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Rheological Properties of Purple Avocado (*Persea Americana* Mill.) Fruits at Different Ripening Stages

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ABSTRACT

Proper postharvest handling and management of perishable horticultural commodities require the proper understanding and the need for basic information on the mechanical properties of these commodities specifically for avocados to preserve quality and reduce losses and waste. Physical characterization and compression tests were conducted on avocados to develop an understanding of the rheological properties of avocados at different ripening stages, sizes, and compression loads. An appropriate equation in predicting volume from its weight and its shape signature that specifically represents the shape of the purple fruited avocado variety in a one-dimensional function were established. The shape of avocado fruits tends toward being spherical and expected to roll not slide as indicated by the mean values of sphericity and aspect ratio. The compressive strength of avocado varied with ripeness were small size can withstand up to 5 kg of load by weight after harvest without significant internal damage and 6 kg of load for medium size.

Avocado fruits had a time-dependent stress relaxation behavior like other viscoelastic material. The three-term Maxwell model with six parameters described the stress relaxation behavior of avocado fruit at different compressive loads, ripeness and sizes based on the maximum relative difference (MRD), R^2 , and residual MSE. The advancing degree of ripeness have a corresponding decrease in the decay stress value (σ_1) and time of relaxation (τ_1) component of the model. To minimize mechanical damage, avocado should be packed in vertical orientation with cushion (bubble wrap, foam, or paper) and can be stacked up to 10 layers for small size and 12 layers for medium size at harvest using 10 kg capacity cartons.

Keywords: avocado, compression, rheology, postharvest handling, physical properties

INTRODUCTION

Avocado is no longer considered an exotic fruit since its economic significance worldwide and existence on the world market has been gradually increasing in the past few decades. It is primarily grown for the local market and the Philippines is considered one of the principal avocado producers in Asia having a 3.9% production within the continent (Hussein, Fawole, & Opara, 2018). The world production of avocado surpassed 5.6 million tons in 2016 which corresponds to a ~56% rise in a decade (FAO, 2018). In 2013, the annual trade for avocado was 1.2 million tons reflecting a ~3-fold growth in trade figures over a decade and the almost doubled average global consumption of avocado fruits reaches ~0.7kg per capita per year (Mazhar, Josyce, Hofman, & Vu, 2018).

Even with the increasing production, trade, and consumption of avocado fruits, the issue for the avocado industry is delivering high-quality fruit to consumers (Mazhar et al., 2018). Yahia (2009) stated that due to improper postharvest handling of produce it affects ~30%-60% of the total production to be lost and wasted. The losses and waste in avocados in some developing countries have been estimated at 43% (Yahia, 2009). An internal defect of more than 10% on the flesh causes dissatisfaction and undesirably impacts the repeat purchasing intentions of consumer (Gamble et al., 2010; M. L. Perkins, Joyce, & Coates, 2019).

Mechanical handling of agricultural products results deformation and flow of the materials and the mechanical properties involved is referred as rheological properties. The different mechanical and physical properties are very significant in handling and subsequent processing because it determines the damage to the fruit transport, and it shows the ability of the fruit to withstand load and stress. Shelf life of a commodity is also influenced by the mechanical damage, consequently proper consideration of mechanical properties contributes to a consequential extension of fruit shelf life. The fundamental basis for designing and adjusting parameters of equipment operations involved in industrial processing is relative to the characterization of rheological behavior related with postharvest maturation of

fruits (Ortiz-Viedma et. al., 2018). Determining the strength properties of fruits leads to proper handling, storage and transportation (Baryeh, 2000).

Several rheological and mechanical properties of a commodity determine the nature and extent of damage along with the physical conditions which it is subjected to (Jamora, 2006). It also determines the fruit resistance to damage during postharvest handling and transport and minimum energy requirement for various postharvest operation such as size reduction and extraction (Jamora, 2006). These properties concerned the traders and the producers, but it also concerns the processors particularly those involved in extracting juice from the fruit because they can benefit on the stress relaxation characteristic of the fruit (Jamora, 2016). Stress relaxation curves are useful in determining the economical way of processing the fruit and the data achieved from the stress relaxation curves can also give a saving energy requirement in various operations like pressing and extraction.

Various rheological properties of different agricultural products (different grain types, apples, papaya, coconut, cherries) have been conducted but none for avocado. Thus, this study was conducted to develop an understanding of the rheological properties of avocado at different ripening stages, compression loads and sizes. Proper postharvest handling and management of perishable horticultural commodities requires the proper understanding and the need for basic information in mechanical properties of these commodities specifically for avocado to preserve quality and to reduce losses and waste. The knowledge of the properties of avocado can enhance parameters of postharvest processes and good design of equipment with an intention of maximizing mechanical efficiency to have the highest product quality and establish maximum allowable load for minimizing bruise and internal damage to the commodity.

METHODOLOGY

Plant Materials

Fruits at commercial maturity was purchased from a farm in Imok, Calauan Laguna. The purple fruited

avocado (*Persea Americana*) variety was used in the study and were packed in a plastic crate lined with bubble wrap and transported to U.P. Los Baños. Fruits at commercial maturity was purchased and sorted to ensure freedom from defects (insects, diseases), and uniformity of shape and size. The fruits were cleaned and stored at room temperature (27° C). The different stages of degree of ripeness of avocado were based on the number of days after harvest. In the compression test, three degree of ripeness (after harvest, 3 days after harvest and 5 days after harvest) were used.

Physical Test

The Philippine National Standard (PNS) was supposedly be used in classifying the avocado but due to the available samples the size classification was modified. The avocado samples were then classified by weight as: small (200-300 grams) and medium (301 grams-above). The shape signature of the avocado fruits was determined by taking a photo of the fruit and further analyzed using the computer vision-based image processing called ImageJ. In determining the shape signature of the samples, 25 fruits were randomly chosen in each size. Before performing operations to estimate the shapes of the avocado from its image, it is important to calibrate the imaging set-up. The samples were imaged with known scale factor (60mm). The image taken was transform into a binary image and the centroid of the contoured image was determined. Using the polar transform of ImageJ, the radius (distance) in every angle of the contoured image was measured. The three (3) axial dimensions (length, width, thickness) of the randomly chosen forty (40) samples in each size were determined using the Vernier Caliper. Volume of the samples were determined by water displacement method. Volume and specific gravity were computed using the following formula (Mohsenin, 1986)

$$\text{Volume (m}^3\text{)} = \frac{\text{weight of displaced water (kg)}}{\text{weight density of water (kg/m}^3\text{)}} \quad (1)$$

$$\text{Specific gravity} = \frac{\text{weight in air} \times \text{specific gravity of water}}{\text{weight of displaced water}} \quad (2)$$

The geometric and gravimetric properties of the samples were established using the measured three axial dimensions. The sphericity (Φ), aspect ratio (R_a), arithmetic mean diameter (D_a), geometric mean diameter (D_g) and equivalent diameter (D_e) of the samples were calculated using the following relationships (Davies, 2018; Mohsenin, 1986)

$$D_a = \frac{L+W+T}{3} \quad (3)$$

$$D_g = (LWT)^{1/3} \quad (4)$$

$$D_{sm} = \left(\frac{LW+WT+LT}{3} \right)^{0.5} \quad (5)$$

$$D_e = \left(\frac{D_a+D_g+D_{sm}}{3} \right)^{0.5} \quad (6)$$

$$\Phi = \frac{\sqrt[3]{(LWT)}}{L} \quad (7)$$

$$R_a = \left(\frac{W}{L} \right) 100 \quad (8)$$

Compression Test

The study followed the ASAE standard for compression test of food materials of convex shape (ASAE, 2008) as modified by Jamora (2006) and Valerio (2001) using the InstronTM Universal Testing Machine 4411 model interfaced with a computer. A round flat plate was used to compress the samples using a crosshead speed of 10 mm/min until reaching the desired load. The samples were coated with black ink to determine the area of contact points. A white bond paper was inserted between the surface of the fruit and the crosshead plate of the InstronTM Universal Testing Machine. The contact area with the flat plate was determine at the top and bottom of the sample by weighing of a known surface area (1 cm²). The relaxation curves were obtained for each ripening level recording the decay in force for ten minutes. Each test was replicated 20 times.

The stress relaxation curves were obtained from the

force-time data set and contact area. In every treatment combination, there were 20 curves obtained and a single master curve was made (Jamora, 2006; Khazaei & Mann, 2004). The method of successive residual can be used to analyze the number of terms in the relaxation model. However, this method was found to be time-consuming, tedious, and subjective (Bargale & Irudayaraj, 2007) so a non-linear regression procedure was used to determine the different parameters in the Maxwell model (Bargale & Irudayaraj, 1995b; Jamora, 2006; Khazaei & Mann, 2004; Pappas, Skinner, & Rao, 1988). The obtained time-dependent stress relaxation data from experiment were fitted to Equation 5 using the SIGMAPLOT statistical software to calculate the parameters of the Maxwell model. The maximum relative difference (MRD) between the experimentally measured values and the model-predicted values was used to select the number of terms in the Maxwell model (Bargale & Irudayaraj, 1995b as cited by Jamora, 2006). The values of R^2 and root mean square error (RMSE) were calculated to indicate the quality of fit. The model with the number of terms corresponding to an MRD value of $\leq 5\%$ was chosen as the best fit model. The MRD value was calculated based on:

$$MRD = \max \left[\frac{\text{measured} - \text{calculated}}{\text{measured}} \right] \times 100 \quad (9)$$

After compressing the fruit sample at different level of ripeness, the samples were allowed to ripen and mechanical damages or internal bruises were examined. The fruit samples were cut across its longitudinal axis. The degree of bruising considered was the inner part of the avocado and it was inspected subjectively per specimen.

Statistical Analysis

A one-factor factorial experiment arranged in Completely Randomized Design (CRD) was used in compression test. A total of six (6) treatment combination was used with twenty (20) replicates per treatment combination as specified in the ASAE standard on the compression test of biological materials (ASAE, 2008). The data collected was subjected to Analysis of Variance (ANOVA) using the SAS (Version 9.4) software. The means was

further compared using Games-Howell test. The significance was expressed at 95% level ($P < 0.05$).

RESULTS AND DISCUSSION

Physical Characteristics of Avocado Fruit

Determining the physical characteristics of a commodity (shape, size, and volume) was significant in the handling process of the material as various problems occur related to the design of a particular machine and in the evaluation of the behavior of the product. Table 1 shows the summary of measured and calculated physical characteristics of avocado fruits. The specific gravity of the small size avocado varies from 0.95 to 1 which implies that the samples used in the study were at commercial maturity since research shows that there is a decrease of specific gravity from 1.02 on a very immature avocado to 0.90 on some varieties of avocado when mature (Harkness, 1954).

The obtained value of sphericity shows that the characteristics of avocado fruits have a higher possibility of rolling than sliding since obtained

$$ss = \frac{Z^2 * p * (1 - p)}{c^2}$$

Equation 1

values fall within the reported aspect ratio and sphericity of most fruits, grains, and seeds (S. V. Irtwange & J. C. Igbeka, 2002; Davies, 2018). The measured parameters were pertinent in designing the aperture sizes which are used in processing machines for maturity/harvesting indices, cleaning, sorting, or classifying, grading, and packaging of produce. It is also needed in the designing of equipment related to aeration, drying, storage, separation equipment, containerization of biomaterials and transport systems.

It was shown in Table 2 that the value of R^2 for all samples was 0.989 which means that 98.9% of variation in volume is attributed to the different levels of weight of samples. The Pearson correlation coefficient ($r = 0.9945$) shows a positively strong linear association between the measured volume and weight of the avocado fruits. The distribution of

Table 1. Geometric and Gravimetric Properties of Avocado Fruit

Avocado Fruit Size	Properties	No. of Samples	Maximum	Minimum	Mean	Standard Deviation
Small	Length (mm)	20	104.84	89.17	95.41	4.846
Small	Width (mm)	20	76.34	64.70	69.39	3.231
Small	Thickness (mm)	20	75.15	64.45	69.52	3.260
Small	Arithmetic Mean Diameter (mm)	20	82.26	73.36	78.11	2.694
Small	Geometric Mean Diameter (mm)	20	81.36	72.25	76.83	2.655
Small	Square Mean Diameter (mm)	20	81.95	72.94	77.60	2.673
Small	Equivalent Mean Diameter (mm)	20	81.83	72.85	77.51	2.670
Small	Sphericity (%)	20	87.58	75.05	81.00	3.350
Small	Aspect Ratio (%)	20	83.39	64.83	72.91	5.013
Small	Weight (g)	20	296.9	203.0	235.9	24.383
Small	Volume (cm ³)	20	304.47	205.98	239.58	1.529
Small	Specific Gravity	20	1.00	0.95	0.98	0.011
Medium	Length (mm)	20	134.54	95.13	112.12	9.113
Medium	Width (mm)	20	95.92	79.40	85.36	3.864
Medium	Thickness (mm)	20	89.96	77.36	83.16	3.664
Medium	Arithmetic Mean Diameter (mm)	20	103.53	88.68	93.54	3.591
Medium	Geometric Mean Diameter (mm)	20	100.89	87.67	92.15	3.269
Medium	Square Mean Diameter (mm)	20	102.35	88.35	93.02	3.414
Medium	Equivalent Mean Diameter (mm)	20	102.26	88.23	92.91	3.419
Medium	Sphericity (%)	20	95.20	74.69	82.92	5.217
Medium	Aspect Ratio (%)	20	96.13	65.33	76.58	6.992
Medium	Weight (g)	20	548.47	353.50	402.56	47.249
Medium	Volume (cm ³)	20	580.26	361.17	424.42	3.208
Medium	Specific Gravity	20	0.99	0.87	0.95	0.032

volume of small and medium size avocado within the range of weight was shown in Figure 1. Correlation and regression analysis were applied to determine the relationship between weight and volume of avocado fruits for small and medium sizes. The most appropriate equation to be used in predicting the volume of the avocado fruits based on weight was the equation for all samples (n=80).

A shape in a one-dimensional function obtained from shape boundaries characterizes the shape signature and gives information about the shape's feature which was shown in Figures 2. A confidence band with 95 % level of confidence was included in the graph to show the degree of variation within the samples. Aside from the fact that shape signature can be used to describe a shape, it can also be used as a preprocessing tool for other algorithms that extract features.

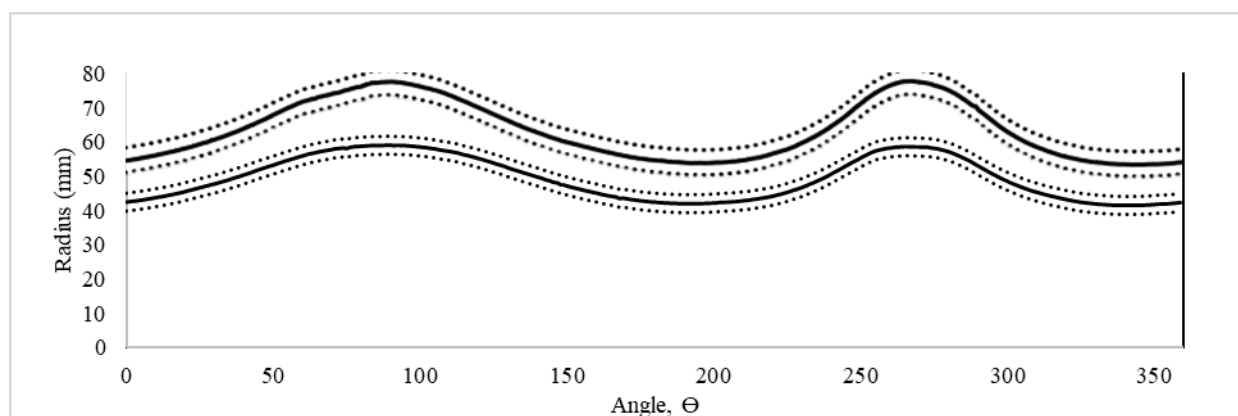


Figure 2. The shape signature of small size avocado

Compressive Properties of Avocado Fruit

The compressive strength determines the ability of fruits to withstand load and stress, it can also lead to estimation of their other properties like texture as shown in Table 3. The maximum compressive load, bioyield and rupture of small size avocado were significantly higher at harvest than after 3 days and 5 days of harvest, these forces continued to decrease after 5 days of harvest indicating a higher susceptibility of the fruits to damage. Small size avocado can withstand up to 5 kg of load by weight after harvest without significant internal damage. The compressive strength was reduced to 4 kg three (3) days after harvest and 3 kg five (5) days after harvest. The obtained result implies that small size avocado has a high compressive strength at harvest and should be transported immediately. The maximum compressive load and rupture of medium size avocado were significantly higher than three days and five days after harvest. The medium size avocado can withstand up to 6 kg of load by weight after harvest without significant internal damage. The compressive strength was reduced to 5 kg three (3) days after harvest and 4 kg five (5) days after harvest.

Result shows that the stress at bioyield and rupture for small size avocado decreases as the level of ripeness increases while the stress at bioyield of medium size avocado was declining with ripening. The decreasing trend of maximum load, bioyield point and rupture point for small

Table 1. Geometric and Gravimetric Properties of Avocado Fruit

Properties	Days	after	harvest
Small Size	0	3	5
Maximum Load (kN)	0.450 ^a	0.151 ^b	0.099 ^b
Bioyield Point (kN)	0.045 ^a	0.044 ^a	0.033 ^b
Rupture Point (kN)	1.962 ^a	1.675 ^a	0.108 ^b
Stress at bioyield (kPa)	228.62 0 ^a	127.209 ^b	87.712 ^c
Stress at rupture (kPa)	9909.0 91 ^a	4875.651 ^b	289.726 ^c
Point of Inflection (kN)	0.034	0.030	0.020
Deformation at Inflection (mm)	2.183	2.067	1.817
Stiffness (kN/mm)	0.016	0.015	0.011
Medium Size			
Maximum Load (kN)	2.360 ^a	0.218 ^b	0.112 ^b
Bioyield Point (kN)	0.056 ^a	0.048 ^a	0.036 ^b
Rupture Point (kN)	2.449 ^a	2.412 ^a	0.097 ^b
Stress at bioyield (kPa)	156.66 1 ^a	118.800 ^b	81.636 ^b
Stress at rupture (kPa)	6851.7 02 ^a	6014.467 ^a	217.454 ^b
Point of Inflection (kN)	0.050	0.039	0.026
Deformation at Inflection (mm)	3.468	3.235	2.951
Stiffness (kN/mm)	0.014	0.012	0.009

*Means with the same letter are not significantly different (at 5% level of significance).

and medium size avocado at different level of ripeness was illustrated in Figure 3 and 4.

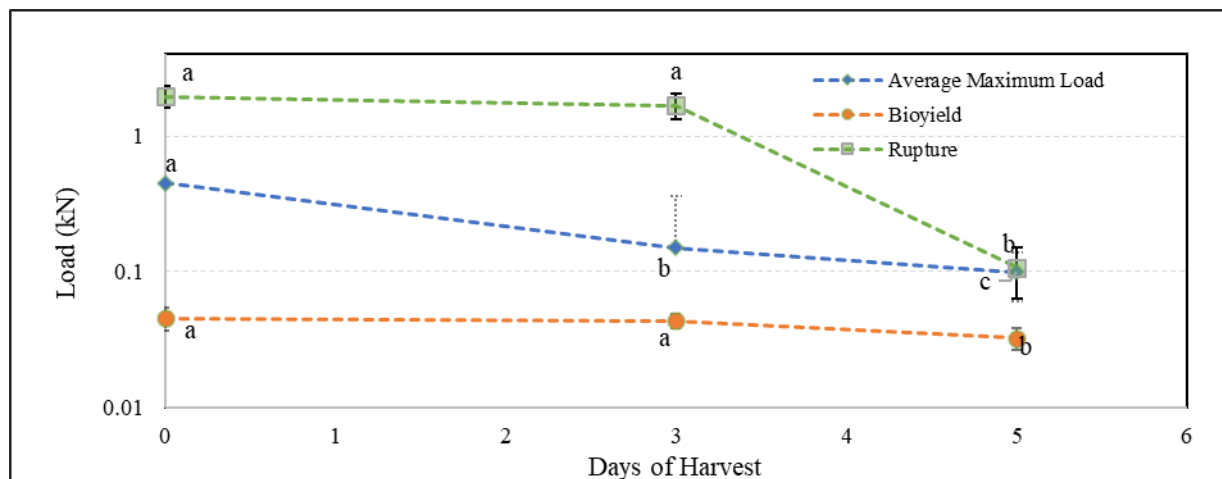


Figure 3. The average maximum compressive load, bioyield, and rupture of small size avocado at different ripening stages

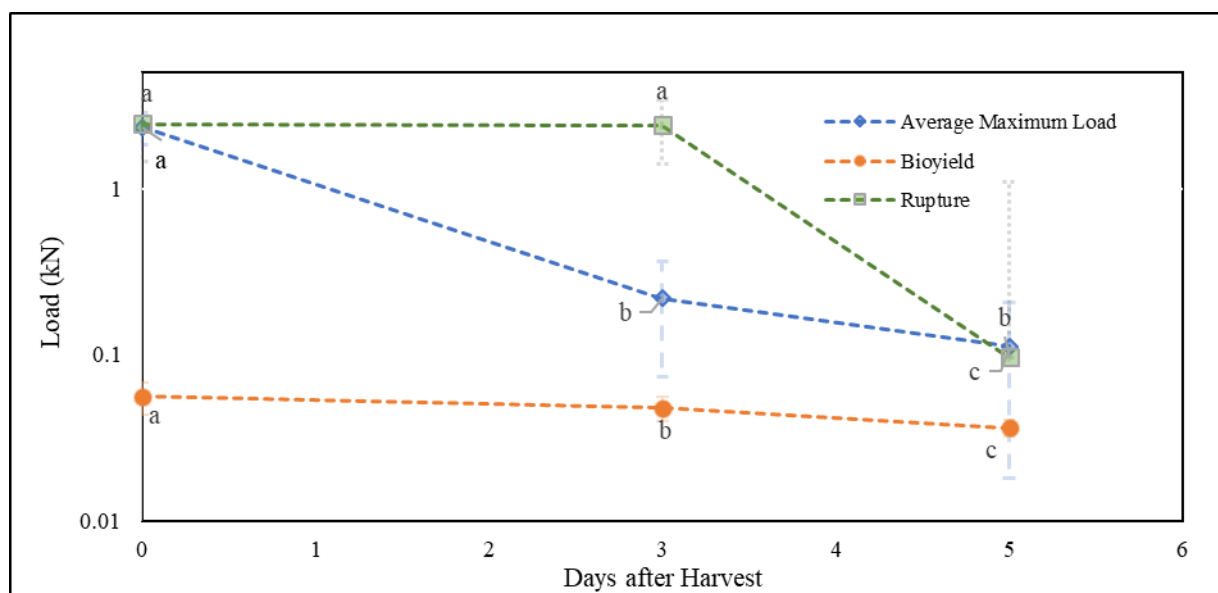


Figure 4. The average maximum compressive load, bioyield, and rupture of medium size avocado at different ripening stages

The point of inflection was also considered in the study, it is the point at which the rate of change in the slope of the curve becomes zero (ASAE, 2008). The point of inflection for both sizes of avocado is inversely proportional to the degree of ripeness. Stiffness is the ratio of force to deformation at point of inflection. The stiffness of small and medium size avocado gradually decreases with ripening.

Stress Relaxation Characteristic of the Avocado Fruits

The contact area during compression was determined because it plays a vital role in the stress on the fruits. The contact area of fruits during compression at different size and degree of ripeness was shown in Figure 5. It was observed that the contact area increases as the degree of ripeness

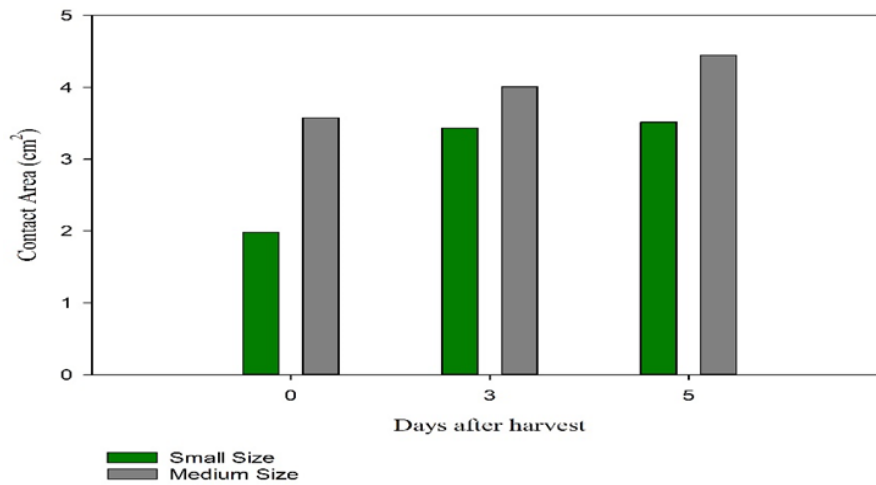


Figure 5. The contact area during compression at different size and degree of ripeness

increase and fruits with larger size have a larger contact area compared to smaller size. Generally, it was observed that higher loads can cause more strain on the fruits which will results to a larger contact area between the parallel plates and the surface of the fruits.

The stress relaxation behavior at different degree of ripeness and sizes was presented in Figure 6. The curve shown was the average of the twenty replicates representing each treatment combination. It was observed for both small and medium size that at a higher load the curve was shifted up and samples at advanced degree of ripeness have its curves shifted downward. This indicates that the avocado fruits were more stressed at higher loads and were subjected to a less concentrated stress at advanced degree of ripeness due to a larger contact area.

The relaxation data in every treatment combination were fitted to three relaxation equations representing Maxwell models with one, two and three terms which are:

$$\sigma(t) = \sigma_1 e^{\left(-\frac{t}{\tau_1}\right)} \quad (10)$$

$$\sigma(t) = \sigma_1 e^{\left(-\frac{t}{\tau_1}\right)} + \sigma_2 e^{\left(-\frac{t}{\tau_2}\right)} \quad (11)$$

$$\sigma(t) = \sigma_1 e^{\left(-\frac{t}{\tau_1}\right)} + \sigma_2 e^{\left(-\frac{t}{\tau_2}\right)} + \sigma_3 e^{\left(-\frac{t}{\tau_3}\right)} \quad (12)$$

The computed values of the different parameters of Maxwell model were presented in Table 4. The values of maximum relative difference (MRD), R^2 (observed vs predicted) and residual MSE for all equations fitted were shown in Table 5. The analysis of variance was determined using the nonlinear module of Sigmaplot version 14 were the statistical

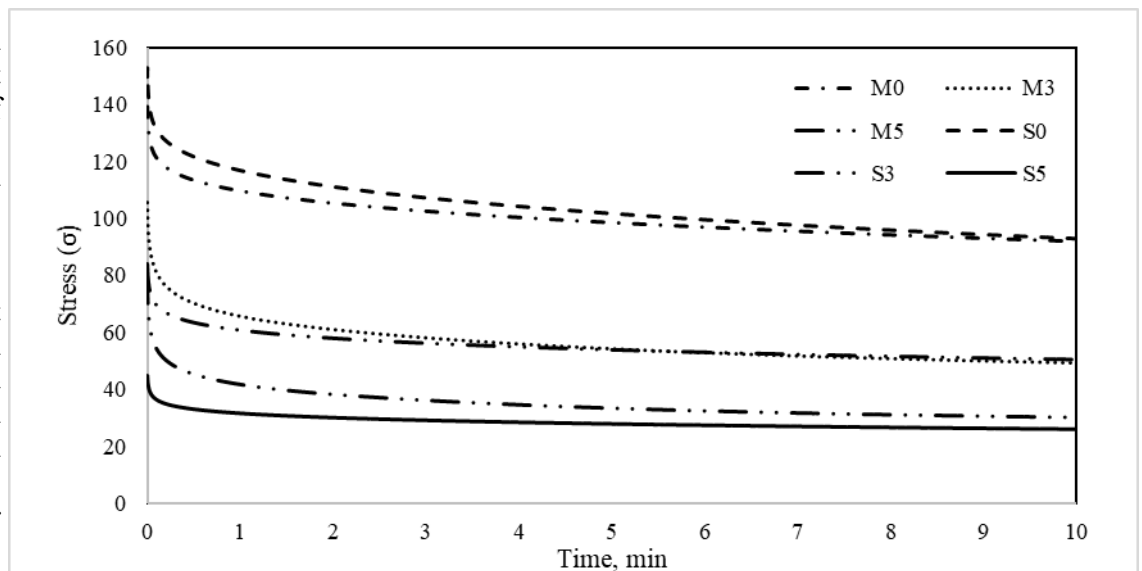


Figure 6. The stress relaxation curves at different degree of ripeness and sizes

Table 4. The parameters for the one and two term Maxwell equations

T	Code	one-term		two-term			
		σ_1	τ_1	σ_1	τ_1	σ_2	τ_2
T1	S0	119.6816	0.0289	20.48679	1.282614	113.4039	0.020879
T2	S3	43.86209	0.04625	19.51947	2.044303	39.61737	0.030321
T3	S5	32.37299	0.025489	7.28209	1.786766	30.72059	0.017592
T4	M0	111.7313	0.022232	16.74735	1.475234	107.286	0.016194
T5	M3	68.2268	0.03931	22.76638	1.717681	62.60025	0.026093
T6	M5	62.11039	0.024415	13.19364	1.684789	58.97022	0.016628

Note: All the stress decay values (σ) were in kPa, stress relaxation time constant (τ) were in minutes. The complete list of the Maxwell equation parameters was shown in the appendices.

Table 5. The estimates for one-, two-, three-term Maxwell models

T	Code	one-term			two-term			three-term		
		MRD	R^2	MSE	MRD	R^2	MSE	MRD	R^2	MSE
T1	S0	21.6775	0.8978	8.3779	12.4057	0.9920	0.6578	5.2397	0.9992	0.0689
T2	S3	44.9529	0.7658	6.3860	25.7831	0.9753	0.6728	11.9140	0.9968	0.0886
T3	S5	27.8715	0.8164	0.9708	15.3284	0.9831	0.0894	5.5628	0.9983	0.0091
T4	M0	19.7227	0.8807	5.5060	10.9123	0.9903	0.4110	10.9124	0.9903	0.4476
T5	M3	35.3861	0.8079	9.3657	19.1539	0.9825	0.8511	8.4270	0.9982	0.0893
T6	M5	26.1593	0.8193	3.2530	14.2071	0.9846	0.2775	5.3825	0.9985	0.0276

coefficients of determination (R^2), standard error of estimates, coefficients of parameters and degrees of freedom were also obtained. Based on the MRD, R^2 and residual MSE values, the three-term Maxwell model was chosen as the best fit for describing the relaxation characteristics of the avocado fruits. Some viscoelastic materials like potato tuber (Mohsenin, 1986), barley kernels (Bargale & Irudayaraj, 1995b), and sea buckthorn berries (Khazaei & Mann, 2004) behave in a similar manner in terms of their relaxation curve characteristics.

A sample curves generated from the fitted equations based on the model was shown in Figure 7. Iteration of the different parameters for one-, two- and three-term model was done to all the treatment combinations. In the sample presented, the predicted values for Treatment 1 for the two-term model was already good based on R^2 (0.9920) alone. However, the evaluated estimates for that treatment revealed that the MRD was greater than the desired 5% value.

Comparing the fitting abilities of the three models, it indicates that the three-term Maxwell model was the best fit for describing stress relaxation of the avocado fruits.

It is important to consider the first term Maxwell model because it had a major contribution to the total stress and found to significantly contributes to the relaxation modulus (Bargale & Irudayaraj, 1995 as cited by Jamora, 2006). There was a decreasing trend of the first decay stress value (σ_1) as the stage of ripeness advances due to a change in cellular composition of the fruit as it matures or ripen. Apples were reported to decrease in the amount of insoluble pectins which was a major component of the cell wall and middle lamella as it matures, this implies to the strength of the whole fruit (Pitt, 1982). The decreasing trend in the values of the parameters on the first term of the Maxwell model leads to the shifting of the relaxation modulus downward.

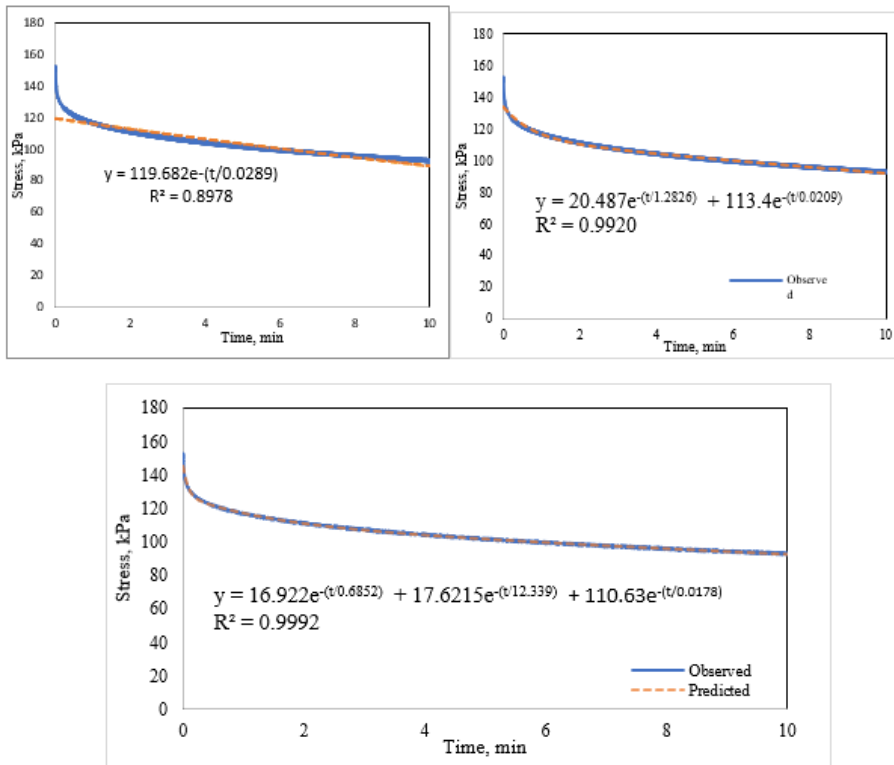


Figure 7. The comparison between predicted and observed stress values for the one-, two- and three-term Maxwell model for Treatment 1-S0.

It was observed that deformation influences the time of relaxation. An inverse relationship between the deformation and time of relaxation was established (Figure 8). The time of relaxation for both small and medium size avocado decreases as the deformation increases. A comparable result for the effect of deformation level on the relaxation time were also observed on sinta papaya (Jamora, 2006) and sea buckthorn berries (Khazaei & Mann, 2004).

Deformation due to Compression

Bioyield point determines the maximum load that a fruits can withstand without causing any failure in their cellular structure (Mohsenin, 1986; Mohsenin, Cooper, & Tukey, 1963; as cited by Valerio et al., 2001), consequently there should be no damage at the

bioyield point. A force below the average bioyield point was defined to establish the loading force that would not cause damage to the fruits at the cellular and physical levels. The deformation on the samples at different level of ripeness was shown in Figure 9 and increasing trend was observed for both sizes. The deformation increases as the level of ripeness advances.

After compressing the fruit sample at different level of ripeness, the samples were allowed to ripen and mechanical damages or internal bruises were examined. The fruit samples were cut across its longitudinal axis as shown in Figure 10. The degree of bruising in the inner part of the fruit was inspected subjectively per specimen. Results of the evaluation shows that there were no internal bruises among the treatment combination. Hence, the bioyield

define the threshold compressive strength of the avocado since internal damage has not occurred.

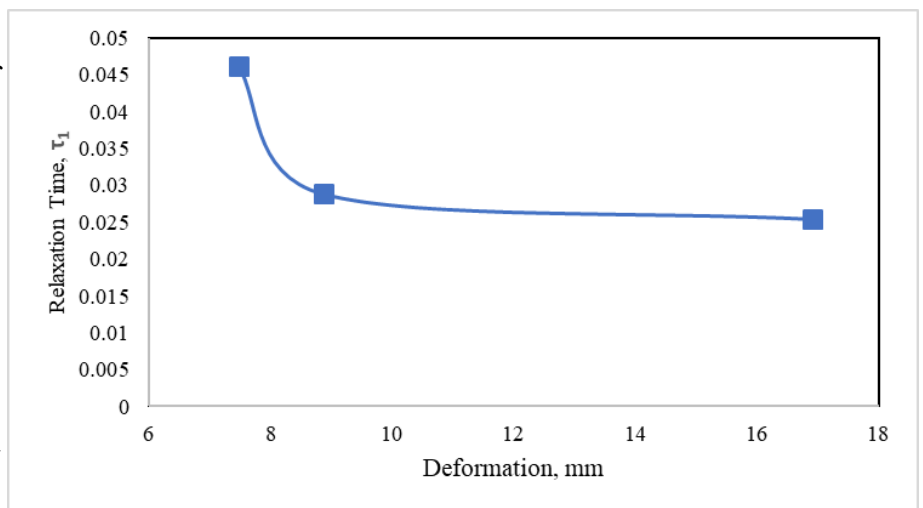


Figure 8. The effect of deformation on the time of relaxation for small size avocado.

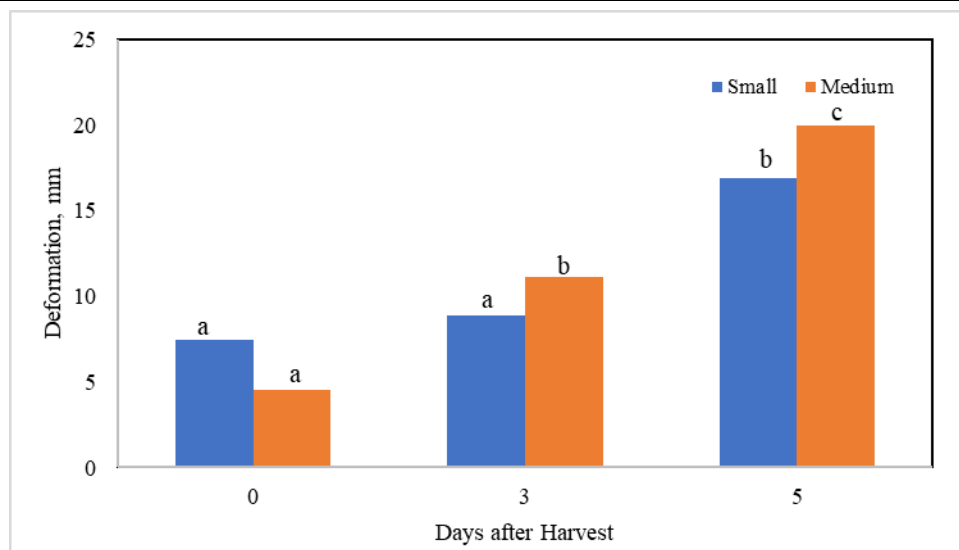


Figure 9. The deformation of avocado samples at different level of ripeness.



Figure 10. The compressed fruit at ripe stage

SUMMARY AND CONCLUSION

This study was conducted to develop an understanding of the rheological properties of avocado at different ripening stages, sizes, and compression loads using a one-factor factorial experiment arranged in Completely Randomized Design (CRD) with a total of six (6) treatment combination with twenty (20) replicates per treatment combination. The degree of ripeness was determined by the number of days after harvest (0 days after harvest were unripe, 3 days after harvest were half unripe and 5 days after harvest were fully ripe). Water displacement method was used to determine the volume of the avocados. The three axial dimensions (length, width, thickness) of the fruits were measured using caliper, and the geometric and gravimetric properties of the fruits were established. The shape signature of the

avocado fruits was determined by taking a photo of the fruit and further analyzed using the computer vision-based image processing called ImageJ. The study followed the ASAE standard for compression test of food materials of convex shape using the InstronTM Universal Testing Machine 4411 model interfaced with a computer. A round flat plate was used to compress the samples using a crosshead speed of 10 mm/min until reaching the desired load. The samples were coated with black ink to determine the area of contact points. A white bond paper was inserted between the

surface of the fruit and the crosshead plate of the InstronTM Universal Testing Machine. The contact area with the flat plate was determine at the top and bottom of the sample by weighing of a known surface area (1 cm²). The relaxation curves were obtained for each ripening level recording the decay in force for ten minutes and each test was replicated 20 times. The

obtained time-dependent stress relaxation data from the experiment were fitted to generalized Maxwell model using the nonlinear regression module of Sigma plot version 14. The number of terms in the Maxwell equation was decided based on the desired maximum relative difference (MRD) values between the predicted and measures values while the quality of fit of the equation was indicated by the values of root mean square error (RMSE) and R². The compressed fruit samples at different level of ripeness were allowed to ripen at a room temperature. The ripe fruit samples were cut across its longitudinal axis and the internal bruises were subjectively examined.

From this study, it revealed that from the shape of avocado fruits tends toward being spherical and expected to roll not slide as indicated by the mean values of sphericity and aspect ratio; the most appropriate equation in predicting volume from

weight of avocado was Volume (in^3) = 0.06725 (weight, grams) -1.2184; the established shape signature specifically represents the shape of the purple fruited avocado variety in a one-dimensional function; The compressive strength of avocado varied with ripeness were in the small size avocado can withstand up to 5 kg of load by weight after harvest without significant internal damage, this compressive strength reduces to 4 kg three days after harvest and 3 kg five days after harvest; The medium size avocado can withstand up to 6 kg of load by weight after harvest without significant internal damage, the compressive strength was reduced to 5 kg three days after harvest and 4 kg five days after harvest; Ripe avocado fruits were more susceptible to damage since the avocado fruits at advance ripeness had a lower instantaneous stress compared to the fruits at harvest; the contact area increases as the degree of ripeness increases and fruits with larger size have a larger contact area compared to smaller size; the stress relaxation curve for both size were shifted up at higher load and was shifted downward at advance degree of ripeness; a three-term Maxwell model with six parameters described the stress relaxation behavior of avocado fruit at different compressive loads, ripeness and sizes based on the maximum relative difference (MRD), R^2 , and residual MSE; the advancing degree of ripeness have a corresponding decrease in the decay stress value (σ_1) and time of relaxation (τ_1) component of the model; an increasing deformation results to lower relaxation time constant (τ_1); and the bioyield define the threshold compressive strength of the avocado since internal damage has not occurred.

The measured geometric and gravimetric properties of the avocado were pertinent in designing the aperture sizes which are used in processing machines for maturity/harvesting indices, cleaning, sorting, or classifying, grading, and packaging of produce. It can also be used in the design of equipment related to aeration, drying, separation equipment, storage, containerization of biomaterials and transport systems. The established shape signature can be used to describe specifically the shape of the purple avocado variety since there was no established shape for this variety of avocado and can also be used as a preprocessing tool for other

algorithms that extract features. To minimize mechanical damage, avocado should be packed with cushion (bubble wrap, foam, or paper) and can be stacked up to 10 layers for small size and 12 layers for medium size at harvest (unripe stage) using 10 kg capacity cartons. In addition, small size avocados that are half ripe can be stacked up to 8 layers and 6 layers when ripe while medium size avocado can be stacked up to 10 layers at half ripe stage and 8 layers at ripe stage using 10 kg capacity cartons. This indicates that avocado should be transported immediately after harvest while their compressive strength is high. Avocado fruits should be arranged in vertical orientation in a packaging system to reduce losses due to postharvest handling during transport. The stress relaxation curves are useful in determining the economical way of processing the fruit and the data achieved from the stress relaxation curves can also give a saving energy requirement in various operations like pressing and extraction.

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