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Effects of moisture content and number of loadings on force relaxation behaviour of chickpea kernels

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A b s t r a c t. Basic rheological property (force relaxation) of a single kernel of chickpea under uni-axial compression was studied. Information on the force relaxation behaviour of chickpea kernels is not available. Meanwhile, no papers was found to study the effects of number of loadings on stress relaxation behaviour of grains and fruits. In this study the effects of moisture content and number of loadings were studied on force relaxation behaviour of chickpea kernels. The results showed that the chickpea kernels had a time dependent behaviour similar to other viscoelastic materials. The three-term Maxwell model with a maximum relative difference (MRD) of ≤5% and R^2 higher than 0.997 was chosen as the best fit equation to the relaxation data. Moisture content had a decreasing effect on the first term of the three-term Maxwell model (F_1, $\dagger_1$), but the number of loadings had an increasing effect on the first term of the Maxwell model. For all moisture contents and number of loadings, the grain tissue dissipates a major proportion of the initially applied force at a relatively slow rate. As the number of loading increases, the kernel becomes more elastic.

Consequently, more force was required to maintain a certain deformation level. A master curve was proposed to determine the force relaxation behaviour of the chickpea kernels at moisture contents between 6.7 and 18% for 1 to 9 cycles of loadings. The Peleg and Pollak model was unsatisfactory for representing the relaxation force for chickpea kernels.

K e y w o r d s: chickpea, relaxation force, rheology, stress

INTRODUCTION

During harvesting, handling, transport, processing, and storage, grains are subjected to a series of static and dynamic loads. These loads causes damage an d loss in food grains, decreases quality, and increases susceptibility to deterioration during storage (Bargale *et al*., 1994). The nature and extent of damage depends on mechanical and rheological characteristics of grains and the forces (or loading condition) to which the grains are subjected.

The mechanical behaviour of agricultural products is time dependent and must be studied by applying the principles of viscoelasticity, in which both the viscous and elastic responses are considered (Pappas *et al*., 1988). The behaviour can be attributed to the elastic and viscous properties of the cell walls (Sakuria and Nevins, 1992). Viscoelastic materials exhibit stress relaxation phenomena which is one of the important factors in characterizing agricultural materials. The relaxation time shows how the material dissipates stress after receiving a sudden deformation. Thus, the results of the relaxation test are useful for estimating susceptibility to damage (Sarig and Orlovsky, 1974).

Although there is some published works on the physical and mechanical properties of chickpea kernels and pods (Khazaei, 2003; Khazaei *et al*., 2003; Khazaei *et al*., 2002), information on the force relaxation behaviour of chickpea kernels is not available. Meanwhile, no papers was found to study the effects of number of loadings on stress relaxation behaviour of grains and fruits. These information are useful for designing the chickpea harvester and sorter. And so, the objective of this study was to determine the effects of moisture content and number of loadings on force relaxation behaviour of chickpea kernels.

MODELING

A generalized Maxwell model with 2 or 3 elements is generally used to represent stress or force relaxation data. Thus, the force relaxation behaviour can be represented by

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an exponential equation (Sarig and Orlovsky, 1974; Husain *et al*., 1971):

$$F(t) = \sum_{i=1}^{n} F_i(e^{-t/\tau_i}), \qquad (1)$$

where: τ_1, τ_2, ... τ_n are the relaxation time constants corresponding to various elements in the Maxwell model, F_1 to F_n are the decay forces, and $F(t)$ is the instantaneous force. The instantaneous force could be replaced by any other decaying parameter such as stress or modulus of elasticity (Pappas and Rao, 1989; Waananen and Okos, 1992).

Another model which normalizes and linearizes the stress relaxation data is the Peleg and Pollak model. In this model, the decaying parameter, $Y(t)$, was expressed as (Kajuna *et al*., 1998):

$$Y(t) = \frac{F_\circ - F(t)}{F_\circ} = \frac{a.b.t}{1+bt}, \qquad (2)$$

where: F_o is the initial force at the begining of the relaxation. The α represents the level at which the stress decays during relaxation. If a=0, the stress does not relax at all. If a=1, the stress level eventually relaxes to zero at time t=∞. The coefficient b represents the rate of relaxation of the stress (decay rate), and $1/b$ is the time necessary to reach the level $a/2$. If b=0, the stress does not relax at all. For viscoelastic materials, the lower the value of b, the slower the relaxation time and vice versa (Kajuna *et al*., 1998).

Applications of this model for foods have been demonstrated by Nussinovitch *et al*. (1989). This model facilitates comparison of the test data of different materials, and enables quantitative evaluation of shape characteristics that are induced by sample deformation history (Kajuna *et al*., 1998).

Research has shown that the effect of a change in moisture content on the viscoelastic properties of many materials is similar to the effect of change in the real time scale (Waananen and Okos, 1992). In other words, data measured for short periods at several different moisture contents can be combined on a single curve, which is equivalent to data measured at a fixed moisture content over an extended period (Waananen and Okos, 1992). Described another way, all relaxation curves are shifted in relation to a reference curve. Let $F_{M_o}(t)$ be the relaxation function at some reference moisture content M_o and be $F_M(t)$ the relaxation function at moisture content of M. One can then write:

$$F_{M_\circ}(t) = F_M(t.a_M). \qquad (3)$$

The quantity of $t.a_M$ and a_M are called the reduced time or pseudo time and moisture shift factor, respectively (Balastreire and Herum, 1978). Hence, it has been shown that t units of time at moisture content M_o are equivalent to $(t.a_M)$ units of time at moisture content M. The shift factor a_M is an inherent property of a given viscoelastic material and must be determined experimentally. For $M<M_o$, the value of a_M will be <1; for $M>M_o$, $a_M>1$; and for $M=M_o$, $a_M=1$.

By applying the shifting procedure as described above to a series of curves measured at different moisture contents, a single 'master curve' may be obtained. Thus, the relaxation force at any moisture content (M) can be estimated using the force at the reference moisture content (M_o) over an extended time scale. The primery tests showed that at any moisture content level, with increasing the number of loadings, the relaxation curves shifted upward. So, it is hypothesized that the shifting procedure can also be used to determine a loading shift factor (a_N) as:

$$F_{N_\circ}(t) = F_N(t.a_N), \qquad (4)$$

where: $F_{N_o}(t)$ be the relaxation function at some reference loading number of N_o, $F_N(t)$ be the relaxation function at loading number of N_{th}, and a_N is the number of loading shift factor.

MATERIALS AND METHODS

Chickpea kernels of the cultivar Kaka from the dry farms of Kangavar, were selected for testing. Chickpea pods were harvested by hand in the summer of 2001 and were tested in the summer of 2002. Kernels were separated from the pods manually. The relaxation tests were performed using a Texture analyzer machine (Model Ta-XT2) equipped with a 250 N load cell having a precision of 0.001 N located at Manitoba University, Canada.

The effect of moisture content, at 6.7, 12, and 18%, on the relaxation behaviour of chickpea kernels was studied. In all tests, the loading velocity was constant at 0.1 mm s^{-1}. This loading velocity was low enough to be considered as quasi-static (Bargale *et al*., 1994).

To increase the moisture content of the chickpea kernels, a calculated quantity of water was added to the samples placed in an airtight glass jar. The samples were stored at 6.5°C and were allowed to equilibrate for a minimum of 48 h. All the tests were conducted on chickpea kernels having a geometric mean diameter of 8.4 mm. Five kernels were tested at each moisture content with a constant strain of 2%.

For each test, the kernel was placed in the most stable position between two parallel plates (Fig. 1) and was loaded until the grain deformation reached a predetermined strain of 2%. At this time, the deformation of the kernel was maintained constant and the force required to maintain this deformation was measured and recorded directly as a function of time. The time dependent force data was obtained for 120 s. After unloading and a 120 s delay, the same kernel

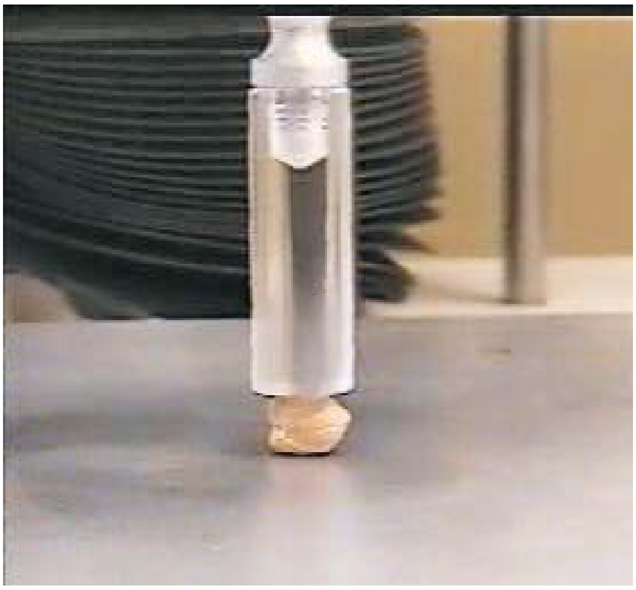

Fig. 1. Chickpea kernel loaded from the side between two parallel plates.

was subjected to a second loading. This process was continued until nine loadings *ie* nine successive relaxation tests, were completed. The time dependent force data obtained from the relaxation experiments were used to calculate the parameters of the models given by Eqs (1) and (2).

For each moisture content, nine average curves were found and thus a total of 27 curve drawn. Then, by using shifting method in two steps, the 27 curves were converted to just one master curve. This curve can be used to estimate the relaxation behaviour of chickpea kernels at moisture content range of 6.7 to 18% and number of loading from one to nine times. This procedure is explained as follows:

At moisture content of 6.7%, having nine relaxation curves, the curve belonging to the third loading was chosen as reference (N_o). After, determination of loading shifting factor (a_N) and also reduced time ($t \,.\, a_N$) for each curve, all relaxation-force curves were drawn in a new scale system. By doing this, all curves were shifted on the third loading curve (or in the same direction) indicating just one curve. This procedure was repeated for moisture contents of 12 and 18%. After that, three general curves were drawn and their mathematical models having maximum R^2 were derived using Sigmaplot Software.

After determining the master curve for each moisture content, the moisture content shift factor (a_M) was determined for these three curves using 12% moisture content as the reference. Finally one master curve was obtained to estimate the relaxation force behaviour of chickpea kernels for moisture contents between 6.7 and 18% for the 1 to 9 cycles of loading.

In this study, the regression wizard option provided with exponential decay models in the Sigmaplot statistical package was used to determine the parameters in the Maxwell model Eq. (1). The number of terms in the Maxwell model was chosen based on the maximum relative difference (MRD) between the model-predicted values and the experimentally measured values (Bargale *et al.*, 1994; Al-Mashat and Zurit, 1993). The model with the number of terms corresponding to MRD value of ≤5% was chosen as the best fit model. The MRD value was calculated based on (Bargale *et al*., 1994; Al-Mashat and Zurit, 1993):

$$\mathrm{MRD} \quad \max\left|\frac{measured \quad calculated}{measured}\right|100. \qquad (5)$$

R^2 values were calculated for each model.

RESULTS AND DISCUSSION

Typical relaxation force curves for chickpea kernels at different moisture contents and number of loadings are presented in Figs 2, 3, and 4. Chickpea kernels exhibited a time dependent behaviour similar to other viscoelastic materials.

Beyond the third loading, the curves could not be distinguished for kernels at 6.7% moisture content (Fig. 2). At 12% moisture content, only the 8th and 9th loading curves could not be distinguished (Fig. 3). At 18% moisture content, the curves for all nine loading cycle were distinct (Fig. 4).

Figures 2 and 3 show that after a specific loading cycle, kernel behaves like an elastic material and thus relaxation curves will be limited to a constant value. No papers were found to have studied the effect of loading number on relaxation force (stress) behaviour of grains, although

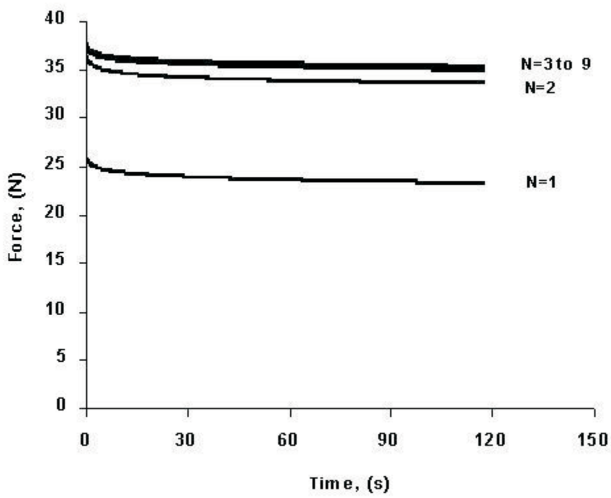

Fig. 2. Relaxation force behaviour of the same chickpea kernel subjected to nine successive relaxation tests at moisture content of 6.7%.

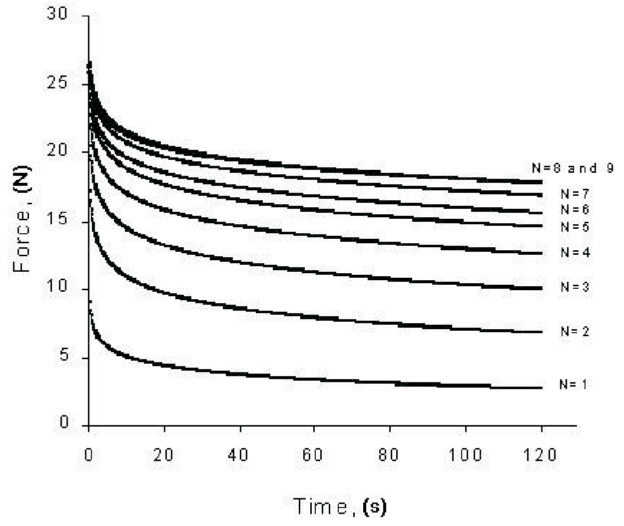

Fig. 3. Relaxation force behaviour of the same chickpea kernel subjected to nine successive relaxation tests at a moisture content of 12%.

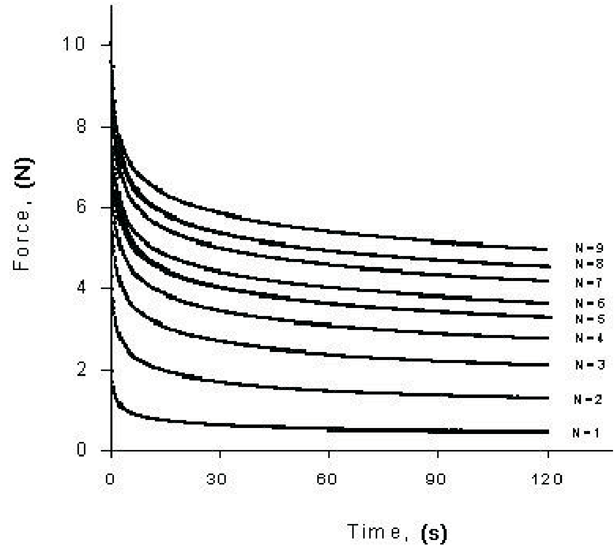

Fig. 4. Relaxation behaviour of the same chickpea kernel subjected to nine successive relaxation tests at a moisture content of 18%.

Cenkowski *et al.* (1991) studied the effect of loading number on creep behaviour in canola kernels.

Shelef and Mohsenin (1967) believed that during loading-unloading cycles, the plastic deformation of grain gradually decreases, reaching a constant value after a definite number of loading-unloading cycles. This means that the kernel loses its plastic deformation. Thus behaving like an elastic material. Moreover, since dry grains have more elastic and wet ones have more elasto-plastic behaviour (Bargale and Irudayaraj, 1995; Pappas *et al.*, 1988), therefore, the behaviour of grains at moisture contents of 6.7, 12, and 18% are different. As it expected, the dry grains lose their plastic behaviour faster than the wet ones during sequential loading-unloading cycles.

The value of the uni-axial force relaxation viscoelastic parameters for Maxwell models with three terms for chickpea kernels, at three moisture contents, are presented in Table 1. It is not sufficient to define the relaxation behaviour using only one exponential term, but it is necessary to represent the relaxation process by a series of exponential terms. The maximum relative difference (MRD) and R^2 values for one-, two- and three-term Maxwell models are compared in Table 2. The MRD values decreased with an increase in number of terms. For a one-term model, the MRD values ranged between 4 and 68.3%; for the two-term model, the MRD values ranged between 2 and 42.8%. For the three-term model, all MRD values were below 5%, with a maximum value of 4.6%. Furthermore, a comparison based on R^2 values revealed that the three-term Maxwell model was found to fit the data the best (Table 2).

For most treatments, the elastic component of the three-term Maxwell model (F_1) contributed 40-97% of the total decay force (Table 1). For all moisture contents and number of loadings, the grain tissue dissipates a major proportion of the initially applied force at a relatively slow rate. For instance, at a moisture content of 6.7, 96% of the initially induced force *ie* sum of F_1, F_2, and F_3, was dissipated during a 10 000 period (Table 1).

The first term of the three-term Maxwell model is negatively correlated to the moisture content *ie* as the moisture content increased, the decay forces decreased (Table 1). As the moisture content increased from 6.7 to 18%, F_1 for the first loading decreased 97%. Corresponding value for second, third, fourth…., and ninth loading were 95, 92, 90, …., and 83%, respectively. Meanwhile, it is clear that moisture content had a decreasing effect on the relaxation time parameter. The decay forces, F_1, F_2, and F_3 represent the elastic components in the Maxwell elements, and indirectly, these are the measures of the elasticity of the material being tested (Kajuna *et al.*, 1998). The relaxation time indirectly represents the viscous properties of the cell wall (Sakuria and Nevins, 1992). Thus, a lower value of relaxation force and time at higher moisture contents was mostly due to the plasticizing effect which reduced the value of the relaxation force. In fact, as moisture content of the kernel increases, the kernel becomes more viscous. Consequently, less force was required to maintain a certain deformation level. Previous researchers have reported similar results for other grains (Bargale *et al.*, 1994; Bargale and Irudayaraj, 1995; Husain *et al.*, 1971).

The results also showed that the first term of the three-term Maxwell model is correlated to the number of loading *ie* as the number of loading increased, the decay forces increased (Table 1). Meanwhile, it is clear that the

T a b l e 1. Effects of moisture content and number of loadings on parameters for three-term Maxwell model Eq. (1)

Moisture content (%)	Number of loadings	F_1	F_2	F_3	t_1	t_2	t_3
			(N)			(s)	
6.7	1	23.82	0.962	0.885	5 000	20.5	1.89
	2	34.09	1.02	0.921	10 000	18.9	2.03
	3	35.50	0.847	0.777	10 000	16.6	1.87
	4	35.70	0.789	0.769	10 000	18.1	1.99
	5	35.83	0.785	0.769	10 000	17.04	1.96
	6	35.55	0.769	0.753	10 000	17.95	1.97
	7	35.54	0.772	0.758	10 000	17.83	1.90
	8	35.50	0.764	0.752	10 000	17.89	1.93
	9	35.50	0.761	0.748	10 000	17.92	1.95
12	1	4.09	2.20	2.39	270.3	14.27	1.26
	2	9.01	3.81	3.86	400	16.03	1.63
	3	12.40	3.95	3.65	526.3	17.09	1.78
	4	14.97	3.75	3.50	666.7	18.15	1.91
	5	16.89	3.65	3.25	769.2	17.57	1.90
	6	17.84	3.40	3.12	833.3	17.42	1.88
	7	19.01	3.22	3.13	1 000	17.67	1.97
	8	19.81	3.24	3.10	1 111	17.36	1.92
	9	19.69	3.21	3.04	1 111	16.61	1.86
18	1	0.61	0.49	0.74	370.4	12.76	0.96
	2	1.69	1.04	1.41	416.7	12.89	1.10
	3	2.67	1.36	1.77	476.2	13.99	1.20
	4	3.46	1.51	1.88	500	13.30	1.18
	5	4.01	1.54	1.95	555.6	13.68	1.24
	6	4.44	1.56	1.95	588.2	13.35	1.26
	7	4.99	1.69	2.08	625	14.16	1.30
	8	5.35	1.72	2.11	666.7	13.93	1.27
	9	5.86	1.77	2.17	714.3	14.27	1.34

number of loading had an increasing effect on the relaxation time parameter. In fact, as the number of loading of the kernel increases, the kernel becomes more elastic. Consequently, more force was required to maintain a certain deformation level.

The calculated values of *a*, *b*, MRD and R^2 for the Peleg and Pollak model Eq. (2) are presented in Table 3. This model was unsatisfactory for representing the relaxation force for chickpea kernels. The R^2 and MRD values were in the range between 0.757 and 0.895 and between 0.65 and 31.5, respectively. Figure 5 illustrates the fit of both the Maxwell model and the Peleg and Pollak model to the experimental data. The Peleg and Pollak model represented the relaxation force well during the first few seconds of relaxation, but was inaccurate for longer time intervals. The one-, and two-term Maxwell models did not show a good fit with the test data during the first seconds of relaxation, but the difference decreased with increasing time. The three-term Maxwell model offered the best fit to the experimental data.

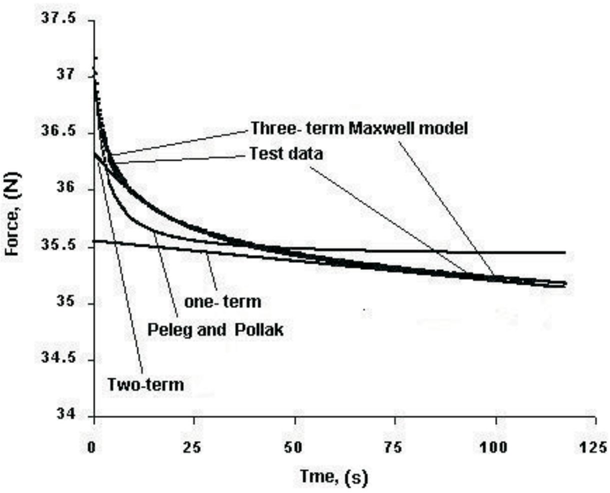

Fig. 5. Force relaxation behaviour of chickpea kernels at 6.7% moisture content as predicted by both the Maxwell and Peleg and Pollak models.

T a b l e 2. Comparison of the R^2 and MRD of the Maxwell models with one-, two- and three-terms for chickpea kernels at different moisture contents and loading numbers

Moisture content (%)	Number of loadings	One-term		Two-terms		Three-terms	
		MRD (%)	R^2	MRD (%)	R^2	MRD (%)	R^2
6.7	1	7.6	0.802	3.9	0.969	0.48	0.999
	2	5.7	0.785	2.9	0.976	0.49	0.999
	3	4.6	0.789	2.3	0.978	0.39	0.999
	4	4.4	0.770	2.3	0.967	0.25	0.999
	5	4.4	0.776	2.3	0.971	0.23	0.999
	6	4.3	0.753	2.3	0.961	0.25	0.999
	7	4.1	0.760	2.3	0.965	0.23	0.999
	8	4.0	0.754	2.4	0.961	0.24	0.999
	9	4.1	0.766	2.0	0.965	0.25	0.999
12	1	54.7	0.791	30.3	0.968	3.8	0.999
	2	47.6	0.783	25.4	0.968	3.0	0.999
	3	39.4	0.801	20.1	0.973	2.3	0.999
	4	33.9	0808	17.4	0.972	2.0	0.999
	5	30.2	0.808	15.2	0.974	1.7	0.999
	6	27.9	0.809	14.2	0.973	1.6	0.999
	7	26.1	0.803	13.7	0.971	1.5	0.999
	8	25.2	0.794	13.0	0.971	1.3	0.999
	9	25.1	0.782	12.9	0.970	1.4	0.999
18	1	68.3	0.623	42.8	0.927	4.6	0.997
	2	60.6	0.664	36.4	0.940	3.3	0.999
	3	55.5	0.688	32.8	0.945	3.3	0.999
	4	51.0	0.705	29.7	0.952	3.1	0.999
	5	48.1	0.707	28.2	0.949	3.0	0.998
	6	45.7	0.714	26.6	0.953	2.8	0.998
	7	44.5	0.713	25.7	0.953	2.6	0.999
	8	43.4	0.712	25.2	0.952	2.9	0.999
	9	41.7	0.720	24.1	0.953	2.6	0.999

For each moisture content, the loading shift factor (a_N) was determined for each loading number using the third loading as the reference (Table 4). For each moisture content, a master curve was determined (Fig. 6). Each nonlinear curve may be approximated by the following mathematical models:

for 6.7% moisture content:

$$F(t)=\frac{36.6568-7.6385X+0.0556X^2}{1-0.1896X-0.0009X^2-0.0002X^3}, \tag{6}$$

R^2=0.99;

for 12% moisture content:

$$F(t)=\frac{18.1494-10.0624X+1.8985X^2-0.1253X^3}{1-0.3551X+0.0461X^2-0.0040X^3}, \tag{7}$$

R^2=0.99;

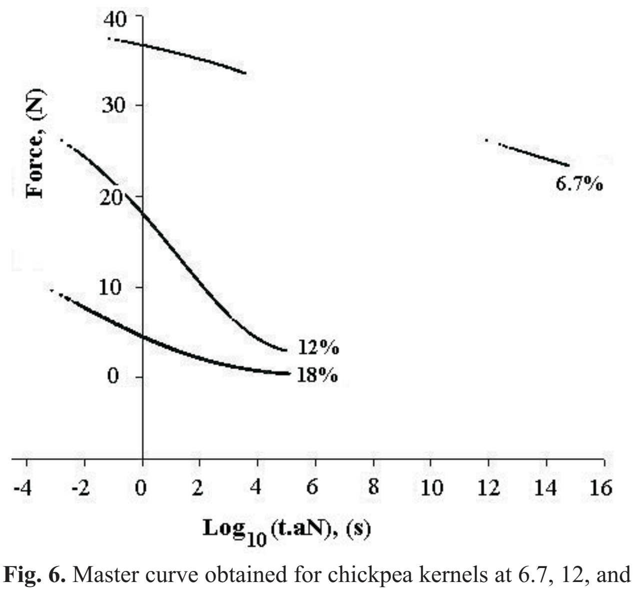

Fig. 6. Master curve obtained for chickpea kernels at 6.7, 12, and 18% moisture content.

Table 3. Parameters for Peleg and Pollak model Eq. (2) for chickpea kernels

Moisture content (%)	Number of loadings	F_o	a	b	MRD (%)	R^2
6.7	1	25.79	0.0830	0.4760	1.72	0.781
	2	36.15	0.0627	0.4237	1.18	0.816
	3	37.22	0.0524	0.4347	0.99	0.812
	4	37.35	0.0488	0.4264	0.82	0.832
	5	37.47	0.0492	0.4342	0.86	0.825
	6	37.16	0.0472	0.4541	0.75	0.836
	7	37.07	0.0483	0.2471	0.69	0.895
	8	37.02	0.0480	0.2435	0.65	0.889
	9	37.00	0.0478	0.2407	0.68	0.880
12	1	9.03	0.6187	0.7090	31.5	0.757
	2	17.19	0.5335	0.5387	20.8	0.800
	3	20.48	0.4456	0.4652	15.8	0.800
	4	22.68	0.3834	0.4433	12.5	0.798
	5	24.21	0.3436	0.4311	10.6	0.800
	6	24.74	0.3182	0.4292	9.3	0.801
	7	25.75	0.2980	0.4306	8.1	0.805
	8	26.50	0.2865	0.4253	7.3	0.815
	9	26.30	0.2838	0.4384	6.9	0.821
18	1	1.93	0.7206	1.0349	22.4	0.834
	2	4.28	0.6545	0.7450	18.3	0.853
	3	6.00	0.6006	0.7111	16.3	0.838
	4	7.07	0.5584	0.7237	15.1	0.822
	5	7.73	0.5263	0.7071	13.4	0.824
	6	8.17	0.5046	0.6798	12.6	0.824
	7	9.00	0.4884	0.6498	11.7	0.828
	8	9.46	0.4735	0.7398	11.4	0.807
	9	10.05	0.4587	0.6587	10.9	0.820

Table 4. Loading shift factor (a_N) for chickpea kernels at different moisture contents

Number of loadings	Moisture content (%)		
	6.7	12	18
1	$5.5\ 10^{+12}$	870	1050
2	31.96	8.3	11.1
3	1	1	1
4	0.75493	0.21482	0.21480
5	0.45452	0.07376	0.07987
6	0.77056	0.04052	0.04246
7	0.71705	0.01820	0.01682
8	0.89580	0.01027	0.00914
9	0.99986	0.01142	0.00469

for 18% moisture content:

$$F(t)=\frac{4.5580-1.3468X+0.1120X^2}{1+0.0192X+0.0085X^2}, \quad (8)$$

R^2=0.99;

where: $X = Log_{10}\ (t.a_N)$, $F(t)$ is force (N), and t is time (s).

The best mathematical model for the relationship between moisture content and a_N was determined for each loading number as:

$$Log_{10}(a_N)=a_o+\frac{b}{M}+\frac{c}{M^2}, \quad (9)$$

where: M is moisture content (%). For each loading number, the value of the parameters in Eq. (9) were calculated and listed in Table 5.

Based on Fig. 6, using moisture content of 12% as the reference moisture content, relaxation force data at moisture content levels of 6.7 and 18% were shifted until superposition of data was achived (Fig. 7). For each moisture content, the mean values of time required for determination of a_M were derived as given in Fig. 8. The relationship between moisture content of the kernels and a_M was determined to be:

$$Log_{10}(a_M)=10.2558-\frac{57.1126}{M}-\frac{791.4775}{M^2}. \quad (10)$$

If it is desirable to know the value of $F(t)$ at any time after compression and at any moisture content in the range between 6.7 and 18% for 1 to 9 loading cycles, the best mathematical model to estimate the curve illustrated in Fig. 7 is:

Table 5. Calculated values of the parameters in Eq. (9) for estimating a_N at any moisture content from 6.7 to 18%

Number of loadings	a_o	b	c
1	10.6759	-227.6822	1618.1432
2	1.9612	-24.4479	143.3024
3	0	0	0
4	-0.2590	-12.2701	88.3555
5	-0.3751	-20.8467	141.1376
6	-0.3364	-30.5816	214.9145
7	-0.7083	-32.8042	245.0996
8	-0.7760	-39.1095	294.7222
9	-2.3355	-9.0987	165.8008

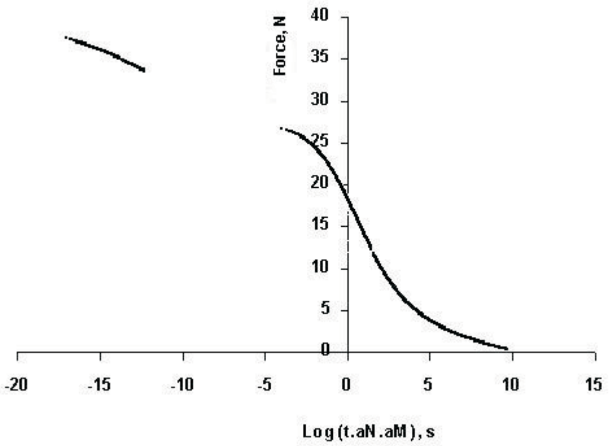

Fig. 7. Master curve obtained for estimating the relaxation force of chickpea kernels at moisture contents between 6.7 and 18% and number of loadings from 1 to 9 cycles.

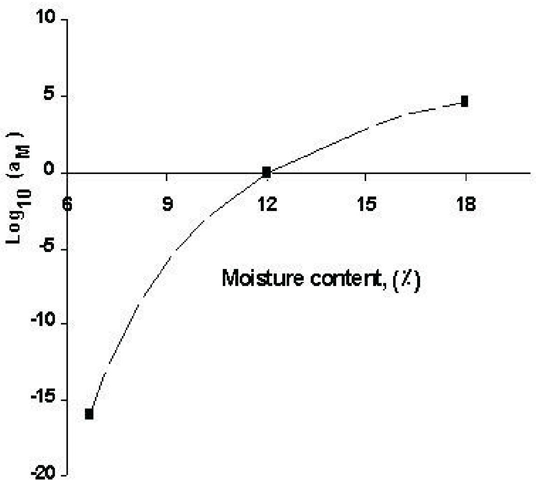

Fig. 8. Relationship between moisture content shift factor (a_M) and moisture content of the chickpea kernels.

$$F(t) = \frac{18.2496 - 2.7382Y + 0.4825Y^2 - 0.0364Y^3}{1 + 0.0739Y + 0.0565Y^2 + 0.0025Y^3 + 0.0001Y^4}, \qquad (11)$$

R^2=0.999;

where: $Y = Log_{10}(t.a_N\, a_M)$ and $F(t)$ is force (N), and t is time (s).

CONCLUSIONS

1. The kernels had a time dependent behaviour similar to other viscoelastic materials.
2. The three-term Maxwell model with a maximum relative difference (MRD) of ≤5% and R^2 higher than 0.997 was chosen as the best fit equation to the relaxation data.
3. Moisture content had a decreasing effect on the first term of the three-term Maxwell model (F_1, t_1).
4. The number of loadings had an increasing effect on the first term of the three-term Maxwell model (F_1, t_1).
5. As the number of loading of the kernel increases, the kernel becomes more elastic. Consequently, more force was required to maintain a certain deformation level.
6. For all moisture contents and number of loadings, the grain tissue dissipates a major proportion of the initially applied force at a relatively slow rate.

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