Moisture-Dependent Physical and Mechanical Properties of White Sesame Seed

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Abstract: The effect of moisture content on the physical and mechanical properties of white sesame seed was determined to explore the possibility of developing its bulk handling and processing equipment. The average length, width and thickness, geometric mean diameter, volume of the seed and 100 seed mass ranged from 3.019 to 3.074 mm, 1.844 to 1.935 mm and 0.724 to 0.771 mm, 1.589 to 1.659 mm and 1.165 to 1.20g³ as the moisture content increased from 4.5 to 15% wet basis, respectively. As the moisture content increased, the bulk density, true density and porosity were found to decrease from 607.3 to 542.1 kg/m³, 1140 to 943.5 kg/m³ and 46.73 to 42.54%, respectively, whereas the angle of repose increased 20.16 to 28.67°. When moisture content increased, the aspect ratio and surface area increased from 52.75 to 54.04%, from 24.06 to 25.12% and from 6.785 to 7.367 mm, respectively. The static coefficient of friction on various surfaces, namely, steel sheet, aluminium, galvanized metal also increased linearly with increase in moisture content. The highest static coefficient of friction was found on the steel sheet surface. The rupture force decreased with increasing moisture from 9.90 to 10.625 N.

Key words: Physical and mechanical properties • White sesame seed • Moisture content

INTRODUCTION

Sesame (Sesamum indicum L.) is an oilseed herbaceous crop of the Pedaliaceae family. Sesame is rich in oil, protein and carbohydrate. Chemical analysis of Sesame averaged 57-63% oil, 23-25% protein, 20-25% carbohydrate and 3-4% ash and the oil contains vitamins A, B, D and E, minerals and amino acids.

Sesame seeds are small; the dimensions of the seed vary approximately 2.8-3.8 mm in length, 1.69-2.5 mm in width and 0.7 - 0.9 mm in thickness and 1000-1224 kg/m³ in true density [1, 2]. The seeds also vary in color. The two main colors are white and black. Sesame is grown in many parts of the world on over 5 million acres. The largest producer of the sesame seed in 2007 was India, China, Myanmar, Sudan, Ethiopia, Uganda and Nigeria.

Knowledge of the physical and mechanical properties of the agricultural products is of fundamental importance for the appropriate storage procedure and for design, dimensioning, manufacturing and operating different equipments used in post harvest processing operations of these products.

The objective of this study was to investigate the moisture dependent physical and mechanical properties of white sesame seeds namely, linear dimensions, geometric mean diameter, thousand seed weight, true density, bulk density, porosity, angle of repose, static coefficient of friction against three structural surfaces and rupture force at different levels of moisture content.

MATERIALS AND METHODS

Sample Preparation: The white sesame seeds which were selected for this research work consisted of a major commercial variety of sesame seeds, at average moisture contents of 4.5% (w.b.). The samples were obtained from the Agricultural Garden of Ilam University, Iran. The seeds were manually cleaned to remove all foreign matter such as dust, dirt and stones. The initial moisture content of the seeds was determined by following a standard oven method [3].

To obtain samples with higher moisture contents, a calculated quantity of distilled water was added; the samples were placed in sealed plastic bags and kept at 277 K in the refrigerator for at least a week to enable the moisture to distribute uniformly throughout the sample. Before starting a test, the required quantity of seeds was taken out of the refrigerator and allowed to warm up to room temperature [4]. The quantity of distilled water was calculated from the following equation [5]:

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\[ W_2 = W_1 \frac{M_1 - M_2}{100 - M_1} \]

Where: \( W_1 \) is the mass of distilled water added (kg), \( W_2 \) is the initial sample mass (kg), \( M_1 \) is the initial moisture content of sample (%w.b.) and \( M_2 \), desired moisture content of sample (%w.b.). Physical and mechanical properties of white sesame seeds were measured at four moisture levels of 4.5, 8, 12 and 15%.

**Dimensions, Size and Mass:** The geometric mean diameter \((D_g, \text{mm})\), sphericity index \((\phi, \%)\) and aspect ratio \((R_a, \%)\) of the seed was calculated by using the following relationship [6], respectively:

\[
D_g = \left( \frac{L}{W} \right)^{\frac{1}{3}}
\]

\[
\phi = \left( \frac{L}{W} \right)^{\frac{1}{3}}
\]

\[
R_a = 100 \times \frac{W}{L}
\]

Where, \( L \) is the length (mm), \( W \) is the width (mm) and \( T \) is the thickness (mm).

Mass of 100 seeds of white sesame was determined by taking 10 seeds randomly and measured mass of seeds at different moisture contents using an electrical balance (GF-600, A & D, Japan) and then multiplied by 10 to give the mass of 100 seeds. The measurements were taken at room temperature of 18°C.

**Seed Surface and Volume:** The surface area \((S, \text{mm}^2)\) and volume \((V, \text{mm}^3)\) of white sesame seeds was obtained using the formula given by Mohsenin [6] and Jain and Ball [7] as follows:

\[
S = \frac{\pi BL^2}{2L - B}
\]

\[
V = \frac{\pi B^2 L^2}{6(2L - B)}
\]

Where, \( B \) is equal to \((WT)^{0.5}\).

**True Density, Bulk Density and Porosity:** The true density of a seed is defined as the ratio of the mass of a sample of a seed to the solid volume occupied by the sample. The seed volume and its true density were determined using the liquid displacement method. Toluene \((C_8H_8)\) was used rather than water because it is absorbed by seeds to a lesser extent. Also, its surface tension is low, so that it fills even shallow dips in a seed and its dissolution power is low.

The bulk density is the ratio of the mass of a sample of a seed to its total volume and it was determined by filling the seeds in a cylinder of known volume (30 mm diameter and 60 mm height) and weighed in an electronic balance.

The porosity \((\varepsilon, \%)\) of bulk seed was computed from the values of seed density and bulk density using the relationship given by Mohsenin [6] as follows:

\[
\varepsilon = 100 \times \left(1 - \frac{\rho_b}{\rho_t}\right)
\]

**Angle of Repose and Static Friction:** The angle of repose \((\varphi)\) is the angle with the horizontal at which the material will stand when piled. This was determined by using a hollow cylindrical mould of 100 mm diameter and 150 mm height. The cylinder was placed at the center of a raised circular plate and was filled with white sesame seeds. The cylinder was raised slowly until it formed a cone on a circular plate. The angle of repose was calculated from the measurement of the height of the cone and the diameter of cone.

\[
\varphi = \tan^{-1}\left(\frac{2H}{D}\right)
\]

Where, \( H \) is high (mm) and \( D \) is diameter (mm) of hollow cylindrical.

The static friction coefficients \((\mu)\) of the white sesame seeds against three different surfaces, namely galvanized steel, iron and aluminum sheet, were determined using a fiber glass box of 150mm length, 100mm width and 40 mm height without base and lid was filled with seeds. With the box resting on the surface, the surface was raised gradually until the filled box just started to slide down. The friction coefficient, \(\mu\), was calculated from the following relationship:

\[
\mu = \tan(\alpha)
\]

Where, \( \alpha \) is the angle of tilt in degrees.

**Rupture Force:** Quasi-static compression tests were performed with an Instron Testing Machine (H50 K-S, Hounsfield, UK). The force applied to the sesame seed which by two parallel plate cases at a loading velocity at 3mm/min.
RESULTS AND DISCUSSION

White Sesame Seed Size: The results of white sesame seed size at different moisture content were displayed in Table 1. All the dimensions increased with moisture content in the moisture range of 4.5-15% (w.b.). The relationship between length, width and geometric mean diameter and moisture content was found to be linear:

\[
L = 2.997 + 0.0053M \quad R^2 = 0.994
\]
\[
W = 1.806 + 0.0087M \quad R^2 = 0.998
\]
\[
T = 0.702 + 0.0045M \quad R^2 = 0.989
\]
\[
D_g = 1.555 + 0.0065M \quad R^2 = 0.966
\]

Table 1: Some physical properties of sesame seed at different moisture content

<table>
<thead>
<tr>
<th>Properties</th>
<th>Moisture content (%w.b)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>4.5</td>
</tr>
<tr>
<td>Length (mm)</td>
<td>3.019</td>
</tr>
<tr>
<td>Width (mm)</td>
<td>1.844</td>
</tr>
<tr>
<td>Thickness (mm)</td>
<td>0.724</td>
</tr>
<tr>
<td>Geometric mean diameter (mm)</td>
<td>1.589</td>
</tr>
</tbody>
</table>

Fig. 1: Volume and 100 mass of sesame seeds as a function of moisture content

As it is seen in Fig. 3, surface area increased with increase in moisture content from 6.785 to 7.367 mm$^2$. This shows that the surface area increased linearly with increasing in moisture content. The results were in conformity with those of other researchers [12, 13, 14]. The relationship between surface area and moisture content of sesame seeds was as follows:

\[
S = 0.055M + 6.522 \quad R^2 = 0.995
\]

True Density, Bulk Density and Porosity: The bulk and true density of the seed were observed to decrease from 607.3 to 542.1 kg/m$^3$ and 1140 to 943.5 kg/m$^3$, respectively, as the moisture content increased from 4.5% to 15% (Fig. 4). This was due to the higher rate of increase in volume (16.1%) than weight (3%). The relationship can be expressed by the following equations:

\[
\rho_b = -0.161M^2 + 3.063M + 624.34 \quad R^2 = 0.999
\]
\[
\rho_t = 0.741M^2 - 33.150M + 1274 \quad R^2 = 0.999
\]

The porosity was found to decrease from 46.73 to 42.54% with increase in moisture content from 4.5% to 15% (Fig. 5). The relationship between porosity and moisture content can be represented as:

\[
\varepsilon = 0.048M^2 - 1.333M + 51.758 \quad R^2 = 0.998
\]
Similar results have been reported by Davies and El-Oken [10]; Kingsly et al. [14]; Sessiz et al. [15]; and Koocheki [11].

**Angle of Repose and Static Friction:** A linear increase of repose angle from 20.16 to 28.67° was observed with increasing moisture content (Fig. 5). The increase in the angle of repose with increase in moisture content of the seed could be cause to the higher surface area which may increase the internal friction of the seeds. The results are similar to those reported by Tabatabaeefar [16]; Bagherpour et al. [17]; Fraser et al. [18] and Amin et al. [19]. The relationship between the angle of repose and the moisture content can be represented as:

$$\psi = 16.445 + 0.810M \quad R^2 = 0.998$$

As it is seen in Fig. 6, the coefficient of static friction increased with increasing moisture content on all three surfaces. This is due to the increased adhesion between the seed and the material surfaces at higher moisture values. Results of analysis showed that the surface of materials had an effect on values of the static coefficient of friction. Coefficient of static friction of sesame seed ranged from 0.395 to 0.570, 0.374 to 0.554 and 0.337 to 0.546, for galvanized steel, iron and aluminum sheet, respectively. At all moisture contents, the least static coefficient of friction were on aluminum sheet. This may be owing to smoother and more polished surface of the aluminum sheet than the other materials used. The relationships between coefficients of static friction and moisture content on all surfaces are given in Table 2. Other researchers had reported that as the moisture content increases, the static coefficient of friction increases as well [8, 16, 17, 20-23].

**Table 2:** Relationships between coefficient of static friction and moisture content of sesame seed

<table>
<thead>
<tr>
<th>Material</th>
<th>Equations</th>
<th>$R^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Steel</td>
<td>$\mu = -0.0013M^2 + 0.0427M + 0.230$</td>
<td>0.996</td>
</tr>
<tr>
<td>Galvanized steel</td>
<td>$\mu = -0.0019M^2 + 0.0547M + 0.167$</td>
<td>0.998</td>
</tr>
<tr>
<td>Aluminum</td>
<td>$\mu = -0.0006M^2 + 0.0324M + 0.204$</td>
<td>0.998</td>
</tr>
</tbody>
</table>
**Rupture Force:** With increasing moisture content, as shown in Fig. 7, rupture force of sesame seeds was found to decrease from 9.90 to 10.625 N. The small rupture force at higher moisture content might have resulted from the fact that the seeds have soft texture at higher moisture content. Similar trends were also observed by Bagherpour et al. [17] Fatollahzadeh and Rajabipour [24]; Altuntas and Yildiz [25] and Kiani Deh Kiani et al. [8].

The relationship between the rupture force and the moisture content can be represented as:

\[ F = 0.008M^2 - 0.222M + 11.464 \]  
\[ R^2 = 0.997 \]

Where, \( F \) is rupture force (N).

**CONCLUSION**

- The following conclusions are drawn from the investigation on the physical and mechanical properties of white sesame seeds as functions of the moisture content.
- The length, width, thickness, volume, 100 seed mass, geometric mean diameter and aspect ratio of white sesame seeds increased linearly with increase of moisture content.
- True and bulk density and porosity slightly decreased linearly with increase of moisture content but porosity increased with increase in moisture content.
- The results of this study indicated that the angle of repose and coefficient of static friction increased as the moisture content increased.
- Rupture force decreased with decrease of moisture content.