Young's Modulus for Packaged Roma Tomatoes under Compressive Loading

F. A. Babarinsa and M. T. Ige

Abstract — Young's modulus denotes the inherent rigidity or stiffness, and resistance of a fruit to elastic deformation, and expresses the fruit's tendency to be deformed elastically under applied force. This study related the deformations encountered in packaged Roma tomatoes to Young's modulus as a strength parameter that characterizes mechanical behavior of the packaged tomatoes under compression. A 2^2x3 factorial experimental design was applied in conducting compression tests to investigate the effects of ripeness stage, vibration level and container type on Young's modulus of the packaged tomatoes. Tomatoes of three ripeness stages: unripe (5.6 Brix%), half-ripe (3.9 Brix%) and full-ripe (3.2 Brix%), were packed in plastic crate and raffia basket. They were subjected to three levels of vibration: non-vibrated, low vibration (frequency 3.7 Hz) and high vibration (frequency 6.7 Hz), using a laboratory vibrator. The fruits were compressed in a Universal Testing Machine at a speed of 2.50mm/min; Young's Modulus was measured and force-deformation curves were obtained. Young's Modulus decreased significantly (P=0.05) with advancing ripeness stage of tomatoes and with vibration level (P=0.001) but was independent of packaging container. Average Young's Modulus ranged from 1.140Nmm to 1.875Nmm at bioyield, 13.597Nmm to 27.221Nmm at break and 15.629Nmm to 23.618Nmm at peak. These findings will be useful in predicting and controlling the deformation or complete failure that occurs in packaged tomatoes caused by compression stress during road transportation. Containers can be adequately designed with due consideration for physical characteristics of tomatoes such as shape, size, and firmness in relation to externally applied compression stresses.

Keywords: Container, Compressive loading, Packaging, Ripeness, Roma tomato, Vibration, Young's modulus.

1 Introduction

Tomato (*Lycopersicon esculentum* Mill.) represents a typical example of a tender fruit, so classified in consideration of the extent of damage inflicted on the fruit in response to externally applied forces, forces. In Nigeria considerable losses are encountered during transportation of the packaged fruit, mostly the Roma variety, from producers to the inter-state market places due to compression damage. Certain characteristics and requirements of tomatoes therefore demand special considerations and emphasis.

Tomato, being a viscoelastic tender commodity experiences compression stress when packaged in unit loads, which leads to deformation, bruising or, complete failure. This form of mechanical damage can be controlled remarkably by designing containers with due consideration for the physical characteristics of the commodity such as shape, size, firmness and bioyield pressure. This helps, among others, to prevent excessive stress and provide appropriate structural protection. The development of an appropriate system of packaging for this perishable commodity calls for a greater understanding of the various mechanical properties, especially strength parameters, of packaged tomatoes. Strength parameters of maximum load, deformation and stress under compressive loading of packaged tomatoes been studied for the bioyield point [1] and break point [2]. The effects of stage of ripeness and level of vibration encountered in the packages on these pameters, as well as energy absorption capacity [3], were reported.

Young's modulus (or modulus of elasticity) is another important strength parameter used in predicting the deformation that occurs in fruits and vegetables under loading. Kabas and Ozmerzi [4] determined mechanical properties of tomato in terms of average Young's modulus (or modulus of elasticity), along with some other properties. This parameter is a measure of the inherent rigidity or stiffness, and resistance to elastic deformation and mathematically expresses the fruit's tendency to be deformed elastically under compression. It is used to characterize the elastic range of viscoelastic materials like tomato. It is numerically evaluated as the ratio of the applied stress (or load) to corresponding strain (or deformation) within the elastic range, that is, below the bioyield point. Tomato fruit is characterized by a low Young's modulus; it changes shape considerably and is thus liable to deform by a substantial amount under compressive loading. Typical of external symptoms for such mechanical deformation in tomatoes are fruits being permanently pressed out of shape with flattered sides, V-shaped or rounded surface indentation [5]. The strategic reduction of postharvest losses attributed to tomato packaging therefore requires a clear knowledge of such properties as Young's modulus. The knowledge of the Young's modulus of tomatoes, (among other mechanical characteristics) is essential in planning transport of the fruit vegetable as it is affected by mechanical damage [6. In tomatoes, as well, as other fruit and vegetables, mechanical properties (such as elasticity) vary with age and physiological conditions [7]. These biological materials, being alive, constantly undergo changes in shape, size, respiration and other aspects of life processes.

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During transportation and handling, the fruit is particularly prone to the vibration effects of the vehicular motion. A study of the young's modulus therefore needs to take these effects into consideration.

. The present work aims at investigating the Young's modulus of Roma tomatoes in multiple layered packs, when subjected to compression

2. MATERIALS AND METHODS

2.1 Experimental Plant Material

Commercially grown tomatoes of the Roma variety were hand-harvested from a local market farm in Ilorin suburb and sorted into at three stages of maturity namely: unripe, half-ripe and ripe. Wholesome fruits were sorted for reasonable uniformity into size range of 2.5 to 3.0cm and taken to the Engineering Material Testing Laboratory at the National Center for Agricultural Mechanization (NCAM), Ilorin. Stages of tomato ripeness were first judged subjectively by skin colour as 1) unripe (mature green/breaker or green pink), consisting of the first point of skin colour change from complete green to about 30% pink 2) half-ripe, consisting of 30-70% pink to red skin and 3) the full-ripe, consisting of 70-100% red skin but still firm. These were comparable to skin colour levels 1, 5 and 9 on the tomato colour chart of the Organisation de Cooperation et de Development Economiques, Paris [8].

Further objective evaluation of the ripeness stages was done by measuring the total soluble solids (as Brix %) in the undiluted juice of samples of the tomato fruit. The digital hand-held refractometer (ATAGO® PAL-1 No.3810) used had an automatic internal temperature compensation feature, a measurement resolution of Brix 0.1% and accuracy of Brix ±0.2%. Approximately 0.3ml of the tomato samples was blended to a uniform juice, and placed on the prism of the digital refractometer. The total soluble solids content (in Brix %), measured in triplicates, were 5.6, 3.9 and 3.2 for the unripe, half- ripe and full ripe stages respectively.

2.2 Packaging containers

The two packaging containers used are plastic crate (manufactured by Shongai Packaging Industries Ltd) and raffia woven basket. The plastic crate is the a nest/stack type that has been previously recommended by the Nigerian Stored Products Research Institute for packaging tomatoes for road transportation [9]. It is similar to that described by Thompson [8]. The crate has external dimensions of 60cm x 40cm x 25cm high and is capable of holding 25kg of tomatoes. The basket, which is extensively used in road transportation of tomatoes in Nigeria, is 30cm deep and 43cm in diameter, capable of holding 20kg of tomato fruit. Both containers were adequately ventilated and are sufficiently strong to resist failure by buckling.

2.3 Experimental design

A 2 x 3^2 factorial experiment was conducted to study the effect of three ripening stages, three vibration levels and two containers on load, deformation and stress at bioyield point of Roma tomatoes under compressive loading.

2.4 Vibration treatment

The packaged tomatoes were vibrated using a mechanical vibrator, the Gallenhamn Orbital Shaker (App. No 9B 3742 E), The respective containers carried on the carriage platform vibrated by internally fitted oscillating cams, imparting oscillation at the variable speed of 0-400 rev/min. Vibration, designated either as low-level or high level, was applied at fixed frequencies of oscillation, 3.5 and 6.7 Hz respectively, by setting the operating speed at 200 or 400 rev/min for duration of 60 minutes.

2.5 Compression test

A standard universal testing machine (Fig. 1) was applied to compress and characterize the packaged tomato fruit mechanically. The basic methodology for compression testing of the packaged tomatoes was described by Babarinsa and Ige [1]. Briefly, fruits are compressed between the cross head of the testing machine. Data sheets of measured values and load-deformation plots were obtained directly as produced with the aid of a PC.

2.6 Statistical Analysis

Data collected from compression test runs were subjected to statistical analysis using randomized complete block design based on a 3^2x2 factorial experiment. Statistical analysis was carried out using SPSS 110 software package. Treatment means were compared using Duncan's Multiple Range Test ($P < 0.05$).

3 RESULTS AND DISCUSSION

3.1 Force-Deformation curve

A typical compression force-deformation (or load-deflection) curve for the compressed tomatoes is shown in Fig. 2. The curve does not clearly denote an initial linear part up to the elastic limit which forms the elastic range. Rather the various curves, like Fig. 1, created during the compression tests are concave toward the force axis and are flat. Phirke [10] noted that, in contrast with the polymertric materias, force-deformation curves for soft biomaterials like fruits and vegetables are concave toward the force axis. He stated that this is probably because moisture in the biological materials offers little resistance to shear stress, causing relatively large deformations with corresponding small initial stress. It is also reported that soft plant materials have usually flat curves (low modulus), while polymertric materials have steep curves (high modulus). In the present measurement, the shape of the force-deformation curve indicates that the fruit walls may not only be elastic but may be non-linear elastic (that is, does not have a constant Young's modulus) up to the elastic limit. The Young's modulus is the tangent modulus of the initial portion of the force-deformation curve or the initial gradient of the curve. The observed occurrence of sharp peaks following the elastic deformation at the end of each compression has also been attributed to soft, weak brittle materials by Fellows [11]. He particularly remarked that the point of maximum force or rupture could also occur at bioyield point.

3.2 Statistical analysis

A set of data representing the numerical values of the Young's modulus for tomatoes was directly obtained from the compression tests, corresponding to the respective plots of force-deformation curve. The statistical analysis of variance (ANOVA) for the data on Young's modulus for the compression testing is presented in Table 1. From the ANOVA table, it is observed that the effect of the three subject factors (vibration, stage of ripeness and container type) were all significant on Young's modulus. The two-factor interaction vibration*container is also had significant (P=0.001) effects on the Young's modulus.

3.3 Effects of Stage of Ripeness

From the Table 1, showing the analysis of variance (ANOVA) for the Young's modulus of compressed tomatoes, it can be seen that the effects of stage of ripeness had highly significant (P=0.001) effects on Young's modulus.

Table 2 shows the statistical analysis of variance means and differences among the three stages of ripeness, three levels of vibration and two container types tested during the compression of Roma tomatoes. The Young's modulus had no significant differences between the unripe and half-ripe stages but the differences were significant (P=0.001) between half-ripe and full-ripe stages. Regardless of packaging container, the highest Young's modulus of 5.629E-02 N/mm² was observed in the unripe tomatoes. This was found to reduce significantly by 15% in half-ripe fruit and reduced further by 32% in full-ripe fruit. [12] Wang et al. (2006) studied low turgor cells, such as those found during ripening. The workers adopted the approach of testing pieces of tissue to investigating plant mechanical properties. They assumed that studies on single cells, using force-deformation data, can provide the information needed to predict the behavior of tissue. In earlier work, however mechanical measurements have been applied to the whole fruit [13]. Compression of intact fruits in this work showed a typical loss of fruit stiffness from unripe to half-ripe and complete flexibility at full-ripe stage. The Young's modulus in full-ripe fruit was 56% significantly lower than that obtained for unripe fruit. While recognizing fruit ripeness as an important factor that affects tomato compression tolerance, Pereira & Calbo [14] stated that the riper the fruit the bigger the fruit compression, because ripe fruits have lager plasticity and elasticity. Wang et al. [12] studied softening as an important part of the ripening process, as it is widely recognized that changes in cell walls accompany fruit softening [15]. For example, tomato fruit ripening is accompanied by significant degradation of cell wall pectin [13]. Andrews et al. [16] noted that the stiffness of tomato fruit increased three-fold with fruit age. The results support the hypothesis that ripening plays an integral role in the fruit stiffness and that changes in the mechanical properties of tomato cell walls can be mediated by peroxidase [16], [17]. Because the Young's modulus (stiffness) of tomatoes at the unripe stage is larger than the riper stages, the tomatoes at this ripeness stage are most convenient for transportation.

The Young's modulus, like other strength parameters of tomatoes, is closely associated with the structural composition of the materials. The lower values obtained for Young's modulus at higher stages of ripeness may be attributed to the strong adhesion between the protoplast and the cell wall. Falk,et al. [18] indicate that this strong adhesion results in negative tugor (pressure) under natural conditions and its existence may significantly alter static elastic modulus and certain other mechanical properties. The softening of tomato, during ripening is generally reported to result principally from reduction of intercellular adhesion resulting from disassembly of the primary cell wall and middle lamella [19]. Changes that occur during ripening reflect conversion of starch to sugar, structural aspect of the cell wall, cementing agents (particularly pectic substances), turgor pressure and tissue rigidity. These cause the cell membranes to lose their integrity causing the turgor pressure to fall [20], [21]. Several workers [18], [22], [23] have reported that the elastic modulus of an agricultural material depends on the turgor of its cells. This overall elastic modulus depends upon, but is not equal to, the elastic moduli of the cell walls.

These results show that structural failure, in the packaged fruit, may be remarkably prevented or controlled by selecting fruit at an early stage of ripeness. Fully ripe tomatoes should particularly be excluded while packaging for transportation because, with the Young's modulus reduced by as high as 58.8% (compared to the unripe fruit), **t**hese are liable to larger deformation.

3.4 Effects of Vibration Levels

A reduction of 32% in Young's modulus was recorded upon the application of low- level vibration to fruits while subsequent reduction of 15% resulted from high-level vibration application. The relatively high reduction in Young's modulus recorded following the initial application of vibration (at low level) was because it seems to be driven, in part, by the existence of interspaces' (void) volumes within the bulk. The larger amount of the void has been removed by compaction when the tomatoes were initially vibrated (at low level). This might have offered an initial resistance to pressure application during the subsequent compression process. During subsequent application of vibration (at high level), the available fractions of voids for reduction by compression become smaller and movements become restricted, hence less reduction in the associated Young's modulus. It can then be understood that during vehicular vibration the tomatoes first get compacted as the contact surfaces are moving down. The interstitial space is reduced while little bruising may occur. This effect of vibration will, thus, be greater with or even limited to the low-level vibration when the initially large void volume would have been greatly reduced or removed. Hinsch et al. [24] reported that, although frequencies of 3.5, 9, 18.5 and 25 Hz were of frequent occurrence during transportation, the most significative ones are the levels of 3.5 and 18.5. Shahbazi et al. [25] particularly noted that if the vibration frequency of the truck during watermelon transportation is close to 7.5 Hz in a short distance (duration) the flesh of the watermelon may be damaged.

With the results obtained in this work it can be noted that vibration appears to be weakening tomato fruit and this is seen to generally affect Young's modulus. This is perhaps because vibration force relocates the individual fruits relative to other fruits in the bulk, leading to an initial compaction of fruits. The percentage of the difference (decay) in modulus of elasticity (Young's modulus) was assumed to denote fruit damage [26]. Young's modulus values from whole fruit compression variously represent fruit morphology, size, shape, cellular structure, strength, and turgor. This strength parameter is often used by engineers as an index of product firmness [27].

3.5 Effects of container type

"As seen from the results of the analysis of variance (ANOVA) shown in Tables 3, The effects of container type Young's modulus show significant differences (P=0.001). For at the respective levels tested during the compression testing of Roma tomato fruits.

The Statistical analysis of variance means and differences (Table 4), however, indicated that the parameter recorded lower values in basket packaged tomatoes.

4 Conclusion

A direct measure of Young's modulus of packaged tomatoes has been used to characterize stiffness of the fruit and to quantify the responses to applied compression loading, which stimulates forces encountered during road transportation. The results show that the Young's modulus, hence stiffness, of the tomatoes reduces with advancing stage of fruit ripeness and increasing level of vibration imparted onto the fruit before compression. This indicates that the two factors affected the structural components responsible for stiffness. Moreover the effects of both vibration and ripeness on stiffness and stress were closely related.

The effects of ripeness are attributed to certain structural changes occurring during ripening, particularly changes associated with turgidity of the cell, structure of the cell wall, turgor pressure and tissue rigidity. The observed decrease in Young's modulus with increasing vibration is attributed to the reduction of the interspaces' (void) volumes within the bulk, associated with compaction during vibration. This offered an initial resistance to pressure application during the subsequent compression process. On the other hand, the measured Young's modulus in non-vibrated fruit was driven, in part, by the existence of interspaces' (void) volumes within the bulk.

The results, thus, elucidate the technical and economical importance of harvesting Roma tomatoes to be packaged for road transportation at an early ripeness stage. Likely conditions of imparting vibration on the packaged fruit also need be controlled or avoided. Knowledge of the Young's modulus of tomatoes under compression loading will help in predicting occurrence of failure under externally applied stress and enhance the design of improved packaging materials for transported tomato fruit. Young's the modulus is often useful in relating the mechanical properties of the fruit to its composition and structure.

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TABLE 1.

STATISTICAL ANALYSIS OF VARIANCE (ANOVA) OF DATA ON YOUNG'S MODULUS OF ROMA TOMATO FRUIT

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	1,193E02[a]	11	1,083E-03	6,974	.000
Intercept	8,526E-02	1	8,526E-02	548,801	.000
Vibration	4,853E-03	2	2,427E-03	15,620	.000
Container	5,632E-03	1	5,632E-03	36,253	.000
Ripeness	3.302E-03	2	1,651E-03	10,627	.000
Vibration*Container	1,193E-03	2	5,965E-04	3,840	.029
Vibration*Ripeness	1,035E-03	4	2,587E-04	1,665	.176
Container*Ripeness	.000	0	.	.	.
Vibration*Container*Ripeness	.000	0	.	.	.
Error	6.525E-03	42	1,554E-04		
Total	.105	54			
Corrected Total	1,844E-02	53			

a. R Squared =.646 (Adjusted R Squared = .553)

TABLE 2:
STATISTICAL ANALYSIS FOR VARIANCE MEANS OF YOUNG'S MODULUS

Factor	Young's modulus, N/mm²
Stage of ripeness	
Unripe	5.629E-02a
Half-ripe	4.072E-02a
Full-ripe	2.318E-02b
Vibration level	
Non-vibrated	5.323E-02 a
Low-vibration	3.624E-02b
High-vibration	3.072E-02b
Type of container	
Crate	2.238E-02a
Basket	5.775E-02b

Means with the same letter were not significantly (p = 0.05) different.

Fig. 1. Compression of Roma tomatoes in raffia basket using Testometric Universal Testing Machine. (UTM).

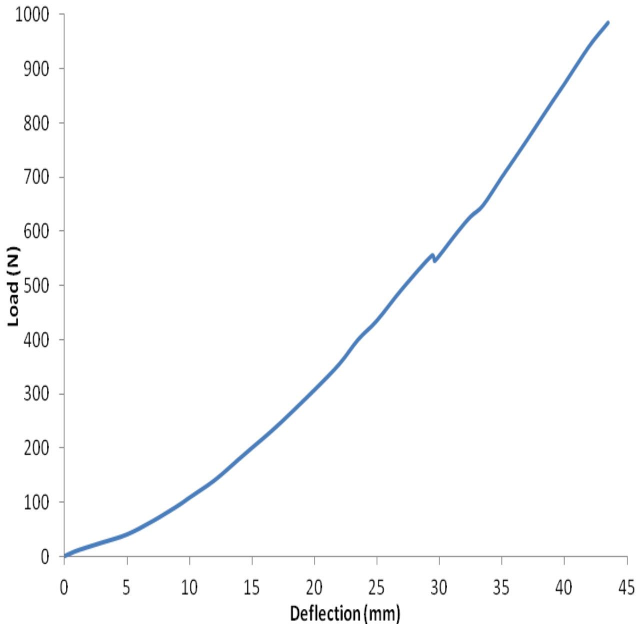

Fig. 2. Load-deformation curve for vibrated unripe tomatoes packaged in basket