Moisture dependent mechanical and thermal properties of Locust bean (*Parkia biglobosa*)

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Abstract: The mechanical and thermal properties of African locust bean (*Parkia biglobosa*) seeds were investigated as a function of moisture content in the range of 5.9%–28.2% dry basis (d.b.). These properties are required for the engineering design of equipment for handling and processing locust bean. Universal Testing Machine was used to determine the mechanical properties at 5 mm/min load rating transversely. Normal and shear stresses were determined for 200–500 g loads at 100 g interval. Specific heat and thermal conductivity were determined using the method of mixtures and steady-state heat flow method respectively. Linear decreases in rupture force (214.42–129.86 N) and rupture energy (109.17–73.46 N mm) were recorded, while deformation of the seed samples increased (0.98-1.13 mm). Linear increase in normal stress at 200, 300, 400 and 500 g loads were 8.38–8.69, 9.39–9.70, 10.40–10.71 and 11.41–11.72 g/cm^2 respectively, while shear stress ranged from 0.589 to 0.845, 0.688 to 0.998, 0.638–1.213 and 0.688–1.359 g/cm^2 at 200, 300, 400 and 500 g with increasing seed moisture content. The specific heat and thermal conductivity of locust bean increased from 2.74 to 4.38 kJ kg^{-1} ^{o}C^{-1} and 0.052 to 0.118 W m^{-1} ^{o}C^{-1} respectively. Seed moisture content effect was statistically significant (p<0.05) on all properties investigated except rupture force, rupture energy and thermal diffusivity while baseline data were generated for the development of necessary handling and processing equipment.

Keywords: bulk density; deformation; rupture force, shear stress, moisture content, thermal conductivity

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1 Introduction

Locust bean seed, among some of its uses, is an important raw material for the production of a natural, nutritious and medicinal food condiment largely consumed in at least, 17 West African countries including Nigeria (Oni, 1997). The seed has high protein content (40%), high vitamin, moderate fat content (35%), carbohydrate and macronutrients such as potassium, sodium, magnesium, calcium, nitrogen and phosphorus (Klanjcar, 2002). In Nigeria, the processing of locust bean into the food condiment is manual and tedious hence, not practical for large scale production. The demand for this condiment is on the rise because of the increased awareness of the nutritive and medicinal benefits it provides. In processing the seeds into food condiment, the seeds are boiled in water for 8–12 hours. The seed coat is split to remove the cotyledons (dehulling). Parboiling of the cotyledons, after washing them with water, takes 30 minutes to one hour. The parboiled cotyledons are allowed to cool and finally wrapped in leaves (banana leaves) for fermentation. Therefore, in order to increase supply, it is necessary to modernize production techniques and optimize processing conditions (Audu et al., 2004). To achieve this, adequate information on the mechanical and thermal properties of locust bean required for the design of equipment for its

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handling and processing is necessary.

Thermal properties are useful in modeling thermal behavior of seeds during thermal processing operations such as drying, fermentation, boiling, baking and frying (Alagusundaram et al., 1991; Yang et al., 2002). Knowledge of the mechanical properties of grains is important in the analysis and prediction of their cracking and or breaking behavior during handling and processing. Hydration and drying of seeds will cause physical and physiological changes in the seed. Therefore, it will be safe to determine the mechanical and thermal properties of locust bean as functions of variation in the seed moisture content. This will also generate baseline data required for the engineering design of equipment necessary for handling and processing of seeds.

Many researchers have determined the mechanical and thermal properties of various crops as a function of seed moisture content, such as Ekinci et al. (2010) for carob pod; Ahmadi et al. (2009) for apricot fruits, pits and kernels; Tavakoli et al. (2009) for barley and soybean grains; Bamgboye and Adejumo (2010) for roselle seeds; Aviara and Haque (2001) for sheanut kernel. Therefore this research investigated the influence of seed moisture content on the mechanical and thermal properties of locust bean.

2 Materials and methods

2.1 Collection and preparation of samples

Samples were collected from Saki town, in the northern part of Oyo State of Nigeria. Locust bean trees naturally exist in abundance in the area, and also known for the processing of the condiment. The seed bulk collected was cleaned manually to remove all foreign matter, broken and immature seeds. The initial moisture content of the seeds was determined using the ASAE (1998) standard; S 352.2 which involved oven-drying at 103°C ± 1°C for 72 hours. The samples of other desired moisture content levels were prepared by adding calculated amount of distilled water using the equation given by Mohsenin (1986), expressed as follows:

$$Q = [W_i\,(m_f - m_i)]\,/(100 - m_f) \qquad (1)$$

The seed bulk was divided into five sample lots at 5.9%, 11.1%, 16.6%, 22.0% and 28.2% (d.b.) moisture levels. The samples were packaged in doubled with low density polythene bags to preserve the moisture content and was stored afterwards in a refrigerator at 5°C for five days (Davies, 2010; Akbarpour et al., 2009) to allow for uniform distribution of moisture within the seed mass in each sample lot. Before each experiment was conducted, the required quantity of seeds was taken out from each sample lot in the refrigerator for two hours to equilibrate with room temperature.

2.2 Bulk density

The bulk density is the ratio of the mass of a sample of a seed to total volume (Shafiee et al., 2009). Bulk density for all the samples were determined by filling an empty 300 mL beaker with locust bean seeds and weighing it (Mohsenin, 1986). The weight of the seeds was obtained by deducting the weight of the empty beaker from the weight of the seed-filled beaker. To achieve uniformity in bulk density, the beaker was tapped 10 times for the seeds to consolidate in the beaker (Ahmadi et al, 2009). The beaker was filled with seeds dropped from a 15 cm height and a sharp–edged, flat metal file was used to remove excess seeds to level the surface at the top of the graduated beaker (Nalbandi et al, 2010). Bulk density was calculated using the following equation:

$$\rho_b = m/v \qquad (2)$$

This was replicated five times and the mean calculated for each sample.

2.3 Normal and shear stresses

A rectangular guide frame of size 11×9×5 cm put under a cell of size 7×5×5 cm as described by Stepanoff (1969) and Irtwange (2000) were filled with the sample. A normal load was placed on top of the cell. The cell was tied with a cord passing over a frictionless pulley and attached to a pan. Weights (w_3) were put into the empty pan to cause the seed-filled cell to just slide. After this, new weights (w_4) were also put into the empty pan to cause the cell and the normal load to slide over the guide frame. The measurements were carried out for 200, 300, 400 and 500 g loads and three replications were taken for each sample and load. The normal stress (σ) in g/cm^2 was calculated as:

$$\sigma = (w_3 + w_4)\,/\,A - \rho h \qquad (3)$$

The shear stress (τ) was calculated as:

$$\tau = [w_5 (1 - w\sqrt{2})] / A \quad (4)$$

2.4 Maximum rupture force and deformation

A preparatory tension/compression-testing machine (Instron Universal Testing Machine - U.K. model) was used to determine maximum rupture force and deformation of locust bean samples. Maximum load employed was 151 kg and test for each sample was replicated five times. Individual seed was loaded between two parallel plates of the machine and compressed along its thickness until rupture occurred as denoted by a rupture point in the force deformation curve. Similar method was adopted by Tavakoli et al. (2009) and Ahmadi et al. (2009).

2.5 Rupture energy

The mechanical behavior of locust bean samples were expressed in terms of rupture force and rupture energy required for initial rupture. Energy absorbed by the sample at rupture was determined by calculating the area under the force-deformation curve from the following relationship (Braga et al., 1998):

$$E_r = (F_r D_r) /2 \quad (5)$$

2.6 Specific heat capacity

The specific heat capacity was determined using the method of mixtures as described by Aviara and Haque (2001). A sample of known weight, temperature and moisture content was dropped into the calorimeter containing water of known weight and temperature. The mixture was stirred continuously using a copper stirrer and the temperature was recorded at an interval of one minute using a digital thermometer with a probe–thermocouple. At equilibrium, the final or equilibrium temperature was recorded and the specific heat was calculated using the equation:

$$C_s = (m_c c_c + m_w c_w) [T_w - (T_e + t'R')]/m_s[(T_e + t'R') - T_s] \quad (6)$$

At each moisture level of the samples, (five levels from 5.6% to 28.2%) the experiment was replicated three times and the average values of the specific heat were recorded.

2.7 Thermal conductivity

Thermal conductivity of locust bean was determined using the steady-state heat flow method. Measurements were made using indicating digital ammeter, voltmeter and thermometer. A sample at specified moisture content was put in a 75 mm diameter, circular plastic ware plate and 10 mm thickness. The sample assumed the size of the plate. The probe thermocouple pierced through the cylinder bottom and through the plastic but slightly penetrating into the sample to avoid touching the hot plate directly. The plastic dish containing the sample was placed at the base of the cylinder. The hot plate was lowered down the cylinder gently until it touched the sample. The temperature of the hot plate was pegged around 70°C. The fluctuations in temperature of the hot plate and the changes in temperature of the sample were monitored and recorded for one hour at five minutes interval. At the equilibrium condition, the temperature difference and heat flux were recorded and used in calculating the thermal conductivity of the sample from Equation (6).

$$q = \frac{KdT}{L} \quad (7)$$

2.8 Thermal diffusivity

The thermal diffusivity was calculated using experimental values of specific heat, thermal conductivity and bulk density using Equation (7).

$$\infty = K / (\rho_b C_s) \quad (8)$$

The data generated were analyzed using the Analysis of variance (ANOVA) and Duncan Multiple Range Test (DMRT).

3 Results and discussion

3.1 Normal and shear stress

The graphs (Figures 1a – d) show that normal stress increased with increasing seed moisture content for all loads and the relationship between moisture content of locust bean seed and normal stress was linear for all the loads. Normal stress increased from 8.38 to 8.69, 9.39 to 9.70, 10.40 to 10.71, and 11.41 to 11.72 g cm^{-2} for 200, 300, 400 and 500 g respectively. Shear stress ranged from 0.589 to 0.845, 0.688 to 0.998, 0.638 to 1.213 and 0.688 to1.359 g cm^{-2} under 200, 300, 400 and 500 g respectively, denoting a relative increase when comparing the lowest and the highest moisture levels, but the increase was irregular due to some decreases recorded at moisture levels within the moisture range. Therefore, the relationship between seed moisture content and shear stress for locust bean is non-linear. The effect of seed moisture content on shear stress was statistically significant (p<0.05) as shown in Table 1. Increase in stresses is due to the seeds' ability to stick together at high moisture content levels thereby increasing the normal and shear stresses within the grain bulk. As a result of low porosity and high internal friction within the grain bulk at high moisture levels, the normal and shear stresses of the bulk grain increased. Because of low porosity at high moisture levels, the amount of pore spaces reduced, thereby increasing surface contact among seeds. Since the surfaces are moist and sticky at high moisture levels, locust bean seeds tend to bind together, hence the internal friction (that is, grain to grain friction) increases. Stress exerted by agricultural seeds on material surfaces is important in the choice of material for the design of storage facilities and machine components like hoppers, chutes and conveyors. It is also important in choosing packaging materials and methods for the seeds.

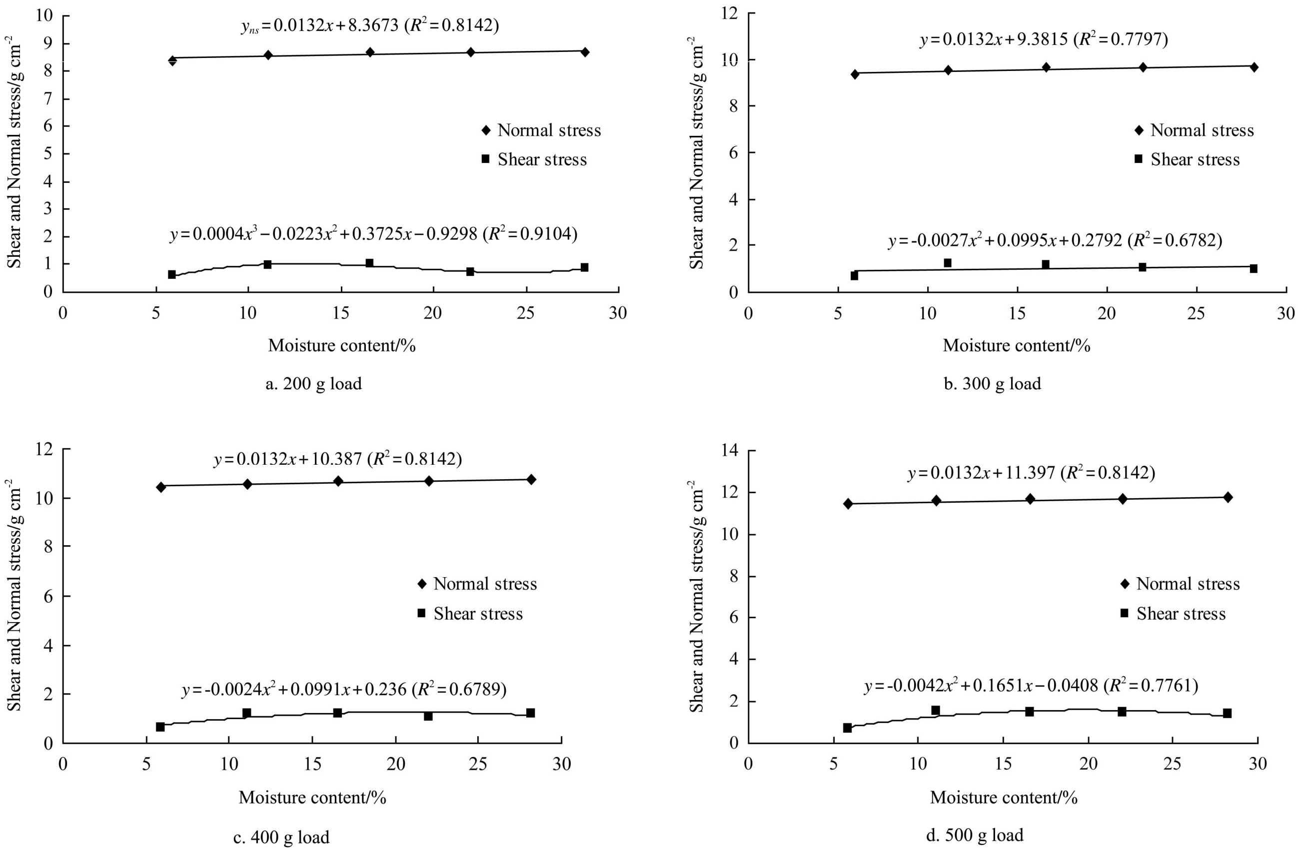

Figure 1 Graphs of normal and shear stresses against moisture content, under 200 g, 300 g, 400 g and 500 g loads

Table 1 Shear stress mean values under different load and moisture levels

Load /g	Moisture content (d.b.), %				
	5.9	11.1	16.6	22	28.2
200	0.589c ± 0.07	0.954ab ± 0.08	1.023a ± 0.08	0.696c ± 0.01	0.845b ± 0.09
300	0.688c ± 0.09	1.220a ± 0.08	1.160ab ± 0.12	1.036b ± 0.11	0.996b ± 0.06
400	0.638b ± 0.03	1.231a ± 0.12	1.228a ± 0.14	1.086a ± 0.01	1.213a ± 0.16
500	0.666c ± 0.06	1.545a ± 0.05	1.440ab ± 0.09	1.450ab ± 0.06	1.359b ± 0.03

Note: Values in the same row followed by different letters (a-c) are significant (p<0.05).

3.2 Rupture force, deformation and rupture energy

Rupture force (F_r) determines the magnitude of force required to cause a material to rupture. For *parkia biglobosa* seeds, rupture force decreased linearly (Table 2) from 214.40 to 129.86 N as moisture content of seed increased in the range 5.9%-28.2% (d.b). The lower rupture forces were obtained at higher moisture contents. This is as a result of the soft texture of the seeds at high moisture content levels. Similar results were reported by Tavakoli et al. (2009) for Soybean grains, Altuntas and Yidiz (2007) for Faba beans, Olaniyan and Oje (2002) for Shea nut, Ekinci et al. (2010) for Carob pod, Ahmadi et al. (2009) for Apricot fruits.

Table 2 Significance of moisture content on rupture force, deformation and rupture energy

Moisture content /%	Rupture force/N	Deformation /mm	Rupture energy /N mm
5.9	214.42a ± 82.29	0.98b ± 0.14	109.17a ± 59.42
11.1	199.32a ± 109.09	0.97b ± 0.30	109.09a ± 78.91
16.6	179.69a ± 50.19	1.21ab ± 0,21	108.67a ± 38.80
22	144.96a ± 40.79	1.61a ± 058	105.77a ± 41.33
28.2	129.86a ± 51.87	1.13ab ± 0.43	73.46a ± 38.86

Note: Values in the same column followed by different letters (a-b) are significant (p<0.05).

Deformation (ε_d) in *parkia biglobosa* was found to initially drop from 0.98 to 0.97 mm at 11.1% and increased to 1.61 mm at 22% before it finally dropped at 28.2% to 1.13 mm. Irregular (non-linear) increase in deformation in locust bean seeds was suspected to be due to non-uniformity in the texture of the seeds even as moisture content increased. It therefore means that some locust bean seeds may absorb moisture slowly because of the hardness of their seed coat. Increase in deformation with increase in moisture content is generally due to the soft texture of seeds at high moisture content. The decrease in deformation at 28.2% moisture level showed that further increase in load will yield no further significant deformation as moisture increases. The relationship between moisture content and deformation was statistically significant (p<0.05) at 22% compared to 5.9% moisture content (Table 2) and expressed as a third degree polynomial equation (Table 3).

Table 3 Equations representing relationship between moisture content of locust bean seeds and their mechanical and thermal properties

Equations	R^2
$F_r = -22.348M + 240.69$	0.979
$\varepsilon_d = -0.0942M^3 + 0.7918M^2 - 1.794M + 2.09$	0.952
$R_E = -0.1514M^2 + 3.7811M + 89.739$	0.928
$C_s = -0.2493M^2 + 1.9387M + 0.962$	0.972
$k = -0.0041M^2 + 0.0417M + 0.0134$	0.993
$\alpha = 0.0352M + 2.7041$	0.934

Note: R^2 = Coefficient of determination; M = Moisture content.

Rupture energy (R_E) for *parkia biglobosa* decreased from 109.17 to 73.46 N mm as moisture content increased from 5.9% to 28.2%. This is as a result of the soft texture developed by the seed as moisture content increased. Energy required to rupture locust bean is needed for the design of dehullers, pod shellers, mills and for pulp removal equipment etc. especially in the determination of the power requirement of the equipment. Relationship between rupture energy and seed moisture content is a second order polynomial equation and not statistically significant (Table 2).

3.3 Specific heat capacity

Specific heat capacity (C_s) is needed in estimating the amount of heat energy required to change the temperature of locust bean seeds by 1°C. The specific heat capacity of *Parkia* seeds increased from 2.74 to 4.38 kJ kg^{-1} °C^{-1} with increase in seed moisture content from 5.9% to 28.2% d.b. and was statistically significant (Table 4). The relationship between moisture content and specific heat capacity of *Parkia biglobosa* seeds is a second order polynomial equation (Table 1). Similar trend was reported by Singh and Goswani (2000) for Cumin seed, Tang et al. (1991) for lentil seeds, Chakrabarty and Johnson (1972) for Tobacco, Wang and Brennan (1993) for Potato and Razavi and Taghizadeh (2007) for Pistachio nuts. Other researchers who reported a non-linear behavior are Kazarian and Hall (1965) for some grains, Murata et al. (1987) for cereal grains and Dutta et al. (1988) for gram. The rate of increase was significant and more rapid at 5.9%–16.6% moisture content. The highest value was recorded at 22% before dropping at 28.2% moisture content. Increased specific heat with increasing moisture content is due to the high specific heat of water compared to the dry material, and the water occupying the air-filled pores faster at lower moisture contents. In the manual processing of locust bean seeds, especially in Nigeria, boiling of seeds in water at different stages takes several hours except when parboiling (30 minutes) for fermentation. Therefore, the results of specific heat capacity will be useful in determining heat energy required for these stages of the process and the optimization of the process to reduce the boiling duration to the barest minimum. This is important in the design of dehullers.

Table 4 Effect of moisture content on thermal properties of locust bean seed

Moisture content/%	Specific heat capacity /kJ kg^{-1} ^{0}C^{-1}	Thermal conductivity /W m^{-1} ^{0}C^{-1}	Thermal diffusivity ×10^{-8}/m^2 s^{-1}
5.9	2.74a ±0.04	0.052a ±0.01	2.93a ± 0.285
11.1	3.62b ±0.47	0.077ab ±0.02	3.14a ± 1.063
16.6	4.67c ±0.68	0.104b ±0.01	3.25a ± 0.963
22	4.77c ±0.36	0.113b ±0.02	3.36a ± 0.709
28.2	4.38c ±0.38	0.118b ±0.01	3.79a ± 0.286

Note: Values in the same column followed by different letters (a-c) are significant (P<0.05).

3.4 Thermal conductivity

This is the possibility of transmission of heat within seeds in a bulk. With increase in moisture in the range of 5.9%–28.2% d.b., thermal conductivity (K) of *parkia* seeds increased from 0.052 to 0.118 W m^{-1} ^{o}C^{-1}. Therefore, it means that heat transmission in locust bean seeds is better when wet than when they are dried. The relationship is expressed in a second order polynomial equation (Table 3). Similar result was reported for Cumin seed by Singh and Goswani (2000). The result of thermal conductivity of *Parkia* seeds is in agreement with the findings of Chandra and Muir (1971) for Wheat. Table 4 showed the effect of moisture on the thermal conductivity of locust bean seeds and there is a statistically significant difference when comparing 16.6% and 5.9% seed moisture content levels (p<0.05).

3.5 Thermal diffusivity

Table 4 shows that thermal diffusivity (α) of *parkia biglobosa* seeds increased from 2.93 × 10^{-8} to 3.79 × 10^{-8} m^2/s^1 with an increase in moisture content in the range 5.9%–28.2% d.b., though the moisture effect was not statistically significant (p<0.05). The relationship between moisture and thermal diffusivity of *parkia* seeds is linear (Table 3). This means that for every unit increase in seed moisture content of locust bean seed, there will be a corresponding unit increase in its thermal diffusivity.

A linear relationship between moisture content and thermal diffusivity was reported for Sheanut kernels by Aviara and Haque (2001). Bamgboye and Adejumo (2010) also reported similar result for Roselle seeds. Therefore, it means that *parkia biglobosa* seed has high ability to gain and retain heat as moisture content increases. Thermal diffusivity is necessary in the design of steamers and dehullers for processing of locust bean.

4 Conclusions

The following conclusions were drawn from this work:

1) Linear increase in normal stress was obtained under 200, 300, 400 and 500 g loads as 8.38–8.69, 9.39–9.70, 10.40–10.71 and 11.41–11.72 g/cm^2 respectively while the shear stress ranged from 0.589 to 0.845, 0.688 to 0.998, 0.638 to 1.213 and 0.688 to 1.359 g/cm^2 under 200, 300, 400 and 500 g loads in a polynomial trend with increase in moisture content of the seeds.

2) There was a linear decrease in rupture force for locust bean from 214.42-129.86 N as the moisture content of the seeds increased in the range 5.9%- 28.2%. The rupture energy also decreased in a polynomial trend from 109.17 to 73.46 N mm. Specific heat capacity, thermal conductivity and thermal diffusivity increased from 2.74 to 4.38 kJ kg^{-1} ^{0}C^{-1}, 0.052 to 0.118 W m^{-1} ^{0}C^{-1} and 2.93×10^{-8} to 3.79×10^{-8} m^2/s respectively with increase in moisture content of seeds in the range 5.9%–28.2% d.b.

3) Seed moisture content effect was statistically significant on all the properties investigated except rupture force, rupture energy and thermal diffusivity.

4) Baseline data necessary for the design and development of processing equipment (such as dehullers, decorticators, steamers) for locust bean have been generated in this work.

Nomenclature

ASAE, American Society of Agricultural Engineers
Q, mass of added water, g
W_i, mass of sample, g
m_f, final moisture content, wet basis
m_i, initial moisture content, wet basis
ρ_b, bulk density, kg/m^3
m, mass of seed bulk
σ, normal stress, g/cm^1
τ, shear stress, g/cm^2
w, coefficient of friction of pulley

w_1, weight required to slide the empty cell, g
w_2, weight required to slide sample material with load, g
w_3, weight of the cell, loaded with seeds; g
w_4, weight due to the normal load on top of the cell, g
w_5, weight required to slide sample material and load, g
t', time taken for the sample and water mixture to come to equilibrium, sec.
R', rate of temperature fall of mixture after equilibrium, $^oC\ s^{-1}$
L, thickness of sample material, m
q, Heat flux, W/m^2
M, moisture content of locust bean seeds, %
C_c, specific heat of calorimeter, kJ $kg^{-1}\ ^0C^{-1}$
C_s, specific heat of sample, kJ $kg^{-1}\ ^0C^{-1}$
C_w, specific heat of water, kJ $kg^{-1}\ ^0C^{-1}$
m_c, mass of calorimeter, kg
m_s, mass of sample, kg
m_w, mass of water, kg
v, volume occupied by seed bulk
E_r, rupture energy, N mm
F_r, rupture force, N
T_s, Initial temperature of sample, ^0C
T_w, Initial temperature of water, ^0C
D_r, Deformation at point of rupture, mm
A, Area of the cell, cm^2
h, height of sample materials in the cell, cm
ρ, density of sample materials, g/cm^3
T_e, Equilibrium temperature of sample and water mixture, ^oC
K, thermal conductivity, W $m^{-1}\ ^oC^{-1}$
dT, temperature difference at equilibrium conditions, ^oC
∞, thermal diffusivity, $m^{-2}\ s^{-1}$

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