13 Rheological and Mechanical Properties of Apricot Fruit

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ABSTRACT The rheological behavior of apricot puree measured in shear rate range 0.0 to 100 s^{-1} and Oscillatory tests were studied at a wide range of temperatures (0 - 50 °C) using a Physica UDS 200 rheometer. The results indicated that the apricot puree behave as non-Newtonian fluids (pseudoplastic) and have a definite yield stress. The relationship between (η_{eff}) and temperature of apricot puree was examined. High correlation was found between (η_{eff}) and temperature. The η_{eff} decrease with increase in temperature. Oscillatory test data revealed weak gel-like (dispersion structure) behavior of the apricot puree: magnitudes of G′ were higher than those of G′′, and both increased with Oscillatory frequencies. The effect of temperature on their viscosity can be described by means of an Arrhenius-type equation. The flow activation energy for viscous flow depends on the chemical composition. Chemical and physical tests for apricot puree were made. On the other hand, the mechanical properties for apricot fruits were studied by using Instron Universal Testing Machine model 4301. The effects of storage at different temperatures on physico-mechanical properties were studied by using the flat plate compression test and penetration test. Maximum force (N) and elastic modulus values (MPa) decreased with increasing storage time. Maximum force, Young's modulus and energy for apricot fruit were decreased in the non chilled condition and with increasing storage time.

Keywords: Apricot fruit . Chemical composition . Rheological parameters . Flow behavior . Oscillatory test . Mechanical Properties . Compression and Penetration tests .

INTRODUCTION

Apricot is of paramount importance to both local markets and exportation. Its juice is considered as excellent source of vitamins particularly vitamin C, E and also considered as an important source of mineral elements necessary for human nutrition. Apricot fruits can be used fresh, dried or processed. Apricot is important for Egypt because of its export potential. Viscosity is usually considered an important physical property related to the quality of food products. Viscometric data are also essential for the design evaluation of food processing equipment such as pumps, piping, heat exchangers, evaporators, sterilizes filters and mixtures. Many foods of commercial importance, such as fruits puree are concentrated dispersions of insoluble matter in aqueous media.

Their rheological behavior, especially the yield point, is important in the handling, storage, processing and transport of concentrated suspensions in industry, Rao (1987). The viscosity of fluid foods is an important parameter of their texture. The viscosity of liquid and semi solid foods has been of interest to researchers and industrialists. Correlation between sensory and instrumental values of texture parameters can be used for industrial quality control to keep the sensory viscosity within a range assuring good consumer acceptance, Szczeniak (1987) and Houska *et al.* (1998). The examined different brands differed essentially only in viscosity and yield point values. All the test modes discussed so far involve subjecting the foodstuff to a step change in γ&or τ and measuring the stress as a function of time. A useful procedure in the study of food rheology is to subject the same to a periodic deformation. Small amplitude Oscillatory (dynamic) rheological (DR) tests have been used for studying the structure/ network development of many food. In a DR test, the energy stored (storage modulus G′, in Pa) and the energy dissipated (loss modulus G′′, in Pa) by a test sample are determined during a sinusoidal strain cycle, so that both the elastic and the viscous properties are measured,(DaSilva and Rao, 1995). If the rheological behavior is studied through a dynamic test, the stress is made to vary sinusoidally with time at a determined frequency (ω). Oscillation is a non-destructive technique for investigating the structure of foods. It is an ideal method for measuring structural formation changes. From the application of this technique, which is especially valuable for small values of times, several rheological parameters were defined, Bistany and Kokini (1983a,b). Information on the mechanical properties of fruits is of use in characterisation of material, fixing optimum time for harvest, separation from undesirable materials, texture and quality evaluation, assessment of the extent and nature of damage in collection, handling, storage and processing, and identification of basic anatomical structure (Gurhan *et al.,* 2001). The present work was done to determine the rheological behavior of Apricot fruit in steady and dynamic shear, with relationship of mechanical properties, temperature and chemical characteristics.

2.MATERIALS AND METHODS

2.1.Materials:

Apricot fruits (*Prunus armeniaca L.,*) were obtained from company (S.E.F., Qu. St Dominique 84200 Carpentras, France) growing season 2002 and 2003.

Apricot puree prepared at laboratory: Apricot fruits were picked at the ripe stage from (S.E.F., Qu. St Dominique 84200 Carpentras; France). Thereafter fruits were washed, dried in air and cut into small parts. The apricot puree was extracted by Moulinex blender (Blender Mixer, type: 741). It took five minutes blending to get the apricot puree. The puree was strained by a stainless steel strainer, then strained again by a clean muslin cloth to get rid peels for obtaining pure apricot puree.

2.2.Methods:

2.2.1. Analytical methods:

Moisture content, total solids, ash, ascorbic acid and starch, were determined according to A.O.A.C. (1995) methods. The pH was measured with a pH-meter Schott CG840. Titratable acidity was determined by titration with NaOH 0.1 N solution using phenolphthalein as indicator according to A.O.A.C. (1995). Total sugars and reducing sugars determined by Shaffer and Hartman method as described in the A.O.A.C. (1995). Total pectic substances contents were determined by the method of Carre and Hayness, which was described by Pearson (1976). Pulp content determined according to El-Mansy *et al.* (2000a). Color index of apricot puree was determined by the method of Meydov *et al.* (1977). Carotenoids were determined according to Wettestein (1957). Specific heat (c_p) was determined according to Alvarado (1991). Density was determined with a pyknometer at 5 and 30 °C according to A.O.A.C. (1995).

2.2.2. Rheological measurements:

All measurements: Rotational measurements and Oscillatory measurements have been performed on a Physica UDS 200 rheometer (Universal Dynamic Spectrometer) equipped with an electronically commutated synchronous motor allowing rheological testing in controlled stress and control strain modes.

The instrument allows the individual creation of complex real time tests containing a large number of different intervals in controlled stress and control strain control, both in rotational and oscillatory modes. The direct strain Oscillation option based on a real position control as described above has been used for oscillatory testing.

Precise temperature control was done by a Peltier Cylinder temperature system TEZ150P that assures minimal temperature gradients across the measuring gap by a patent protected design.

The data analysed by using Universal Software US200. The following models have been used (Yoo and Rao, 1995 and Senge *et al.,* 1996).

The Herschel-Bulkley model: This model describes the flow curve of a material with a yield point and shear thinning or shear thickening behavior at stresses above the yield in compression with the Casson or Ostwald equations with a higher correlation coefficient.

$$\tau = \tau_0 + K \cdot \dot{\gamma}^{n} \qquad (1)$$

Casson model: Application for fluids with yield point: the flow behavior beyond yield points often differs from that of ideal-viscous fluids. The Casson dynamic viscosity also useful because it is equivalent to the infinite shear viscosity of shear thinning dispersions. Therefore, it can be used to calculate relative viscosity.

$$(\tau)^{0.5} = (\tau_{0C})^{0.5} + (\eta C \cdot \dot{\gamma})^{0.5} \qquad (2)$$

Ostwald model: In this model the viscosity decreases with increasing load. This behavior is a characteristic feature of pseudoplastic substances.

$$\tau = m\ \dot{\gamma}^{p} \qquad (3)$$

Effective viscosity: The effective viscosity was calculated by using equations (4-5) as mentioned by Senge *et al.*(1996) and Senge (2001).

$$\eta_{eff\,HB} = (\tau_{0HB} / \dot{\gamma}) + K\ .\ \dot{\gamma}^{\,n-1} \qquad (4)$$

$$\eta_{eff\,CA} = (\tau_{0CA} / \dot{\gamma}) + \eta_{CA} + 2\ [(\tau_{0CA})^{0.5}\ .(\ \eta_{CA} / \dot{\gamma})^{0.5}\ ] \qquad (5)$$

Hysteresis area: the evaluation method Hysteresis Area calculates the area between two curves, commonly the up and down curve of a shear rate sweep. This area is given in (Pa/s)

Oscillatory measurements analysis:

The oscillatory evaluated variables: Storage modulus G`, loss modulus G`` and angular frequency ω were described by equations 6 and 7.

$$G' = K_1'\ (\omega)^{x'} \qquad (6)$$

$$G'' = K_2''\ (\omega)^{y''} \qquad (7)$$

Plots of log ω vs log G′ and log G′′ dynamic rheological data were subjected to linear regression and the magnitudes of intercepts, slopes, and R^2 were tabled according to Rao and Cooley (1992) and Yoo and Rao (1996).

Flow activation energy and the effect of temperature on viscosity:

Flow activation energy was calculated using Arrhenius-type equation as mentioned by Ibarz *et al.* (1996) and El-Mansy *et al.,*(2000a,b):

$$\eta = \eta_{\infty} \exp\,(E_a / RT) \qquad (8)$$

2.2.3. Mechanical properties measurements:

All mechanical properties were made using the Instron Universal Testing Machine (Model 4301) equipped with: A 3-mm diameter tip probe and flat plate probe (with 100, 500, 1000 and 5000 N load cell) for compression.

The force corresponding to the maximum compression is defined as the maximum force (F_{max}). The maximum puncture force (F_{max}) was measured in Newtons. The mean slope of the force–deformation curve was taken as stiffness and the actual area under the curve was expressed as work which has been referred to as toughness in the literature (Thiagu *et al.,* 1993).

Apricot fruits samples were weighed, and apricot fruits diameters were measured. The fruits samples were divided into two parts;

The first part of apricot fruits was stored at 4 ± 0.5 °C, 90 ± 5% relative humidity, chilled (C).

The second part of apricot fruits was stored at 25 ± 0.5 °C, 90 ± 5% relative humidity, non chilled (NC). Mechanical properties were studied by penetration test (PT). Each piece of fruit tested was placed in a hole of the bevelled ring. The pin penetrated with a constant speed of 5 $mm.min^{-1}$ into each piece of fruit tested (5 penetration points for each fruit and 5 fruits for each sample).

RESULTS AND DISCUSSION

Physical and chemical properties of apricot puree:

Results recorded in Table (1) show some chemical and physical properties of the obtained apricot puree. Numerous reports on the chemical composition of apricot purees have appeared in the literature but refer to old cultivars which are used less and less by industry. Hence, there is a need to characterize new varieties of apricots, which have been utilized by the food industry for some years. These results of apricot puree were in agreement with Voi *et al.* (1995) who found that the chemical composition of apricot puree ranged from 6.2 to 8.9 % for total sugars, from 3.4 to 4.2 for pH and from 1.78 to 2.75 % for total acidity. Also, these results were in agreement with Holland *et al.* (1992) and Artik (1993).

Table (1): Physical and chemical properties of apricot puree

Components*	Values**
Moisture %	**83.06±0.68**
Total solids %	**16.94±0.68**
Ash %	**1.15±0.09**
Titratable acidity % (as citric acid)	**1.66±0.03**
pH value	**4.11±0.06**
Ascorbic acid (mg/100 ml)	**19.84±0.18**
Starch%	**0.46±0.04**
Total sugars %	**7.58**
Reducing sugars %	**2.87±0.11**
Non-reducing sugars %	**4.71±0.24**
Total pectic substances %	**3.84**
Water soluble pectin %	**1.29±0.13**
Ammonium oxalate soluble pectin %	**1.57±0.08**
Acid soluble pectin %	**0.98±0.09**
Pulp content (V/V) %	**30.17±0.81**
Color index (O.D. at 420 nm)	**0.7677±0.001**
Anthocyanine (O.D.)	**0.175±0.002**
Carotenoids (mg/L)	**29.78±0.13**
Specific heat capacity kJ/kg K	**1.833±0.04**
Density at temperature 5 °C (kg/m^3)	**1089.86±0.96**
Density at temperature 30 °C (kg/m^3)	**1081.09±0.89**

**Chemical composition on wet weight basis*

***Each value is the mean of three replicates ± S.E.*

Rheological behavior of apricot puree:

Knowledge of the rheological properties of apricot puree is of value in relation to momentum, heat and mass transfer phenomena and to process and plant design. Equations or mathematical models Herschel-Bulkley, Casson and Ostwald have been widely used in quantifying the flow of fruit products (juices, purees, and concentrates) because of their simplicity and because, in most cases, a plot of log ($\tau - \tau_0$) or of log τ versus log $\dot{\gamma}$ is a straight line for a wide range of shear rate values. Data obtained by applying both models are of practical value for identifying flow and for engineering design.

Viscosity of apricot puree had a complex non Newtonian pseudoplastic behavior and it decreased as shear rate increased (Fig. 1). When the aggregates in a network are broken down by shear forces, the suspended liquid entrapped within the network is released and causes the decrease in viscosity as shear rate increases. Therefore, at an infinite shear rate, the viscosity of a suspension is the viscosity of the suspending medium (Rha, 1975).

Use of Herschel-Bulkley and Casson models:

The calculation of the rheological parameters was carried out according to the Herschel-Bulkley, and Casson models. There was no good correlation between temperature and HB-consistency index (K) value for apricot puree, while there was a good correlation between $\tau_{0HB,}$ τ_{0CA} and temperature, the same results were obtained by Trifiro *et al.* (1994) and Chiampo *et al.* (1996). The yield stress decreased with increasing temperature in H-B and CA models. These results were agreement with Duran and Costell (1982), Castaldo *et al.*(1990) and Shah and Bains (1991). To completely characterize the flow of fruit products it is important to take into account the value of the yield stress in those products which show this characteristic. Thixotropy values are tabulated also in Table 2. Apricot puree exhibits thixotropic properties. The thixotropy decreased as temperature increasing, it was 280.55 and 22.60 Pa/s at 0 and 50 °C, respectively, The results were agreement with Chiampo *et al.* (1996).

Table (2): Herschel-Bulkley and Casson parameters of apricot puree

T	Herschel-Bulkley						Casson					A_{TH}
	τ_0	K	n	r	S.D.	η_{eff}	τ_0	η_{CA}	r	S.D.	η_{eff}	
°C	Pa	Pa.s^n	-	-	Pa	Pa s	Pa	Pa.s	-	Pa	Pa.s	Pa/s
0	**10.53**	**2.854**	**0.510**	**0.996**	**0.741**	**0.405**	**11.68**	**0.094**	**0.995**	**0.811**	**0.420**	**280.55**
10	**10.38**	**1.380**	**0.607**	**0.992**	**0.793**	**0.330**	**10.24**	**0.066**	**0.994**	**0.716**	**0.332**	**239.53**
20	**6.84**	**3.714**	**0.383**	**0.981**	**1.016**	**0.285**	**9.38**	**0.061**	**0.979**	**1.077**	**0.305**	**168.66**
30	**4.80**	**3.288**	**0.370**	**0.990**	**0.603**	**0.229**	**8.59**	**0.056**	**0.929**	**1.660**	**0.281**	**108.58**
40	**2.33**	**7.767**	**0.234**	**0.984**	**0.799**	**0.252**	**7.06**	**0.053**	**0.981**	**0.838**	**0.247**	**53.77**
50	**0.95**	**6.842**	**0.214**	**0.985**	**0.591**	**0.192**	**6.52**	**0.044**	**0.932**	**1.248**	**0.216**	**22.60**

Use of Ostwald model:

Flow curves measured at different temperatures (Fig.1) illustrated that shear stress vs shear rate curves for apricot puree were non linear which related to non Newtonian behavior. The viscosity was decreased with increasing shear rate. It showed pseudoplastic behavior and slightly time-dependent at all assayed temperatures. The flow data fitted to the Ostwald model which is very simple and is used extensively in engineering applications. In all cases the correlation coefficients (r) were higher than 0.91, Table 3. The flow index values lie in the range: (0.18 < P < 0.19). There was no effect of temperature on the flow behavior index. The consistency index was decreased as temperature increased. In this case the Ostwald model was most successful.

Table (3): Ostwald parameters of apricot puree

T	Ostwald Parameters			
	m	P	S.D.	r
°C	Pa.s^n		Pa	
0	14.6921	0.1969	2.6472	0.9422
10	12.7241	0.1779	2.6285	0.9083
20	11.4321	0.1851	1.6612	0.9500
30	8.7201	0.1969	1.1376	0.9651
40	10.3734	0.1900	0.8629	0.9814
50	7.9064	0.1920	0.6187	0.9838

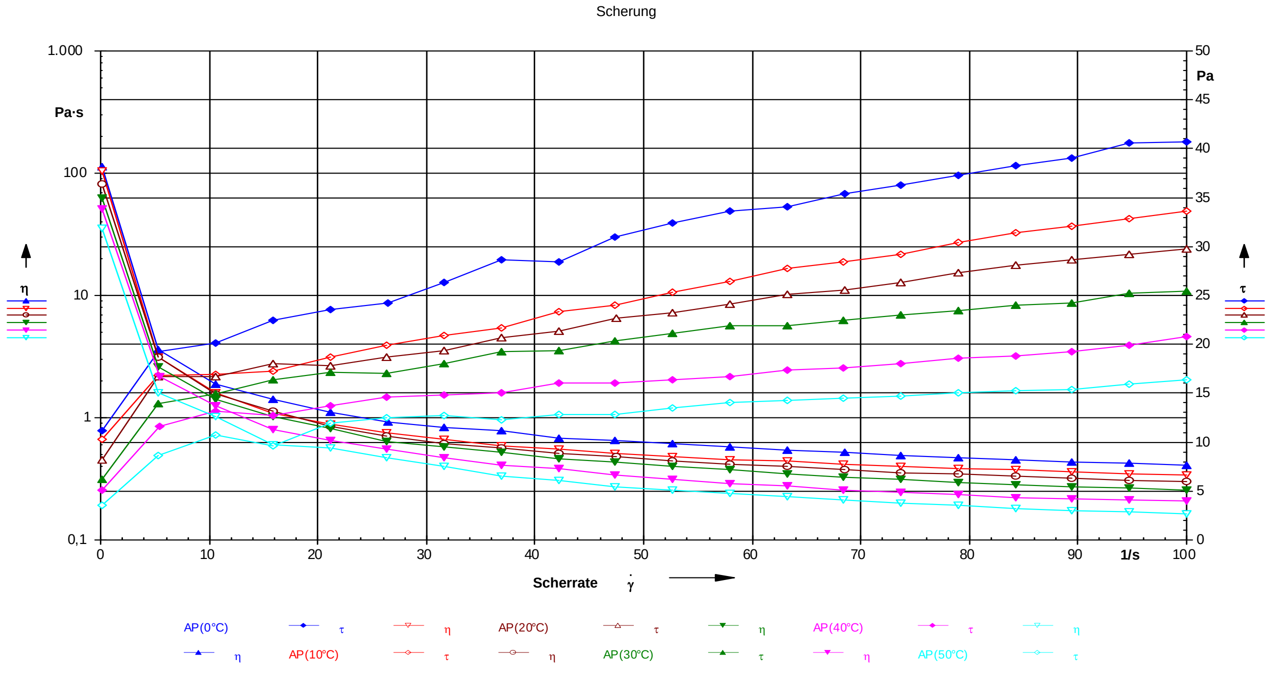

Fig. (1): The flow and viscosity curves for the apricot puree at all investigated temperatures.

Activation energy and the effect of temperature on viscosity of apricot puree:

Design of equipment for fluid flow and heat transfer operations involved in the manufacture of apricot puree require data on the rheological properties of this product. The viscosity of apricot puree decreased with temperature increasing, the same trend was observed by El-Mansy *et al.* (2000a,b). The Ea of apricot puree was 9.68 (kJ/mol) with coefficient of correlation (R^2) 0.997 and the η_∞ was 1.762 (mPa.s) at the temperature ranged from 0 to 50 °C .

Oscillation tests:

Figs. (2-3) show the changes in storage modulus (G´), loss modulus (G´´) and tan δ as a function of the frequency for apricot puree at 0, 10, 20, 30, 40 and 50 °C.

Frequency sweeps(FS):

The oscillatory test is carried out with frequency range 10E^{-3} to 100 Hz and at temperatures 0, 10, 20, 30, 40 and 50 °C, Figs. (2-3). The dynamic moduli G´, G´´ and tan δ as a function of frequency (f) are plotted in Fig. (2) for the apricot puree. Apricot puree is clearly viscoelastic. The dynamic parameters including tan δ increase with increasing f . At low f tan δ has lower values indicating a more solid like behavior. A possible, but at present hypothetical explanation for the higher tan δ at high f is that it is caused by an extra contribution due to entanglements between long dissolved macromolecules, which only contribute to the network at higher frequencies.

The dynamic rheological data of ln (G´, G´´) versus ln frequency for apricot puree at different temperature (0 –50 °C) were also subjected to linear regression, as suggested by Rao and Cooley (1992) and Yoo (2004). Table (4) contains the magnitudes of slopes (x' and y''), intercepts (K_1' and K_2''), and R^2 for the previous equations:

From these dynamic rheological data, it was found that the apricot puree displayed a more solid like behavior because the magnitudes of K_1' are much higher than those of K_2'' with a high dependence on frequency. Also from a structural point of view, such plots for true gels have near zero slopes, while for weak gels they have positive slopes (Giboreau *et al.,* 1994). The magnitudes of K_1' and K_2'' also decreased with increase in temperature. It is a well-known phenomenon that increasing temperature would decrease the viscosity of many fluid foods due to an increase in kinetic energy (Katsuta and Kinsella, 1990).

The dependence on temperature of G´, G´´ appeared to follow the usual expectation of decreasing G´, G´´ with increase in temperature with a high dependency on frequency.

Table (4): Dynamic shear data of apricot puree [constants of (G′, G′′) versus (frequency, rad s^{-1})]

T	G′			G′′		
°C	Constant (K_1′)	Constant (x′)	R^2	Constant (K_2′′)	Constant (y′′)	R^2
0	351.03	0.127	0.997	60.12	0.312	0.999
10	323.05	0.118	0.999	40.74	0.291	0.999
20	292.46	0.104	0.998	39.88	0.283	0.998
30	274.62	0.099	0.998	35.03	0.269	0.999
40	263.76	0.093	0.998	28.31	0.257	0.997
50	216.24	0.080	0.998	26.18	0.256	0.996

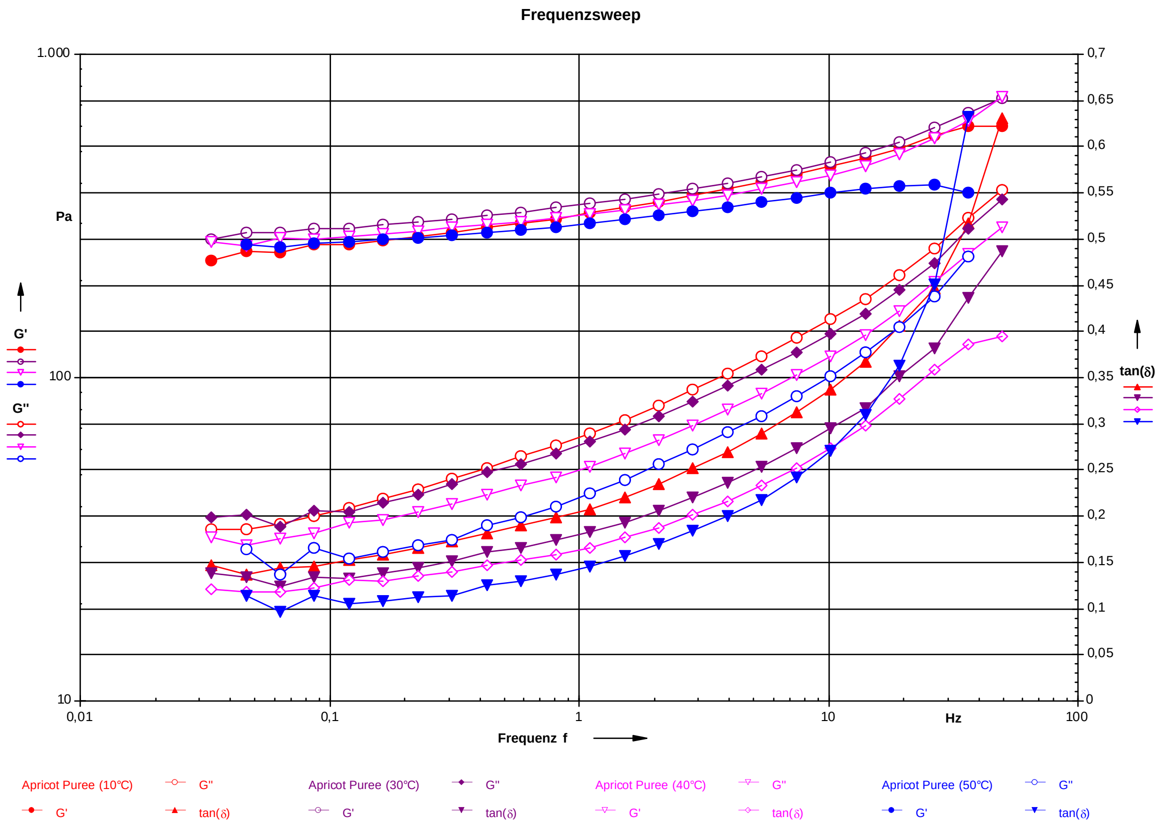

Fig. (2): Frequency sweeps: Storage (G′) and loss (G′′) modulus for apricot puree are shown as a function of the frequency

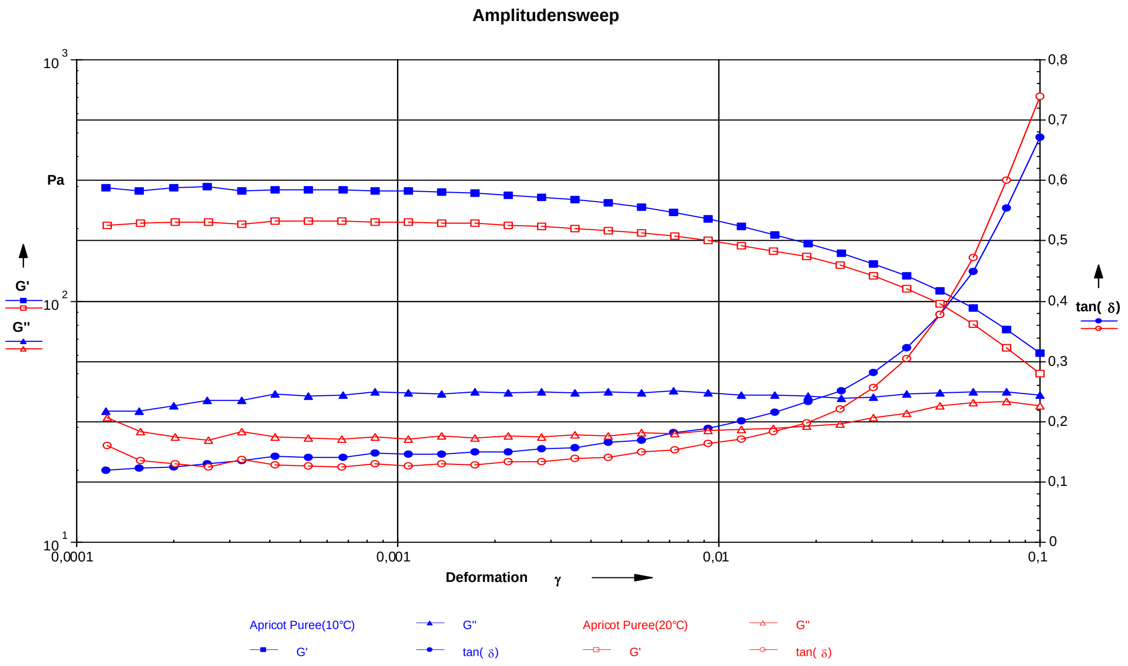

Fig.(3): Amplitude sweeps for apricot puree. The storage modulus(G′) and loss modulus (G′′) curves are shown as a function of the deformation (γ)

Loss angle values:

The loss angle was described by equation (9) as mentioned by Kunzek *et al.* (1997)

$$\tan \delta = G''/ G' = \eta'/ \eta'' \qquad (9)$$

The loss angle for apricot puree at ω = 1 Hz was (0.227, 0.221, 0.205, 0.199, 0.189 and 0.178°) at temperatures (0, 10, 20, 30, 40 and 50 °C), respectively.

Mechanical properties of apricot fruit:

Few data on the storage of apricot fruit in refrigerated and another conditions are available in the literature. Fruit texture, maturity, and ripeness are measured by a variety of techniques. These range from physical and chemical measurements to purely visual inspection. While, many tests are used, few are entirely reliable, and there is a need for better or faster testing methods. For some fruits a suitable field test has yet to be identified. For mechanical properties of fruit flesh, compression, tension, and shear tests have been used.

Penetration test:

Softening of the fleshy tissues of fruits is one of the most important changes occurring during storage and has a major influence on customer acceptability. As shown in Table (5), the apricot fruits at the different stored conditions were about the same size, with a diameter of (5.94 - 5.19 cm). The density was 1089.86 kg/m^3, and the total solids was 16.94 %.

The mechanical parameters (Penetration test) for apricot fruit, firmness were expressed as the maximum force (N), Young's modulus (MPa), energy (the area under loading curve by J), the energy1 (the area between the loading curve to maximum force and the deformation axis represents the total work of loading) and deformation (mm) are presented in Tables (5-6). Throughout storage the mechanical parameters values decreased for fruits under all conditions. Apricot stored under chilled condition showed higher in maximum force, Young's modulus, energy and energy1. While the deformation was the same in all conditions and all storage days [see Figs. (4-5)]. The same results were observed by Iwata and Kinoshita (1978) they found the chilling condition at 0 and 5 °C were better than 10 °C non chilling condition for storage Japanese apricot.

The fruits weight and size decrease with storage time increasing, this results were in agreement with Andrich and Fiorentini (1986).

Table (5): Physico-Mechanical parameters1(Penetration test) for apricot fruits stored under nonchilled conditions

Storage time	Weight	Diameter	Length	Maximum Force	Young's modulus	Energy	Energy1
(days)	gm	cm	cm	N	MPa	J	J
0	64.39±0.21	5.94±0.12	4.98±0.07	6.404±0.423	0.019±0.002	0.030±0.002	0.029±0.002
1	64.54±0.16	5.81±0.14	5.04±0.03	4.568±0.046	0.018±0.001	0.025±0.001	0.023±0.001
2	64.02±0.25	5.84±0.16	4.89±0.09	3.964±0.165	0.016±0.001	0.022±0.002	0.018±0.001
3	63.47±0.19	5.72±0.14	4.80±0.08	3.168±0.124	0.015±0.000	0.013±0.001	0.010±0.000
4	63.54±0.10	5.88±0.11	4.75±0.11	1.875±0.071	0.012±0.001	0.011±0.001	0.007±0.000
5	63.11±0.19	5.54±0.07	4.63±0.13	1.727±0.081	0.010±0.001	0.010±0.000	0.007±0.000
6	62.86±0.27	5.47±0.16	4.56±0.17	1.429±0.081	0.010±0.001	0.009±0.001	0.005±0.001
7	61.33±0.23	5.25±0.06	4.57±0.21	1.339±0.053	0.009±0.001	0.008±0.000	0.005±0.000
8	61.07±0.15	5.14±0.14	4.49±0.19	1.148±0.078	0.005±0.000	0.007±0.001	0.005±0.000
9	60.34±0.25	5.19±0.17	4.55±0.15	1.057±0.056	0.004±0.000	0.006±0.000	0.004±0.000

Mean values ± Standard errors

Deformation =11 mm

Table (6): Physico-Mechanical parameters (Penetration test) for apricot fruits stored under chilled conditions

ST	Weight	Diameter	Length	Maximum Force	Young's modulus	Energy	Energy1
(days)	gm	cm	cm	N	MPa	J	J
0	64.39±0.21	5.94±0.12	4.98±0.07	6.404 ±0.423	0.0225±0.0008	0.0304±0.0019	0.0289±0.0020
1	64.77±0.16	5.98±0.05	5.03±0.09	5.805±0.282	0.0220± 0.0014	0.0306±0.0009	0.0251±0.0009
2	64.56±0.42	5.95±0.09	4.96±0.18	5.622±0.349	0.0214±0.0023	0.0299±0.0011	0.0269±0.0017
3	64.39±0.60	5.93±0.27	4.91±0.22	4.882±0.219	0.0205±0.0007	0.0242±0.0023	0.0227±0.0018
4	64.37±0.29	5.91±0.17	4.94±0.14	4.683±0.157	0.0208±0.0007	0.0222±0.0012	0.0207±0.0012
5	64.45±0.48	5.93±0.25	4.94±0.22	4.129±0.075	0.0205±0.0006	0.0198±0.0005	0.0193±0.0006
6	64.63±0.45	5.95±0.23	4.99±0.27	4.023±0.047	0.0176±0.0011	0.0197±0.0006	0.0191±0.0007
7	64.46±0.52	5.95±0.21	4.95±0.24	3.905±0.099	0.0165±0.0013	0.0193±0.0009	0.0182±0.0008
8	64.02±0.61	5.87±0.35	4.81±0.26	3.754±0.062	0.0164±0.0007	0.0192±0.0004	0.0176±0.0006
9	63.87±0.34	5.81±0.23	4.72±0.13	3.615±0.055	0.0157±0.0011	0.019±0.0006	0.0169±0.0006
10	63.66±0.30	5.77±0.17	4.68±0.11	3.557±0.048	0.0149±0.0010	0.0186±0.0006	0.0163±0.0009
11	63.59±0.12	5.74±0.15	4.64±0.07	3.406±0.068	0.0144±0.0007	0.0187±0.0005	0.0155±0.0009
12	63.54±0.38	5.69±0.19	4.62±0.12	3.280±0.110	0.0143±0.0009	0.0167±0.0014	0.0153±0.0004
13	63.19±0.16	5.51±0.10	4.48±0.09	3.252±0.045	0.0135±0.0010	0.016±0.0007	0.0149±0.0007
14	63.24±0.36	5.53±0.24	4.47±0.13	3.238±0.024	0.0129±0.0006	0.0159±0.0005	0.0144±0.0004
15	62.99±0.51	5.42±0.26	4.39±0.20	3.211±0.087	0.0127±0.0003	0.0158±0.0007	0.0140±0.0006
16	62.78±0.17	5.44±0.09	4.53±0.08	3.167±0.068	0.0126±0.0005	0.0154±0.0006	0.0129±0.0006
17	62.67±0.24	5.45±0.14	4.50±0.09	3.056±0.089	0.0112±0.0007	0.0141±0.0006	0.0127±0.0006
18	62.06±0.35	5.32±0.19	4.34±0.12	2.844±0.085	0.0103±0.0005	0.0142±0.0005	0.0122±0.0004
19	61.89±0.42	5.28±0.27	4.31±0.15	2.703±0.085	0.0098±0.0005	0.0126±0.0004	0.0113±0.0006
20	61.55±0.53	5.22±0.29	4.29±0.18	2.720±0.053	0.0093±0.0002	0.0118±0.0005	0.0109±0.0004
21	60.97±0.47	5.19±0.36	4.28±0.11	2.232±0.080	0.0087±0.0002	0.0111±0.0008	0.0098±0.0007
22	61.09±0.30	5.14±0.18	4.26±0.09	1.791±0.122	0.0074±0.0002	0.009±0.0004	0.0081±0.0004
23	60.78±0.25	5.12±0.12	4.23±0.13	1.591±0.075	0.0070±0.0002	0.0082±0.0005	0.0076±0.0005
24	60.77±0.41	5.15±0.21	4.19±0.18	1.450±0.064	0.0065±0.0006	0.0077±0.0005	0.0070±0.0003
25	60.54±0.19	5.14±0.08	4.21±0.09	1.221±0.074	0.0044±0.0005	0.0065±0.0003	0.0053±0.0003
26	60.00±0.31	5.11±0.17	4.14±0.13	1.149±0.051	0.0039±0.0001	0.0058±0.0003	0.0053±0.0003
27	60.01±0.33	5.14±0.18	4.17±0.15	1.056±0.038	0.0037±0.0001	0.0056±0.0003	0.005±0.0002
28	60.03±0.29	5.14±0.16	4.19±0.09	1.026±0.038	0.0036±0.0001	0.0049±0.0003	0.0045±0.0003
29	59.97±0.25	5.11±0.17	4.18±0.10	0.947±0.065	0.0031±0.0003	0.0041±0.0002	0.0038±0.0003
30	59.93±0.34	5.13±0.19	4.16±0.17	0.772±0.024	0.0028±0.0001	0.0037±0.0002	0.0035±0.0002

Mean values ± Standard errors

ST (Storage time)   Deformation =11 mm

Compression test:

During compression the part of the apricot fruit in contact with the substrate deforms the most and bruises due to the rupture of cells. The bruise usually starts when isolated cell layers collapse at right angles to the direction of loading (Khan, 1989). The collapsed bands increase in density, merging together to give an impression of a continuous hemispherical bruise.

The mechanical parameters (compression test) for apricot fruit, firmness was expressed as the maximum force (N), Young's modulus (MPa), energy (the area under loading curve by J) and the energy1 (the area between the loading curve to maximum force and the deformation axis represents the total work of loading) are presented in Tables (7-8). All mechanical parameters values decreased throughout storage time for apricot fruits under all conditions [see Figs.(6-7)]. These parameters for apricot fruit stored at non chilled condition were ranged from 25.23 to 5.71 N ; 0.0233 to 0.0068 MPa ; 0.3062 to 0.0471 J ; 0.2494 to 0.0462 J and 13.01 to 10.61 mm for maximum force, Young's modulus, energy, energy1 and deformation, respectively. In the same time these parameters were ranged from 25.23 to 5.02 N ; 0.0233 to 0.0049 MPa ; 0.3062 to 0.0348 J ; 0.2494 to 0.0319 J and 13.01 to 9.66 mm, for apricot fruit stored at chilled condition. These results were agreement with Gurhan *et al.* (2001).

Table (7): Physico-Mechanical parameters (Compression test) for apricot fruits stored under non chilled conditions

ST	Weight	Diameter	Length	Maximum Force	Young's modulus	Energy	Energy1	Deformation
(days)	**gm**	**cm**	**cm**	**N**	**MPa**	**J**	**J**	**mm**
0	**64.79 ±0.29**	**5.99 ±0.07**	**5.06 ±0.04**	**25.23 ±0.24**	**0.0233 ±0.004**	**0.3062 ±0.002**	**0.2494 ±0.009**	**13.01 ±0.16**
1	**64.73 ±0.21**	**5.95 ±0.10**	**5.07 ±0.09**	**22.81 ±0.25**	**0.0196 ±0.006**	**0.2659 ±0.009**	**0.1909 ±0.008**	**12.66 ±0.11**
2	**64.35 ±0.21**	**5.89 ±0.10**	**4.90 ±0.05**	**19.03 ±0.25**	**0.0185 ±0.002**	**0.2100 ±0.002**	**0.1695 ±0.004**	**12.57 ±0.14**
3	**63.68 ±0.32**	**5.76 ±0.08**	**4.83 ±0.12**	**16.72 ±0.17**	**0.0132 ±0.007**	**0.1811 ±0.005**	**0.1402 ±0.001**	**12.03 ±0.08**
4	**63.39 ±0.24**	**5.74 ±0.11**	**4.79 ±0.14**	**14.68 ±0.12**	**0.0129 ±0.009**	**0.1246 ±0.001**	**0.0989 ±0.007**	**11.85 ±0.11**
5	**63.17 ±0.15**	**5.62 ±0.08**	**4.68 ±0.14**	**11.58 ±0.25**	**0.0113 ±0.003**	**0.0973 ±0.006**	**0.0872 ±0.006**	**11.10 ±0.22**
6	**62.91 ±0.23**	**5.52 ±0.05**	**4.60 ±0.12**	**9.52 ±0.09**	**0.0085 ±0.004**	**0.0748 ±0.003**	**0.0676 ±0.003**	**11.11 ±0.05**
7	**61.75 ±0.26**	**5.34 ±0.09**	**4.46 ±0.17**	**8.38 ±0.15**	**0.0077 ±0.002**	**0.0669 ±0.009**	**0.0624 ±0.004**	**11.02 ±0.34**
8	**61.28 ±0.22**	**5.21 ±0.08**	**4.46 ±0.15**	**6.10 ±0.27**	**0.0075 ±0.008**	**0.0516 ±0.001**	**0.0509 ±0.009**	**11.03 ±0.07**
9	**60.57 ±0.20**	**5.22 ±0.11**	**4.45 ±0.10**	**5.71 ±0.14**	**0.0068 ±0.005**	**0.0471 ±0.008**	**0.0462 ±0.006**	**10.61 ±0.09**

Mean values ± Standard errors

ST (Storage time)

Table (8): Physico-Mechanical parameters (Compression test) for apricot fruits stored under chilled conditions

Storage time	Weight	Diameter	Length	Maximum Force	Young's modulus	Energy	Energy1	Defor-mation
(days)	gm	cm	cm	N	MPa	J	J	mm
0	64.79 ±0.29	5.99 ±0.07	5.06 ±0.04	25.23 ±0.24	0.0233 ±0.004	0.3062 ±0.002	0.2494 ±0.009	13.01 ±0.16
1	64.78 ±0.20	5.97 ±0.33	5.09 ±0.12	24.89 ±0.31	0.0219 ±0.005	0.3010 ±0.008	0.2153 ±0.004	14.30 ±0.34
2	64.76 ±0.39	5.97 ±0.31	5.06 ±0.27	24.02 ±0.57	0.0211 ±0.002	0.2743 ±0.008	0.1997 ±0.007	14.55 ±0.38
3	64.64 ±0.52	5.91 ±0.36	5.01 ±0.18	23.47 ±0.48	0.0201 ±0.004	0.2728 ±0.001	0.1950 ±0.002	15.34 ±0.41
4	64.44 ±0.37	5.92 ±0.24	4.97 ±0.31	22.38 ±0.32	0.0199 ±0.009	0.2631 ±0.006	0.1937 ±0.004	15.04 ±0.27
5	64.41 ±0.30	5.90 ±0.21	4.95 ±0.18	21.49 ±0.41	0.0196 ±0.002	0.2535 ±0.007	0.1846 ±0.000	14.98 ±0.24
6	64.43 ±0.32	5.90 ±0.20	4.96 ±0.21	20.42 ±0.36	0.0190 ±0.001	0.2399 ±0.003	0.1823 ±0.003	14.98 ±0.36
7	64.28 ±0.31	5.87 ±0.24	4.93 ±0.20	19.05 ±0.51	0.0185 ±0.005	0.2247 ±0.001	0.1809 ±0.004	14.88 ±0.39
8	64.14 ±0.43	5.84 ±0.12	4.87 ±0.09	18.30 ±0.48	0.0175 ±0.006	0.2108 ±0.001	0.1811 ±0.005	13.44 ±0.45
9	63.92 ±0.51	5.86 ±0.42	4.74 ±0.11	17.79 ±0.33	0.0170 ±0.005	0.2062 ±0.004	0.1830 ±0.009	13.25 ±0.26
10	63.62 ±0.47	5.79 ±0.23	4.65 ±0.24	17.35 ±0.36	0.0166 ±0.004	0.1971 ±0.005	0.1794 ±0.003	12.92 ±0.37
11	63.56 ±0.55	5.78 ±0.36	4.62 ±0.19	16.05 ±0.47	0.0150 ±0.002	0.1816 ±0.002	0.1795 ±0.004	12.64 ±0.32
12	63.37 ±0.29	5.63 ±0.25	4.56 ±0.08	15.81 ±0.28	0.0149 ±0.002	0.1662 ±0.009	0.1606 ±0.001	12.19 ±0.22
13	63.24 ±0.41	5.58 ±0.37	4.49 ±0.11	15.18 ±0.32	0.0144 ±0.003	0.1590 ±0.007	0.1507 ±0.005	12.10 ±0.19
14	63.25 ±0.53	5.59 ±0.39	4.50 ±0.17	14.45 ±0.45	0.0139 ±0.004	0.1568 ±0.001	0.1490 ±0.009	11.95 ±0.26
15	63.05 ±0.51	5.46 ±0.21	4.37 ±0.25	14.28 ±0.47	0.0126 ±0.006	0.1386 ±0.008	0.1303 ±0.003	11.56 ±0.32
16	62.84 ±0.43	5.43 ±0.36	4.41 ±0.12	13.14 ±0.38	0.0123 ±0.003	0.1243 ±0.006	0.1198 ±0.007	11.11 ±0.18
17	62.62 ±0.32	5.41 ±0.18	4.43 ±0.17	12.62 ±0.36	0.0122 ±0.007	0.1155 ±0.001	0.1068 ±0.005	11.18 ±0.31
18	62.21 ±0.47	5.40 ±0.31	4.35 ±0.16	12.45 ±0.51	0.0119 ±0.002	0.1013 ±0.003	0.0915 ±0.009	11.03 ±0.15
19	61.90 ±0.56	5.33 ±0.29	4.30 ±0.24	12.09 ±0.48	0.0114 ±0.001	0.0928 ±0.001	0.0846 ±0.008	11.03 ±0.24
20	61.74 ±0.45	5.28 ±0.22	4.26 ±0.23	11.60 ±0.26	0.0110 ±0.005	0.0847 ±0.001	0.0759 ±0.007	10.96 ±0.20
21	61.12 ±0.45	5.21 ±0.31	4.27 ±0.21	10.90 ±0.38	0.0108 ±0.003	0.0801 ±0.004	0.0725 ±0.004	10.91 ±0.27
22	60.92 ±0.38	5.18 ±0.21	4.27 ±0.17	10.10 ±0.42	0.0104 ±0.001	0.0759 ±0.007	0.0706 ±0.001	10.65 ±0.19
23	60.92 ±0.53	5.22 ±0.34	4.25 ±0.16	9.97 ±0.36	0.0103 ±0.001	0.0673 ±0.003	0.0601 ±0.008	10.56 ±0.13
24	60.72 ±0.41	5.23 ±0.24	4.22 ±0.23	9.77 ±0.25	0.0099 ±0.001	0.0617 ±0.001	0.0541 ±0.004	10.51 ±0.35
25	60.39 ±0.26	5.19 ±0.12	4.23 ±0.21	8.96 ±0.23	0.0093 ±0.002	0.0571 ±0.009	0.0503 ±0.007	10.39 ±0.28
26	60.13 ±0.38	5.17 ±0.15	4.19 ±0.18	8.09 ±0.18	0.0085 ±0.001	0.0575 ±0.005	0.0488 ±0.002	10.45 ±0.24
27	60.06 ±0.50	5.16 ±0.30	4.20 ±0.22	7.24 ±0.17	0.0077 ±0.004	0.0475 ±0.005	0.0411 ±0.004	9.73 ±0.17
28	60.08 ±0.44	5.17 ±0.36	4.18 ±0.07	6.66 ±0.14	0.0064 ±0.007	0.0464 ±0.002	0.0395 ±0.008	9.51 ±0.22
29	59.93 ±0.32	5.14 ±0.11	4.16 ±0.18	6.39 ±0.21	0.0055 ±0.001	0.0425 ±0.009	0.0388 ±0.004	9.52 ±0.25
30	60.02 ±0.21	5.13 ±0.16	4.19 ±0.08	5.02 ±0.16	0.0049 ±0.001	0.0348 ±0.007	0.0319 ±0.002	9.66 ±0.19

Mean values ± Standard errors
ST (Storage time)

Effect of storage at different temperatures on mechanical properties of apricot fruit:

All the experimental data Tables (5-8) and Figs. (4-9) have been correlated to the storage time. From the results obtained, the following regression equations were proposed, it was indicated that the storage temperature had a clear effect on storage period. The mechanical parameters of apricot fruits, which are probably the most important from the customer's viewpoint, decreases moderately during the stored of apricot fruit.

Table (9): Equation describing the relationship between the storage days and mechanical properties of apricot fruits storage at different conditions

Equ.-Nr.	Equ.	R^2
Penetration test and non chilled storage conditions		
10	Weight = (-0.463 * Storage days) + 64.95	0.918
11	Maximum force = (-0.549 * Storage days) +5.138	0.851
12	Young's modulus = (-0.0017 * Storage days) +0.0194	0.978
13	Energy = (-0.0026 * Storage days) +0.0257	0.854
14	Energy1 = (-0.0026 * Storage days) +0.0231	0.797
Penetration test and chilled storage conditions		
15	Weight = (-0.4707 * Storage days) + 65.18	0.959
16	Maximum force = (-0.1607 * Storage days) +5.459	0.949
17	Young's modulus = (-0.0007 * Storage days) +0.0225	0.990
18	Energy = (-0.0008 * Storage days) +0.0274	0.951
19	Energy1 = (-0.0007* Storage days) +0.0249	0.966
Compression test and non chilled storage conditions		
20	Weight = (-0.1847 * Storage days) + 65.32	0.957
21	Maximum force = (-2.2461 * Storage days) +24.083	0.978
22	Young's modulus = (-0.0018 * Storage days) +0. 0212	0.927
23	Energy = (-0.0297 * Storage days) +0.276	0.929
24	Energy1 = (-0.0217* Storage days) +0.2138	0.915
25	Deformation = (-0.2683 * Storage days) +12.906	0.938
Compression test and chilled storage conditions		
26	Weight = (-0.187 * Storage days) + 65.40	0.971
27	Maximum force = (-0.6425 * Storage days) +24.32	0.986
28	Young's modulus = (-0.0006 * Storage days) +0.0221	0.985
29	Energy = (-0.0094 * Storage days) +0.2911	0.977
30	Energy1 = (-0.0070* Storage days) +0.2309	0.966
31	Deformation = (0.1924 * Storage days) +14.961	0.884

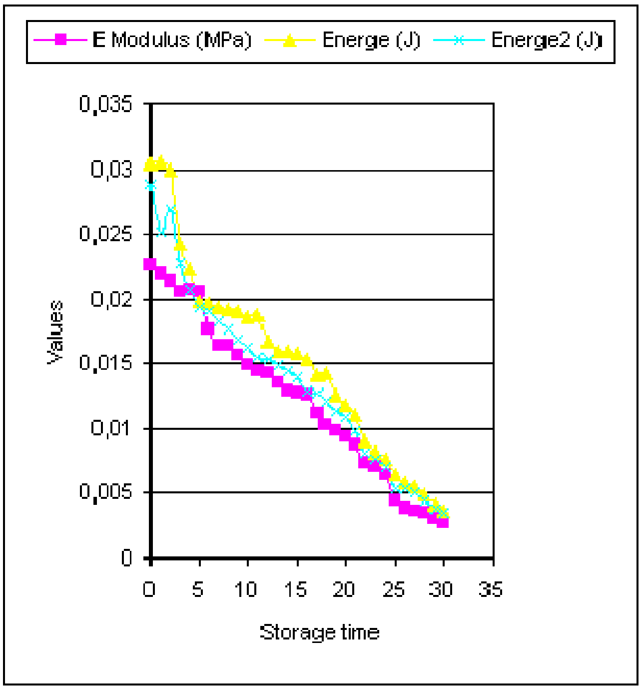

Fig. 4 Penetration test for apricot fruits stored at chilled conditions

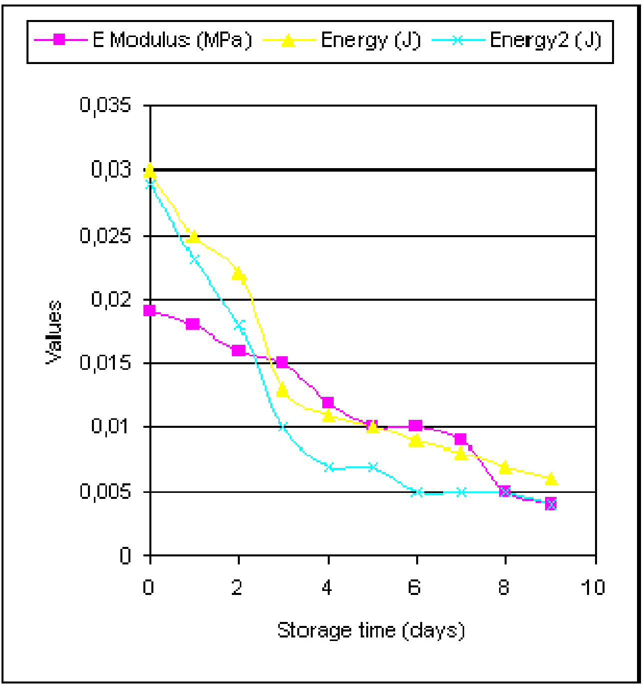

Fig. 5 Penetration test for apricot fruits stored at non chilled conditions

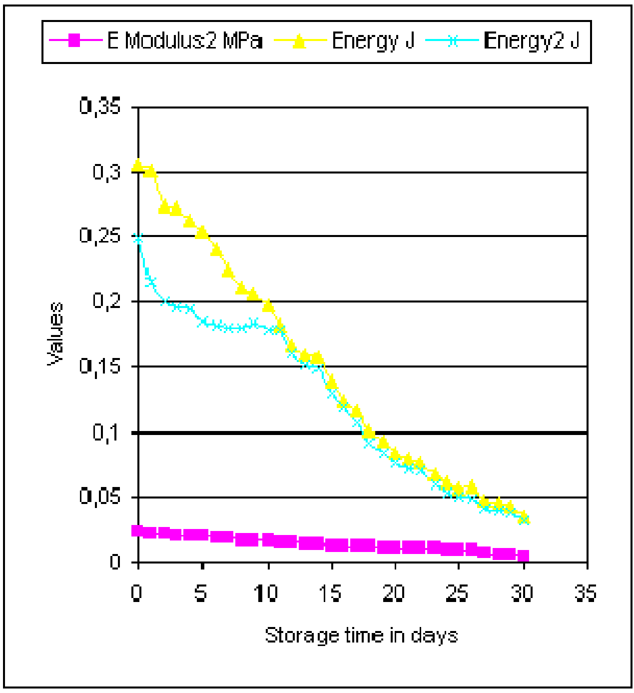

Fig. 6 Compression test for apricot fruits stored at chilled conditions

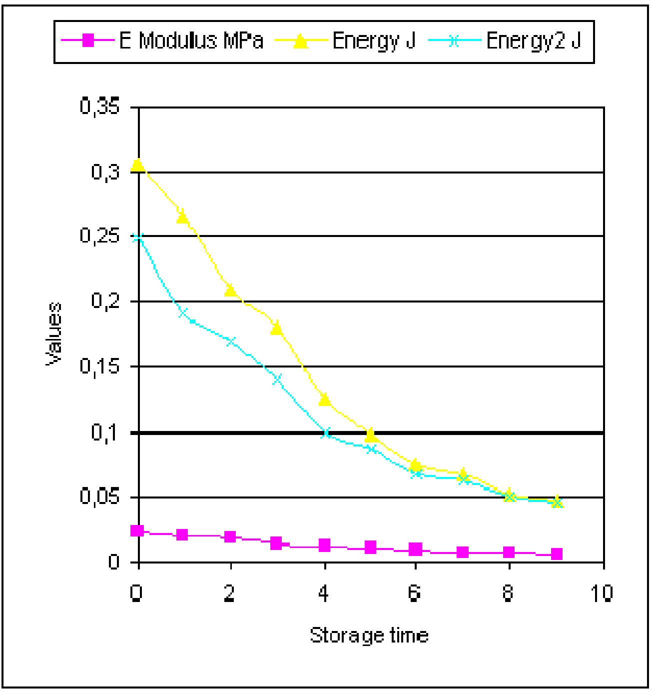

Fig. 7 Compression test for apricot fruits stored at non chilled conditions

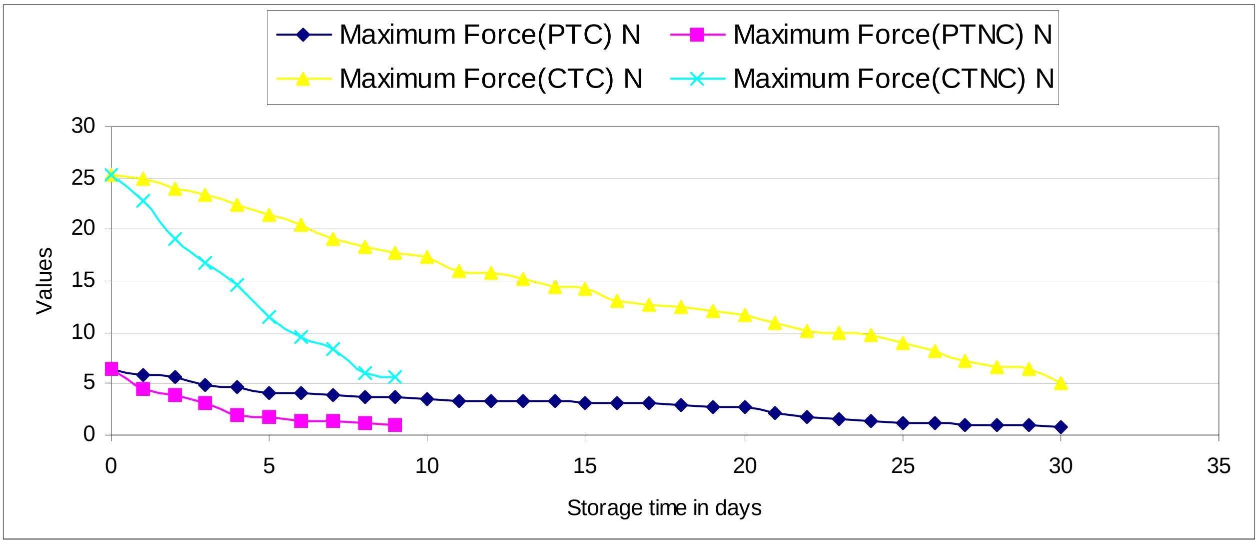

Fig. 8 Maximum force for Compression and Penetration tests for apricot fruits stored at chilled and nonchilled conditions .

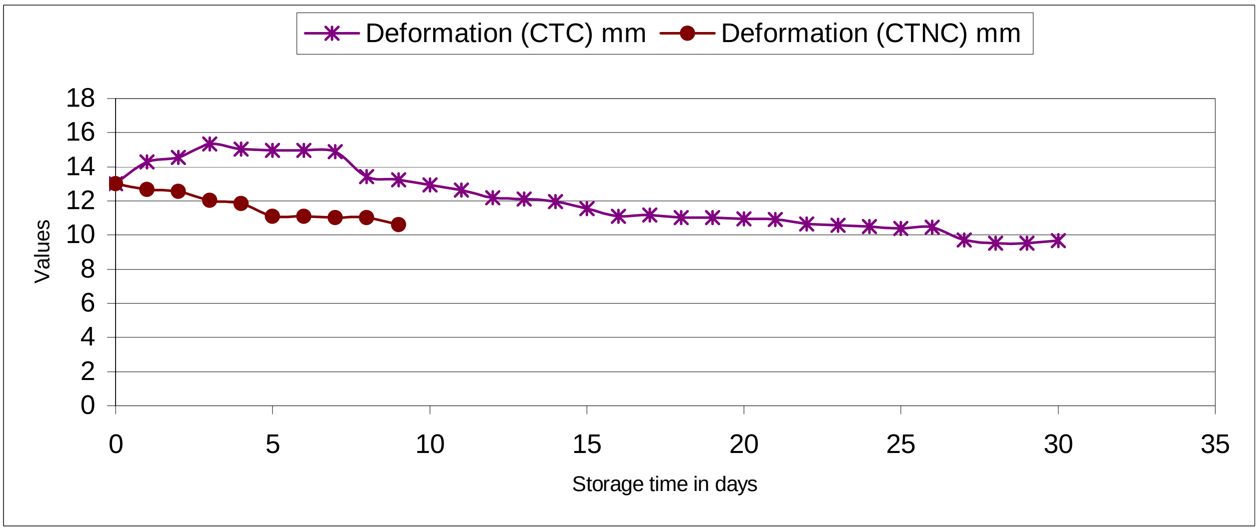

Fig. 9 Deformation for Compression test for apricot fruits stored at chilled (CTC) and nonchilled conditions (CTNC) .

Nomenclature

Symbol	Term	Unit or definition
A_{TH}	Thixotropy	Pa/s
CA	Casson model	-
c_p	Specific heat capacity	kJ/kg .K
Ea	Activation energy for flow	k J/mol
F	Force	N
f	Frequency	Hz
G'	Storage modulus	Pa
G''	Loss modulus	Pa
HB	Herschel-Bulkley model	-
K	Consistency index for HB model	Pa.s^n
K_1'	Constant in eqn (6)	Pa
K_2''	Constant in eqn (7)	Pa
LSD	Least significant difference	
m	Consistency index for Ostwald model	Pa.sn
N	Numbers of samples	-
n	Flow index for HB model	dimensionless
P	Flow index for Ostwald model	dimensionless
R	Gas constant	8.314 kJ/kg mol. K
r	Correlation coefficients	-
R^2	Adjusted determination coefficient	
S.D.	Standard deviation	
ST	Storage time	day
T	Temperature	K
t	Temperature	°C
tan δ	Loss angle	°
V/V	Volume per volume	
W	Work (the area between the loading curve and the deformation axis)	J
x'	Constant in eqn (6)	Dimensionless
y''	Constant in eqn (7)	Dimensionless
τ	Shear stress	Pa
τ_{0CA}	Yield Stress for CA model	Pa
τ_{0HB}	Yield stress for HB model	Pa
γ	Deformation	-
$\dot{\gamma}$	Shear rate	s^{-1}
η	Viscosity	Pa.s
η_{effHB}	Herschel-Bulkley effective viscosity	Pa.s
η_{effCA}	Casson effective viscosity	Pa.s
η_{∞}	Constant in eqn (5)	mPa.s
ω	Angular frequency	rad/s
ρ	Density	kg/m^3

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