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Thermal properties of guna seed

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A b s t r a c t. The specific heat, thermal conductivity and thermal diffusivity of whole and ground guna seed and kernel were evaluated and their change with moisture content and temperature investigated. The specific heat of whole and ground seed increased from 1391.1 to 3020.13 and from 1459.14 to 3058.15 J kg^{-1} K^{-1}, respectively, as the moisture content and temperature increased from 4.7 to 25.35% (d.b.) and 307.12 to 368 K. The specific heat of whole and ground kernel also increased from 2135.15 to 4275.56 and from 2173.4 to 4340.06 J kg^{-1} K^{-1}, respectively, as the moisture content and temperature increased from 5.6 to 19.13% (d.b.) and 308 to 368 K. The thermal conductivity of whole seed and kernel increased from 0.0711 to 0.1282 and 0.087 to 0.126 W m^{-1}K^{-1}, respectively, as the moisture content and temperature increased. Thermal conductivity of ground seed and kernel increased also from 0.1 25 to 0.223 and 0.107 to 0.191 W m^{-1}K^{-1}, respectively, as the moisture content and temperature increased. The thermal diffusivity of whole seed and kernel decreased from 8.5 10^{-8} to 9.311 10^{-8} and 3.42 10^{-8} to 4.397 10^{-8} m^2 s^{-1}, respectively, as the moisture content and temperature increased. The thermal diffusivity of ground seed and kernel decreased from 3 10^{-7} to 8.468 10^{-8} and 1.768 10^{-7} to 4.214 10^{-8} m^2 s^{-1}, respectively, as the moisture content and temperature increased.

K e y w o r d s: guna seed, thermal properties, specific heat, thermal conductivity, thermal diffusivity

INTRODUCTION

Guna (*Citrullus colocynthis*) is an important oil and protein yielding crop in the North-East Region of Nigeria. The oil obtained from the seed kernel has an adequate content of essential amino acids and a complete absence of α-linoleic acid that can cause stability problem in refined oil (Norton, 1993). The oil is extracted using methods and processes that involve size reduction and heat transfer operations (Aviara and Haque, 2002), therefore, information on the thermal properties of the seed is essential in the development of the processes and equipment needed in its thermal processing, as well as in drying and storage.

The primary thermal properties of food and agricultural products are specific heat, thermal conductivity and thermal diffusivity. Specific heat is the property needed in the estimation of the amount of energy required to change the temperature of a product, while thermal conductivity and thermal diffusivity are involved in the determination of the rate of heat transfer for efficient process and equipment design (Wallapapan and Sweat, 1982).

Several researchers have used the methods described by Mohsenin (1980) to investigate the specific heat of food and agricultural materials. Fasina and Sokhansanj (1995) determined the specific heat of alfalfa pellets using a procedure that employed the measured thermal conductivity, thermal diffusivity and bulk density. Choi and Okos (1986) and Yang *et al*. (2002) determined the specific heat of major food components and borage seed using the differential scanning calorimeter, while Ezeike (1987) described the use of a modified adiabatic bomb calorimeter in determining the specific heat of tropical food crops. Aviara and Haque (2001), Aviara *et al*. (2003), Dutta *et al*. (1988), and Shepherd and Bhardwaj (1986) used calibrated aluminium and copper calorimeters placed inside insulated vacuum flasks to measure the specific heat of pigeon pea, gram, sheanut kernel and soybean, respectively. Other workers who used the method of mixtures include Oje and Ugbor (1991), Taiwo *et al*. (1996), Deshpande and Bal (1999), Ogunjimi *et al*. (2002) and Subramanian and Viswanathan (2003). Dutta *et al*. (1988), Fraser *et al*. (1978), Telis-Romero *et al*. (1998), Singh and Goswami (2000) and Aviara and Haque (2001) reported that the specific heat of faba beans, Brazilian

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orange juice, cumin seed, gram and sheanut kernel, respectively, increased with increase in moisture content and temperature, while Taiwo *et al*. (1996) and Aviara *et al*. (2003) noted that that of ground cowpea and soybean seed, respectively, increased with increase in moisture content and temperature up to a certain level, and decreased with further increase in temperature. Fasina and Sokhansanj (1995) noted the existence of a polynomial relationship of the second order between the specific heat of alfalfa pellets and moisture content, and Timber (1975) reported that the specific heat of whole rapeseed was higher than that of ground seed. Similar results were obtained for millet grains and flours by Subramanian and Viswanathan (2003).

The transient heat flow and one dimensional steady-state heat flow methods have been used in determining the thermal conductivity of food and agricultural material. The property can also be calculated from the specific heat and bulk density if the thermal diffusivity is known. Reidy and Rippen (1971) discussed the various measurement techniques in the above methods and highlighted their merits and shortcomings. Wallapapan and Sweat (1982), Shepherd and Bhardwaj (1986), Dutta *et al*. (1988), Rahman and Potluri (1991), Fasina and Sokhansanj (1995), Taiwo *et al*. (1996,) Singh and Goswani (2000), Yang *et al*. (2002), Yang *et al*. (2003) and Subramanian and Viswanathan (2003) used the line heat source thermal conductivity probe to measure the thermal conductivity of defatted soyflour, pigeon pea, gram, squid meat, alfalfa pellets, ground cowpea, cumin seed, borage seeds, rough rice and millet grains and flours, respectively, and reported that thermal conductivity increased with increase in moisture content. Dua and Ojha (1969) measured the thermal conductivity of paddy grain and its by-products using a steady state apparatus, while Drusas *et al*. (1986) determined the thermal conductivity of starch gels using the steady state and transient heat flow methods and reported that both methods yielded similar results. Aviara and Haque (2001) measured the thermal conductivity of sheanut kernel using the steady state heat flow method and noted that the thermal conductivity increased with increase in moisture content. Timber (1975) reported that the thermal conductivity of whole rapeseed was higher than that of ground seed. Similar results were obtained by Subramanian and Viswanathan (2003) on millet grains and flours. Drusas *et al*. (1986) and Fasina and Sokhansanj (1995) measured the thermal diffusivity of starch gels and alfalfa pellets using the Dickerson (1965) apparatus. Drusas *et al*. (1986) found no satisfactory relationship between the thermal conductivity and thermal diffusivity of starch gel with moisture content and temperature, while Fasina and Sokhansanj (1995) reported a linear increase of thermal diffusivity of alfalfa pellet with moisture content. Shepherd and Bhardwaj (1986), Dutta *et al*. (1988), Deshpande *et al*. (1996), Aviara and Haque (2001) and Yang *et al*. (2002) evaluated the thermal diffusivity of pigeon pea, gram, soybean, sheanut kernel and borage seeds, and noted that the thermal diffusivity of these products increased with increase in moisture content. Singh and Goswami (2000) observed that the thermal diffusivity of cumin seed increased with temperature and moisture content up to a level, and decreased with further increase in temperature and moisture content. Subramanian and Viswanathan (2003) and Mariani *et al*. (2008) reported that the thermal diffusivity of millet grains and flours and banana, respectively, decreased with increase in moisture content. Timber (1975) observed that the thermal diffusivity of whole rapeseed was higher than that of ground seed.

A perusal of literature shows that data on the thermal properties of guna seed and kernel does not appear to be available. The objective of this study was, therefore, to determine the thermal properties of guna seed and kernel and to investigate their dependence on moisture content and temperature.

MATERIAL AND METHODS

A bulk quantity of dried guna seeds at stable storage conditions was obtained from Nguru in Yobe state, Nigeria. The seeds were cleaned and sampled for experiments using a multi-slot riffle box divider. The samples were pooled and divided into two portions. One portion was left as unshelled seeds and the other was manually shelled to obtain intact kernels. The moisture content of the seeds and kernels was determined using the method reported by Ajibola *et al*. (1990), as applied by Aviara *et al*. (2005). Tests were carried out on samples of whole and ground seeds and kernels at four moisture levels in the ranges of 4.7 to 25.35% (d.b.) and 5.6 to 19.13%, respectively. Samples at the desired moisture level in the above ranges were prepared by conditioning them using the method that was reported by Ezeike (1986).

The specific heat of whole and ground seed and kernel was determined using calibrated copper calorimeters placed inside flasks, using the method of mixtures. The calorimeters were calibrated following the procedure described by Aviara and Haque (2001). To determine the specific heat of either whole or ground guna seed or kernel, a sample of known mass, temperature and moisture content was dropped into the calorimeter containing water of known mass and temperature. The mixture was stirred continuously using a copper stirrer and the temperature was recorded at an interval of three seconds. At equilibrium, the final temperature was noted and the specific heat was calculated using the equation:

$$C_S \approx \frac{\left(m_C C_C + m_W C_W\right)\left[T_W - \left(T_e + t'R'\right)\right]}{m_S\left[\left(T_e + t'R'\right) - T_S\right]}, \qquad (1)$$

where: C_C, C_S and C_W are the specific heats of calorimeter, sample and water, respectively (J kg^{-1} K^{-1}), m_C, m_S and m_W are the masses of calorimeter, sample and water (kg), respectively, R' is the rate of temperature fall of the mixture after equilibrium (K s^{-1}), T_e is the equilibrium temperature of the sample and water mixture (K), T_S, and T_W are the initial temperatures of sample and water, respectively (K), and t' is the time taken for the sample and water mixture to come to equilibrium (s). The term $t'R'$ accounts for the heat of hydration and heat exchange with the surroundings.

At each moisture level of the samples, five temperature ranges between the initial temperature of sample and final temperature of the water and sample mixture and their average values were used to investigate the effect of temperature on the specific heat of guna seed and kernel. The experiment was replicated three times at each moisture content and temperature range and the average values of the specific heat were recorded.

The thermal conductivity of whole and ground seed and kernel was determined using the guarded hot-plate apparatus with steady state heat flow method described by Aviara and Haque (2001). The thickness of whole sample was maintained as the minor axial dimension of the seed or kernel at the moisture content in which the experiment was conducted, while that of the ground sample was varied to yield the desired temperature differences at equilibrium, which with the obtained heat flux, was used to calculate the thermal conductivity of the sample. Each experiment was repeated twice and the average values of thermal conductivity were recorded.

The thermal diffusivity of whole and ground seed and kernel was calculated using the values of specific heat, thermal conductivity and bulk density from the following expression:

$$\alpha \approx \frac{k}{\rho_b C_S}, \qquad (2)$$

where: α is the thermal diffusivity (m^2 s^{-1}), k is the thermal conductivity (W $m^{-1}K^{-1}$), ρ_b is the bulk density of sample (kg m^{-3}) and C_S is the specific heat of sample (J kg^{-1} K^{-1}). The bulk density that was substituted in the above relationship was obtained using the regression equations reported by Aviara *et al.* (1999) and Aviara and Haque (2000), for whole guna seed and kernel, respectively. The equations are as follows:

$$\rho_{bs} \approx 564.4 - 4.2M, \qquad R^2 = 0.99, \qquad (3)$$

$$\rho_{bk} \approx 620.058 - 2.024M, \qquad R^2 = 0.92, \qquad (4)$$

where: ρ_{bs} is the bulk density of whole seed (kg m^{-3}), ρ_{bk} is the bulk density of whole kernel (kg m^{-3}) and M is the moisture content (%, d.b.).

The relationships existing between guna seed and kernel thermal properties and their moisture content and temperature were established using the multiple regression procedure in SPSS 10.0 for Windows.

RESULTS AND DISCUSSION

Specific heat

The changes in the specific heat of whole and ground guna seed and kernel with moisture content at different temperature ranges are presented in Figs 1-2, respectively. From these figures, it can be seen that the specific heat of both seed and kernel increased linearly with moisture content as the range between the initial temperature of the sample and the final temperature of sample and water mixture varied from 307.12-328 and 308-328 to 313.45-368 and 315.27-368 K, respectively. Similar trend was observed in the specific heat of cumin seed (Singh and Goswami, 2000), sheanut kernel (Aviara and Haque, 2001), soybean (Aviara *et al.*,

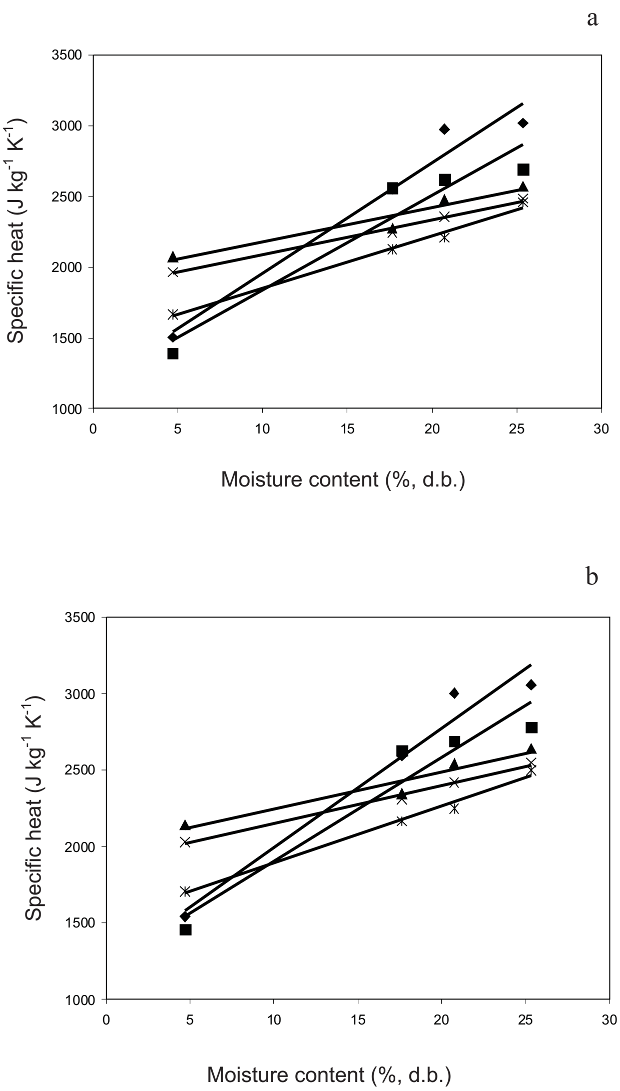

Fig. 1. Change of the specific heat of: a – whole, b – ground guna seeds with moisture content at different temperature ranges: ◆307.12-328 K, ■309.12-338 K, ▲310.30-348 K, x313-358 K, ✱313.45-368 K.

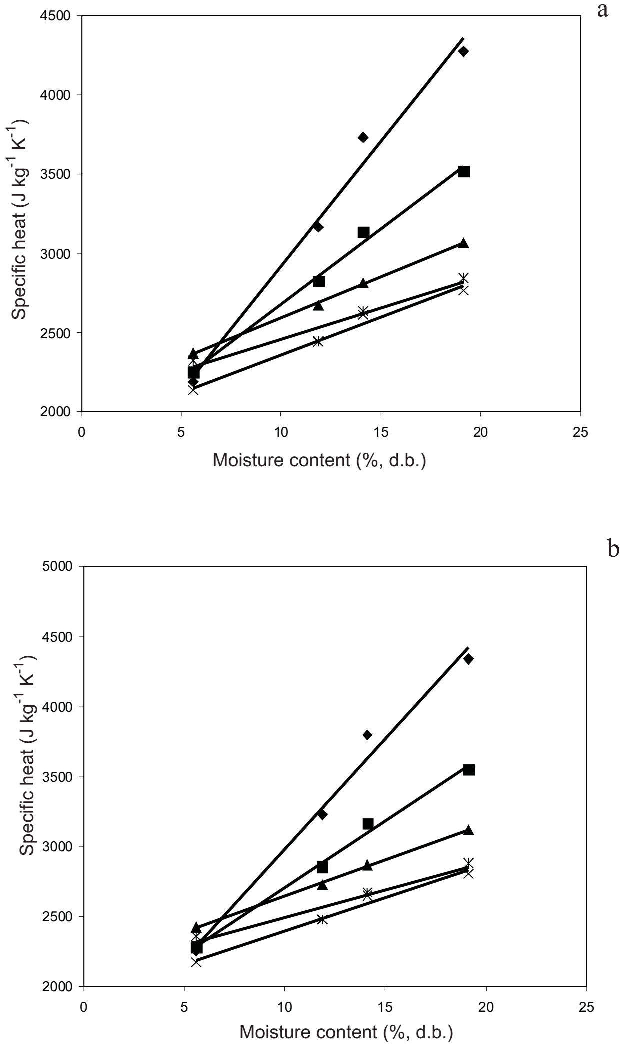

Fig. 2. Change of the specific heat of: a – whole, b – ground guna seeds kernel with moisture content at different temperature ranges: ◆308-328 K, ■310-338 K, ▲311.32-348 K, x312.25-358 K, ✱315.27-368 K.

2003; Deshpande and Bal, 1999; Deshpande *et al.*, 1996), timothy hay, alfalfa pellets (Fasina and Sokhansanj, 1995) and borage seed (Yang *et al.*, 2002).

The specific heat of whole and ground seed ranged from 1391.10 to 3020.13 and 1459.15 to 3058.15 J kg^{-1} K^{-1}, respectively, and showed that the ground seed had a higher specific heat than the whole seed. The specific heat of whole and ground kernel ranged between 2135.15 and 4275.56, and from 2173.4 to 4340.06 J kg^{-1} K^{-1}, showing that the specific heat of ground kernel was higher than that of whole kernel. The kernel, whether in whole or ground form, was found to have higher specific heat than the seed.

Based on the experimental data, the specific heat of whole and ground seed and kernel, respectively, as a function of moisture content and average temperature, can be expressed using the following regression equations:

$$C_{ws} \approx -9796.5 + 772.27M - 0.688M^2 + 46.011T_a - 3.62\ 10^{-2}\,T_a^2 - 2.145MT_a, \quad R^2 = 0.889, \tag{5}$$

$$C_{gs} \approx -38365.8 + 773.7M - 0.652M^2 + 219.93T_a - 0.3T_a^2 - 2.152MT_a, \quad R^2 = 0.893, \tag{6}$$

$$C_{wk} \approx 172599.6 + 1616.94M + 4.865M^2 - 1065.5T_a + 1.662T_a^2 - 4.915MT_a, \quad R^2 = 0.935, \tag{7}$$

$$C_{gk} \approx 172856.5 + 1641.8M + 4.932M^2 - 1064.718T_a + 1.66T_a^2 - 4.965MT_a, \quad R^2 = 0.936, \tag{8}$$

where: C_{ws}, C_{gs}, C_{wk} and C_{gk} are the specific heat of whole seed, ground seed, whole kernel and ground kernel, respectively (J kg^{-1} K^{-1}); M is moisture content (%, d.b.), and T_a is the average temperature (K).

The t-test of coefficients showed that M and MT_a were the terms that made statistically significant contributions to the predictive performance of Eqs (5) and (6) at 1% level, and this confirmed the existence of a linear relationship between the specific heat of guna seed, whether whole or ground, with moisture content and average temperature. For Eqs (7) and (8), the main predictors were shown to be the constant, T_a and T_a^2 at 5%, and M and MT_a at 1% levels. This shows that the specific heat of guna kernel, whether whole or ground, has a linear relationship with moisture content and a polynomial of the second order with average temperature.

Thermal conductivity

The thermal conductivity of whole guna seed and kernel (Fig. 3) was found to increase from 0.0711 to 0.1282 and from 0.087 to 0.1260 W $m^{-1}K^{-1}$, as the moisture content and temperature increased. Similar trend was observed in the

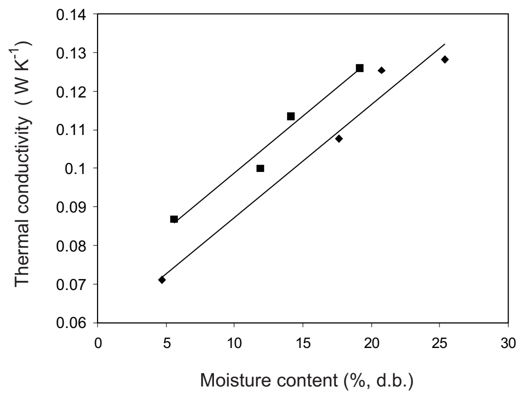

Fig. 3. Thermal conductivity of whole guna seed and kernel as a function of moisture content: ◆ whole guna seed, ■ whole guna seed kernel.

thermal conductivity of soybean (Deshpande *et al*., 1996), cumin seed (Singh and Goswami, 2000), sheanut kernel (Aviara and Haque, 2001), borage seed (Yang *et al*., 2002), rough rice (Yang *et al*., 2003), and millet grains (Subramanian and Viswanathan, 2003).

The relationship existing between thermal conductivity and whole seed and kernel moisture content can be expressed using the following equations:

$$k_{ws} \approx 0.0029M + 0.0581, \qquad R^2 = 0.935, \qquad (9)$$

$$k_{wk} \approx 0.003M + 0.0691, \qquad R^2 = 0.970, \qquad (10)$$

where: k_{ws} and k_{wk} are thermal conductivity of whole seed and kernel, respectively (W m^{-1}K^{-1}), and M is moisture content (%, d.b.). At a similar moisture level the thermal conductivity of whole kernel was observed to be higher than that of whole seed.

The change of the thermal conductivity of ground seed and kernel with moisture content at different temperatures, presented in Figs 4 and 5, shows that it increased from 0.125 to 0.223 and 0.107 to 0.191 W m^{-1}K^{-1}, respectively, as the moisture content and temperature increased. Similar trend

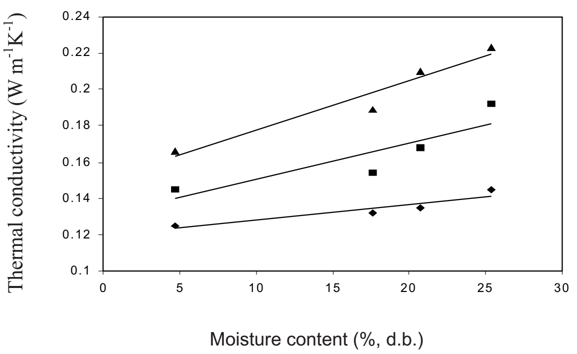

Fig. 4. Change of the thermal conductivity of ground guna seed with moisture content at different temperatures: ◆ 296.85 K, ■ 304.08 K, ▲ 308.75 K.

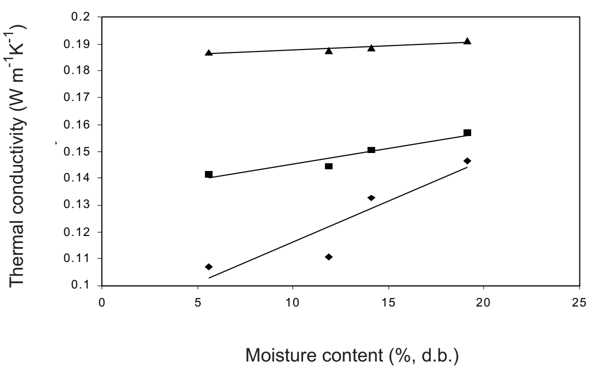

Fig. 5. Change of the thermal conductivity of ground guna seed kernel with moisture content at different temperatures: ◆ 297.68 K, ■ 305.75 K, ▲ 309.25 K.

with moisture content was reported for the thermal conductivity of soyflour (Wallapapan and Sweat, 1982) and ground cowpea (Taiwo *et al*., 1996). The equations that could be used to express the relationship existing between the thermal conductivity of ground seed and kernel and their moisture content and temperature were found to be the following:

$$k_{gs} \approx -0.235 - 0.0485M + 1.19\,10^{-4} M^2 + 4.189\,10^{-6} T^2 + 1.547\,10^{-4} MT, \qquad R^2 = 0.975, \qquad (11)$$

$$k_{gk} \approx -1.106 + 0.07316M + 7.887\,10^{-5} M^2 + 1.345\,10^{-5} T^2 - 2.40\,10^{-4} MT, \qquad R^2 = 0.872, \qquad (12)$$

where: k_{gs} and k_{gk} are thermal conductivity of ground seed and kernel, respectively (W m^{-1}K^{-1}), M is moisture content (%, d.b.), and T is temperature (K). The t-test of coefficient of terms in Eqs (11) and (12) shows that the thermal conductivity of ground guna seed and kernel has a linear relationship with moisture content and a polynomial of the second order with temperature. The thermal conductivity of ground seed and kernel was found to be higher than that of the whole products. The thermal conductivity of ground kernel was higher than that of ground seed.

Thermal diffusivity

The change of thermal diffusivity of whole seed and kernel with moisture content, presented in Fig. 6, shows that it decreased linearly from 8.5 10^{-8} to 9.31 10^{-8} and 3.42 10^{-8} to 4.397 10^{-8} m^2 s^{-1}, respectively, with increase in moisture content. Similar trend was reported for the thermal diffusivity of millet grains and flour (Subramanian and Viswanathan, 2003) and banana (Mariani *et al*., 2008). The following

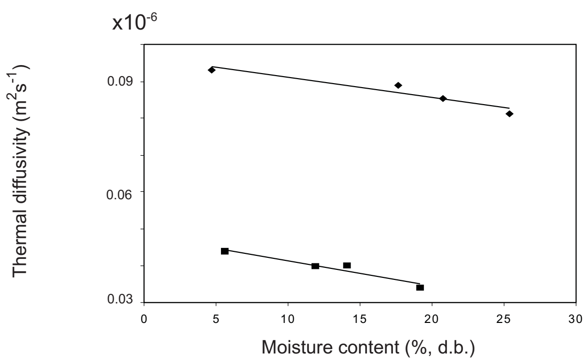

Fig. 6. Thermal diffusivity of whole guna seed and kernel as a function of moisture content: ◆ whole guna seed, ■ whole guna seed kernel.

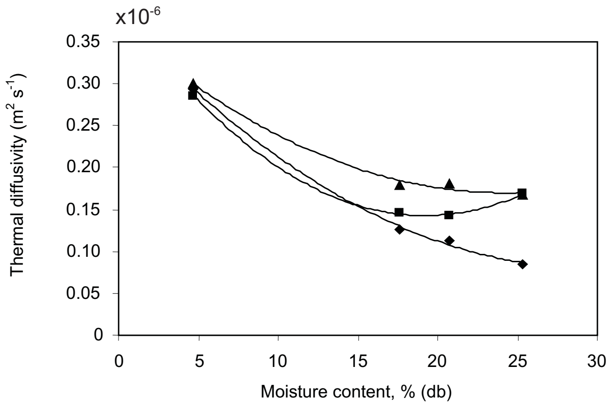

Fig. 7. Change of the thermal diffusivity of ground guna seed with moisture content at different temperatures: ◆ 296.85 K, ■ 304.08 K, ▲ 308.75 K.

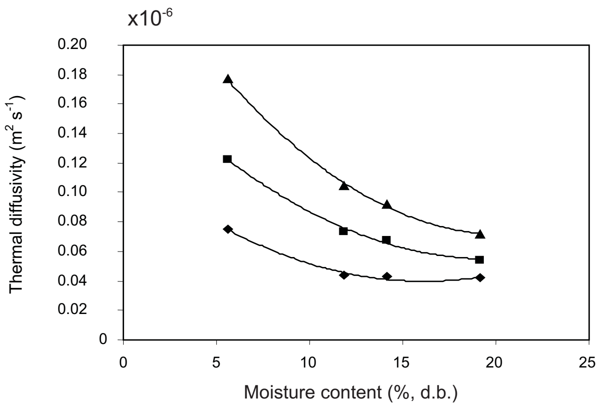

Fig. 8. Change of the thermal diffusivity of ground guna seed kernel with moisture content at different temperatures: ◆ 297.68 K, ■ 305.75 K, ▲ 309.25 K.

equations could be used to express the relationship existing between the thermal diffusivity of the whole seed and kernel and the product moisture content:

$$\alpha_{ws} \approx -7\,10^{-10} M + 5\,10^{-8}, \quad R^2 = 0.935, \quad (13)$$

$$\alpha_{wk} \approx -5\,10^{-10} M + 1\,10^{-7}, \quad R^2 = 0.913, \quad (14)$$

where: α_{ws}, α_{wk} – are thermal conductivity of whole seed and kernal, M – is moisture content (% d.b.)

The thermal diffusivity of the whole seed lies within the same range as that of 'eregli' and 'saruham' granular food, but it is higher than that of 'bulgar' (Tavmani and Tavmans, 1997) and whole kernel.

The thermal diffusivity of ground seed and kernel decreased from 8.468 10^{-8} to 3.0 10^{-7} and from 4.214 10^{-8} to 1.768 10^{-7} m^2 s^{-1}, respectively, as the moisture content increased (Figs 7 and 8). It increased with increase in temperature. The relationship existing between the thermal diffusivity of ground seed and kernel, moisture content and temperature can be represented with the equations:

$$\alpha_{gs} \approx 5.31\,10^{-7} - 1.12\,10^{-7} M + 3.227\,10^{-10} M^2 - $$
$$- 1.75\,10^{-12} T^2 + 3.113\,10^{-10} MT, \quad R^2 = 0.988, \quad (15)$$

$$\alpha_{gk} \approx 1.49\,10^{-6} + 1.363\,10^{-7} M - 4.19\,10^{-10} M^2 - $$
$$- 1.735\,10^{-11} T^2 - 4.41\,10^{-10} MT, \quad R^2 = 0.927, \quad (16)$$

where: α_{gs} and α_{gk} are thermal diffusivity of ground seed and kernel, respectively (m^2 s^{-1}), M is moisture content (%, d.b.), and T is temperature (K).

The t-test of coefficient of terms showed that the constant at 5%, M, M^2, and MT at 1% made statistically significant contributions to the performance of Eqs (15) and (16). The thermal diffusivity of ground seed at a similar moisture level is higher than that of whole seed, whole kernel, ground kernel, and ground sheanut kernel (Aviara and Haque, 2001).

CONCLUSIONS

1. The specific heat of whole and ground guna seed increased with increase in moisture content and temperature. Similar trend was observed in the specific heat of whole and ground kernel.

2. The thermal conductivity of whole and ground seed and kernel increased with moisture content and temperature.

3. The thermal diffusivity of ground seed and kernel decreased with increase in moisture content and increased with increase in temperature.

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