Moisture dependent physical properties of cardamom (*Elettaria Cardamomum M.*) seed

Tamirat Redae Gebreselassie*

(Department of Chemical Engineering, Adama Science and Technology University, P.O.Box 1888, Adama-Ethiopia)

Abstract: Design of unit operations for mechanical and pneumatic cleaning, transportation (conveying), processing and storage of cardamom seeds are dependent on moisture content. Some of moisture dependent physical properties of cardamom seeds were studied at moisture contents 9.9%, 13.57%, 18.41%, and 23.29% wet basis (w.b.) The length, width, thickness, geometric mean diameter, thousand seed mass, and sphericity increased from 17.01 to 17.30mm, 5.68 to 6.57 mm, 5.02 to 5.35 mm, 7.86 to 8.47 mm, 120.83 to 165.60 g, and 0.46 to 0.49, respectively, with the increase in the moisture content from 9.9 to 23.29% w.b. As the moisture content increased from 9.9 to 23.29% the bulk density, true density, and porosity decreased from 408.2 to 358.90 kg/m^3, 926.57 to787.19 kg/m^3, and 55.94 to 54.41%, respectively. The angle of repose increased from 72.16^o at 9.9% to 73.80^o at 23.29% moisture content. Whereas, the static coefficient of friction increased with the increase in moisture content from 9.9 to 23.29% on three different surfaces. The highest static coefficient of friction was recorded when cardamom seed against plywood (0.47 to 0.56), and lowest static coefficient of friction against mild steel (0.41 to 0.50). The static coefficient of friction between cardamom seeds and galvanized iron surface increased from 0.44 to 0.53 within the studied moisture content range.

Keywords: cardamom, moisture content, physical properties, static coefficient of friction, bulk and true density, angle of repose

Citation: Tamirat Redae Gebreselassie. 2012. Moisture dependent physical properties of cardamom (Elettaria Cardamomum M.) seed. Agric Eng Int: CIGR Journal, 21 (1): Manuscript No. 2025.

1 Introduction

Cardamom (*Elettaria cardamomum* M.) is herbaceous plant belonging to the family *Zingiberaceae.* This plant is also named as Cardamon or Lesser Cardamom. It is cultivated mostly in Southern India, Nepal, Bhutan, Sri Lanka, Ethiopia, Indonesia, Honduras, Burma, Thailand, Vietnam, Cambodia, and Laos (George, Ramesh and Bastiaan, 2007). Cardamom is one of the most expensive and important spice seeds used traditionally to prevent different diseases like fever, cough, gallbladder problems, colic, acute respiratory disorders, stomach complaints, haemorrhoids, bad breath, and sore throat. In Ethiopia, “kesher” is the most popular beverage like tea, which is a mixture of cardamom, wet ginger and little sugar and is used in preventing cough and different diseases. Scientifically, according to Green Pharmacy Study (Duke, 1997), cardamom is a stimulant for preventing fainting together with coffee. The chemical composition of cardamom differs significantly with variety, region and age of the product. Cardamom is the richest known source of cineole and borneol compounds (Duke, 1992). Cineole is

----

Received date: 2012-01-14 **Accepted date:** 2012-02-26

***Corresponding author: Tamirat Redae Gebreselassie.** Adama Science and Technology University. P.O.Box 1888, Adama-Ethiopia. Tel: +251221119279. E-mail: ztamirat021@gmail.com

present in most oils used by aromatherapists for preventing fainting. Cineole is not only a potent antiseptic that kills bad breath bacteria and treats other infections but also it has expectorant activity for clearing breathing passages (Duke, 1997). Borneol is used to prevent and treat gallbladder and kidney stones (Duke, 1997).

Knowledge on physical properties of seeds is of paramount importance in designing equipment for handling, storing or processing. Wu *et al.* (1999) reported the importance of difference in size and density during separating particles by segregating on gravity tables. Size, shape and density are important in the separation of seed from undesirable materials on oscillating chafers (Zewdu, 2004; Scherer and Kutzbach, 1978; Hauhouot-o'hara *et. al.*, 2000). Bulk density and porosity are crucial properties in the development of aeration and drying systems as these properties affect the resistance of stored mass to airflow (Jekayinfa, 2006; Tran, Srzednicki and Driscoll, 1999), whereas angle of repose is very important in designing equipment for mass flow and storage structures. Friction between seed and a surface has an influence on the movement of particles on oscillating conveyors, cleaning using oscillating sieves and loading and unloading operations (Zewdu, 2004; Kutzbach and Scherer, 1977, Molenda *et. al*., 2002).

Several studies have been conducted on the physical properties such as size, shape, bulk density, true density, porosity, angle of repose and coefficient of static and dynamic friction of different cereals and beans in relation to moisture content. Asoegwu *et al*. (2006) investigated the physical properties of African oil bean seed and reported the dependence of these properties against mass of the grain. Moisture-dependent physical properties of chick pea seeds (Konak, Carman and Adyin, 2002), coriander seeds (Coskuner and Karababa, 2006), rapeseeds (Calisir *et. al.*, 2005), linseed (Selvi, Pinar and Yesilogu, 2006), pumpkin seeds (Joshi, Das and Mukherjee, 1993), sunflower seeds (Gupta and Das, 1997), safflower seeds (Baumler, *et. al.*, 2005), white lupin (Ogut, 1998), wheat, oats, rye, maize, rape and barley seeds (Scherer and Kutzbach, 1978) and tef seeds (Zewdu and Solomon, 2007) had been reported indicating that these properties are indeed affected by moisture content. However, information on such properties of cardamom seeds is non-existent in literature. Hence, the study was conducted to determine some moisture-dependent physical properties of cardamom seeds such as size, shape, thousand-seed mass (m_{1000}), sphericity, bulk density, true density, porosity, angle of repose and static coefficient of friction.

2 Materials and methods

2.1 Sample preparation

Cardamom seed was procured from the local market near Adama, Ethiopia and cleaned manually to remove foreign materials and impurities. The moisture content of the seeds was determined by drying samples in a circulating air oven set at 105 ± 2°C for 24 h according to ASAE standards S352.3 (ASAE, 1994). In order to attain the desired moisture levels for the study, samples were conditioned by adding a calculated amount of water based on Equation (1) (Zewdu and Solomon, 2007). This was followed by thorough mixing and sealing in plastic bags,

$$Q = \left(\frac{100 - M_i}{100 - M_f} - 1 \right) W_i \qquad (1)$$

The samples were stored at 5 ± 1°C for 7 days for the moisture to distribute uniformly throughout the sample (Carmen, 1996; Zewdu and Solomon, 2007). The moisture content after equilibration was determined at the time of each experiment using the method mentioned above. The required amount of sample was withdrawn from the refrigerator and reconditioned at room temperature (≈ 25°C) for at least two hours before conducting each test (Carmen, 1996). Every test was repeated five times to determine the mean values, unless stated.

2.2 Determination of physical properties

The average length, width and thickness were determined based on 100 randomly selected seeds. Digital calliper with an accuracy of 0.01 mm was used to measure these dimensions. The geometric mean diameter, D_g was calculated using the relationship in Equation (2) (Mohsenin, 1986).

$$D_g = (LWT)^{1/3} \tag{2}$$

The sphericity was determined from the ratio of geometric mean diameter and the largest axial dimension of the seed using Equation (3) (Mohsenin, 1986).

$$\phi = \frac{D_g}{L} \times 100 \tag{3}$$

Seeds were counted using a seed counter (Numigral, Chopin) for (m_{1000}) measurement. Randomly sample dockage free cardamom seeds poured on the hopper grain counter with pre-adjusted reading to 1000 seeds. The instrument gradually count 1000 seeds and delivered them into the received bucket. Then, the 1000 seeds were weighed using a digital electronic balance reading 0.0001g.

The bulk density was measured by filling into stainless steel cylinder of known volume to overflowing and removing excess seeds by rolling cylindrical glass rod on the rim of the container without compacting the seeds (Carmen, 1996; Zewdu and Solomon, 2007). The mass of the seeds filled in the cylinder divided by the volume of cylinder gave the bulk density. Bulk density was calculated as is shown in Equation 4:

$$\rho_b = \frac{M_x}{V_c} \tag{4}$$

True density was determined as the ratio of sample mass to the true volume of the particles using toluene ($C_6H_5.CH_3$) displacement method (Konak, Carman and Aydin, 2002; Nimkar and Chattopadhyay, 2001). True density was calculated as is shown in Equation 5:

$$\rho_t = \frac{M_s}{V_f - V_i} = \frac{M_s}{V_d} \tag{5}$$

The porosity ε was determined using Equation (6) (Mohsenin, 1986).

$$\varepsilon = \left(1 - \frac{\rho_b}{\rho_t}\right) \times 100 \tag{6}$$

A tapering hopper made of sheet metal with the top and bottom having a dimension of 300 mm × 300 mm and 100 mm × 100 mm, respectively and a height of 300 mm was used to measure the angle of repose. At 200 mm from the top, a circular disc of 100 mm diameter was fixed so that enough gap was left between the hopper walls and the disc, which allows the seeds to flow through during the test. A horizontal sliding gate was provided right below the disc for sudden release of the seed during the test. Similar device was used to determine angle of repose for green gram (Nimkar and Chattopadhyay, 2001) and tef seed (Zewdu and Solomon, 2007). While testing, seeds were filled in the hopper and the horizontal sliding gate was suddenly opened. The height of seeds piled on the circular disc was measured and used to calculate the angle of repose, θ using Equation (7):

$$\theta = \tan^{-1}\left(\frac{h}{r}\right) \tag{7}$$

The static coefficient of friction μ was determined for three different surfaces (plywood, galvanized iron and mild steel). A plastic cylinder of 155 mm diameter and 105 mm height was filled with sample and placed on tilting table covered with the different surfaces and having a scale to read the tilting angle directly. The seed-filled cylinder was raised slightly so that it will not have contact with the surface. The table was raised gradually using a screw device till the cylinder just started to slide down and the corresponding tilting angle, φ was recorded. The value of μ was calculated using Equation (8) (Mahapatra *et al.*, 2002):

$$\mu = \tan\varphi \tag{8}$$

2.3 Statistical analysis

Descriptive statistics was used to determine mean values and regression analysis was employed to describe the moisture-dependence of physical properties. One-way analysis of variance (ANOVA) was run to test the significance of the effect of moisture content on physical properties using SPSS version 10 (SPSS, 1999).

3 Results and discussion

3.1 Moisture content

As seeds were procured from market, the moisture content was determined as loss in weight of the sample by heating in oven-drying method and was found to be 9.9 % w.b. In order to test physical properties dependence on moisture content, different amount of distilled water was added to cardamom seeds. Accordingly, four levels of moisture content of 9.9, 13.57, 18.41 and 23.29 % w.b. were obtained.

3.2 Seed size

The length, width and thickness of cardamom seeds increased significantly *($p<0.05$)* from 17.01 to 17.30 mm, 5.68 to 6.57 mm, and 5.02 to 5.35 mm, respectively with the increase in moisture content from 9.90 to 23.29% w.b. Similarly, the geometric mean diameter increased from 7.86 to 8.47 mm in the same moisture content range indicating that moisture content influences these properties as is shown in

Figure 1 and Figure 2. The increase in the dimensions are attributed to expansion or swelling as a result of moisture uptake in the intracellular spaces within the seeds. The relationship between these seed dimensions and moisture content was found to be linear and can be given by Equations (9 to 12).

$$L = 0.020Mc + 16.80 \qquad R^2 = 0.91 \qquad (9)$$
$$W = 0.063Mc + 5.072 \qquad R^2 = 0.98 \qquad (10)$$
$$T = 0.022Mc + 4.783 \qquad R^2 = 0.90 \qquad (11)$$
$$D_g = 0.043Mc + 7.431 \qquad R^2 = 0.97 \qquad (12)$$

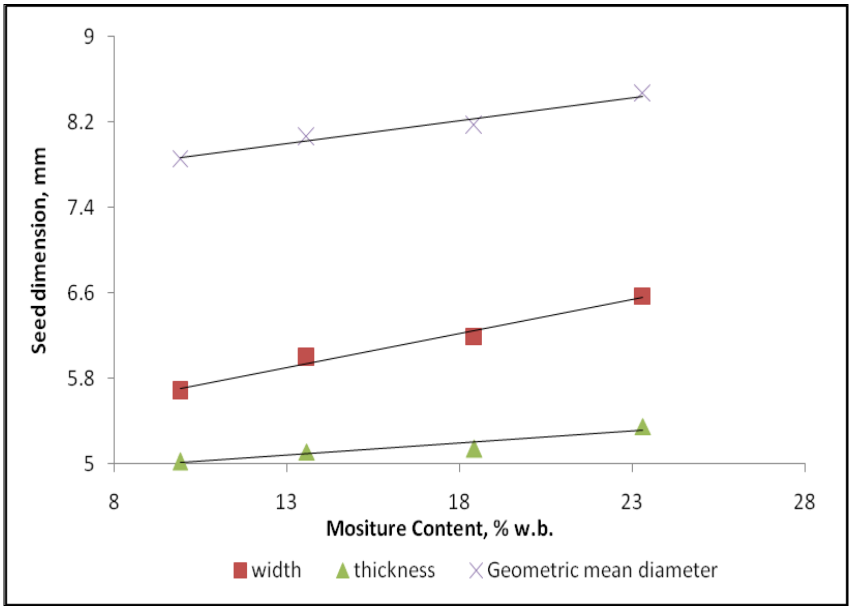

Figure 1 Effect of moisture content on seed dimension of cardamom seed

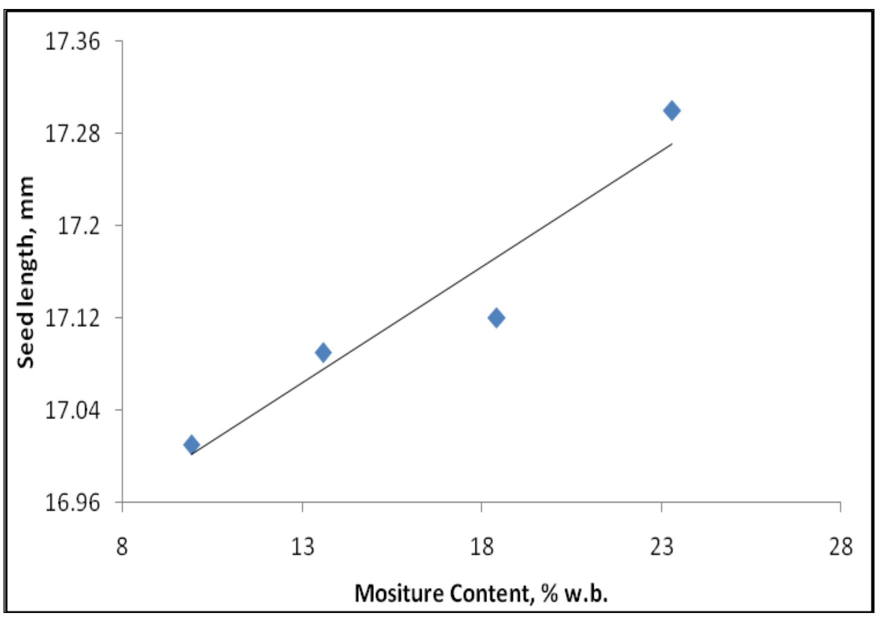

Figure 2 Effect of moisture content on seed length of cardamom seed

The increase in all dimensions of cardamom seeds shows the expansion of the seed with the increase in moisture content. Similarly, the diameter and thickness of lentil seeds, (Amin, Hossain and Roy, 2004), the length, diameter and geometric mean diameter of tef seed (Zewdu and Solomon, 2007), length, width, thickness and geometric mean diameter of popcorn (Karababa, 2006) were also reported to increase linearly with the increase in moisture content. A linear decrease in seed length was reported for coriander seed, but the width and thickness increased with higher moisture content (Coskuner and Karababa, 2006).

3.3 One thousand seed mass (m_{1000})

One thousand seed mass increased from 120.83 to 165.60 g (*p<0.05*) significantly with the corresponding increase in moisture content from 9.9 to 23.29% w.b. which accounts for the weight of the added moisture into the seed (Figure 3). Thousand seed mass of cardamom is relatively big compared with other crops in literature. The relationship between m_{1000} and moisture content was found to be linear and described in Equation (14):

$$m_{1000} = 3.174Mc + 92.69 \quad R^2 = 0.97 \tag{14}$$

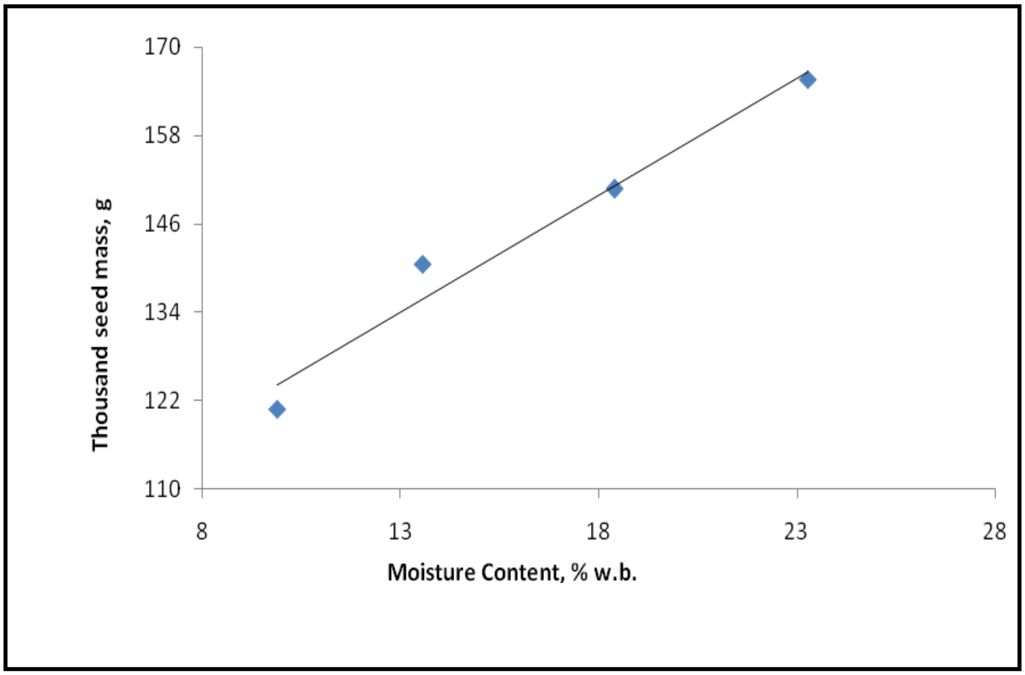

Figure 3 Effect of moisture content on thousand seed mass of cardamom seed

Such linear relationship between m_{1000} and moisture content was reported for caper seed (Dursun and Dursun, 2005), sorghum (Mahapatra, Patrick, and Diau, 2002) green gram (Nimkar and Chattopadhyay, 2001), wheat, oats, rye, rape seed and barley (Scherer and Kutzbach, 1978).

3.4 Sphericity

The increase in sphericity was not significant (*p>0.05*) from 0.46 to 0.49 with the increase in the moisture content from 9.9 to 23.29% (Figure 4). The increase in sphericity was a result of the relative increase in width and thickness is exceeding the relative increase in length. Linear relationship described better the dependence of sphericity on moisture content and it is presented as in Equation (13):

$$\phi = 0.002Mc + 0.442 \qquad R^2 = 0.98 \qquad (13)$$

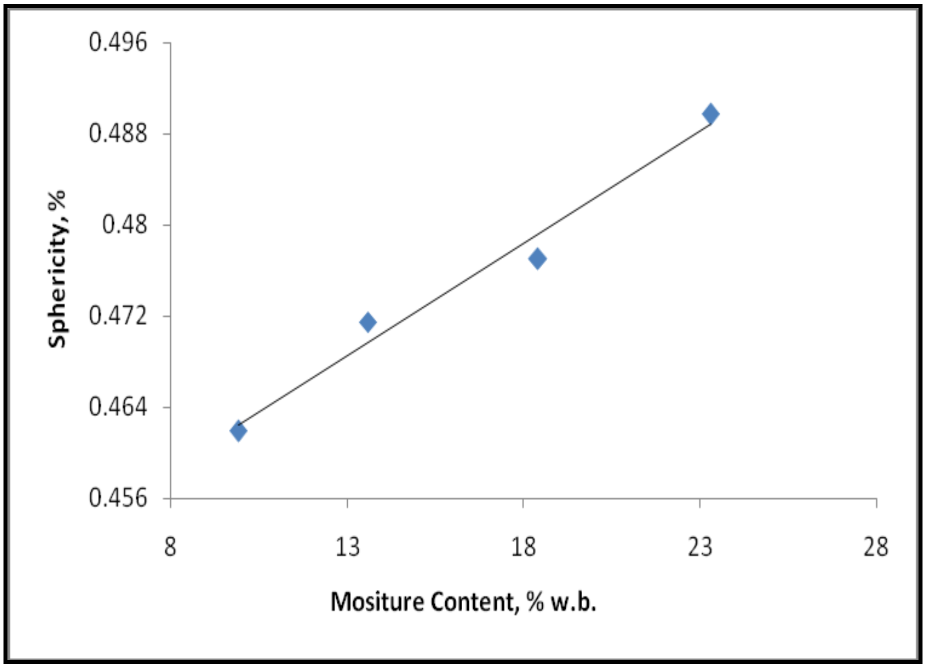

Figure 4 Effect of moisture content on sphericity of cardamom seed

An increase in the sphericity with increase in moisture content was observed for pistachio kernel (Kashaninejad *et al.*, 2006), vetch seed (Yalcin and Ozarslan, 2004), and fenugreek seeds (Altuntas, Ozgoz and Tase, 2005). The sphericity of sorghum seeds (Mahaptra, Patrick and Diau, 2002) and linseeds (Coskuner and Karababa, 2006) appeared to be less affected by moisture content. Zewdu and Solomon (2007) found a quadratic relationship between sphericity and moisture content for tef seed.

3.5 Bulk and true density

The bulk and true densities of cardamom seeds decreased with increase in moisture content (in Figure 5). A decrease which was not significant ($p>0.05$) from 408.20 to 358.90 kg/m^3 and a significant decrease ($p<0.05$) 926.57 to 787.10 kg/m^3 was observed for bulk and true densities, respectively, with the increase in moisture content from 9.9 to 23.29% w.b. The relative reduction in the densities at high moisture content could be attributed to less weight gain due to the added moisture in relation to the concomitant volumetric expansion of the seeds. This can be cited as the cause in decrease of both the bulk and true density. A linear relationship described the moisture dependence of both true and bulk densities as is shown in Equation (15) and (16):

$$\rho_t = -10.54Mc + 1024 \qquad R^2 = 0.98 \qquad (15)$$

$$\rho_b = -3.803Mc + 443 \qquad R^2 = 0.95 \qquad (16)$$

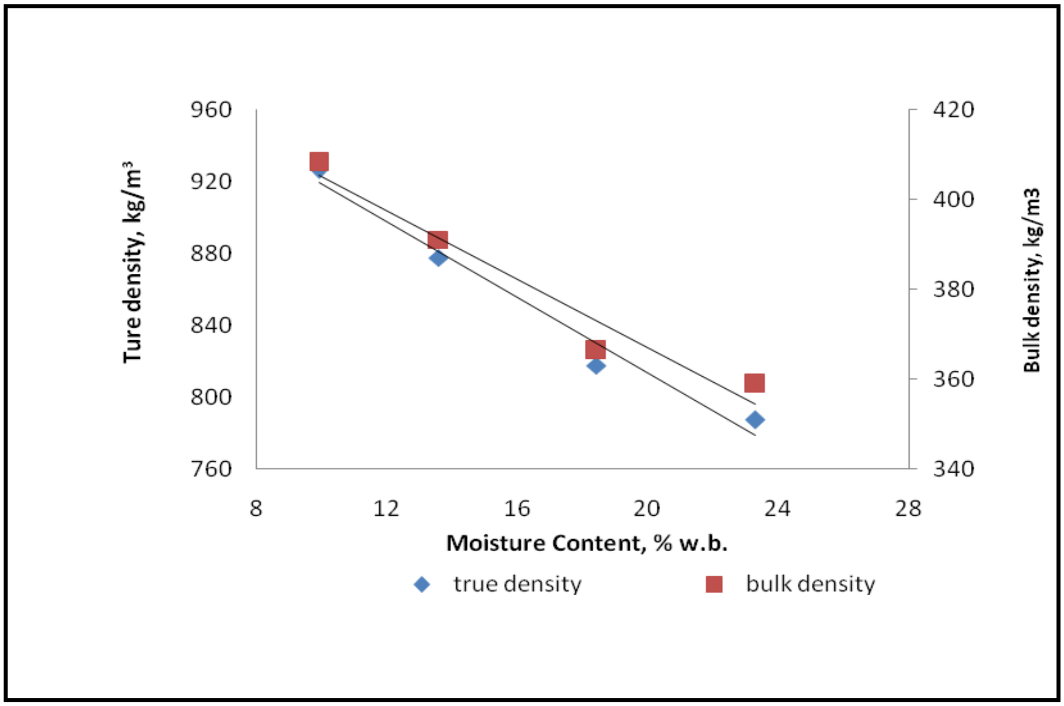

Figure 5 Effect of moisture content on true and bulk density of cardamom seed

The linear decrease of both bulk and true densities as moisture content increases was observed in sorghum seeds (Mahapatra, Patrick and Diau, 2002), green gram (Nimkar and Chattopadhyay, 2001), and wheat, rye, maize, rape seed and barley (Scherer and Kutzbach, 1978). But for coffee berries (Chandrasekar and Viswanathan, 1999) both bulk and true densities increased with the increase in moisture content.

3.6 Porosity

The porosity showed a slight reduction which was not significant (p>0.05) from 55.94 to 54.41% with the increase in moisture content. The decrease in porosity resulted as the bulk density relatively decreased slightly, with relatively higher reduction in true density (in Figure 6). The porosity values of cardamom seeds are higher as the bulk density is smaller than true density. cardamom seeds' porosity demonstrates to be high compared with most crops, whose porosity lies between 55.94-54.41% in range, but the seeds with lower bulk density such as faba bean (Altuntas and Yildiz, 2007), oats (Scherer and Kutzbach, 1978), pumpkin seeds (Joshi, Das and Mukherjee, 1993), and rice (Kibar, Öztürk, and Esen, 2010) showed higher porosity values.

Moreover, porosity was found to be a linear function of moisture content with a decreasing trend as in Equation (17):

$$\varepsilon = -0.107Mc + 57 \qquad R^2 = 0.96 \qquad (17)$$

Porosity of pumpkin (Joshi, Das and Mukherjee, 1993), and sorghum (Mahapatra, Patrick and Diau, 2002) seed showed a decreasing trend with increasing moisture content, but porosity of tef seeds (Zewdu and Solomon, 2007), green gram (Nimkar and Chattopadhyay, 2001) and barley and rapeseed (Scherer and Kutzbach, 1978) showed an increase with the increase in moisture content. This indicated that porosity of seeds of different crops could respond differently for changes in the moisture content, which could be attributed to their morphological characteristics.

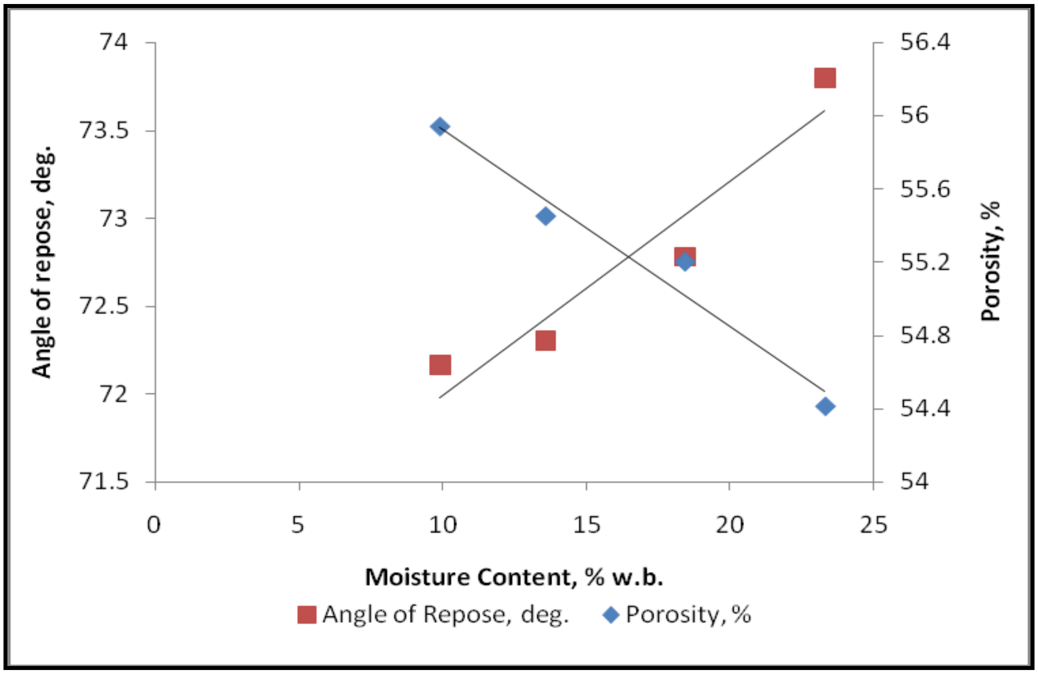

Figure 6 Effect of moisture content on angle of repose and porosity of cardamom seed

3.7 Angle of repose

The angle of repose θ obtained at different moisture contents is shown in Figure 6. An increase in the moisture content from 9.9 to 23.29% w.b. resulted in the increase of angle of repose θ from 72.16° to 73.80°. A linear relationship described the dependence of angle of repose on moisture content as presented in Equation (18):

$$\theta = 0.122Mc + 70.77 \qquad R^2 = 0.92 \qquad (18)$$

Increasing trend in angle of repose was observed for chickpea seeds (Konak, Carman and Aydin, 2002), green gram (Nimkar and Chattopadhyay, 2001) canola and sunflower meal pellets (White and Jayas, 2001), and tef seed (Zewdu and Solomon, 2007). Scherer and Kutzbach, (1978) fitted a parabolic equation with an initial decreasing angle of repose with the increase in moisture content followed by a positive relationship between the two parameters for wheat, oats, rye, maize, rape seed and barley.

3.8 Static coefficient of friction

The static coefficient of friction determined at different moisture content levels on three different surfaces (mild steel, galvanized iron and plywood) increased following a linear relationship as moisture content increased from 9.9 to 23.29% for both surfaces (Figure 7). Accordingly, μ increased from 0.41 to 0.50, 0.44 to 0.53 and 0.47 to 0.56 for mild steel, galvanized iron and plywood, respectively. The increase could be due to the fact that the increased adhesion between seeds and sliding surfaces and the decrease in sphericity, which have effects in reducing seed's smooth surface and affecting sliding characteristics. But initially, for cardamom seeds, too the static coefficient of friction at lower moisture contents are high, similar results were reported for white lupin (Ogut, 1998) in which at lower moisture content higher static coefficient of friction was demonstrated. This fact can be associated with the nature of the surface of the cardamom seeds which are rough compared to many other seeds. The maximum static coefficient of friction was found to be 0.56 at 23.29% Mc for plywood. The trend observed was in agreement with the studies made for sorghum (Mahapatra, Patrick and Diau, 2002), chickpea seeds (Konak, Carman and Aydin, 2002) and okra seeds (Sahoo and Srivastava, 2002). The relationship between μ and moisture content was found to be linear as is shown in Equations (19) and (20):

$$\mu_{pw} = 0.006Mc + 0.401 \qquad R^2 = 0.96 \qquad (19)$$

$$\mu_{ms} = 0.006Mc + 0.377 \qquad R^2 = 0.92 \qquad (20)$$

$$\mu_{gi} = 0.006Mc + 0.351 \qquad R^2 = 0.98 \qquad (21)$$

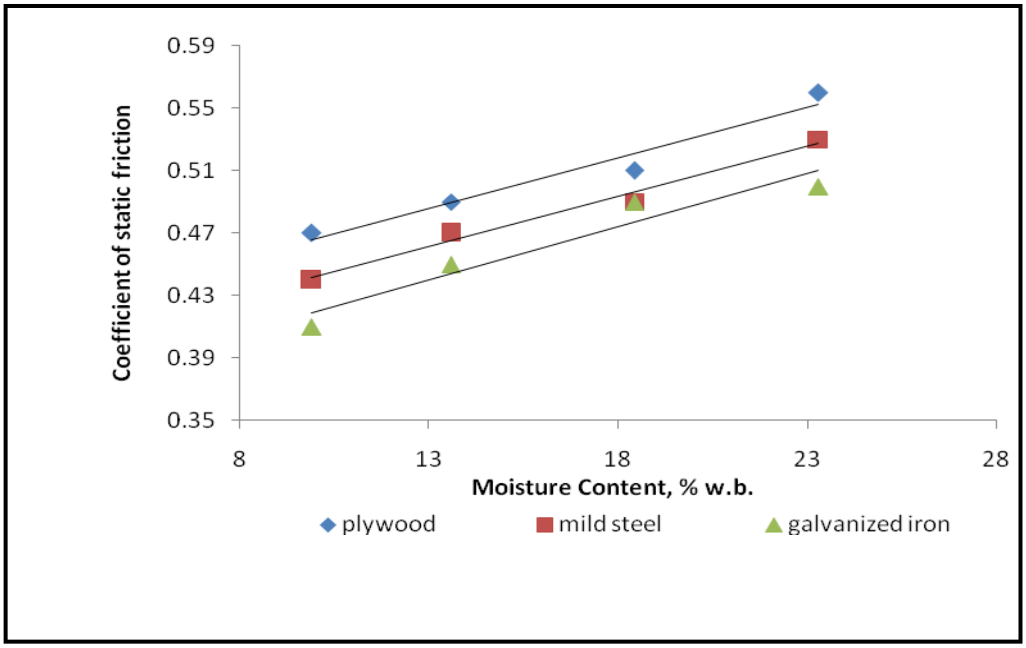

Figure 7 Effect of moisture content on static coefficient of friction of cardamom seed

4 Conclusions

The following conclusions were reached from the experiment of determining the effect of moisture content on the physical property of cardamom seeds. The axial dimensions of cardamom seed were increased with the moisture content. The increases in the dimensions are attributed to expansion or swelling as the result of moisture uptake in the intracellular spaces within the seeds. The length, width, thickness, geometric mean diameter, thousand seed mass and sphericity of seeds increased from 17.01 to 17.30 mm, 5.68 to 6.57 mm, 5.02 to 5.35 mm, 7.86 to 8.47 mm, 120.83 to 165.60 g and 46.19 to 48.97%, respectively, with the increase in moisture content from 9.9 to 23.29% w.b. The bulk density and porosity are crucial properties in the development of aeration and drying system as these properties affect the resistance to airflow of stored mass. As the moisture content increased from 9.9 to 23.29% the bulk density, true density and porosity of cardamom seed decreased linearly from 408.20 to 358.90 kg/m^3, 926.57 to 787.19 kg/m^3 and 55.94 to 54.41% respectively . The angle of repose increased from

72.16° at 9.9% to 73.80° at 23.29% moisture content with linear relationship. Whereas, the static coefficient of friction increased with the increase in moisture content from 9.9 to 23.29% on three different surfaces. The highest static coefficient of friction was recorded when cardamom seed against plywood (0.47 to 0.56), and lowest static coefficient of friction against mild steel (0.41 to 0.50). The static coefficient of friction between cardamom seeds and galvanized iron surface increased from 0.44 to 0.53 within the studied moisture content range.

Acknowledgments

I would like to express my deepest gratitude to Dr.-Ing Zewdu Abdi for giving me comments and moral support throughout the entire work of my research. I am also happy to give my thanks to the Head Department of Chemical Engineering, Mr. Tatek Temesgen and staff for helping me in many aspects of during my research work.

References

Altuntas, E., E. Ozgoz, and Tase. 2005. Some physical properties of fenugreek (*Trigonella foenum-graceum* L.) seeds. *Journal of Food Engineering,* 71 (1): 37-43.

Altuntas, E., M. Yildiz. 2007. Effect of moisture content on some physical and mechanical properties of faba bean (*Vicia faba L.*) grains. *Journal of Food Engineering,* 78 (1): 174-183.

Amin, M. N., M. A. Hossain, and K. C. Roy. 2004. Effect of moisture content on some physical properties of lentil seeds. *Journal of Food Engineering,* 65 (1): 83-87.

ASAE. 1994. ASAE standards S352.3-moisture measurement-ungrounded grains and seeds. In: ASAE standards 1994, 469 St. Joseph, mi: ASAE

Asoegwu, S. S., O. O., Kanu, and C. Iwueke. 2006. Physical properties of African oil bean seed (pentaclethra macrophylla). *Agric Eng Int: CIGR Journal,* Vol. VIII, Manuscript No. 673.

Baumler, E., A. Cuniberti., S. M. Nolasco, and I. C. Riccobene. 2005. Moisture dependent physical and compressional properties of safflower seed. *Journal of Food Engineering*, 102 (1): 58-65.

Calisir, C., T. Marakoglu, H. Ogut, and O. Ozturk. 2005. Physical properties of rapeseed (*Brassica napus oleifera* L.). *Journal of Food Engineering*, 69 (1): 61-66.

Carmen, K. 1996. Some physical properties of lentil seeds. *Journal of Agricultural Engineering Research,* 63 (2): 87-92.

Chandrasekar, V., and R. Viswanathan. 1999. Physical and thermal properties of coffee. *Journal of Agricultural Engineering Research*, 73 (3): 227-234.

Coskuner, Y., and E. Karababa. 2006. Physical properties of coriander seeds (*Coriandrum sativum* L.). *Journal of Food Engineering,* 80 (2): 408-416.

Duke, J. 1992. *Handbook of phytochemical constituents of GRAS herbs and other economic plants.* CRC Press, Boca Raton, FL, 239-240.

Duke, J. 1997. *The green pharmacy, the ultimate compendium of natural remedies from the world's foremost authority on healing and herbs.* Pp. 15; 82; 94; 223; 232-33; 237; 253-54; 293; 370-71; 536. Rodale Press.

Dursun, E., and I. Dursun. 2005. Some physical properties of caper seed. *Biosystems Engineering*, 92 (2): 237-245.

George, C. K., M. Ramesh, and B. Bastiaan. 2007. International Trade Center Nepal, sector study on large cardamom seed.

Gupta, R. K., and S. K. Das. 1997. Physical properties of sunflower seeds. *Journal of Agricultural Engineering Research*, 66(1), 1-8.

Hauhouot-o'hara, M., B. R. Criner, G. H. Brusewitz, and J. B. Soli. 2000. Selected physical characteristics and aerodynamic properties of cheat seed for the separation of wheat. *Agric Eng Int: CIGR Journal*, Vol. VII, Manuscript No. 82.

Jekayinfa, S.O. 2006. Effect of airflow rate, moisture content and pressure drop on the airflow resistance of locust bean seed. *Agric Eng Int: CIGR Journal*, Vol. VIII, Manuscript No. 653.

Joshi, D. C., S. K. Das, and K. R. Mukherjee. 1993. Physical properties of pumpkin seeds. *Journal of Agricultural Engineering Research*, 54 (3): 219-229.

Karababa, E. 2006. Physical properties of popcorn kernels. *Journal of Food Engineering*, 72 (1): 100-107.

Kashaninejad, M., A. Mortazavi, A. Safekordi, and L.G. Tabil. 2006. Some physical properties of pistachio (Pistacia vera L.). *Journal of Food Engineering*, 72 (1), 30-38.

Kibar, H., T. Öztürk, and B. Esen. 2010. The effect of moisture content on physical and mechanical properties of rice (Oryza sativa L.). *Spanish Journal of Agricultural Research*, 8(3): 741-749

Konak, M., K. Carman, and C. Aydin. 2002. Physical properties of chickpea seeds. Biosystems Engineering, 82 (1): 73-78.

Kutzbach, H. D., and R. Scherer. 1977. Das Reibverhalten von Koernerfruechten - eine Schrifttumsuebersicht [Frictional properties of seeds – a literature survey]. *Grundlage der Landtechnik*, 27 (6): 213-219.

Mahapatra, A. K., C. Patrick, and P. Diau. 2002. Effect of moisture content on some physical properties of sorghum (mahube variety) seeds. *Agricultural Engineering Journal,* 11 (1): 1-10.

Mohsenin, N. N. 1986. *Physical properties of plant and animal materials* (2nd ed.). Gordon and Breach Science Publishers, New York.

Molenda, M., J. Horabik, I. J Ross, and M. D. Montross. 2002. Friction of wheat: grain on grain and on corrugated steel. *Transactions of the American society of agricultural engineers*, 45 (2): 415-420.

Nimkar, P. M., and P. K. Chattopadhyay. 2001. Some physical properties of green gram. *Journal of Agricultural Engineering Research*, 80 (2): 183-189.

Ogut, H. 1998. Some physical properties of white lupin. *Journal of Agricultural Engineering Researc*, 69 (3): 273-277.

Sahoo, P. K., and A. P. Srivastava. 2002. Physical properties of okra seed. *Biosystems Engineering*, 83 (4): 441-448.

Scherer, R., and H. D. Kutzbach. 1978. Mechanische eigenschaften von koerner-fruechten [mechanical properties of grains]. *Grundlage der landtechnik*, 28 (1): 6-12.

Selvi, C. S., Y. Pinar, and E. Yesiloglu. 2006. Some physical properties of Linseed. *Biosystems Engineering*, 95 (4): 607-612.

SPSS. 1999. Statistical package for social scientists, Printice hall, Chicago, il.

Tran, T. T., G. S. Srzednicki, and R. H. Driscoll. 1999. Aeration on the quality of popcorn. *Agric Eng Int: CIGR Journal*, Vol. I, Manuscript No. 1043.

White, N. D. G., and D. S. Jayas. 2001. Physical properties of canola and sunflower meal pellets. *Canadian Biosystems Engineering*, 43 (3): 49-52.

Wu, S., S. Sokhansanj, R. Fang, and A. Opoku. 1999. Influence of physical properties and operating conditions on particle segregation on gravity table. *Applied Engineering in Agriculture,* 15 (5): 495-499.

Yalcin, I., and C. Ozarslan. 2004. Physical properties of vetch seed. *Biosystems Engineering*, 88 (4): 507-512.

Zewdu, A. D. 2004. Untersuchungen zur leistungssteigerung der reinigungsanlage eines maehdreschers durch zusaetzlichen querschwingungen (Investigations into performance improvement of combine cleaning shoe through additional lateral oscillations), Ph.D thesis, Technical University of Dresden, Germany. 125 pp.

Zewdu, A. D., and W. K. Solomon. 2007. Moisture-dependent physical properties of tef seed. *Biosystems Engineering,* 96 (1): 57-63.

Nomenclatures

Mc	moisture content of seed sample, % w.b.
M_i	initial moisture content of the sample, % w.b.
M_f	final moisture content of the seed sample, % w.b.
W_i	initial mass of the sample of to be rewetted, kg
Q	mass of water to be added during rewetting, kg
L	length of the seed, mm
W	width of the seed, mm
T	thickness of the seed, mm
A_m	arithmetic mean diameter, mm
D_g	geometric mean diameter, mm
m_{1000}	thousand-seed mass, g
ϕ	sphericity
ρ_b	bulk density, kg/m^3
M_x	the mass of the seed filled in cylinder, g
V_c	the volume of cylinder, cm^3
ρ_t	true density, kg /m^3
M_s	the mass of seed, g
V_i	initial volume of toluene, mL
V_f	the sum of the initial volume of toluene (V_i) plus volume of the seed, mL

ε	porosity, %
R^2	correlation coefficient
θ	angle of repose, deg
h	height of piled seed in the determination of angle of repose, mm
r	radius of disc in the determination of angle of repose, mm
μ	static coefficient of friction
φ	angle of tilt in determination of static coefficient of frication, deg
μ_{ms}	static coefficient friction of the seed on mild steel surface
μ_{gi}	static coefficient of friction of the seed on galvanized iron surface
μ_{pw}	static coefficient of friction of the seed on plywood surface