Energy Absorption Capacity of Packaged Roma Tomatoes under Compressive Loading

F. A. Babarinsa and M. T. Ige.

Abstract — This study focused on the energy absorption capacity of Roma tomatoes as a strength parameter that characterizes mechanical damage of the packaged fruit when subjected to compression, in multi-layers. The aim was to relate the measured strength properties of the bulk fruit to mechanical failure at the bioyield, break and peak points of deformation. Compression tests were conducted on Roma tomatoes to investigate the effects of ripeness stage, vibration level and container type on energy absorption in the packaged tomatoes under compressive loading, using a 2^2x3 factorial experimental design. 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. These 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 and absorbed energy at bioyield, break and peak points was measured. Energy absorption decreased significantly (P=0.05) with advancing ripeness stage of tomatoes and vibration level (P=0.001). Container effects were significant at peak. Average absorbed energy ranged from 1.140Nmm to 1.875Nmm at bioyield, 13.597Nmm to 27.221Nmm at break and 15.629Nmm to 23.618Nmm at peak. The work will facilitate our understanding of the contribution of fruit ripeness and transit vibration to mechanical damage in packaged tomatoes. The results obtained can be used by designers of packaging materials, and handlers of fresh tomato fruits in Nigeria to reduce mechanical damage, especially those due to compression.

Keywords: Compressive loading, Container, Energy absorption, Packaging, Ripeness, Roma tomato, Vibration.

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1 INTRODUCTION

Packaged tomato (*Lycopersicon esculentum* Mill.) is highly susceptible to mechanical damage during transportation because the fruits are more perishable and tender than other fruits and vegetables. In Nigeria, major areas of tomato production are concentrated in the northern part of the country and the main variety transported is the Roma, in consideration of its relative firmness. Nearly all the transported tomatoes are packaged in raffia baskets in very large quantities and carried in open trucks over long distances by inter-state roads. The greatest concentration

As noted by Rorbertson [1], requirements of modern packaging of fresh horticultural produce include the prevention of mechanical damage resulting from compression. The development of a promising packaging system for tomato distribution will depend much on the clear understanding of the mode spoilage resulting from their resultant effects of vibration and compressive forces [2]. Every mechanical damage results from the transformation of energy from one form to another as energy is persistently imparted to and absorbed by the bulk of packaged commodity. During transportation and handling of fruits and vegetables, the vegetative cells are sensitive to such external influences as energy consumption [3]. Energy transformation occurs at the different points of mechanical deformation denoted as the bioyield, break and peak points. Energy imparted to packaged commodities during transportation originate from drops or from accelerations transmitted to the fruit through the chassis and suspension system and finally through packaging container. Hinsch et al. [4] 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 Hz. The sequence of collisions occurring between the various layers of fruit,, as a vehicle passes over a hump, are energy absorbing [5]. Distribution system can therefore be viewed as a series of discrete energy inputs for the analysis and prediction of mechanical damage. Mechanical injury through imparted energy may either destroy the physical integrity of the produce, resulting in breakage, cutting, splitting, or cause bruising [6]. Wills *et al.* [7] categorized mechanical damage to some fruits into compression, impact and vibration injuries. O'Brien *et. al.* [5] associated extent of damage to level of energy imparted to and absorbed by the produce during transportation. The amount of damage to produce is thus directly related to the energy absorbed. Energy absorption is closely related to mechanical properties and, like other terms of strength parameters such as load (force), deformation and stress, energy is measured at points of bioyield, break and peak. The strength

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parameters of force (load), deformation and stress in packaged Roma tomatoes have been studied in relation to the bioyield point [8] and break point [9]. The measurement and understanding of the energy absorption capacity of packaged tomatoes under compression will facilitate prediction of failure modes and the total amount of tissue damage in the pack [10]. Villarreal [11] noted that a method of predicting damage to packaged tomatoes from packaging studies could be based on the fact that bruising in the fruits is related to the energy absorbed by the individual fruit.

The evaluation of packaging system for fruit and vegetables in terms of mechanical damage using energy inputs has, thus, been proposed by Holt and Schoorl [12]. The authors found that the degree of resulting spoilage depends on the capacity of the fruit to absorb and withstand energy imparted by the resultant forces, particularly vibration and compression forces.

This study investigated energy absorption capacity of packaged Roma tomatoes at bioyield, break and peak points under compressive loading. It particularly studied the effects of stage of fruit ripeness, level of vibration and packaging container on the absorbed energy.

2. MATERIALS AND METHODS

2.1 Experimental plant material

Tomatoes used in this study were of the Roma variety, hand-harvested from a local market farm in Ilorin suburb and sorted into three stages of maturity namely: unripe, half-ripe and full-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 1) using a number, 3) the full-ripe, consisting of 70-100% red skin but still firm, These were comparable to skin colour levels 2, 4 and 6 on another chart presented by McGlasson *et al.* [13]. The ripening stages are also equivalent to colour levels depicted as 1, 5 and 9 on the recommended tomato colour chart of the Organisation de Cooperation et de Development Economiques, Paris [14] .

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 [15]; it is similar to that described by Thompson [14] . 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 effects 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 were carried on the carriage platform vibrated by internally fitted oscillating cams, and 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

Absorbed energy was measured while compressing the tomatoes using the Testometric Universal Testing Machine (UTM), (manufactured by Testometric Co. Ltd. UK), with a force exerting capacity of 50kN (Fig. 1). The machine was installed in the Engineering Material Testing Laboratory of the National Center for Agricultural Mechanization (NCAM), Ilorin. The functional components of the testing machine include the load frame, load cell, crosshead, control console and a printer.

The compression test was conducted in triplicates by mounting and compressing the tomatoes in the loading space of the UTM. A pair of rigid plates of 1.27cm thick plywood was used as the force-transmitting devices, one as bottom support and the other as top loading device for the fruit. Loading rate (crosshead speed) of 2.50 mm/min was applied as recommended by Mohsenin [3]. The electronic computing unit of the UTM was set to measure selected strength parameters (load, deformation and stress) at the break point of the compressed tomatoes. 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 Load-deformation curves

A typical compression load-deformation curve generated for a strength parameter at break of the compressed tomatoes is shown in Fig. 2. The curves generated for the fruit compression generally had sharp peaks following the elastic deformation at the end of each compression, just as observed in our previous works [8], [9]. rather than rounded peaks. The point of maximum force or rupture coincided with the peak point on the force-deformation curves The observed behavior in compression has been attributed to soft, weak brittle materials by Fellows [16]. He particularly remarked that the point of maximum force or rupture could also occur at bioyield point. This, thus, explains why break and peak points may not be distinguishable from bioyield point in curves such as that in Fig. 1. The energy required to deform tomato fruit from the bioyield point is referred to as the modulus of resilence. The energy required to deform the fruit to its maximum maximum strength is referred to as the modulus of toughness. These two properties, however, could not be clearly differentiated on the force-deformation curves for the stated reason.

3.1 Statistical analysis

Table 1 gives the result of the statistical Analysis of Variance (ANOVA) of the data showing the effects of ripeness stage, vibration level and container type on the energy absorbed at the bioyield point. The statistical analysis indicates that the effects of level of vibration and those of ripeness stage were both significant (at $P=0.001$) on energy at bioyield. The effects of vibration, with F-value 20,661, were however stronger than the effects of ripeness with lower F-value of 8,835. The effects of container type were not significant on energy at bioyield. Vibration*Container interaction was the only two-factor interaction observed to be significant (at $P=0.05$).

The statistical Analysis of Variance (ANOVA) of the data on the energy at break of compressed tomatoes is presented in Table 2. The effects of level of vibration and those of ripeness stage were significant (at $P=0.001$ and $P=0.005$, respectively) on energy at break. The effects of container type, however, were not significant on energy at break. None of the two-factor interactions showed significant effect. This implies that container type was not as important as vibration level and stage of ripeness in determining energy at break during compression of packaged Roma tomatoes.

Table 3 gives the result of the statistical Analysis of Variance (ANOVA) of the data for energy at peak of compressed tomatoes. The effects of level of vibration and those of container type were both significant at $P=0.001$ on energy at peak while those of ripeness stage were significant at $P=0.05$. The effects of container type, with F-value 4,759, were not as strong as the effect of ripeness and vibration with higher F-values of 10,032. None of the two-factor interactions had significant effects on energy at peak.

3.2 Effect of stage of ripeness

The statistical analysis of variance means and differences among the three stages of ripeness tested were presented in Table 4. Energy absorption capacity of the compressed fruit is influenced by the stage of ripeness at the three points of deformation tested namely: bioyield, break and peak points. The energy absorbed decreased with advancing stage of ripeness. Energy at bioyield reduced by 11.6% and 28.5%in the half-ripe and full-ripe stages respectively, as compared to values obtained for the unripe fruit. Following a similar trend, energy at break reduced from by 21.8% and 36.5% in the half-ripe and full-ripe stages respectively. Values of absorbed energy recorded for both break and peak points show just marginal differences. This can be attributed to the observation that the point of maximum force or rupture coincided with the peak point on the force-deformation curves as noted ealier.

Fruit at full-ripe stage consistently had the least energy absorption, indicating that they are most susceptible to compression damage at all points. The observed decrease in absorbed energy with advancing stage of ripeness implies that tomato fruit at an early stage of ripeness is capable of absorbing greater amount of imparted energy before yielding under compression. Thus, fruits at full-ripe stage had the least energy absorption capacity, and are likely to be most susceptible to compression damage at the respective points of deformation. On the other hand, fruits at unripe stage, with the highest energy absorption capacity, are considered to be least susceptible to compression damage. This explains the observation of Villarreal [11] that unripe tomatoes form an energy-absorbing load. The author noted that these unripe tomatoes are more affected in energy dissipation such that all the imparted energy could be dissipated in compaction rather than bruising. The energy available for deformation, hence damage, is related to the energy absorbed into the system as a function of strength properties of fruits.

Although the absorbed energy at peak point increased steadily with increasing ripeness stage, the mean values had no significant differences. The differences were significant only between the half-ripe and full-ripe stages, but not between the unripe and half-ripe stages. In absolute terms, the decrease of energy absorption was greater below half-ripe than towards full-ripe stages. The observed reduction in energy absorption capacity of compressed tomatoes as ripening advanced can be attributed to a variety of bio-chemical and textural changes which are known to contribute to the deterioration of the commodity texture and finally leading to disruption of the cellular structure [17]. Upon the absorption of energy, the tissues of the fruit undergo yielding, whereby its ability to resist the applied load is drastically reduced and exhibits a continuous rupture plane where it has weakened substantially [18]. Rupture will also vary with cell turgidity, cell wall stiffness, and cell wall (plasmalemma) permeability, which all change as the tissue ripens. Schouten et al. [19]. thus reported that mechanical damage, perhaps, results in immediate loss in cell wall only in the riper fruit of tomato.

3.3 Effect of vibration

The statistical analysis of variance means and differences among the three levels of vibration is given in Table 5. Energy at bioyield, break and peak of the compressed tomato all reduced with increase in level of vibration. Average absorbed energy, at bioyield, for example, reduced by 21% when low vibration was applied to the fruit and by 39% when vibration was applied at high level. Similar trends of response to vibration application occurred at the break and peak levels of deformation. This indicates that the resistance of the fruit to mechanical damage (by yielding, breaking or rupture) of the tissues reduces according to the level of vibration imparted to them before compression. Wills *et al.* [7] noted that bruising of tissue damage results from strain energy being dissipated in the tissue. The amount of damage (measured as bruise volume) depends on the amount of energy that is absorbed and the nature of the tissue. In line with the classification of failure in some fruit and vegetables by Schoorl & Holt [10] from energy consideration, damage at bioyield can be associated with bruising. The energy absorption by the tomato fruit greatly determines the quality of the fruit during handling because yielding of the tissues, which results from compression, accelerates subsequent deterioration of the fruit. Hence, if quality is to be ensured, the vibration resulting to such damage must be minimized.

The higher absorbed energy obtained for non-vibrated tomato at break point implies higher resistance to mechanical damage of cracking than vibrated fruit imparted with the same compression energy. Damage resulting from the break point in tomato is classified, from energy consideration, as cracking and is also associated with the amount of strain energy being dissipated in the tissue [10]. Hence, while it is convenient to model failure conditions in terms of stress, the basic failure mechanisms are defined in terms of energy required for cleavage to occur. For example, there must be sufficient energy stored in the material to provide for the creation of new surface.

The results (Table 2) show that subjection of packaged tomatoes to vibration reduced their ability to withstand stress at break during compression. During vehicular vibration the tomatoes first get compacted as vibration force relocates the individual fruits relative to other fruits in the bulk and the contact surfaces move down. This resulting initial compaction of fruits thereby reduces interstitial space with little or no bruising. The compression effect on individual tomatoes is then determined by the relative motion of the upper compressing fruit and the lower compressed fruit at the contact surfaces. This modifies the deformation and changes the total amount and distribution of energy dissipated into the fruit layers. The change in energy is thus affected by vibration at the various interfaces of each layer with increased number of contact points for contact compression. This eventually governs the distribution of energy dissipation, during subsequent inter-layer compression when external load is applied.

3.4 Effect of Container types

Table 6 shows the statistical analysis of variance means and differences among the two types of container, plastic crate and raffia basket, tested during the compression testing of tomatoes. Energy at bioyield, break and peak points was all marginally higher in crate than in basket, with the container effects being significant (P=0.001) only at the peak point.

Results obtained on the effects of ripeness stage and vibration level on energy absorption capacity of Roma tomato are useful to designers of packaging materials and handlers of fresh tomatoes. The results will facilitate reduction of mechanical damage in packaged tomatoes, especially those due to compression, thereby preserving the fruit quality. It has been noted that damage inflicted on fruits is related to energy available for bruising and the characteristics of particular fruits [20]. The energy available is in turn related to the energy input to the system, suspension characteristic of the vehicle and the properties and the packaging of the fruits. As can be clearly seen from the results, the fruits vibrated at high level absorbed the greatest energy.

CONCLUSION

Results of the present work investigated the resistance of packaged Roma tomatoes to compression damage based on the measurement of energy absorption capacity of the fruit as a strength parameter in multi-layers. The results revealed that advance in fruit ripeness stage as well as increase in level of applied vibration lower energy absorbing capacity of Roma tomato fruit. This implies that the compressed fruit, when handled at an early stage of ripeness can absorb greater amount of imparted energy before mechanical (compression) damage by yielding or breaking. The findings also point to the need to minimize the magnitude of forced vibration transmitted from the road during transportation of the packaged tomatoes. This prevents tissue failure, classified as cracking, slip or bruising that result from strain energy being dissipated in the tissue. The information obtained from this study can be of great help to designers of packaging containers and handlers of tomatoes at various stages of distribution. This will minimize the mechanical damage especially those due to compression and ensure deliverance of good quality fruit to consumers and processors.

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TABLE 1.

STATISTICAL ANALYSIS OF VARIANCE OF RESULTS FOR ENERGY AT BIOYIELD OF ROMA TOMATO FRUIT

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	9,739[a]	11	,885	8,137	.000
Intercept	118,294	1	118,294	1087,230	.000
Vibration	4,496	2	2,248	20,661	.000
Container	,433	1	,433	3,981	.053
Ripeness	1,922	2	,961	8,835	.001
Vibration*Container	,971	2	,486	4,463	.017
Vibration*Ripeness	,115	4	2,866E-02	,263	.900
Container*Ripeness	,000	0			
Vibration*Container*Ripeness	,000	0			
Error	4,570	42	,109		
Total	144,492	54			
Corrected Total	14,309	53			

a R Squared = 681 (Adjusted R Squared = 597)

TABLE 2.

STATISTICAL ANALYSIS OF VARIANCE OF RESULTS FOR ENERGY AT BREAK OF ROMA TOMATO FRUIT

Source	Type III Sum of Squares	Df	Mean Square	F	Sig.
Corrected Model	2874.014[a]	11	261.274	5.190	.000
Intercept	21157.851	1	21157.851	420.255	.000
Vibration	1698.359	2	849.180	16.867	.000
Container	177.504	1	177.504	3.526	.067
Ripeness	718.459	2	359.229	7.135	.002
Vibration*Container	163.341	2	81.671	1.622	.210
Vibration*Ripeness	118.319	4	29.580	.588	.673
Container*Ripeness	.000	0			
Vibration*Container*Ripeness	.000	0			
Error	2114.504	42	50.345		
Total	26696.091	54			
Corrected Total	4988.518	53			

[a] R Squared =.576 (Adjusted R Squared = .465)

TABLE 3.

STATISTICAL ANALYSIS OF VARIANCE OF RESULTS FOR ENERGY AT PEAK OF ROMA TOMATO FRUIT

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	1925.776[a]	11	175.071	6.438	.000
Intercept	19806.401	1	19806.401	728.326	.000
Vibration	545.619	2	272.809	10.032	.000
Container	129.407	1	129.407	4.759	.000
Ripeness	702.798	2	351.399	12.922	.035
Vibration*Container	288.330	2	144.165	5.301	.009
Vibration*Ripeness	88.624	4	22.156	.815	.523
Container*Ripeness	.000	0			
Vibration*Container*Ripeness	.000	0			
Error	1142.165	42	27.194		
Total	23389.363	54			
Corrected Total	3067.941	53			

[a] R Squared =.628 (Adjusted R Squared = .530)

TABLE 4.

STATISTICAL ANALYSIS OF VARIANCE MEANS AND RIPENESS STAGES.

Strength parameter	Stage of ripeness		
	Un-ripe	Half-ripe	Full-ripe
Energy at bioyield (N.m)	1.720a	1.521ab	1.234b
Energy at break (N.m)	24.890a	19.464a	15.795b
Energy at peak (N.m)	23.618a	18.524ab	15.629b

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

TABLE 5.

STATISTICAL ANALYSIS OF VARIANCE MEANS AND VIBRATION LEVEL.

Strength parameter	Level of vibration		
	Non-vibrated	Low-vibration	High-vibration
Energy at bioyield (N.m)	1.875a	1.482b	1.140b
Energy at break (N.m)	27.221a	18.892b	13.597c
Energy at peak (N.m)	23..618a	18.524b	15.629c

Means with the same letter were not significantly (p =

TABLE 6.

STATISTICAL ANALYSIS OF VARIANCE MEANS AND CONTAINER TYPE.

Strength parameter	Type of container	
	Crate	Basket
Energy at yield (N.m)	1.543a	1.455a
Energy at break (N.m)	20.607a	19.200a
Energy at peak (N.m)	20.378a	18.136b

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

Fig. 1. Compression of tomatoes in plastic crate using Testometric Universal Testing Machine. (UTM).

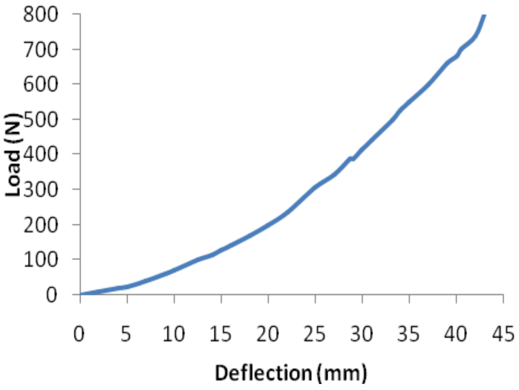

Fig. 2. Load-deformation curve for vibrated unripe tomatoes packaged in basket