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Application of Peleg model to study water absorption in chickpea during soaking

Mahir Turhan [a,*], Sedat Sayar [a], Sundaram Gunasekaran [b]

[a] Department of Food Engineering, University of Mersin, Ciftlikköy, Mersin 33 342, Turkey
[b] Biological Systems Engineering Department, University of Wisconsin-Madison, Madison, WI 53 706, USA

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Abstract

Application of the Peleg model was investigated for predicting water absorption by five winter- and five spring-planted chickpea genotypes during soaking between temperature (T) of 20 and 100 °C. The Peleg model can predict kinetics of the chickpea soaking till equilibrium using short-term data at the given conditions. Its specific form for infinite time may also be used to estimate equilibrium moisture content (M_e) at $T \geqslant 40$ °C. Spring and winter chickpeas showed no significant difference ($P < 0.05$) in the Peleg rate constant (K_1) and Peleg capacity constant (K_2) within and between the groups at all temperatures except for K_1 at $T < 40$ °C. The discrepancy for K_1 was attributed to characteristic water permeabilities of spring and winter chickpeas which were prominent at $T < 40$ °C. The Peleg constant K_1 decreased from 17.1×10^{-3} to 0.95×10^{-3} h $\%^{-1}$ for the spring chickpeas, and from 22.2×10^{-3} to 1.02×10^{-3} h $\%^{-1}$ for the winter chickpeas with increasing temperature from 20 to 100 °C. An Arrhenius plot for K_1 exhibited a slope change around 55 °C corresponding to approximate gelatinization temperature of the chickpea samples. The Peleg constant K_2 for the samples linearly increased from 7.26×10^{-3} to 9.48×10^{-3} $\%^{-1}$ with increasing temperature from 20 to 100 °C.

Keywords: Peleg model; Soaking; Water absorption; Chickpea

1. Introduction

Chickpea (*Cicer arietinum* L.) is an important protein source in several developing countries. It is the third most commonly consumed legume in the world, and Turkey is among the leading chickpea producing countries (Singh, 1990). Soaking is the first step during manufacture of edible chickpea, and other edible seeds and grains. 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.

Understanding water absorption in legumes during soaking is of practical importance since it governs the subsequent operations and quality of the final product. Hence, modeling water transfer in grains during soaking has attracted considerable attention. Many theoretical and empirical approaches have been employed and in some cases empirical models were preferred because of their relative ease of use (Nussinovitch & Peleg, 1990; Singh & Kulshrestha, 1987). Peleg (1988) proposed a two-parameter sorption equation and tested its prediction accuracy during water vapor adsorption of milk powder and whole rice, and soaking of whole rice. This equation has since been known as the Peleg model (Eq. (1))

$$M = M_0 \pm \frac{t}{K_1 + K_2 t}, \qquad (1)$$

where M is moisture content at time t (%), M_0 is initial moisture content (%), K_1 is the Peleg rate constant (h $\%^{-1}$), and K_2 is the Peleg 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

$$R = \frac{\mathrm{d}M}{\mathrm{d}t} = \pm \frac{K_1}{(K_1 + K_2 t)^2}. \qquad (2)$$

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[*] Corresponding author. Tel.: +90-324-361-0001x601; fax: +90-324-361-0032.
E-mail address: mturhan@mersin.edu.tr (M. Turhan).

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Nomenclature

C_K	Arrhenius constant in Eq. (6) (h %$^{-1}$)
E_a	activation energy (kJ mol^{-1})
K_1	Peleg rate constant (h %$^{-1}$)
K_2	Peleg capacity constant (%$^{-1}$)
M	dry basis moisture content (%)
n	number of observations
R	rate of water transfer (% h^{-1})
R_g	universal gas constant (8.314 kJ mol^{-1} K^{-1})
R^2	coefficient of determination
t	time (h)
T	temperature (°C or K)

Subscripts

ave	average
e	equilibrium
exp	experimental
pre	predicted
0	initial

Greeks

Δ	average difference (%)
∞	infinity

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

$$R_0 = \left.\frac{\mathrm{d}M}{\mathrm{d}t}\right|_{t_0} = \pm\frac{1}{K_1}. \tag{3}$$

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

$$M|_{t_\infty} = M_e = M_0 \pm \frac{1}{K_2}. \tag{4}$$

The Peleg model has been used to describe sorption processes in various foods. Maharaj and Sankat (2000) applied the model for studying water absorption of dasheen leaves. Sopade and Kaimur (1999) used it for describing water desorption of sago starch. Palou, Lopez-Malo, Argaiz, and Welti (1994) studied simultaneous water desorption and sucrose absorption of papaya using the model. The Peleg model was also exploited to model water absorption of many starchy and oily kernels (Abu-Ghannam & McKenna, 1997a; Hung, Liu, Black, & Trewhella, 1993; Lopez et al., 1995; Sopade, Ajisegiri, & Badau, 1992; Sopade, Ajisegiri, & Okonmah, 1994; Sopade & Obekpa, 1990). In these reports mostly the fit of the model was investigated below the gelatinization temperature (conditioning step) rather than above the gelatinization temperature (cooking step) of the starchy grains.

The objective of this work was to study suitability of the Peleg model for describing water absorption of chickpea during soaking over a wide temperature range covering the conditioning and cooking temperatures.

2. Materials and methods

10 kabuli chickpea genotypes were used in the work. They were harvested in 1996 and obtained from the Cukurova Field Crops Research Institute, Adana, Turkey. Five of the samples were winter type (FLIP 91-60, FLIP 91-61, FLIP 92-169, FLIP 93-128, FLIP 99-181) and the rest were spring type (FLIP 91-187, FLIP 91-202, FLIP 92-142, FLIP 93-118, FLIP 82-150). Samples were hand selected to remove foreign materials, and broken, cracked and damaged grains. Care was exercised to select only grains that are 7–8 mm in diameter to minimize size effect on the experimental data. Chemical analyses of the samples were done according to AOAC (1990) using analytical grade reagents. Average chemical composition of the chickpea samples is summarized in Table 1.

Experiments were conducted in 250 ml beakers containing 200 ml deionized water between 20 and 100 °C. Temperature uniformity during tests was assured by placing beakers in a constant temperature water bath. For each experiment, five grains were randomly selected and placed in a beaker. During soaking, grains were periodically removed, superficially dried with a tissue paper and weighed using an electronic balance (Chyo, MP-300, 0.001 g, Japan) and returned to the beaker. Experiments were terminated when kernel moisture content attained an equilibrium value, i.e., when the incremental change in sample mass was less than 0.001 g when measured after 1 h of soaking. At least two experiments were conducted for every chickpea genotype at each soaking temperature.

Moisture content of the samples (M) at each time step was calculated based on the increase in sample mass at

Table 1
Average chemical composition of the spring and winter chickpea samples (%)

Component	Spring	Winter
Moisture	14.6	14.2
Ash	2.55	2.45
Fat	4.96	4.50
Protein[a]	29.62	29.82
Carbohydrate[b]	48.27	49.03

[a] Nitrogen × 6.25.

[b] By difference from 100%.

corresponding times. Dry basis (d.b.) moisture content was used in calculations and all units. The linearized form of the Peleg equation (Eq. (5)) was used to regress the moisture content vs soaking time

$$\frac{t}{M - M_0} = K_1 + K_2 t. \tag{5}$$

3. Results and discussion

3.1. Data selection

The major advantage of the Peleg model is to save time by predicting water sorption kinetics of foods including equilibrium moisture content (Eq. (4)) using short-time experimental data (Peleg, 1988). In his original work, Peleg (1988) used the absorption data between the beginning and somewhere on the curved part of the sorption curves for testing the model. He did not set a definite criterion for selecting the last data on the curved part. However, it is known that the range of data selected affects values of K_1 and K_2 and the model fit (Peleg, 1988; Sopade et al., 1994; Sopade & Kaimur, 1999; Sopade & Obekpa, 1990). Subsequently, some researchers using the Peleg model selected data in accordance with Peleg (1988) and some followed different procedures without any prescribed criteria. Sopade et al. (1992), Sopade and Obekpa (1990) and Hung et al. (1993) used the entire sorption data from beginning till equilibrium. This kind of data selection does not benefit from the Peleg equation to estimate M_e since it is already obtained experimentally. Sopade et al. (1994) used data from some point on the curved part through equilibrium plateau and Abu-Ghannam and McKenna (1997a) used data in the neighborhood of the curved part of the curve. In this case, the selection criteria for both first and last data points are unclear.

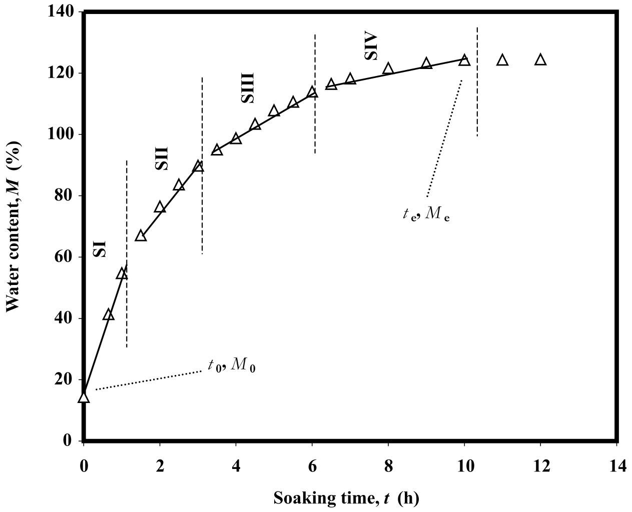

Fig. 1. Water absorption curve during soaking of chickpea (FLIP 91-187, 20 °C). SI, SII, SIII, and SIV represent linear segments of the curve.

Chickpea mass vs soaking time exhibited a typical absorption behavior (Fig. 1) at all temperatures. Since there was no consensus in the literature on how to select the data for applying the Peleg equation, establishing a reasonable data selection was first task in this work. However, attempts did not result in a generalized objective procedure. Nonetheless, sorption curves of all chickpea samples could be divided into four linear sections ($R^2 \geqslant 0.990$) between t_0 and t_e, e.g., SI, SII, SIII,

Table 2

Effect of data selection on the fit of the Peleg model in terms of deviation between predicted and experimental chickpea moisture contents, ΔM (%)[a]

Sample	Sections	20 °C	30 °C	40 °C	60 °C	80 °C	100 °C
FLIP 91-61	SI	19.7	6.9	6.3	22.0	30.2	16.5
	SI–SII	7.9	2.7	3.7	14.5	4.6	3.0
	SI–SIII	2.8	2.0	2.8	4.0	2.7	2.3
	SI–SIV	2.8	2.4	3.5	3.9	3.3	2.7
FLIP 93-181	SI	12.0	19.3	5.9	11.1	9.8	46.0
	SI–SII	4.9	2.9	3.7	8.3	10.9	5.1
	SI–SIII	2.7	2.4	2.9	5.4	6.7	2.5
	SI–SIV	2.6	2.2	4.0	8.1	4.9	2.3
FLIP 82-150	SI	8.4	8.1	30.7	22.3	17.4	11.0
	SI–SII	6.2	4.1	6.9	11.4	2.9	4.3
	SI–SIII	2.3	2.4	3.3	5.4	2.5	3.1
	SI–SIV	2.2	2.8	2.7	4.3	1.8	3.3
FLIP 91-202	SI	16.1	12.7	8.8	16.5	11.0	24.4
	SI–SII	6.2	8.9	2.5	3.0	3.5	5.4
	SI–SIII	2.3	4.8	2.1	2.3	2.6	4.2
	SI–SIV	2.1	4.2	3.2	2.7	3.1	3.9

[a] $\Delta M = 1/n \sum (M_{\text{pre}} - M_{\text{exp}})/M_{\text{exp}} \times 100$, K_1 and K_2 values obtained from the given sections were used to get M_{pre} values between t_0 and t_e (Fig. 1). Then, they were compared with M_{exp} values to calculate ΔM.

and SIV as presented in Fig. 1. The fit of the Peleg equation (Eq. (1)) was tested exploiting data stepwise such as SI, SI to SII; SI to SIII, and SI to SIV (Fig. 1). Using Peleg constants K_1 and K_2 obtained from the given data, M_{pre} were obtained and compared with M_{exp} between t_0 and t_e (Table 2). The fit of the equation improved with increasing sections included in the data selection as observed from decreasing ΔM values (Table 2). However, inclusion of data of SIV did not change ΔM significantly (Table 2). This suggests that the Peleg model describes the water absorption of chickpea using data through SI–SIII.

3.2. Performance of Peleg model in estimating moisture content of chickpea

Data through SI to SIII were used to determine the goodness of fit of the Peleg model between t_0 and t_e (Fig. 1). The model fit resulted in $R^2 \geqslant 0.990$ at all conditions and a typical fit is presented in Fig. 2. Table 3 provides R^2 and ΔM values obtained from fit of Eq. (1). It also contains ΔM_e values obtained from Eq. (1) ($\Delta M_{e,1}$) and Eq. (4) ($\Delta M_{e,4}$). Based on ΔM_e values in Table 3, Eq. (1) performs well in estimating both M and M_e and Eq. (4) is not as good as Eq. (1). Though $\Delta M_{e,4}$ was high at $T < 40$ °C, it was acceptable and inclined to decrease with increasing temperature between 40 and 100 °C for both spring and winter chickpeas.

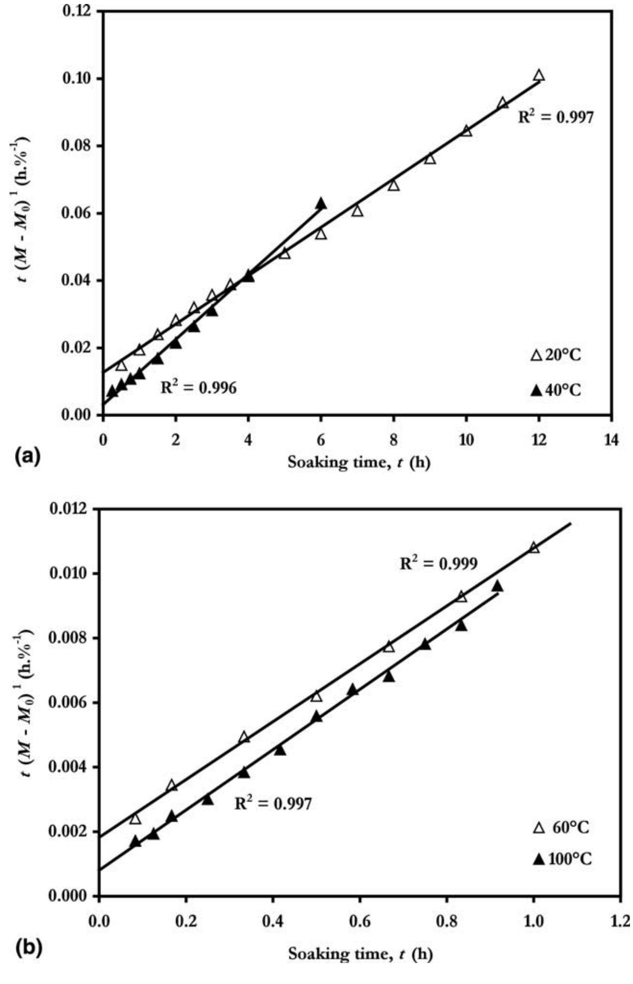

Fig. 2. Fitting of the Peleg model to water absorption data during soaking of chickpea (FLIP 82-150).

The discrepancy between $\Delta M_{e,1}$ and $\Delta M_{e,4}$ is expected since the former assumes that M reaches M_e at t_e (Fig. 1) while the latter assumes that M reaches M_e at t_∞. Accordingly, predicted $M_{e,1}$ must be always smaller than predicted $M_{e,4}$ and then $\Delta M_{e,1}$ must be smaller than $\Delta M_{e,4}$ (Table 3). The above scheme is worth considering in studying how the Peleg equation can be advantageous in estimating M_e using short-term data and Eq. (4).

3.3. Assessment of Peleg rate constant K_1

K_1 is a constant related to mass transfer rate, e.g., the lower the K_1, the higher the initial water absorption rate. Spring and winter chickpeas did not exhibit statistically significant difference in K_1 ($P < 0.05$) at $T \geqslant 40$ °C (Table 3). Insignificant difference between the same samples was observed for the water diffusivity in chickpea in a previous study (Sayar, Turhan, & Gunasekaran, 2001). Spring and winter chickpeas have different seed coat structures and hence different permeabilities for water and it is apparent at $T < 40$ °C. The seed coat permeability of the samples becomes practically the same within a short-time due to plasticizing effect of water facilitated by $T \geqslant 40$ °C (Abu-Ghannam & McKenna, 1997b; Sayar et al., 2001).

The order of magnitude of K_1 values of this work is in agreement with those of other kabuli chickpeas in the literature. The average K_1 values for Kaniva, Garnet, and Macareena varieties were 11×10^{-3} and 8×10^{-3} h %$^{-1}$ at 25 and 42 °C, respectively (Hung et al., 1993). The average of the interpolated K_1 values of this work is 13×10^{-3} and 4×10^{-3} h %$^{-1}$ at 25 and 42 °C (Table 3), respectively.

The K_1 decreased as temperature increased suggesting a corresponding increase in the initial water absorption rate. The linearized Arrhenius equation (Eq. (6)) interpreting effect of temperature on K_1 exhibited two linear regions intersecting around 55 °C (Fig. 3).

$$\ln K_1 = \ln C_K - \frac{E_a}{R_g T}, \qquad (6)$$

where C_K is a constant (h %$^{-1}$), E_a is activation energy (kJ mol^{-1}), R_g is universal gas constant (8.314 kJ mol^{-1} K^{-1}), and T is absolute temperature (K).

This type of Arrhenius plot implies a structural change in the chickpea starting around 55 °C that affects the initial water absorption rate. This temperature corresponds to gelatinization temperature of chickpea and Arrhenius plot for the water diffusivity and water–starch reaction rate constant in chickpea exhibited a disconti-

Table 3
Average Peleg constants and goodness of fit of Peleg model for water absorption of chickpea[a]

T (°C)	$K_1 \times 10^3$ (h $\%^{-1}$)	$K_2 \times 10^3$ ($\%^{-1}$)	R^2	ΔM[b]	$\Delta M_{e,1}$[c]	$\Delta M_{e,4}$[d]
Spring						
20	17.1	7.36	0.996	2.2	−2.5	15.6
30	11.8	7.51	0.995	3.3	−3.8	17.8
40	4.44	8.09	0.997	3.7	−3.7	6.9
45	3.38	8.24	0.996	4.7	−2.6	7.4
55	1.83	8.22	0.996	1.6	−0.8	10.8
60	1.66	8.47	0.997	2.9	−1.6	9.1
80	1.35	8.71	0.992	2.5	−4.6	4.7
100	0.95	9.24	0.988	3.4	−2.0	4.7
			Average	3.0	−2.7[e]	7.3[e]
Winter						
20	22.2	7.15	0.993	2.7	−5.6	17.9
30	16.2	7.71	0.994	3.2	−3.2	25.8
40	4.32	7.71	0.997	3.8	−0.9	10.2
45	3.05	8.12	0.993	4.2	−1.0	9.6
55	2.04	8.46	0.999	2.8	−0.2	12.5
60	2.77	8.52	0.993	4.2	−7.9	8.8
80	1.21	9.37	0.998	4.1	−1.1	6.9
100	1.02	9.71	0.991	3.8	−0.4	6.6
			Average	3.6	−2.5[e]	9.1[e]

[a] K_1 and K_2 values were estimated using data through SI–SIII.

[b] $\Delta M = 1/n \sum (M_{pre} - M_{exp})/M_{exp} \times 100$, K_1 and K_2 values obtained from the given sections were used to get M_{pre} values between t_0 and t_e (Fig. 1). Then, they were compared with M_{exp} values to calculate ΔM.

[c] $\Delta M_e = 1/n \sum (M_{e,pre} - M_{e,exp})/M_{e,exp} \times 100$, using Eq. (1) at $t = t_e$ (Fig. 1).

[d] $\Delta M_e = 1/n \sum (M_{e,pre} - M_{e,exp})/M_{e,exp} \times 100$, using Eq. (4) at $t = t_\infty$.

[e] Excluding 20 and 30 °C.

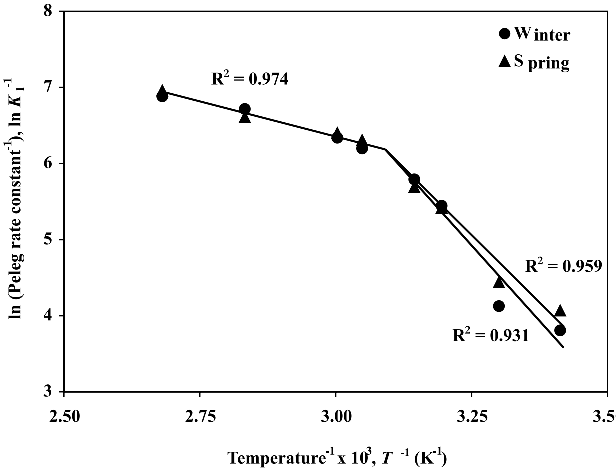

Fig. 3. Arrhenius plot for the Peleg rate constant K_1 during soaking of chickpea.

nuity around 55 °C (Sayar et al., 2001). The Arrhenius plots for the diffusivity and the reaction rate constant in other starchy grains exhibited discontinuity similarly around their gelatinization temperatures (Bakshi & Singh, 1980; Birch & Priestley, 1973; Cabrera, Pineda, Duran De Bazua, Segurajauregeui, & Vernon, 1984; Kubota, 1979; Turhan & Gunasekaran, 2001).

The average E_a values for the K_1 was 59.3 kJ mol^{-1} and 14.8 kJ mol^{-1} below and above 55 °C for spring and winter samples, respectively. For the water diffusivity in chickpea, the average E_a values were determined to be 47.6 and 17.8 kJ mol^{-1} below and above 55 °C, respectively (Sayar et al., 2001). The lower activation energy for the rate of water transfer above the gelatinization temperature implies that water travels faster in gelatinized chickpea than in ungelatinized chickpea.

Increasing water absorption rate, namely decreasing K_1, with increasing temperature is an expected sorption behavior. During water absorption of hazelnut kernels between 15 and 30 °C, K_1 was reported to linearly increase with increasing temperature (Lopez et al., 1995). Value of K_1 is supposed to be negative during a desorption process. For water vapor desorption of sago starch, 11 out of 72 K_1 values for many relative humidity and temperature combinations were determined to be positive (Sopade & Kaimur, 1999). These unexpected results were not brought up in the cited studies. Evaluation of K_1 values for dasheen leaves showed that K_1 for steam blanched and control samples linearly decreased with increasing temperature and for water and alkali blanched samples it was not affected by temperature between 60 and 100 °C (Maharaj & Sankat, 2000). Several investigators (Abu-Ghannam & McKenna, 1997a; Hung et al., 1993; Lopez et al., 1995; Sopade et al., 1992; Sopade et al., 1994; Sopade & Obekpa, 1990) reported that K_1 decreased linearly with temperature during soaking of whole grains. In some cases the variation of K_1 with temperature was not linear. According to reevaluation of the reported K_1 values, all chickpea cultivars except Semsen and three field pea cultivars fitted a nonlinear regression model better than the linear regression model between 5 and 42 °C (Hung et al., 1993). The fit of a nonlinear model was particularly very obvious in case of blanched red kidney beans between 20 and 60 °C (Abu-Ghannam & McKenna, 1997a).

3.4. Assessment of Peleg capacity constant K_2

K_2 is a constant related to maximum water absorption capacity, i.e., the lower the K_2, the higher the water absorption capacity. The K_2 for the spring and winter chickpeas were not statistically different ($P < 0.05$, Table 3) and linearly increased with increasing temperature (Fig. 4). This is due to decreasing water absorption capacity of the chickpeas with increasing temperature that was consistent with a previous report on chickpea soaking (Sayar et al., 2001).

K_2 values of this work are in close agreement with those of other kabuli chickpea cultivars in the literature. The average K_2 value for Kaniva, Garnet, and Macareena varieties was 8.9×10^{-3} $\%^{-1}$ between 25 and 42 °C (Hung et al., 1993). In this study, average of the interpolated K_2 values (Table 3) is 7.6×10^{-3} $\%^{-1}$ within the same temperature range.

Effect of temperature on water absorption capacity 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 (Abu-Ghannam & McKenna, 1997b; Sayar et al., 2001). For hazelnut kernel and whole hazelnut, K_2 was reported to decrease with increasing temperature between 15 and 35 °C (Lopez et al., 1995). In the previous water absorption studies using the Peleg model, no effect of temperature on K_2 was reported (Abu-Ghannam & McKenna, 1997a; Hung et al., 1993; Maharaj & Sankat, 2000; Sopade et al., 1992; Sopade et al., 1994; Sopade & Obekpa, 1990). On the contrary to what was reported, K_2 values were not always constant with temperature. For example, while it was constant at 30 and 50 °C, it dramatically increased at 7 °C during soaking of Exchadi, Kananado, and Black-eye susie varieties of cowpea (Sopade et al., 1994). Though it had the same value at 25 and 40 °C, it jumped up a maximum value at 2 °C during soaking of soybean (Sopade & Obekpa, 1990). K_2 steadily changed with temperature for steam-blanched and unblanched dasheen leaves between 60 and 100 °C (Maharaj & Sankat, 2000), for Dun variety of chickpea between 5 and 42 °C (Hung et al., 1993), for Borno variety and TVX3236 genotype of cowpea between 7 and 50 °C (Sopade et al., 1994), for unblanched red kidney bean between 20 and 60 °C (Abu-Ghannam & McKenna, 1997a), for maize between 10 and 50 °C, and for undehulled peanut between 2 and 40 °C (Sopade & Obekpa, 1990).

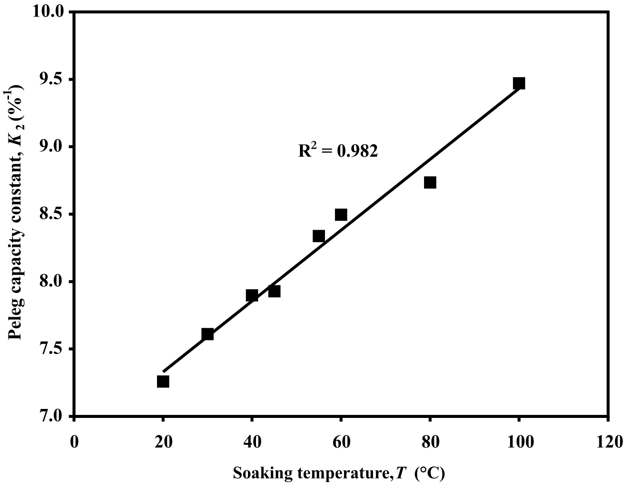

Fig. 4. Effect of temperature on the Peleg capacity constant K_2 during soaking of chickpea.

4. Conclusions

The Peleg model can be used to describe water absorption of chickpea between t_0 and t_e between 20 and 100 °C using short-time data through SI–SIII (Fig. 1) and Eq. (1). It can be acceptable for predicting M_e using Eq. (4) especially at $T \geqslant 40$ °C. A generalized quantitative data selection method is still required for broader application of the Peleg model. The Peleg rate constant K_1 increases with temperature linearly or nonlinearly depending on the product and can be useful in estimating approximate gelatinization temperature of starchy grains utilizing Arrhenius plot. The Peleg capacity constant K_2 is not necessarily constant with temperature. It increases or decreases with increasing temperature depending on the sample and the method of moisture content calculation used.

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