moisture content can be described by the following equation:

$$\theta = 0.2777Mc + 14.511 \quad (19)$$

with R^2 value of 0.9676.Similar behavior of the angle of repose with respect to moisture has been observed for sorghum, jatropha and karanja (Mwithiga and Sifuna, 2006; Garnayak et al., 2008; Pradhan et al., 2008). The angles of repose at different moisture contents for barley *cv. Scarlett* were lower compared with those reported for niger, cumin and guna (Solomon and Zewdu, 2009; Aviara et al., 1999; Singh and Goswami, 1996).

3.9. *Coefficient of static friction*

The static coefficient of friction of barley in the three surfaces (plywood, galvanized steel and aluminum) showed a significant increase ($p < 0.01$) with the moisture content in the range of 13.15–45.86% (Fig. 5). The static coefficient of friction showed an increase of 60.17%, 38.41% and 59.35% for the surfaces of plywood, galvanized steel and aluminum, respectively. The reason for this increase may be due to the fact that higher moisture content increases the water present in the grains and the material has a greater force of friction with the contact surface (Visvanathan et al., 1996). The galvanized steel showed the maximum friction followed by aluminum and plywood. This behavior may be based on the fact that the foil has a surface that is smoother and less porous than other materials used (Singh and Goswami, 1996; Tavakoli et al., 2009a).

The relationship between the static coefficient of friction of plywood (μ_{PW}), galvanized steel (μ_{AG}) and aluminum (μ_{AL}) with the moisture content were represented by the following equations:

$$\mu_{\mathrm{AG}} = 0.0925Ln(Mc) + 0.0439 \quad (20)$$

$$\mu_{\mathrm{AL}} = 0.1185Ln(Mc) - 0.0609 \quad (21)$$

$$\mu_{\mathrm{PW}} = 0.1214Ln(Mc) - 0.0764 \quad (22)$$

with R^2 of 0.9954, 0.9973 and 0.9958, respectively. The behavior observed in this study was similar to that found for niger seed (Solomon and Zewdu, 2009), okra (Sahoo and Srivastava, 2002) and cumin (Singh and Goswami, 1996).

4. Conclusions

In this work, the dependence of physical properties of barley (*cv. Scarlett*) in humidity range of 13.15–45.82% db was achieved.

The dimensions width and thickness showed a positive linear relationship ($R^2 > 0.93$ in all cases) with moisture content range from 3.41 to 3.74 and from 2.61 to 2.84 mm, respectively, while length exhibited a second order relationship with Mc ($R^2 = 0.94$), ranging between 7.97 and 8.62 mm.

Thousand grain weight and surface area increased from 39.46 to 51.13 g and from 54.60 to 63.79 mm^2.

On the other hand, the arithmetic and geometric mean diameters increased in a range between 4.71 and 5.07 mm, from 4.16 to 4.50 mm respectively. The sphericity varied in the range between 51.39 and 53.15% showing a maximum value at intermediate moisture content.

Besides, the true and bulk densities decreased from 1220.30 to 1164.62 kg m^{-3} and from 699.38 to 647.04 kg m^{-3}, while the porosity varies between 42.69 and 44.44%. The angle of repose increased from 18.18 to 27.31°.

Finally, it could be observed the effect of the material in the coefficient of friction; it increased in the three materials under study, i.e., plywood (0.24–0.39, 60.17%), galvanized steel (0.29–0.40, 38.41%) and aluminum (0.25–0.39, 59.35%).

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