Volume 92, Issue 2, May 2009, Pages 182–188

Journal of Food Engineering

Modeling of water absorption of Botswana bambara varieties using Peleg's equation

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article info

Article history:
Received 12 August 2008
Received in revised form 24 October 2008
Accepted 25 October 2008
Available online 19 November 2008

Keywords:
Bambara seeds
Hydration kinetics
Peleg equation
Activation energy
Temperature
Time

abstract

Hydration kinetics of five bambara seed varieties from Botswana was studied by soaking in water at temperatures 25–100 C in constant-temperature water bath for 0.5–24 h using Peleg equation. Peleg's equation adequately described the hydration characteristics of bambara seeds under the experimental condition with the mean relative percentage deviation modulus (*E*) of less than 10% for each variety. For each variety, Peleg's rate constant K_1 decreased significantly as the hydration temperature was increased from 25 to 100 C suggesting a corresponding increase in the initial water absorption rate. Peleg capacity constant K_2 increased with increase in temperature (25–75 C) and dropped at 100 C in all varieties, demonstrating that the water absorption rate increased and water absorption capacity decreased with increase in temperature. While an E_a of 37.83, 39.60, 33.02, and 33.33 kJ/mol was calculated for NTSR, BotR, DipC1, DipC2 bambara seeds, respectively, a lower value of 16.46 kJ/mol was obtained for AS17. The negative values of enthalpy (DH^*) for all the variety indicate that changes during the hydration of bambara seeds are associated with exothermic and energetically favorable transformation. The higher values of E_a and free energy of activation (DG^*) for NTSR, BotR, DipC1, and DipC2 indicate that the seeds experience a large change and hydration was more influenced by temperature. However, the lower value of E_a and the negative values of entropy of activation (DS^*) for AS17 indicate that the seeds were more thermally stable and hydration changes was less influenced by temperature. The optimum soaking time for bambara seeds for all the varieties appear to be 6 h at temperature 6 75 C.

1. Introduction

Bambara groundnut (*Vigna subterranea* (L.) verdc.) is an indigenous African crop that is now grown across the continent from Senegal to Kenya and from the Sahara to South Africa (Atiku et al., 2004). The bambara groundnut has become less important in many parts of Africa because of the expansion of groundnut production. In recent years there has, however, been renewed interest in the crop for cultivation in the arid savannah zones. In Botswana bambara groundnut ("Ditloo" in Setswana) is cultivated by 90% of the farmers. Of the farmers, about 63% grew the crop for consumption, about 12% for sale and 25% for both consumption and sale (Karikari et al., 1997).

Whether used at home to prepare a variety of dishes or in commercial practice (e.g. canning), dry legumes need to be rehydrated by soaking in water or salt solutions before further processing (Seyhan-Gürtas et al., 2001). Turhan et al. (2002) stated that the principal reason for soaking is to gelatinize the starch in the grain. It can be achieved either through conditioning below the gelatinization temperature and then cooking above the gelatinization temperature, or through direct cooking above the gelatinization temperature. Other reasons for soaking are to achieve desired palatability and digestibility and to reduce cooking time (Seyhan-Gürtas et al., 2001). Researchers have already demonstrated that increasing the temperature of the soaking medium is an effective way to accelerate water uptake by various seeds and hence, to shorten the soaking time (Abu-Ghannam and McKenna, 1997a; Thakor et al., 1995). In sorption process and equipment design it is highly desirable and of practical importance to predict the moisture gain by legumes as a function of time and temperature (Seyhan-Gürtas et al., 2001).

Understanding water absorption in legumes during soaking is of practical importance since it affects subsequent processing operations and the quality of the final product (Turhan et al., 2002). Hence, modeling moisture transfer in grains and legumes during soaking has attracted considerable attention. The water absorption kinetics of dry legumes during soaking has been described either by a two-parameter empirical Peleg model (Peleg, 1988) or by analytical expressions derived from Fick's law of diffusion (Tang et al., 1994). The empirical model is simple to apply and has been shown to successfully describe the water absorption behaviour of various legumes (Hung et al., 1993; Sopade and Obekpa, 1990; Nussinovitch and Peleg, 1990).

Peleg (1988) proposed an empirical equation to model water-absorption characteristics of food materials. It has been applied to various food materials by other researchers (Sopade and Obekpa, 1990; Sopade et al., 1992, 1994; Sopade and Okonmah, 1993) and was found suitable. Mpotokwane et al. (2008) reported the physical properties of Botswana bambara seeds. However, data on water absorption characteristics of bambara seeds from Botswana are lacking. Our objective was to determine the applicability of Peleg's equation in modeling the water absorption characteristics of bambara seed varieties from Botswana in an attempt to determine suitable conditions for rehydration.

2. Theoretical background

In an attempt to simplify the mode of water absorption by food materials, a two-parameter, non-exponential, empirical equation was proposed by Peleg (1988). Peleg's equation is

$$M_t \,\text{¼}\, M_0 \quad \frac{t}{K_1 \,\text{þ}\, K^2 t} \qquad \text{ð1Þ}$$

where M_t = moisture content at a known time (t) (% dry basis); M_0 = initial moisture content (% dry basis); t = soaking time (h); K_1 = Peleg's rate constant (h%^{1}); K_2 = Peleg's capacity constant (%^{1}). In Eq. (1), '±' becomes '+' if the process is absorption or adsorption and ' ' if the process is drying or desorption. The rate of sorption (R) can be obtained from first derivative of the Peleg equation

$$R \,\text{¼}\, \frac{dM}{dt} \,\text{¼}\, \frac{K_1}{\text{ð}K_1 \,\text{þ}\, K_2 t\text{Þ}^2} \qquad \text{ð2Þ}$$

The Peleg rate constant K_1 relates to sorption rate at the very beginning (R_0), i.e. R at $t = t_0$

$$R_0 \,\text{¼}\, \frac{dM}{dt}\bigg|_{t_0} \,\text{¼}\, \frac{1}{K_1} \qquad \text{ð3Þ}$$

The Peleg capacity constant K_2 relates to maximum (or minimum) attainable moisture content. As t ? 1, Eq. (1) gives the relation between equilibrium moisture content (M_e) and K_2

$$M\text{j}_{t_1} \,\text{¼}\, M_e \,\text{¼}\, M_0 \quad \frac{1}{K_2} \qquad \text{ð4Þ}$$

where M_e = Equilibrium moisture content (% dry basis). Linearization of Eq. (1) gives

$$\frac{t}{M^t \quad M_0} \,\text{¼}\, K_1 \,\text{þ}\, K_2 t \qquad \text{ð5Þ}$$

A plot of $\frac{t}{M_t\, M_0}$ against time, t, gives a straight line with K_1 as the ordinate-intercept and K_2, the gradient of the line. Such a plot allows the characteristics of Peleg's constants to be determined. Although not derived from any physical laws or diffusion theories, its application for various food materials, e.g. milk powder, rice and various legumes has been demonstrated (Sopade and Obekpa, 1990; Sopade et al., 1994).

Sopade and Obekpa (1990) and Sopade et al. (1994) observed that K_1 was inversely related to temperature and its reciprocal defines the initial hydration rate (Eq. (3)). The constant K_2 is a characteristic sorption parameter of the food material being examined. Peleg's equation is applicable to the curvilinear segment of the sorption curve and the reciprocal of K_2 can be used to predict the equilibrium moisture content (Eq. (4)). Sopade et al. (1992) indicated that K_1 could be compared to a diffusion coefficient and the Arrhenius equation could be used to describe the temperature dependence of the reciprocal of Peleg's constant K_1 in the following manner:

$$\frac{1}{K_1} \,\text{¼}\, K_{\text{ref}} \exp \quad \frac{E_a}{R} \quad \frac{1}{T} \quad \frac{1}{T_{\text{ref}}} \qquad \text{ð6Þ}$$

where K_{ref} = reference hydration constant at a reference temperature; E_a = activation energy (kJ/mol); R = universal gas constant (= 8.314 kJ/mol/K); T and T_{ref} are the soaking and reference temperatures (K), respectively. In order to minimize the co-linearity of K_{ref} and E_a, T_{ref} was chosen as 63 C, the average experimental soaking temperature (Gowen et al., 2007).

On linearization, Eq. (6) becomes

$$\ln \frac{1}{K_1} \,\text{¼}\, \ln K_{\text{ref}} \,\text{þ}\, \frac{E_a}{R} \quad \frac{1}{T_{\text{ref}}} - \frac{1}{T} \qquad \text{ð7Þ}$$

When lnð$\frac{1}{K_1}$Þ is plotted against ð$\frac{1}{T_{\text{ref}}}$ ^{1}Þ$_{\frac{}{T}}$ a straight line with slope ð^{E_a}Þ$_{R}$ is obtained from which the activation energy can be calculated and sensitivity of the constant to temperature can be assessed.

3. Materials and methods

3.1. Source of bambara groundnut

Five bambara seed varieties detailed in Table 1 were purchased from a local market in Gaborone, Botswana. The seeds were cleaned by removing foreign matter, broken, cracked and damaged seeds. They were stored in plastic buckets with cover and kept in cold storage at 5 C. The seeds were removed and kept at room temperature of 25–27 C for 3 h before making any measurements.

3.2. Moisture content

The initial moisture content of the seeds were determined using the ASAE (1983) recommended method for edible beans. The seeds (5 g) were oven dried at 103 C for 72 h in triplicates.

3.3. Water absorption procedures

Experiments were conducted using the modified method of Turhan et al. (2002). Samples were randomly selected excluding foreign materials and broken, cracked and damaged seeds. Before each experiment the sample containers and distilled water were kept in the desired temperature in a water bath for a few hours to reach equilibrium. About 10 g of the seeds (M_0) was placed in 250 ml beakers containing 200 ml distilled water and soaked at room temperature (25 ± 3 C), 50, 75 and 100 C for 30 min to 24 h. The hydrated seeds were blotted free of excess surface moisture with paper tissue and the weight determined ($M_1 + H_2O$). The seeds were then placed in an air-draft oven at 105 C for 16 h for moisture determination (Maharaj and Sankat, 2000) and the dry weight of the seed determined (M_1). The proportion of water absorbed was calculated as true water absorption (WA_t). WA_t is associated with the water absorbed by the insoluble residue. The formula reported by McWatters et al. (2002) was used.

Table 1
Description of bambara landraces used in the study.

Bambara landraces	Colour	Moisture content[a] (% dry basis)
Zimbabwe Red (NTSR)	Red	7.17 ± 0.43^{c}
Botswana Red (BotR)	Reddish brown	8.99 ± 0.35^{a}
Diphiri cream		
DipC1	Black eye	7.87 ± 0.35^{b}
DipC2	Brown eye	8.34 ± 0.39^{a}
Speckled (AS17)	Cream with rhomboid spotting on both sides of hilum	8.67 ± 0.70^{a}

Different superscripts denote significant difference ($P < 0.05$) in the column.

[a] Mean ± standard deviation.

$$WA_t = \frac{[(M_1 + H_2O) - M_1]}{M_1} \times 100 \qquad (8)$$

Determinations were done in triplicate.

3.4. Statistical analysis

Linear regression (SPSS, 2005) was used to fit Peleg's equation to the experimental data. The goodness of fit between the experimental and predicted amounts of water absorbed was determined using the mean relative percentage deviation modulus (E), which is defined by

$$E = \frac{1}{N}\sum_{i=1}^{n}\frac{|m_{\text{exp}} - m_{\text{pred}}|}{m_{\text{exp}}} \times 100\% \qquad (9)$$

where m_{exp} is the experimental value, m_{pred} is the predicted value, and N is the number of experimental data. The mean relative percentage deviation modulus (E) is widely adopted, with a modulus value below 10% indicative of a good fit for practical purposes (Peng et al., 2008; Lomauro et al., 1985).

4. Results and discussion

4.1. Performance of Peleg model in estimating moisture content of bambara seeds

The water absorption curves of dry legumes at three soaking temperatures are shown in Fig. 1. General linear model effect of the dependent variables on water absorption is detailed in Table 2. Variety, temperature and time all had significant ($P < 0.05$) effect on the rate of water absorption. Significant interaction effect existed between temperature and soaking time. The shapes of these curves are typical of water absorption in legumes (Seyhan-Gürtas et al., 2001; Abu-Ghannam and McKenna, 1997a; Sopade et al., 1994). Fig. 2 indicates Peleg's equation (Eq. (1)) fit to the experimental data within the curvilinear segments of Fig. 1 and away from the equilibrium conditions (i.e. during the period of the increase in moisture content). Peleg's model is applicable to what is called the 'clearly curved' part of the sorption curve (Peleg, 1988): an objective method for determining the experimental points for inclusion in the model is not suggested, and it is assumed that visual approximations were employed. The results of

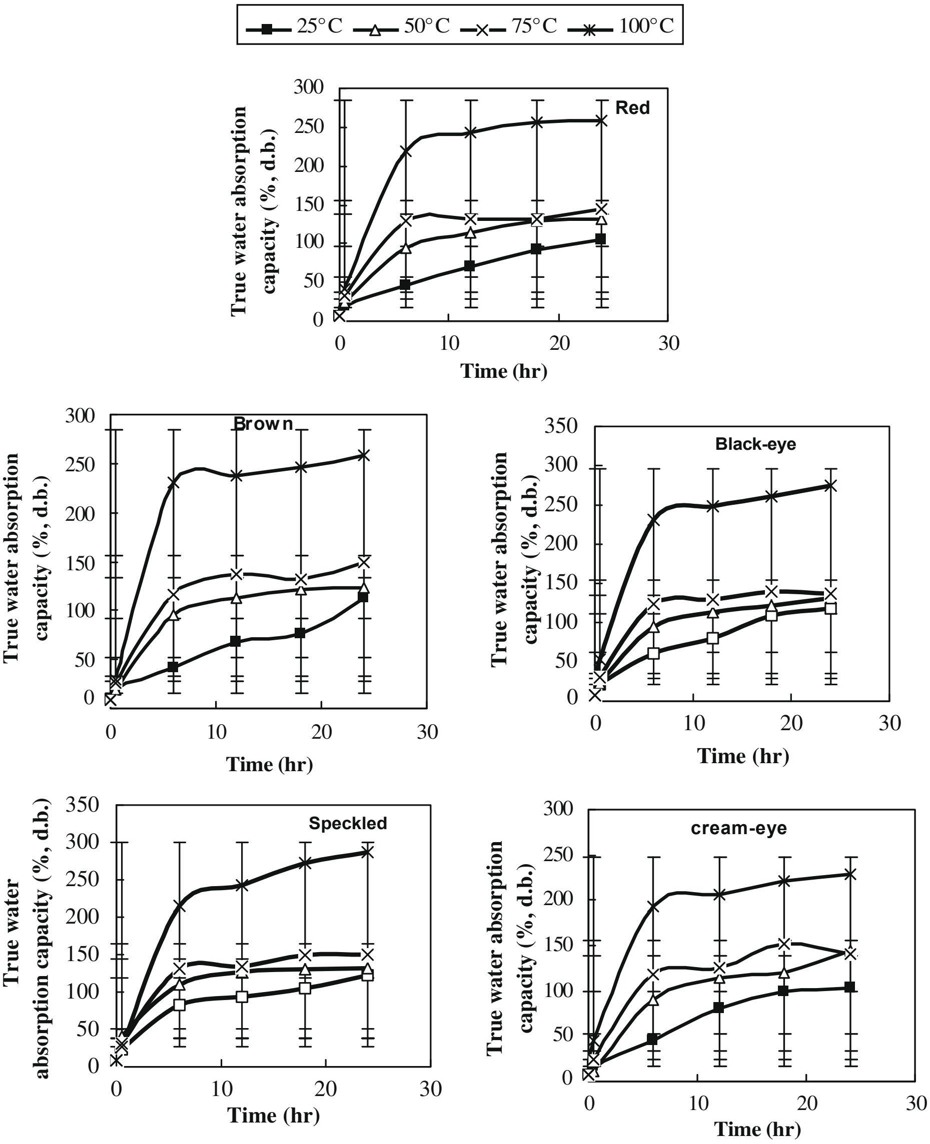

Fig. 1. Water absorption characteristics of bambara seed varieties.

Table 2
General linear model for the effect of variety, temperature and time on water absorption characteristics of bambara seeds.

Source	Sum of squares	df	Mean square	F	Sig.
Corrected model	1374464.838	23	59759.341	90.146	0.000
Intercept	4247051.959	1	4247051.959	6406.574	0.000
Variety	8038.610	4	2009.653	3.032	0.018
Temperature	581201.208	3	193733.736	292.243	0.000
Time	678377.510	4	169594.377	255.829	0.000
Temperature Time	106847.511	12	8903.959	13.431	0.000
Error	182966.171	276	662.921		
Total	5804482.969	300			
Corrected total	1557431.009	299			

the linear regression models fitted to the data at hydration temperatures of 25–100 C are shown in Table 3. The coefficients of determination, R^2 values, varied from 0.5615 to 0.9998 with $P < 0.05$ (probability of null hypothesis of the slope = 0) indicating a good fit to the experimental data. The mean relative percentage deviation modulus (E) is less than 10% for each variety indicative of a good fit. Hence, Peleg's equation was suitable for describing the water absorption characteristics of bambara varieties at the hydration temperature (25–100 C) investigated.

4.2. Peleg's constant K_2 and the equilibrium moisture content

The constant K_2 is related to maximum water absorption capac- ity (Turhan et al., 2002; Peleg, 1988; Sopade and Obekpa, 1990). The constant K_2 is inversely related to the absorption ability of foods (Sopade and Obekpa, 1990). Peleg capacity constant K_2 increased significantly ($P < 0.05$) with an increase in temperature from 25 to 75 C, demonstrating that the water absorption rate increased and water absorption capacity decreased with increase in temperature. Values of K_2 at 100 C were significantly lower compared to hydration at 25–75 C. This observation suggests higher equilibrium moisture content (M_e) values at 100 C. This may be attributed to cellular breakdown and tissue disruption of the bambara seeds at 100 C as such seeds were over-cooked after 6 h of hydration. Irrespective of hydration temperature, Peleg's constant, K_2 (estimated slope in Table 3) did not differ significantly ($P > 0.05$) among the varieties.

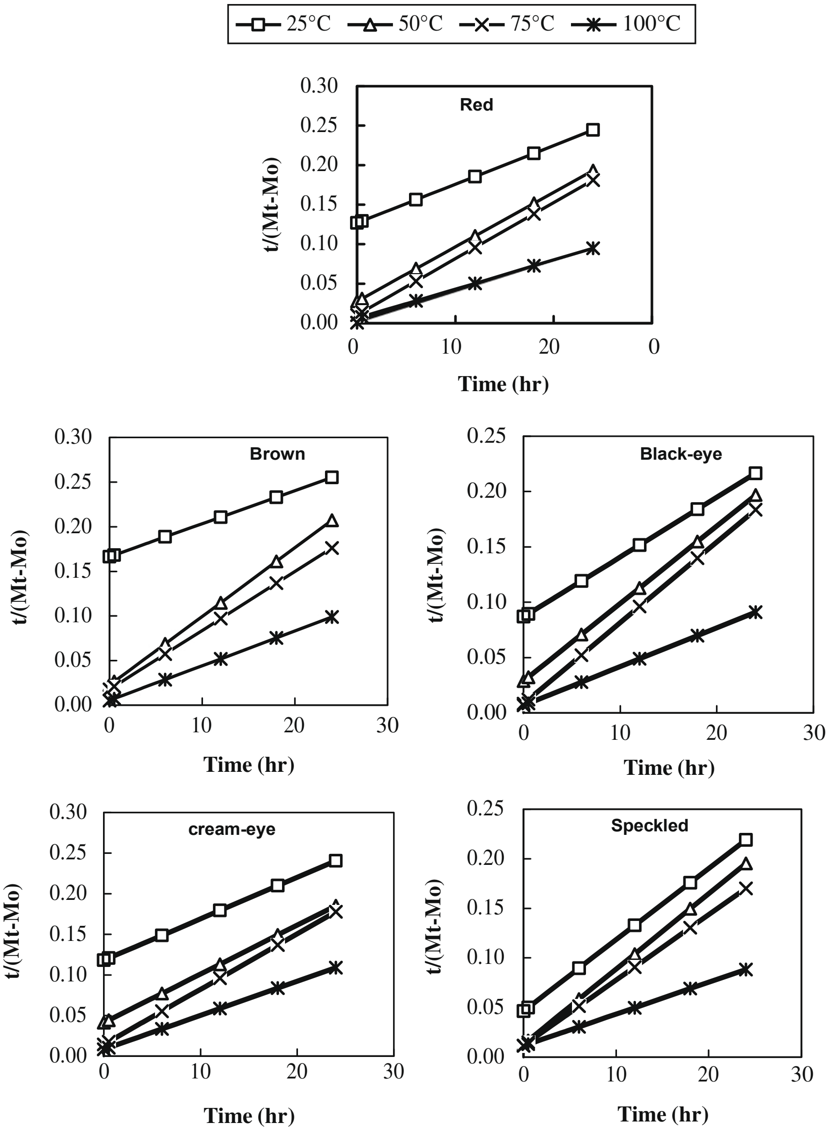

Fig. 2. Application of Peleg's equation to the experimental data from bambara groundnut varieties.

Table 3
Summary of constants in Peleg's equation fitted for $t/M_t\ \ M_0$ vs t for bambara varieties hydrated at 25–100 C.

Variety	Temperature (C)	K_1 (h% ^{1})	$1/K_1$ (% h ^{1}) [a]	Estimated slope K_2 (% ^{1})	R^2	E (%)
NTSR	25	$1.27\ \ 10^{1}$	7.87	$4.9\ \ 10^{3}$	0.9939	0.3445
	50	$2.76\ \ 10^{2}$	36.23	$6.9\ \ 10^{3}$	0.9980	0.1200
	75	$1.05\ \ 10^{2}$	95.24	$7.1\ \ 10^{3}$	0.9907	0.1408
	100	$6.00\ \ 10^{3}$	166.67	$3.7\ \ 10^{3}$	0.9998	0.1586
BotR	25	$1.66\ \ 10^{1}$	6.02	$3.7\ \ 10^{3}$	0.5615	0.5823
	50	$2.25\ \ 10^{2}$	44.44	$7.7\ \ 10^{3}$	0.9996	0.0278
	75	$1.78\ \ 10^{2}$	56.18	$6.6\ \ 10^{3}$	0.9840	0.0482
	100	$5.20\ \ 10^{3}$	192.31	$3.9\ \ 10^{3}$	0.9977	0.1250
DipC1	25	$8.69\ \ 10^{2}$	11.51	$5.4\ \ 10^{3}$	0.9509	0.0611
	50	$2.88\ \ 10^{2}$	34.72	$7.0\ \ 10^{3}$	0.9974	0.0285
	75	$8.40\ \ 10^{3}$	119.05	$7.3\ \ 10^{3}$	0.9976	0.0978
	100	$6.90\ \ 10^{3}$	144.93	$3.5\ \ 10^{3}$	0.9979	0.1679
DipC2	25	$1.18\ \ 10^{1}$	8.48	$5.1\ \ 10^{3}$	0.8819	0.5394
	50	$4.12\ \ 10^{2}$	24.27	$6.0\ \ 10^{3}$	0.9619	0.5105
	75	$1.45\ \ 10^{2}$	68.97	$6.8\ \ 10^{3}$	0.9772	0.0616
	100	$8.40\ \ 10^{3}$	119.05	$4.2\ \ 10^{3}$	0.9984	1.1429
AS17	25	$4.64\ \ 10^{2}$	21.55	$7.2\ \ 10^{3}$	0.9648	0.2760
	50	$1.28\ \ 10^{2}$	78.13	$7.6\ \ 10^{3}$	0.9994	0.2776
	75	$1.17\ \ 10^{2}$	85.47	$6.6\ \ 10^{3}$	0.9958	0.2741
	100	$1.15\ \ 10^{2}$	86.96	$3.2\ \ 10^{3}$	0.9967	0.2378

[a] $1/K_1$ is the initial hydration rate.

Effect of temperature on water absorption of food materials, namely on K_2, is mixed and depends on type of material and if soluble solids loss during soaking is considered in the calculation of moisture content of samples (Sayar et al., 2001). For hazelnut kernel and whole hazelnut, K_2 was reported to decrease with increasing temperature 15 and 35 C (Lopez et al., 1995). Maharaj and Sankat (2000) and Sopade et al. (1994) in their water absorption studies using the Peleg model, reported no effect of temperature on K_2. In this study, K_2 increased with increase in temperature (25–75 C) and dropped at 100 C with all varieties. This is in agreement with the steady change of K_2 with temperature reported by Hung et al. (1993) for Dun variety of chickpea between 5 and 42 C, Sopade et al. (1994) for Borno variety and TVX3236 genotype of cowpea between 7 and 50 C, Abu-Ghannam and McKenna (1997b) for unblanched red kidney bean between 20 and 60 C.

4.3. Peleg's constant K_1 and the initial hydration rate

Peleg's constant K_1 is related to mass transfer rate (Turhan et al., 2002). For each variety, Peleg's rate constant K_1 decreased significantly as the hydration temperature was increased from 25 to 100 C suggesting a corresponding increase in the initial water absorption rate (Table 3). Solomon (2007) also reported a decrease in Peleg rate constant K_1 for lupin seeds. Sopade and Obekpa (1990) and Sopade et al. (1994) found that K_1 was inversely related to temperature. Its reciprocal ($1/K_1$) (% mc db/h) is equivalent to the initial rate of hydration (Eq. (3)) and its sensitivity to temperature is indicative of the positive effect of increased temperature on the rate of water absorbed. This was most pronounced at 100 C where K_1 values were the lowest (Table 3). The large increase in hydration rate observed at 100 C for all the varieties is probably attributed to changes in the properties of the beans at this temperature (Maharaj and Sankat, 2000). Consistent with the hydration curves of Fig. 1, initial hydration rates as determined by $1/K_1$ values, were highest for AS17 ($P < 0.05$) compared to other varieties (Table 3).

4.4. Effect of temperature on Peleg's rate constant

The relationship between the reciprocal of K_1 and temperature was studied using Eq. (7). Table 4 gives the E_a (obtained by regression), the hydration rate constant at reference temperature (k_{ref}), and the coefficient of determination (R^2). The high values of the latter demonstrated that the experimental results could be described by the Arrhenius equation over the temperature range studied. While an E_a of 37.83, 39.60, 33.02, and 33.33 kJ/mol was calculated for NTSR, BotR, DipC1, DipC2 bambara seeds, respectively, a lower value of 16.46 kJ/mol was obtained for AS17. This suggests that the rate of water absorption for AS17 is faster when compared to the other varieties with higher activation energy. The flatter response surface for AS17 (Fig. 3) confirms this trend.

Table 4
Parameters of Arrhenius equation for water absorption during hydration of bambara groundnut varieties[a].

Variety	Temperature (C)	E_a (kJ/mol)	k_{ref}	R^2
Red	25–100	37.83	51.78	0.9794
Brown	25–100	39.60	46.54	0.9317
Black-eye	25–100	33.02	56.67	0.9582
Brown-eye	25–100	33.33	39.91	0.9933
AS17	25–100	16.46	62.54	0.7199

[a] Reference temperature (T_{ref}) set at 336 K (63 C); E_a = activation energy; k_{ref} = hydration rate constant at reference temperature (T_{ref}); R^2 = coefficient of determination.

4.5. Thermodynamic considerations

The E_a value allowed determination of different thermodynamic parameters such as the enthalpy (DH^*), the entropy (DS^*), and the free energy (DG^*) of activation according to the expressions (Jideani et al., 2002; Sánchez et al., 1992):

$$\mathrm{D}H\ ¼\ E_a\ \ RT \qquad ð10Þ$$

$$\mathrm{D}S\ ¼\ R\ \ \ln A\ \ \ln\frac{k_B}{h_p}\ln T \qquad ð11Þ$$

$$\mathrm{D}G\ ¼\ \mathrm{D}H\ \ T\mathrm{D}S \qquad ð12Þ$$

where R = universal gas constant, $\ln A$ = the ordinate intersection when regression analysis is applied to the plot obtained in calculation of E_a, k_B = Boltzmann constant ($1.38\ \ 10^{23}$ J K ^{1}), h_p = Planck constant ($6.626\ \ 10^{34}$ J s) and T = absolute temperature.

The negative values of enthalpy (DH^*) (Table 5) for all the variety indicate that changes during the hydration of bambara seeds

Table 5
Thermodynamic parameters for hydration of bambara groundnut varieties.

Variety	Temperature (C)	E_a (kJ/mol)	DH^* (cal/mol)	DS^* (cal/K mol)	DG^* (kcal/mol)
NSTR	25	37.83	2439.74	212.09	60.76
	50	37.83	2647.59	212.76	66.07
	75	37.83	2855.44	213.38	71.40
	100	37.83	3063.29	213.95	76.74
BotR	25	39.60	2437.97	212.98	61.03
	50	39.60	2645.82	213.65	66.36
	75	39.60	2853.67	214.26	71.71
	100	39.60	3061.52	214.84	77.07
DipC1	25	33.02	2444.55	211.34	60.53
	50	33.02	2652.40	212.01	65.83
	75	33.02	2860.25	212.63	71.13
	100	33.02	3068.10	213.20	76.46
DipC2	25	33.33	2444.24	214.25	61.40
	50	33.33	2652.09	214.92	66.77
	75	33.33	2859.94	215.54	72.15
	100	33.33	3067.79	216.12	77.54
AS17	25	16.46	2461.11	210.52	60.27
	50	16.46	2668.96	211.19	65.54
	75	16.46	2876.81	211.81	70.83
	100	16.46	3084.66	212.38	76.13

were associated with exothermic and energetically favorable transformation (Reusch, 2007). The bambara varieties did not differ significantly ($P > 0.05$) in enthalpy (ΔH^*). There was a decrease in entropy (negative (ΔS^*) on going from reactants to products indicating an increase in system order (a less random system), and this is entropically unfavorable. According to the theory of the activated complex, a substance in a state of activation can only have negative entropy of activation if degrees of freedom of translation or rotation are lost during the formation of the activated complex (Dannenberg and Kessler, 1988). The transitional state is then in a higher state of order than the reactant particles of which it is composed. The entropy (ΔS^*) of the bambara varieties differed significantly ($P < 0.05$) with DipC2 bambara having a higher entropy of activation. The positive ΔG^* is characteristic of an endergonic reaction, one which requires an input of energy from the surroundings (Reusch, 2007). Significant differences existed among the varieties in free energy; BotR and DipC2 were higher in free energy than the others. The higher values of E_a and free energy of activation for NTSR, BotR, DiC1, and DipC2 indicate that the seeds experience a large change and hydration was more influenced by temperature. However, the lower value of E_a and the negative values of entropy of activation for AS17 indicate that the seeds were more thermally stable and hydration changes was less influenced by temperature.

4.6. Effect of time–temperature combination on hydration of bambara seeds

In order to incorporate the Arrhenius temperature dependence of K_1 the following general model (Eq. (12)) was proposed to describe the water intake kinetics of bambara seeds:

$$M_t = M_0 + \frac{t}{K_{\text{ref}}\exp\left(\frac{E_a}{RT}\right)^{-1} + K_2 t} \qquad (13)$$

The estimates of K_{ref}, K_2 and E_a, allowed the prediction of absorbed water for combinations of time (t) and temperature (T) using Eq. (12). The time–temperature relationship of water absorption for

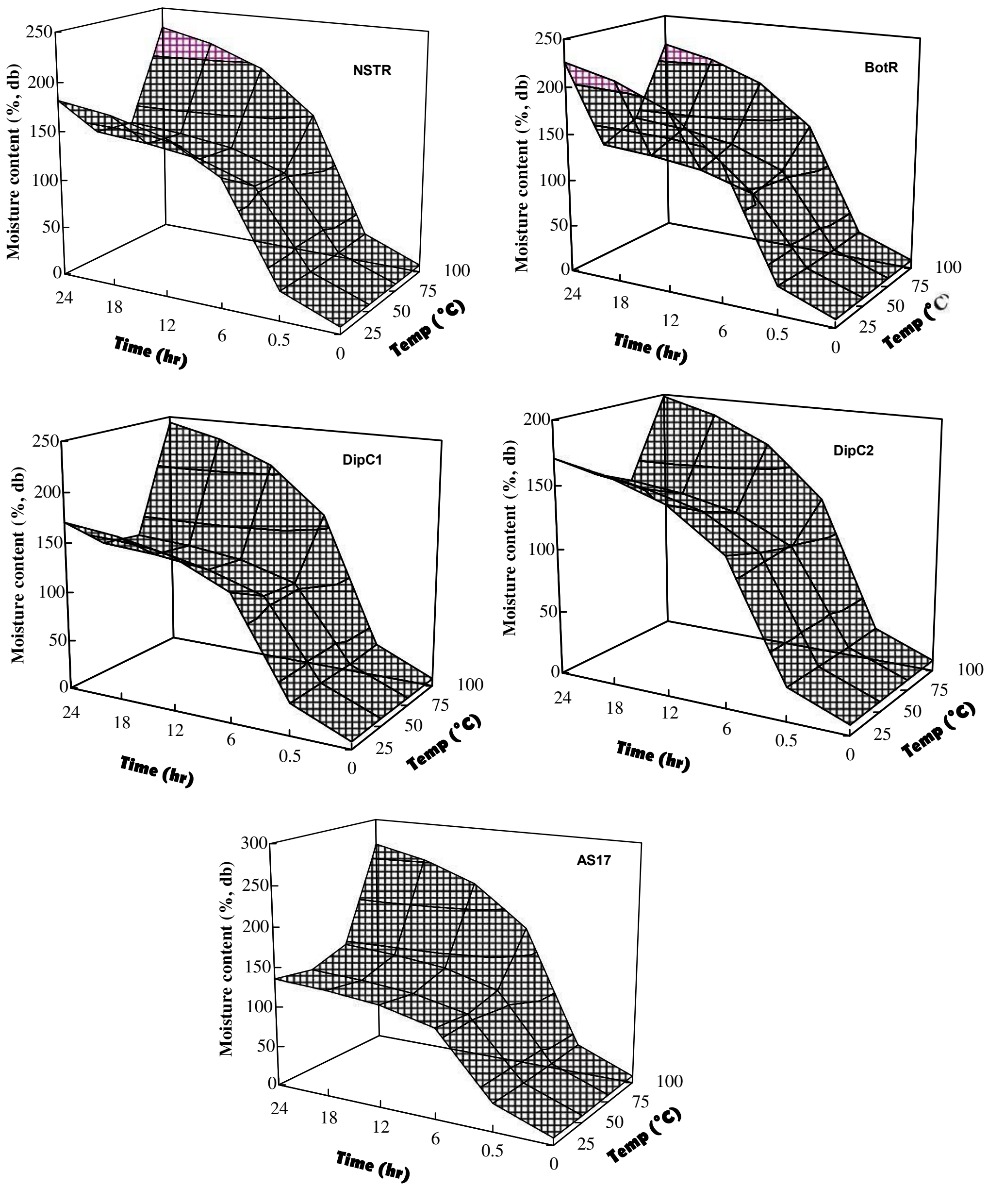

Fig. 3. Response surface pattern of water absorption of bambara seed varieties as predicted by Peleg equation.

bambara varieties is shown in Fig. 3. In these three-dimensional representations, the water absorption of bambara varieties as predicted by Peleg's and Arrhenius equation is depicted as response surface patterns. These provide a geometrical representation of the behaviour of water absorption within the experimental design. There was a slow absorption of water at first 30 min of soaking for all varieties, followed by asymptotic attainment of equilibrium moisture content, after which further water intake was minimal. Sefa-Dedeh and Stanley (1979) observed similar slow absorption at the beginning of soaking for some cultivars of cowpeas and is associated with the thickness of the seed coat and the size of the hilum and micropyle. Some researchers have also demonstrated that these anatomical parts play an important role in controlling the water entry into dry seeds (Marconi et al., 1993; Heil et al., 1992). The temperature–time interaction resulted in quadratic increases of absorbed water. The effect of temperature on absorbed water is more intense shown by the steepness of the temperature curve. As soak-water temperature was increased, the initial slope of the water intake curve increased, and the time taken to achieve equilibrium moisture content consequently decreased. With prolonged soaking, the seeds' moisture contents increased to a maximum and were unaffected by further increases in soak time.

5. Conclusion

Variety, temperature and time all had significant ($P < 0.05$) effect on the rate of water absorption for bambara seeds. Peleg's equation was suitable for describing the water absorption characteristics of bambara varieties at the hydration temperature (25–100 C) investigated. Peleg capacity constant K_2 increased with an increase in temperature from 25 to 75 C, demonstrating that the water absorption rate increased and water absorption capacity decreased with increase in temperature. Changes during the hydration of bambara seeds were associated with exothermic and energetically favorable transformation. The rate of water absorption for AS17 was faster when compared to the other varieties with higher activation energy. The effect of temperature on absorbed water was more intense. Increased temperature resulted in reduced time taken to achieve equilibrium moisture. With prolonged soaking, the seeds' moisture contents increased to a maximum and were unaffected by further increases in soak time. The optimum soaking time for bambara seeds for all the varieties is 6 h at temperature 675 C.