Effects of Time after Harvest and Rate of Loading on Mechanical Properties of Sweet Orange (*Lemunzaki*) Under Quasi-Static Loading

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Abstract: ***Some mechanical properties of a local variety of sweet orange (Lemun zaki) were determined under quasi-static compression loading using Instron Universal Testing Machine at three levels of time after harvest and three rates of loading. The mean load the cultivar can withstand without imposing internal injury when fresh at loading rates of 10, 5, and 1 mm/s were 188.803 ± 78.753, 188.552 ± 79.034, and 187.023 ± 76.954 N respectively. On the seventh day, the mean load was found to be 51.934 ± 18.259, 53.928 ± 18.809, and 52.745 ±18.563 N for the respective rates of loading; this further decreased to 44.399 ± 19.663, 44.273 ± 19.682, and 43.743 ± 18.927 N on the fourteenth day at the same loading rates respectively. The Stress and strain, secant modulus and energy were found to vary significantly with time after harvest at $\alpha = 0.05$ at rupture point.***

Keywords: Sweet Orange, Rupture force, Secant Modulus, Energy

1. Introduction

The commonly grown citrus species belong to the family *Rutacea* which contains about 150 *genera* and nearly 2000 species. The most important citrus species grown worldwide include: sweet orange (*citrus sinensis*), lime (*citrus aurantifolia*), lemon (*citrus limon*), grape fruit (*citrus paradisi*), sour orange (*citrus aurantium*); tangerine (*citrus reticulate*); Shaddock (*citrus grandis*); and tangelo, a breed of c*itrus paradisi* and *citrus reticulate* [13]. In Nigeria, the total citrus production in 2013 was put at about 3,800,000 tons [2]. Sweet orange is the commonly grown species; cultivated in diverse cropping systems which include the multistoried home gardens, Cocoa plantations, food crop plots and a few pure stand citrus orchards.

Although about 80 % of the total sweet orange produced worldwide is processed into juice [13]; in the Mediterranean and African countries however, about 95 % of sweet orange is consumed fresh with the remaining locally processed as pasteurized juice [4]. Apart from juice production and being consumed fresh, Orange peel is used for commercial production of pectin, in pharmaceutical formulations [9]; as a source of animal feed [2], while its fiber can be used for modifying texture and taste of food [10].

Estimates of postharvest losses of citrus fruits due to mishandling are difficult to make but the generally accepted values are between 20-50 % in developing countries [11]. Most fruits are damaged by rough handling such as quasi-static compression and impact loading. Generally, mechanical injury causes internal cell damage whose symptoms are often not visible except in the case of strong impact. The damage often result in polymerization causing enzymic and chemical browning which takes a few hours to develop and is clearly visible when the fruit tissue is sectioned or when the skin is removed.

Citrus cultivars with low resistance to compressive force often result in deformation after long term shipment thus causing rejection of the entire lot [7]. In order to be free from defects, citrus fruits must have a certain level of compressive strength to withstand transportation and handling pressures. This means that mechanical properties of citrus fruits are required for design of packaging systems, transportation and handling as well as processing equipment to minimize if not eliminate these losses.

The mechanical characteristics of C. sinensis for temperate regions are well documented [14], but are rare if not completely absent for local varieties cultivated in sub Saharan Africa, hence the near absence of adequate handling and processing equipment.

Given the growing economic and nutritional importance of the local cultivar (*Lemun Zaki*), it is imperative that mechanical properties of this cultivar be determined accurately so that handling, packaging, storage, transportation systems and processing equipment/machines are designed with utmost efficiency to minimize losses.

The objectives of this study are therefore to determine: (i) the mean force and deformation at linear limit as indices of safe loadings during handling and storage to avoid latent injury, (ii) force and deformation, stress and strain, secant modulus and energy at rupture point under quasi-static compression to bench-mark safe processing and handling at three rates of loading (10, 5, 1 mm/s) and three durations after harvest (when freshly harvested, 7 and 14 days after harvest).

2. Materials and Methods

2.1 Materials

Sweet orange fruits used for this study were obtained from Kaura Citrus Farm in Toto Local Government Area of Nasarawa State, North Central Nigeria. Four trees in plots of trees typical of the variety were selected from which fruits were harvested for the tests. Some fruits were carefully handpicked from the trees while others were chipped off the three with a knife leaving a stalk 10 – 12 cm long and leaves removed [3]; this is to maintain some level of physiological freshness for tests concerning freshly harvested. The fruits were kept cooled in a fruit shed by water spray while harvesting was going on; at the end of harvest (between 1.00 – 2.00 pm), they were then packed in cardboard boxes at ambient temperature of 27 ^{o}C and 78 % relative humidity. The bottoms of these boxes were lined with foam to minimize mechanical injuries and sides perforated to reduce temperature and ethylene build up [12].

They were transported the same day to Advanced Materials Laboratory of the Engineering Materials Development Institute (EMDI), KM 4, Ondo Road, Akure, Ondo State, Southwest Nigeria and stored in a cool room maintained at about 5 ^{o}C, and 87 % relative humidity immediately upon arrival at about 8.30 pm. Tests for freshly harvested were conducted at 7.30 am the following day (about 11 hours after harvest) while other tests were conducted after 7 and 14 days respectively.

2.2 Methods

2.2.1 Quasi-static Compression Test

For each test the fruits are taken from the cool room and surface moisture cleaned, dimension (height and diameter) of each specimen were determined using a digital vernier caliper reading to 0.01mm and the values recorded in the micro-computer connected to the machine. Each specimen was then placed axially in the Instron Universal Testing Machine (Model 3369, No. K334; 50 kN capacity) under parallel steel flat plate (Plate 1). However, extra caution was taken to avoid spillage of citrus juice (which is acidic) on the platform of the machine by covering it with plastic sheet. The test fruit was then loaded to rupture point (plate 2) at the selected loading rate. Each test was replicated twenty (20) times.

Plate 1: Sweet Orange Loaded into the Machine along the Major Axis

Plate 2: Fruit loaded to Rupture

Parameters varied for quasi-static compression test of each sample were: rate of loading (10, 5, and 1 mm/s) and time after harvest; (freshly harvested, 7 and 14 days after harvest). Compressive load and deformation curve for each test specimen was generated automatically. Data for load and deformation, stress and strain, secant modulus, and energy, at rupture were automatically generated. However, because the machine does not generate data at linear limit, load and deformation were estimated by drawing a straight line from the origin to the point where the curve changes and such point was considered as the linear limit [6].

3. Results and Discussions

3.1 Load and Extension Curve

In fig. 1, the force – deformation curve starts irregularly at a very small force (at force less than about 3 % of the total force at linear limit), then becomes approximately linear (from 4 – 24 %), becomes irregular after linear limit; being a little bit concave toward the force axes with series of bioyield points with no well define bioyield point until rupture point, this phenomenon is similar to that of Marsh Grapefruit [5]. This can be explained in terms of the fruits internal structure.

Unlike most fruits whose internal structures are homogeneous, citrus fruits have high compartmentalized internal structure [8]. Juice sacs (which contain juice) are enclosed in a segment covered by a tough lamella; these segments are enclosed in a rind made up of *Albedo* (which has white spongy texture) and *Flavedo* (greenish part dotted with oil glands) (Plate 3).

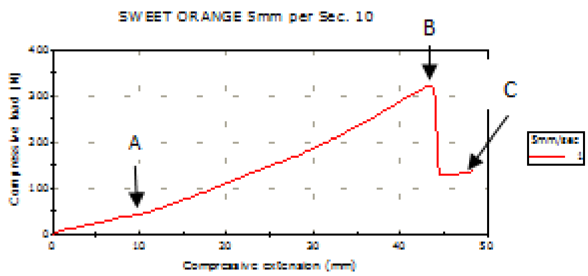

Figure 1: A Typical Load – Deformation Curve of Sweet Orange

*Point A = linear limit: Here the Compressive Load and Extension is linear. A-B: The relationship is non-linear, characterized by series of bio-yield points until the fruit ruptures at point B. B - C: Break Point, Fruit is completely crushed, Juice oozes out.

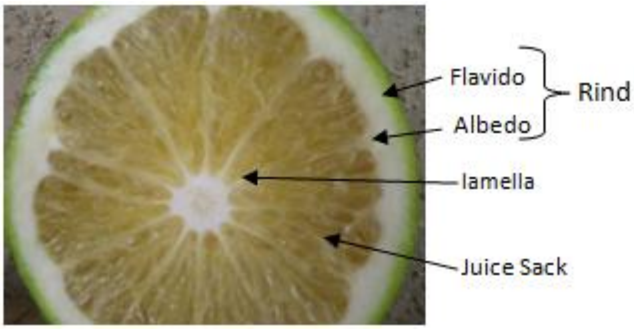

Plate 3: Internal Structure of Orange

At the initial application of compressive load, air and some oil are squeezed out from the rind until the rind makes a perfect contact with the compression surfaces (upper and lower contacting surfaces), this probably accounts for the initial irregular nature of the Force – Deformation curve. On further loading, the load is borne by the whole fruit with hydrostatic pressure building up in individual juice sacs (with extension of these sacs) but with all its internal composition intact; this accounts for the linear nature of the Force – Deformation curve [1].

Beyond this, juice sacs begin to burst accompanied by the extension of lamella membranes and subsequent disarrangement of the segments but with the content held up in the rind; this probably accounts for series of bioyield points and the concave nature of the curve. Rupture of the rind starts at the equator and propagates towards the axis and finally bursts resulting in sudden drop observed in the force – deformation curve [7].

3.2 Compressive Load and Deformation at Linear Limit

Table 1 shows the statistics of load and extension at linear limit. To minimize latent injury, the maximum permissible quasi-static compressive load are 188.803 ± 78.735, 51.935 ± 18.259 and 44.398 ± 19.663 N for freshly harvested, 7 and 14 days after harvest respectively loaded at 10 mm/s representing an average reduction of about 74 % in load bearing capacity on the fourteenth day. The Analysis of Variance (ANOVA) showed that the means of forces and deformation for times after harvest are statistically significant at $\alpha = 0.05$.

Table 1: Load and Extension of Sweet Orange for Different Rates of Loading and Time after Harvest at Linear Limit

		Freshly harvested			1 week after harvest			2 weeks after harvest		
Parameter	Rate (mm/s)	10	5	1	10	5	1	10	5	1
	No. Samp	20	20	20	20	20	20	20	20	20
	Min. Val	45.995	44.488	43.913	5.563	5.743	5.892	13.398	13.435	13.127
Load	Mean	188.803a	188.552a	187.023a	51.934b	53.928b	52.745b	44.399c	44.273c	43.743c
(N)	Max. val	300	299.79	295.44	64.572	64.571	64.572	74.163	74.163	72.002
	Std. Dev.	78.735	79.034	76.954	18.259	18.809	18.563	19.663	19.682	18.927
	Min. Val	6.174	6.174	6.174	7.206	7.206	7.207	10.487	10.479	9.999
Deformation	Mean	8.128d	8.182d	8.131d	10.921e	10.897e	10.921e	12.618f	12.675f	12.586f
(mm)	Max. val	9.369	9.369	9.369	13.288	13.29	13.289	14.077	14.077	14.17
	Std. Dev.	1.067	1.005	1.16	2.521	2.499	2.521	1.109	1.01	1.181

NB: Means with the same letters within rows do not differ significantly at 5% level for LSD test

The results showed that for a given rate of loading, time after harvest has significant effects on both force and deformation as depicted by figs 2 and 3. The reason may be due to the fact that as the time after harvest increases, more starch in the fruit is converted to sugar similar to the case of Pomelo [8], thereby resulting in softening of the fruit tissues hence the decrease in elastic strength and increase in plasticity.

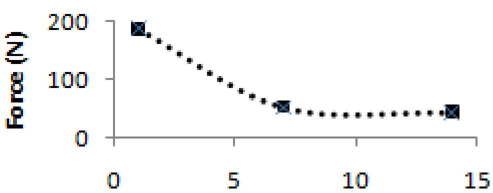

Figure 2: Variation of Force with Time after Harvest at Linear Limit

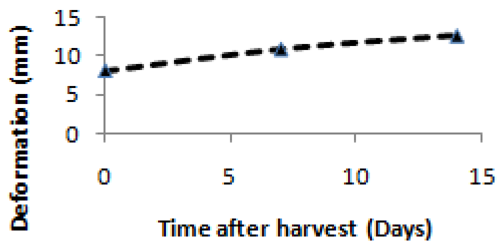

Figure 3: Variation of Deformation with Time after harvest at Linear Limit

3.3 Compressive Parameters at Rupture Point

3.3. 1 Force and Deformation

Table 2 shows that at a loading rate of 10 mm/s, the minimum bursting strength of *lemun zaki* that is freshly harvested, 7 and 14 days after harvest is about 837.266 ± 114.141, 403.167 ± 54.924, and 350.394 ± 64.959 N respectively. This shows that there is a reduction in the force required to process the fruit. The ANOVA showed that only time after harvest is significant for both load and deformation at α = 0.05.

Table 2: Rupture Point Load and Deformation at Different Loading Rates and Time after Harvest

		Freshly harvested			1 week after harvest			2 weeks after harvest		
Parameter	Rate (mm/s)	10	5	1	10	5	1	10	5	1
	No. Samp	20	20	20	20	20	20	20	20	20
	Min. Val	511.172	553.947	378.505	327.397	327.398	304.383	226.424	226.423	212.075
Load	Mean	837.266	676.975	612.892	403.167	395.423	369.232	350.394	343.462	284.579
(N)	Max. val	1384.048	1010.783	1221.374	470.286	470.286	470.286	459.366	501.389	370.429
	Std. Dev.	114.141	118.011	121.247	54.924	47.603	64.518	64.959	69.922	50.490
	Min. Val	43.893	52.200	53.500	36.300	38.499	38.500	48.854	48.853	48.854
Deform.	Mean	64.533	64.958	68.576	50.324	54.709	47.426	57.505	59.134	61.989
(mm)	Max. val	85.000	83.100	105.069	65.735	77.200	64.002	71.458	71.457	71.458
	Std. Dev.	14.882	9.925	17.062	7.891	13.867	7.740	9.827	8.329	8.592

3.3.2 Stress and Strain

The statistics of stress and strain is presented in table 3. The ANOVA showed that only time after harvest is significant for both means stress and strain at α = 0.05. For a given rate of loading, there is a general decrease in stress as the time after harvest increases (Fig. 4), meaning that as time after harvest increases, the rupture strength of the cultivar decreases due to tissue softening. Conversely, strain increases as time after harvest increases for a given rate of loading (Fig.5) because the cell tissues become soft and hence plastic.

Table 3: Rupture Point Stress and Strain of Sweet Orange at Different Loading Rates and Time after Harvest

		Freshly harvested			1 week after harvest			2 weeks after harvest		
Parameter	Rate (mm/s)	10	5	1	10	5	1	10	5	1
	No. Samp	20	20	20	20	20	20	20	20	20
	Min. Val	0.126	0.105	0.119	0.083	0.084	0.082	0.075	0.075	0.013
Stress	Mean	0.184	0.167	0.150	0.091	0.089	0.089	0.078	0.077	0.062
(Mpa)	Max. val	0.269	0.344	0.207	0.098	0.097	0.098	0.079	0.079	0.079
	Std. Dev.	0.058	0.084	0.028	0.006	0.004	0.004	0.002	0.002	0.021
	Min. Val	0.623	0.713	0.720	0.611	0.693	0.718	0.748	0.798	0.717
Strain	Mean	0.736	0.747	0.750	0.752	0.833	0.848	0.879	0.913	0.956
(mm/mm)	Max. val	0.833	0.780	0.780	0.850	0.961	0.968	1.309	1.095	1.125
	Std. Dev.	0.071	0.028	0.023	0.076	0.081	0.101	0.190	0.083	0.157

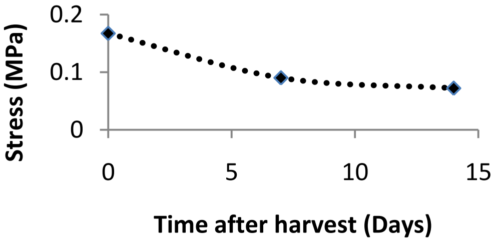

Figure 4: Variation of Stress with Time after Harvest

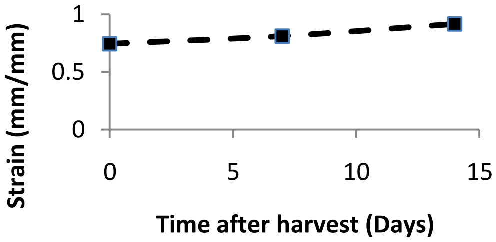

Figure 5: Variation of Strain with Time after Harvest

3.3.3 Secant Modulus and Energy

3.3.3.1 Secant Modulus

The statistics of secant modulus is presented in table 4. There is a general decrease in elasticity for a given rate of loading as the time after harvest increases meaning that as time after harvest increases, the tissues of the fruits becomes less elastic (tend to be plastic) hence the decrease in modulus of elasticity.

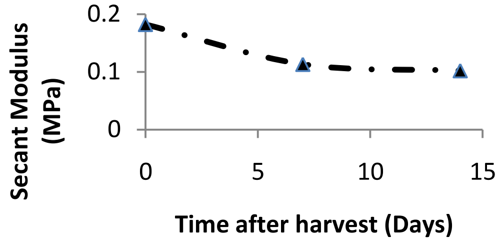

Figure 6: Variation of Secant Modulus with Time after Harvest

Table 4: Rupture Point Secant Modulus and Energy for Sweet Orange at Different Loading Rates and Time after Harvest

		Freshly harvested			1 week after harvest			2 weeks after harvest		
Parameter	Rate (mm/s)	10	5	1	10	5	1	10	5	1
	No. Samp	20	20	20	20	20	20	20	20	20
Secant	Min. Val	0.141	0.090	0.116	0.108	0.099	0.093	0.101	0.101	0.071
Modulus	Mean	0.196	0.177	0.172	0.122	0.109	0.108	0.104	0.102	0.100
(Mpa)	Max. val	0.334	0.210	0.306	0.157	0.136	0.130	0.111	0.104	0.134
	Std. Dev.	0.064	0.041	0.066	0.014	0.015	0.012	0.004	0.001	0.018
	Min. Val	13.859	14.739	7.972	8.650	8.650	7.674	4.309	4.309	3.878
Energy	Mean	25.987	22.371	19.729	11.949	11.586	10.664	10.004	8.302	7.067
(J)	Max. val	45.644	35.249	45.677	15.713	15.713	15.713	18.251	16.459	11.094
	Std. Dev.	11.578	6.763	13.210	2.958	2.499	3.098	4.447	3.267	2.064

3.3.3.2 Energy

There is a general decrease in energy as the time after harvest increases for a given rate of loading (Fig. 7) meaning that as time after harvest increases, the tissues of the fruits becomes less turgid (tend to be plastic) hence the decrease in energy it can absorb before rupture.

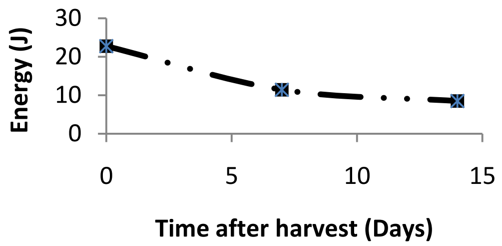

Figure 7: Variation of Secant Modulus with Time after Harvest

These results affirmed the assertion that the rate of loading tend to have less significant effect on agricultural materials with soft tissues like fruits and vegetables [6]. Although fruits and vegetables exhibit viscoelastic behavior under mechanical loading which depends on the amount of applied force, the rate of loading is often ignored (but only reported) for practical purposes with the assumption that they are elastic [1].

4. Conclusion

In this work, it was found that *Lemun zaki* fruit can withstand a load of 188.803 ± 78.735 N without latent injury when fresh; this dropped to 51.934 ± 18.259 and 44.399 ± 19.663 N in the 7th and 14th day respectively after harvest at linear limit. The Stress and strain, secant modulus and energy were found to vary significantly with time after harvest at $\alpha = 0.05$ at rupture point.

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