Modeling the viscoelastic behaviour of the St. Julian mango (Manifera Indica L, var. Julie)

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Abstract: The *St. Julian* mango when handled in postharvest operations becomes susceptible to deformations such as bruising. An investigation of the changes in the physical properties of the *St. Julian* mango while under mechanical loading would assist scientists in understanding the mechanisms that are at play in the handling of the fruit and can aid in better handling practices. Measurements of the depths of penetration or deformation values were obtained for the *St. Julian* mango under a constant load test for four hours duration. During this time the mango exhibited creep. On removal of the load, the change in deformation was measured over an hour and a half and creep recovery behaviour was observed. These tests were performed over seven days and the rate of respiration was monitored. Four rheological models were examined and tested to mathematically model the physical behaviour of the *St. Julian* mango under these tests. The Burgers model was selected as the best fit as over 95% of the samples fitted the model and R^2 values of greater than 0.90 were obtained. It was also observed that there was a significant increase in deformation on the onset of climacteric. This could be attributed to the onset of the softening of the fruit. Creep recovery measurements indicated a permanent indentation of 2.7 mm on the fruit's skin after seven days of harvest. Investigations were also performed on changes in creep recovery, rate of change in creep recovery, and recovery strain. Both changes in creep recovery and the rate of change in creep recovery showed an exponential relationship with time. A new term called recovery time (λ) which was the minimum time required for permanent deformation to set in was developed. Such a value is useful for handling and packing fruits. A linear relationship was developed between the change in creep recovery and days after harvest. This relationship would have used in determining the minimum acceptable change in permanent deformation during the handling and packing processes.

Key words: *St. Julian mango,* visco-elastic behaviour, creep and creep recovery, Burgers model

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1 Introduction

Fruits are living biological entities even after being harvested and have been described as visco-elastic in nature (Xu and Chen, 2013). Many studies that were done on the physical behavior of fruits have permitted a better understanding of the physical changes that occur during maturity (Jahanbakhshi, 2018) which is useful information for the development of agro-processing equipment that would be used in

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harvesting, handling, storage and packing of fruits (Singh and Reddy, 2006).

The *St. Julian* mango is a seasonal tropical fruit that has been described as a fruit of high nutritional value and excellent flavour. The fruit is attractive to consumers and fetches a high price on the local markets for approximately 3 USD per kg of fruit. Commercialization of the fruit is done through an ad hoc arrangement with local farmers and larger supermarkets. There has been limited research on the physical properties of these fruits after harvest, hence many post-harvest losses occur due to improper handling and inadequate storage facilities (Mossad et al., 2016)

The visco-elastic behaviour of materials can be described by constitutive models (Christensen, 1982) and are many times represented as rheological models using arrangements of springs and dashpots. Other researchers have used other techniques to characterize visco-elasticity, for instance, Valente and Ferrandis (2003) developed a near field acoustic method (NFA) to characterize the visco-elastic behaviour of mango pulp. Their work showed promise and they cited further work in relating the NFA parameter to the physical properties of the fruit behaviour.

Kamgar et al. (2017) investigated the viscoelastic properties of dates at six different moisture contents. They performed creep experiments on the fruit and their data fitted a Burgers model. Their research concluded that moisture content has a significant effect on the fruit’s viscoelastic behaviour.

Four rheological models were proposed to describe the physical behaviour of the *St. Julian* mango under a constant load (Birch, 2001). They were

The Burgers model; $J=\frac{1}{J_1}+\frac{1}{J_2}\left[1-e^{-t}/_{Tret}\right]+\frac{t}{\eta_1}$ (1)

The standard linear model A; $J=\frac{1}{J_1}+\frac{1}{J_2}\left[1-e^{-t}/_{Tret}\right]$ (2)

The standard linear model B, $J=\frac{1}{J_1}+\left[1\left(1-\frac{\tau_\varepsilon}{\tau_\sigma}\right)e^{t}/_{\tau_\sigma}\right]$ (3)

And the Generalized Kelvin model; $J=\frac{1}{J_1}+\frac{1}{J_2}\left[1-e^{-t}/_{(Tret)_1}\right]+\frac{1}{J_3}\left[1-e^{-t}/_{(Tret)_2}\right]$ (4)

This paper describes the investigation into creep and creep recovery experiments on the *St. Julian* mangoes under ambient conditions and the modeling of the data to one of the four rheological models described above. It further analyses creep recovery data with the aim of improving post-harvest handling of fresh mango fruits.

2 Materials and methods

Sixty mangoes were harvested from a local government Orchard (Lat: 10.64; Long: -61.36) and represented a subset of the population. They were cleaned and washed in a dilute chlorine solution and then dried and stored under ambient conditions of 28^{o}C and RH 75%-85%. Six samples from this set were randomly chosen to be used as control samples in the test of respiration. For each of the seven days, three fruits were randomly chosen and used for the constant load test under ambient conditions. These fruit samples were placed under a constant load of 9.81 N (Figure 1) for four hours. The load of 9.81 was used to ensure that the experiments were performed within the elastic region. The constant load tester was a simple dead weigh tester (Figure 1). The fruit was placed on a 10 mm steel platform above which there is a moving vertical plate.

Attached to the centre of the moving plate was a spherical indenter. The combined weight of the moving plate and spherical indenter was 9.81 N. The depth of penetration was measured using a linear variable differential transducer (LVDT) and recorded by a flat-bed recorder.

At the end of the four hours, the load (i.e. moving vertical plate) was removed and a vernier was used to measure the impression (indentation) left on the fruit by the indenter for the next hour and a half. This was a measure of the deformation due to creep recovery. Hence the creep recovery at time T_n is equal to the depth (d_n) (Figure 2). The experiment was repeated for another three sets.

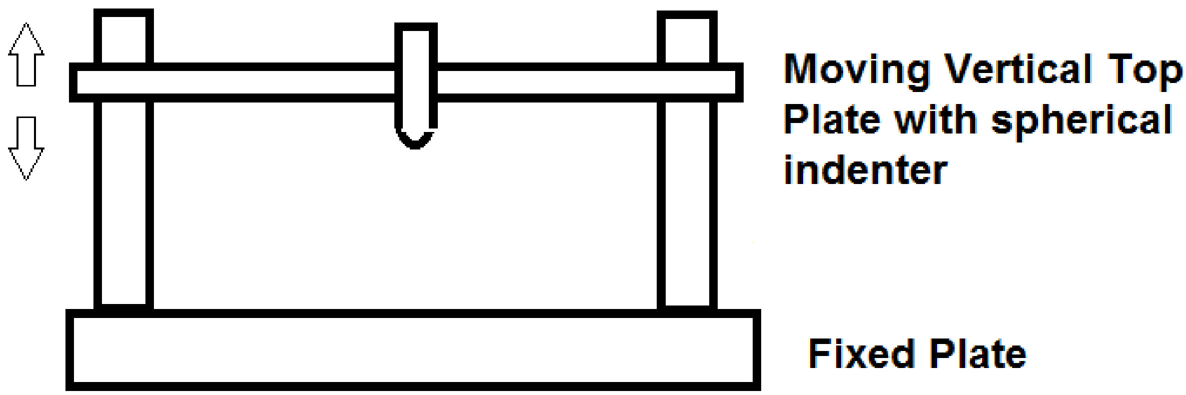

Figure 1 Constant load tester

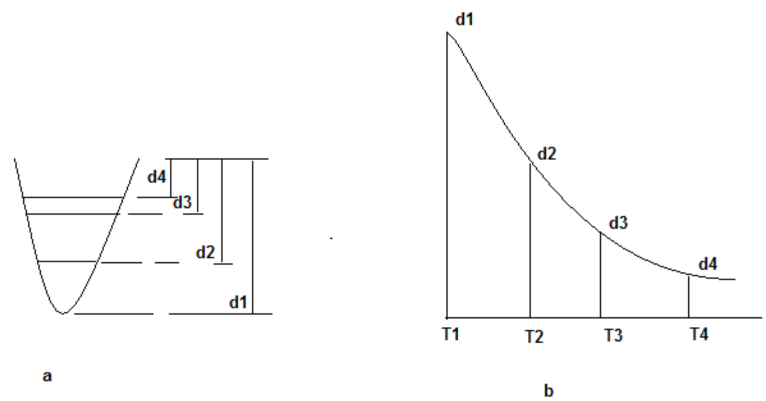

Figure 2 Creep recovery measurements

(a) Measurements taken of fruit sample; (b) Schematic of creep recovery curve at various times (*T*) after load removal

If d_n represents the depth of penetration after load removal

Then the change in creep recovery= $d_{(n-1)}-d_n$

$$Also\ the\ rate\ of\ change\ in\ creep\ recovery = \left|\frac{d_n - d_{n-1}}{T_n - T_{n-1}}\right|$$

$$The\ recovery\ strain\ (\Gamma) = \frac{d_{n-1}-d_n}{d_{n-1}} = 1 - \frac{d_n}{d_{n-1}}$$

2.1 Modelling the creep behaviour of mangoes

The indentation brought about by the spherical indenter is a combination of shear and compression. The following equation was used to convert the values from the depth of penetration (*D (t)*) mm to creep compliance m^2N^{-1} (Mohsenin, 1986) at time t (hr),

$$\mathrm{J}(t) = \frac{[D(t)]^{3/2}[16\sqrt{R}]}{3*F(t)} \tag{5}$$

Where R is the radius of the spherical indenter having a value of 0.00625 m and F is the load applied with a value of 9.81 N.

$$\text{Hence}\quad J(t) = 0.0430 \times D(t)^{\frac{3}{2}} \tag{6}$$

The Quasi Newton method was employed to model the experimental data to that of any of the given rheological equations. The method is a minimization technique that uses numeric estimates of the first and second derivatives of a function f(x) (which in this case is least squares) to seek a minimum.

A statistical software package, SYSTAT was used to perform the variable metric method on the experimental data. The software allowed for the input of the experimental data (i.e. the sample creep response under constant loading) and the rheological equation. The procedure was similar to Kamgar et al. (2017). The rheological equation representing one of the postulated models has a number of unknowns. These unknowns referred to as the physical model parameters of the respective models. For instance in modeling the experimental data to that of the Burgers model, Equation 1 was entered in the form

$$J = \frac{1}{J_1} + A(1 - \exp{}^{-t}/_{B}) + t.C \quad (7)$$

Where A relates to $1/J_2$; B relates to $T_{ret;}$ and C relates to $1/\eta_{1.}$

The creep compliance data, *J* (corrected experimental data) against the relative time spectrum (*t*);

The value of the instantaneous compliance $1/J_{1,}$ which is an educated guess of the value of the creep compliance at time *t*= zero.

The program estimated parameters for the equation using the raw data of *J* against time (*t*). The results would give

The corrected R^2 values i.e. (1- residual/corrected);

The estimates of the parameters ;

The standard errors of the estimates;

The degrees of freedom.

3 Results and discussion

The *St. Julian* mangoes when under constant load for the four hours had an initial instantaneous depth of penetration which was representative of instantaneous elasticity (Figure 3). The rate of penetration then decreased gradually with time. This was retarded elasticity (Ferry, 1980). As time continued and before the load was removed there was a constant increase in penetration depth with time. This pattern is similar to that of the creep curves as reported by Morrow and Mohsenin (1966) and Kamgar et al. (2017).

On removal of the load after the four hours as indicated by the line in Figure 3 there was an instantaneous decrease in penetration depth which represented instantaneous elastic recovery (Alzamora et al., 2008) The highest was recorded for day1 samples. The average penetration depth then followed an exponential decay that was often referred to as delayed recovery. The average penetration depth decreased slowly at a constant rate with time and the material failed to return to its original position resulting in a permanent impression (set) or permanent deformation on the skin of the mangoes which was an unwanted situation. Because the *St. Julian* mangoes showed both creep and creep recovery behaviour, the mangoes can be described as visco-elastic in behaviour (Mohsenin, 1986). The mean values for creep and creep recovery against days after harvest was calculated and is shown in Table 1. The least significant differences (LSD) between the means were determined and it was discovered that the mean values increased from day 1 to day 7 but there was a significant change in the mean deformation after day 4.

Measurements of rate of respiration during the 7 day experiments on the control samples showed that the climacteric peak occurred on day 4. Hence the most significant change in the mean values occurred at the climacteric peak. The mean creep recovery increased gradually from day 1 to day 7. The mean values of creep recovery for day 1 and day 2 are significantly different. The mean values of creep recovery of day 2 to day 4 are not significantly different for p =0.05% and therefore the null hypothesis is accepted. The means of day 4 differed significantly from day 5 for p = 0.05, the null hypothesis was rejected as there had existed significant difference between the means. This stage of maturity also coincided with the climacteric rise.

For climacteric fruits this signified the onset of senescence. As shown in Table 1 the value of the mean creep recovery, between day 4 and day 5 had doubled and continued to rise at day 6 while day 6 and day 7 had similar values. Further analysis on creep recovery would be discussed further on in this paper.

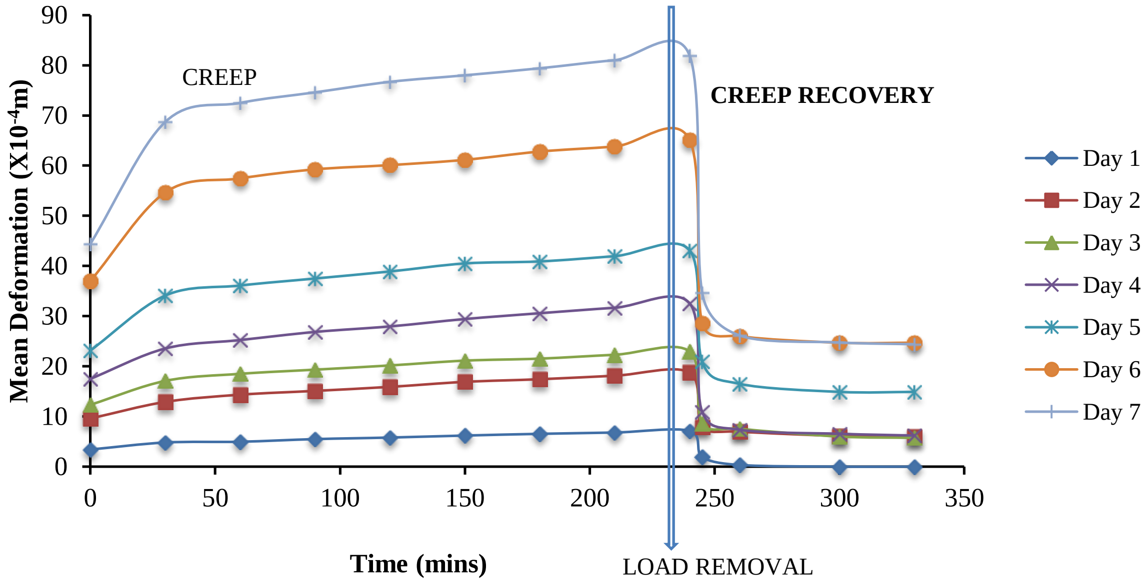

Figure 3 Creep and creep recovery behaviour of *St. Julian* mangoes during seven days after harvest

Table 1 Mean values for creep and creep recovery after days of harvest

Factor level Days after harvest	Mean deformation/ creep (10^{-4}m)	Mean creep recovery (10^{-4}m)
1	5.7a	0.6a
2	15.4b	6.7ab
3	19.5bc	7.0ab
4	27.3c	7.8ab
5	37.3d	16.8c
6	57.9e	26.0d
7	73.0f	27.5d
LSD (*p* = 0.05)	4.1	6.1

In Table 2, the calculated *F* values are significant for the mean creep measurements against days after harvest as well as against time (*T*) after load removal and significant for creep recovery against days after harvest. There seems to be no significant interaction between days after harvest and time (*T*) for both creep and creep recovery measurements. The information inferred that maturity, which was analogous to days after harvest had an effect on the physical behaviour of the fruit and the permanent deformation that may occur during handling. Also the creep recovery experiments have shown that after the fourth day after harvest the permanent deformation was more significant than the days before; as the fruit matured after harvest the extent of permanent deformation occurring during handling increased.

Table 2 'F' values in the ANOVA for creep and creep recovery measurements

Source of variation	Degrees of freedom	creep	Degrees of freedom	Creep recovery
Days after harvest	6	381.35	6	32.80
Time	8	14.70	3	2.34*
Days after harvest X Time	48	0.97*	18	0.15*

Note: *Not significant. Other values are significant at 5%

Table 3 Estimates of the physical model parameter of the Burgers model (day 1 samples)

Fruit Sample	$1/J_1$	$1/J_2$	Std. Error	T_{ret}	Std. Error	$1/\eta_1$	Std. Error[2]	R^2
	x 10^{-8} m^2 N^{-1}	x 10^{-8} m^2 N^{-1}			hr		x 10^{-8} m^2 N^{-1} hr^{-1}	
d1s1[1]	22.3	12.9	1.51	0.05	0.05	10.1	0.74	0.96
*d1s2	22.3	-3.3	1.92	0.10	0.19	4.11	0.87	0.74
d1s3	12.2	69.4	28.9	1.10	0.47	8.68	7.10	0.98
d1s4	41.1	20.48	4.28	0.47	0.19	19.2	1.50	0.99
d1s5	33.1	16.3	12.3	0.62	0.75	11.9	3.80	0.94
d1s6	48.1	52.5	10	0.87	0.20	11.4	2.70	0.99
*d1s7	28.2	4.23	2.09	0.10	0.17	8.43	1.00	0.88
d1s8	34.4	18.1	1.65	0.20	0.06	15.6	0.75	0.99
d1s9	48.1	11	3.14	0.54	0.27	10.7	1.1	0.99
d1s10	79.6	19	2.22	0.28	0.09	22.7	0.92	0.99
d1s11	79.6	19.5	2.28	0.10	0.08	19	1.0	0.98
d1s12	48.1	5.47	1.1	0.02	0.09	26.1	0.58	0.99

Note: [1]dnsm: Sample noted by day and specimen number. *dn* refers to day after harvest ; *m* refers to specimen number

[2]Std. error: Standard error of estimate

* Indicates a rejected sample

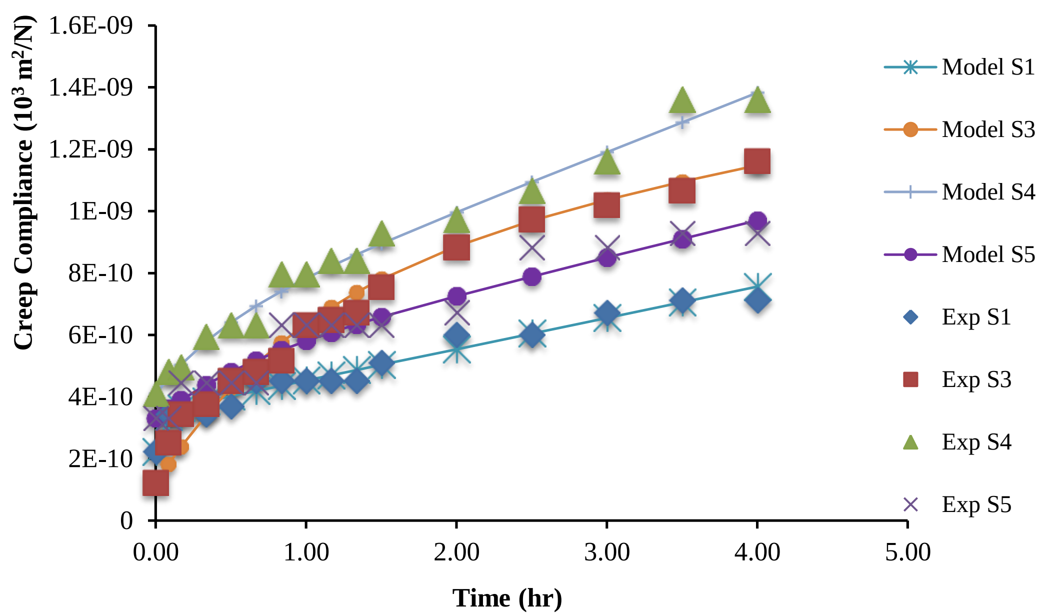

Figure 4 Comparison between the experimental data (EXP Sn) and the generated estimate of the Burgers model (Model Sn) against time for day 1 samples

3.1 Modeling the creep behaviour

The Burgers model (Equation 1) generated higher corrected R^2 values with the experimental data than any of the other three postulated complex models. This agrees with work of Kamgar et al. (2017) which stated that the Burgers model is an adequate model for describing viscoelasticity. The visco-elastic behaviour of over 95% of the samples fitted the Burgers model as R^2 values greater than 0.90 were obtained (Table 3). The generated values were $1/J_2$, T_{ret} and $1/\eta_1$ respectively (Table 3. and Figures 2 and 3 are representative results for day 1 samples. The results for day 2 to day 7 are similar). The standard solid linear Model A (Equation 2) also had high R^2 values in 95% of the tested samples. R^2 values were greater than 0.90 were in 65% of the samples, while the remaining samples had R^2 values of 0.8 to 0.90. The generalized Kelvin (4-parameter) model (Equation 4) had R^2 values ranging from 0 to 0.5 while the standard solid linear model B (Equation 3) had R^2 values of less than 0.1. Figures 4 and 5 showed the closeness of fit between a generated burgers model and the experimental data.

Each tested sample can be described as visco-elastic in nature. The Burgers model (Equation 1) best described the behaviour of the fruits under constant loading. A comparison of the generated model and the experimental data for day 1 samples is shown in Figures 2 and 3. Though the standard linear solid model A, also generated high R^2 values, it was observed that the R^2 values were smaller than those of the Burgers model. (η_1) becomes a dominant factor. The Burgers model took account of the viscous component (η_1) while the standard solid linear model did not. The other physical models failed to obtain high R^2 values because either they took no consideration of the instantaneous elasticity or they failed to consider the phenomenon of creep in the material as was the case of the generalized Kelvin 4-parameter model.

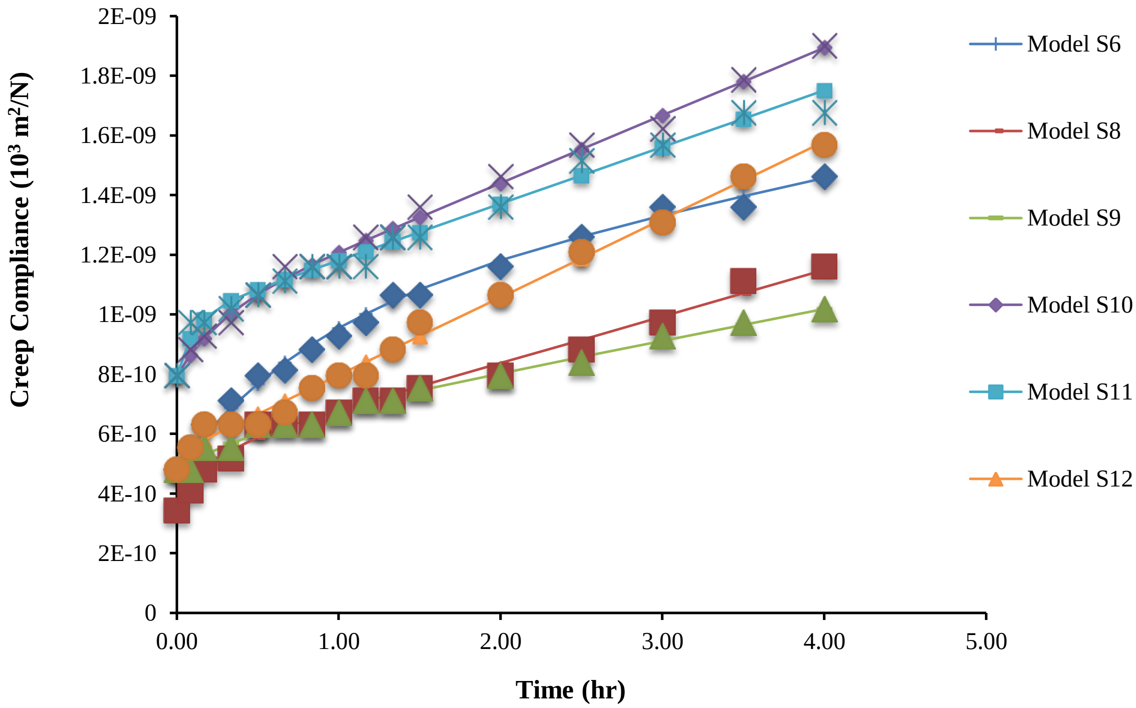

Figure 5 Comparison between the experimental data (EXP Sn) and the generated estimate of the Burgers model (Model Sn) against time for day 1 samples

Table 4 Mean values for change in creep recovery, creep recovery per unit time and recovery strain

Factor level days after harvest	Change in creep recovery (10^{-4} m)	Change in creep recovery per unit time (10^{-4} m min^{-1})	Recovery strain (Γ, %)
1	1.8a	0.3a	63a
2	3.2a	0.6a	22b
3	4.3a	0.8a	24b
4	6.6a	1.2a	30b
5	7.1a	1.2a	20c
6	10.1a	1.9a	18c
7	14.6b	2.5b	22c
LSD (p=0.05)	3.9	0.8	9

Table 5 '*F*' values in the ANOVA for creep recovery measurements

Source of variation	Degrees of freedom	Change in recovery	Rate of change in recovery	Recovery strain (Γ)
Days after harvest	6	9.14	7.61	24.88
Time	3	94.79	106.98	98.91
Days after harvest X Time	18	6.12	6.66	6.96

Also after the respiration climacteric (which occurred on day 4), the R^2 values for the standard solid linear model A decreased from 0.8 to 0.90. It is possible that as the fruit ages the viscous component. The ability to model the physical behaviour of the St Julian mango would allow us to assign quantitative physical parameters to the fruit that can be somehow relate to the macroscopic structure of the fruit (Alzamora et al., 2008). Such information would be helpful in performing simulations for food processing and handling purposes. As an example it may be possible to relate the measured acoustic property of NFA experiments (Valente and Ferrandis, 2003) to the derived values of the Burgers model. Such research can lead to the development of a non-destructive maturity measuring device.

3.2 Creep recovery behaviour of Mangoes

On the removal of constant load on mangoes the cell walls of the mango fruit will try to repair themselves (Alzamora et al., 2008). There would be an instantaneous elastic recovery. Thereafter the depth of penetration followed a decay curve. Alzamora et al. (2008) identified that instantaneous elastic recovery referred to strong structural bonds that were elastically stretched under applied load and reversed to their original position on load removal. For the delayed recovery these were weaker bonds that repaired at different rates on removal of the load. Creep recovery behaviour would examine the extent of permanent deformation after the removal of constant load. Measurements of creep recovery in mango after the constant load experiments were effective as measurements to 0.01 mm were obtained.

Mean recovery increased from 0.06 mm in Day 1 to 2.70 mm on Day 7 (Table 1). This was a 45 times increase in deformation in seven days and illustrated the extent of permanent deformation that could occur in fresh fruits after seven days. As mentioned previously there was a significant difference between day 4, day 5 and day 6 creep recovery means. This also coincided with the climacteric peak.

In Table 4, there is an increase in change in creep recovery and rate of change in creep recovery against days after harvest. The largest values occurred on day 7. On day 7 the cell walls of the fruit had been soften and because the climacteric peak occurred on day 4, the mango fruit on day 7 was in the stage of senescence. For the recovery strain (Γ) the largest value occurred on day 1 while values fluctuated between day 2 and day 7. A value of Γ close to 100%, depicted a biological material that has a large recovery strain and more than likely there is much cell wall repair activity occurring.

The most significant factor in the creep recovery experiment was the "Days after harvest" (Table 2). However, time was the most significant factor for the creep recovery measurements of change recovery, rate of change in recovery and recovery strain (Table 5).

In Figure 6, the rate of change in creep recovery ($\Delta y/\Delta T$) has an exponential relationship with time after removal (T). Then $\Delta y/\Delta T=1.78\times exp(-0.07\times T)$ with an R^2 value of 0.91 for p = 0.05. At the point $\Delta y/\Delta T=0$, then T can be referred to the minimum recovery time (λ). For mangoes λ has a value of 10 minutes (approx.). Hence it can be expected that permanent deformation would set in for mangoes 10 minutes after constant load removal.

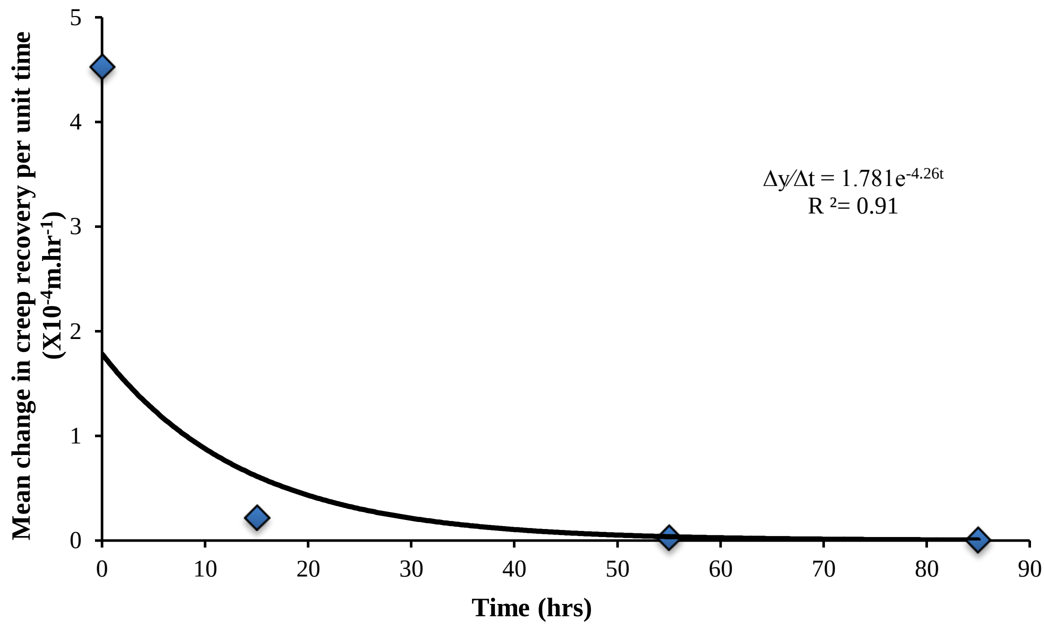

Figure 6 Rate of change in creep recovery against time after load removal

Recovery strain (Γ) is a measure of cells recovering from the deformation due to application of constant loading. The cell walls would try to repair itself and regain its original position and orientation due to the cells' tugor pressure. Values of recovery strain close to one (1) implied a lagre recovery strain. In Figure 7, Γ has a linear relationship with time (T) afetr load removal and a R^2 value of 0.81. At T =0 the mean Γ = 60%. Hence there is an initial large recovery strain that decreased with time (T). As T nears 1.5 hours, the mean Γ approaches zero. The behaviour at T= 0 could also be identifed with the instantaneous elastic recovery. Hence 60% of the strain is recovered due to instantaneous elastic recovery after load removal.

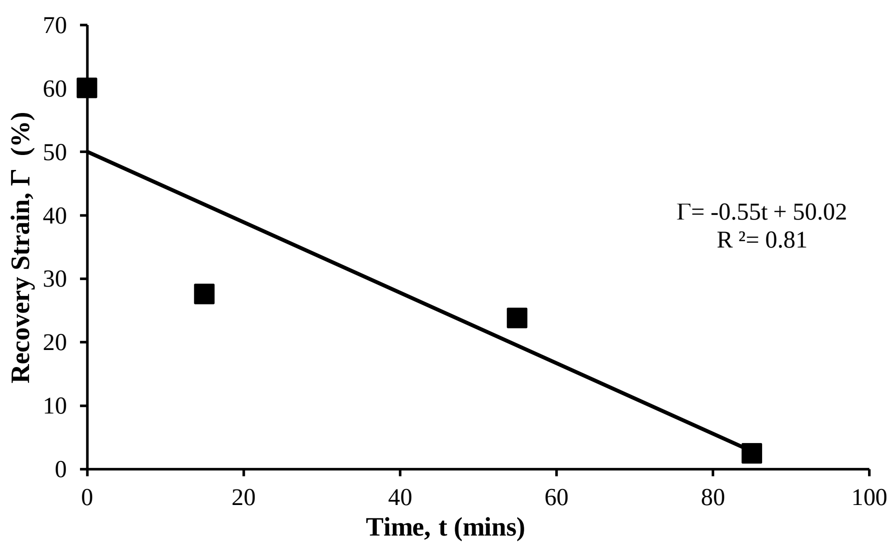

Figure 7 Recovery strain Γ against time after load removal

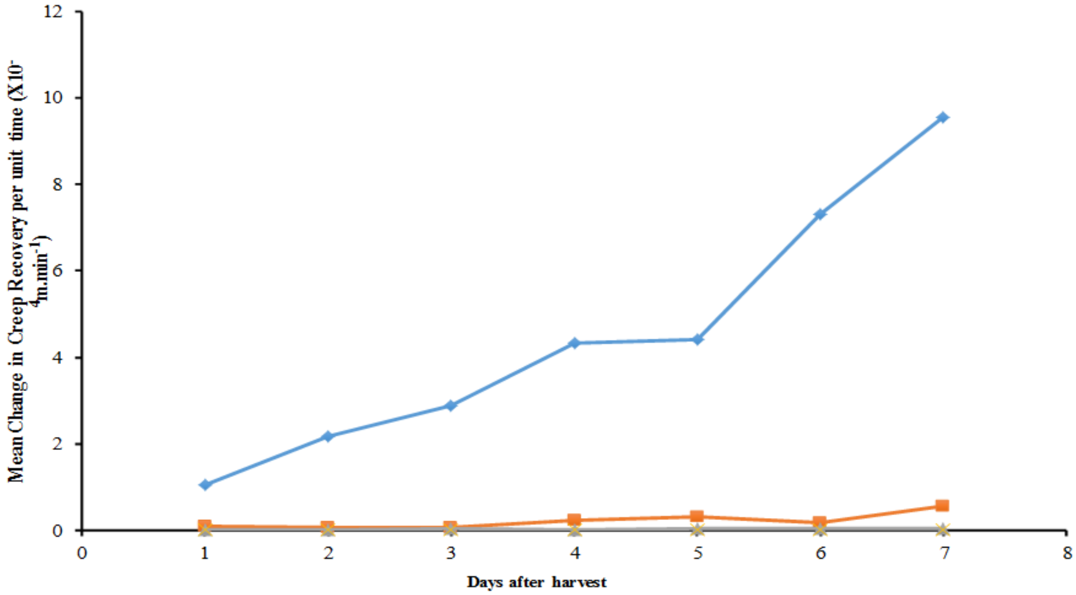

Figure 8 Interaction graph of rate of change in creep recovery against days after harvest (T1 is 15 minutes after load removal, T2 is 20 minutes after load removal, T3 is 60 minutes after load removal and T4 is 90 minutes after load removal.)

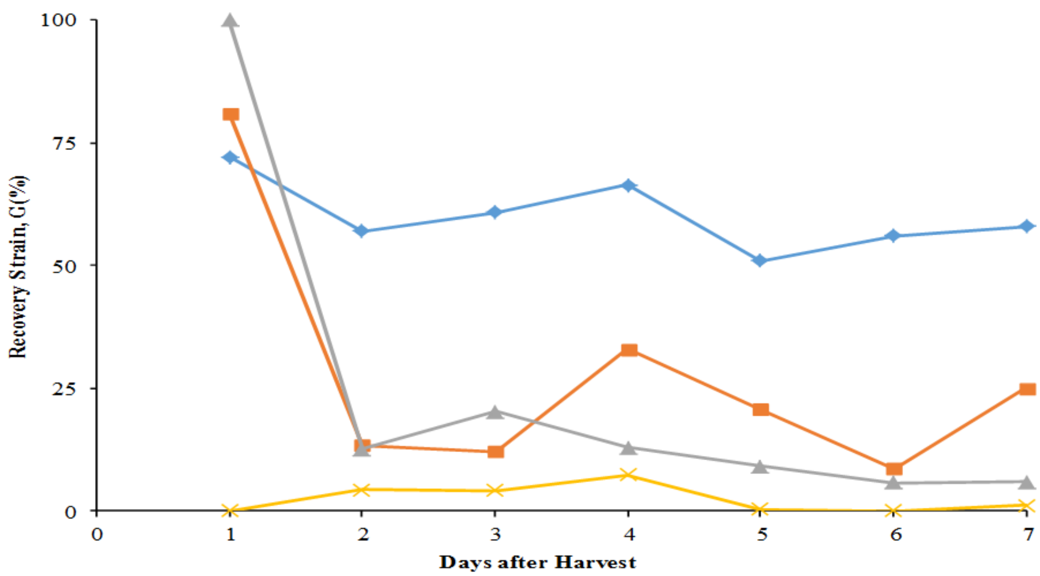

Figure 9 Interaction graph of recovery strain Γ against days after harvest at different test times (*T1* is 15 minutes after load removal, *T2* is 20 minutes after load removal, *T3* is 60 minutes after load removal and *T4* is 90 minutes after load removal.)

The rate of change in creep recovery for periods *T2* and *T4* in Figure 8 are similar for the seven (7) days after harvest. For the T1 period which represented instantaneous elastic recovery, the rate of change in creep recovery at day 1 was higher but close to the other periods *T2*, *T3* and *T4*. However, as days after harvest increased, the rate of change increased and diverged. Hence instantaneous elastic recovery may be an important physical behavior in creep recovery that can be used to measure quality and physiochemical changes in fruits as they mature. In Figure 8, for the *T1* line, there is a plateau between day 4 and day 5 and then a sharp rise between day 5 and day 6. Again, this behavior coincides with the rise and fall of the climacteric. Hence a measurement of the rate of creep recovery may be an ideal method to measure maturity in climacteric fruits.

In Figure 9 the periods *T1*, *T2* and *T3* had a recovery strain (*Γ*) above 70% for day 1 after harvest mangoes. Hence during the first three periods after load removal, the *Γ* is high for day 1 samples. Hence minimal permanent deformation and damage was expected. *T2* and *T3* decreased and converged with *T4* as days after harvest increased. *T1* fluctuated between 72% on day 1 to 55% on day 7. This was a 15% difference within seven (7) days. Only in day 1 was the *Γ* significant during the *T1*, *T2* and *T3* periods. For days 2 to day 7 only *T1* had significant *Γ* values. *T4* had low values for all days. Most of the activity in restructuring the cell walls after load removal may have occurred during *T1* for all days after harvest however, for Day 1 those restricting activities may have occurred during the *T1*, *T2* and *T3* periods. Hence it is better to handle freshly harvested fruits on the same day of harvest.

4 Conclusion

The *St. Julian* mango can be described as a visco-elastic material. There is a significant change in the fruits' physical behaviour after the climacteric peak which in this case is four days after harvest. Changes in the microstructure resulted in softening of fruit tissues. The creep recovery experiments have shown that after four days the mean residual strain (permanent deformation) is 13 times more significant than Day 1 samples. While the mean residual strain on Day 7 samples were 45 times greater than Day 1 samples and approximately four time greater than day four samples.. The mean residual strain for Day 1 samples had a negligible permanent set and would be the best time to handle the fruits. These results are significant for proper handling and storage of the *St. Julian* mangoes.

The Burgers model is the most appropriate model that described the visco-elastic behaviour of the *St. Julian* mango fruit under constant loading. It has been suggested that as the fruit ages the viscous component becomes the dominant factor. Hence not only is the size of loading a factor but the rate of loading becomes a factor as well. The Burgers model takes the instantaneous compliance (elasticity), and the viscous component into account. The standard Linear model A fails to take the viscous component into account, Hence as the fruit ages the R^2 values decrease between 0.8 and 0.9. The other physical models failed to obtain high R^2 values because they took no consideration of the instantaneous elasticity or the phenomenon of creep. The information developed would be helpful in designing adequate food handling and storage facilities.

The investigation into creep recovery has shown λ, the recovery time may be an excellent metric to be used when handling fruits. Also it may be possible to relate rate of creep recovery against some physiological parameter to develop a physical method of measuring maturity.

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Nomenclature

D Depth of penetration (10^{-4} m)

F Applied load (N)

J Creep compliance (m^2N^{-1})

J_1 Instantaneous compliance (m^2N^{-1})

J_2 Retarded compliance (m^2N^{-1})

R Radius (mm)

t time spectrum (hr or mins)

Tret Retardation time constant (hr)

ε strain (%)

Γ Recovery strain (%)

λ Recovery time (mins)

σ stress (Nm^{-2})

η viscous constant (Nm^{-2}.·hr)