Strength Parameters of Packaged Roma Tomatoes at Break Point under Compressive Loading

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

Abstract — Packaged tomatoes are highly perishable and tender, and are highly susceptible to mechanical damage during road transportation due to their low resistance to externally applied forces. This contributes greatly to the transit deformation leading to the breaking point under compression force. The study related mode of mechanical damage in the fruit to the strength parameters measured at break point, using compression tests. Experimental measurements of strength parameters of packaged Roma tomatoes were made to study the effects of ripeness stage, level of vibration and container type on load, deformation and stress at break of the fruit. Tomatoes harvested at three stages of ripeness: unripe (5.6 Brix %),), half-ripe (3.9 Brix %) and full-ripe (3.2 Brix %), were packed in plastic crate and raffia basket. The packaged tomatoes were subjected to three levels of vibration: non-vibrated, low-vibration (frequency 3.7 Hz) and high-vibration (frequency 6.7 Hz). These were compressed at a loading rate of 2.50 mm/min^{-1} in a Universal Testing Machine. Data obtained were statistically analyzed using the SPSS 110 software package. Load and stress at break decreased significantly (P=0.05) with advancing ripeness stage of the fruit. Vibration level significantly (P=0.001) lowered deformation at break. The two-factor interactions vibration*container and vibration*ripeness were significant (P=0.001 and P=0.005, respectively) on stress at break. The results obtained increase substantially our knowledge about the properties of tomato affecting mechanical damage in the tomatoes. This enables designers of tomato packaging to control mechanical damage in packaged tomatoes with due consideration for the breaking strength of the fruit.

Keywords — Break point, Mechanical damage, Packaging, Ripeness stage, Roma tomato, Strength parameter, Universal Testing Machine, Vibration level.

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1 Introduction

LARGE quantities of Tomato (*Lycopersicon esculentum* Mill.) are transported over long distances in Nigeria for inter-state distribution. Almost all tomatoes, mainly the Roma variety, are packaged in raffia baskets and carried in open trucks from the northern part of the country, being the area of greatest concentration of production. During transportation, the tomatoes are highly susceptible to mechanical damage due to poor packaging because they are more perishable and tender than other types of fruits and vegetables. The mechanical damage encountered during road transportation is usually due to the complex effects of various forces on the packaged fruit. All sorts of variation of mechanical forces are persistently imparted to and absorbed by the packaged fruit. The resulting mechanical stresses encountered in the bulk of commodity eventually lead to spoilage [1], which directly lowers the fruit quality. An understanding of the mode of mechanical damage to the plant tissues in packaging is, therefore, a prerequisite to the establishment of any promising packaging system for them.

The forms of mechanical damage, which progressively lead to complete failure, can be controlled remarkably by designing packaging ystems with due consideration for the breaking strength of the fruit. Low resistance of the packaged fruit to externally applied forces contributes greatly to the disruption of the cellular structure of the tissues. Knowledge of the strength parameters of the vegetable tissues of fresh tomatoes therefore enables the designers of tomato packaging to predict the amount of tissue damage under externally applied forces.

Mechanical properties of fruit and vegetables are those having to do with the behavior of the material under applied forces. They describe how the action of forces encountered in packaging during transportation result or manifest in mechanical damage in the material. Strength parameters at the break point relate to the mechanical response of the vegetative tissues at the point of rupture (where major tissue failure occurs). In tomato, mechanical properties vary with age and physiological conditions [2] because the fruit is alive and constantly undergoes changes in various aspects of life processes. Babarinsa and Ige [3] noted that strength parameters of compressed Roma tomatoes at bioyield point, in particular, are influenced by stage of ripeness and level of vibration to which the fruit is subjected.

The mechanics of failure in fruit and vegetables has been discussed by Holt & Schoorl [4]. Mohsenin [5] related mechanical failure in fruits and vegetables to the structural aspect of the cell wall, cell contents, cementing agents, such as pectic substances, and the relationship of turgor pressure and tissue

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rigidity. The worker [5] reported that, in intact fruits, failure is usually manifested through a rupture in the internal or external cellular structure of the material. Mechanical damage caused by imparted breaking stress may either destroy the physical integrity of the produce, resulting in breakage, cutting splitting, or cause bruising. The damage is characterized by cell bursting (in bruising), scuffing and scoring (in abrasion) [6]. Resulting damage of fruit during transit has also been related to vibration on trucks by Hinsch et al. [7]. They reported that, although frequencies of 3.5 Hz, 9 Hz, 18.5 Hz and 25 Hz were of frequent occurrence during transportation, the most significative ones are the levels of 3.5 Hz and 18.5 Hz. Strength parameters at break (or rupture) of packaged Roma tomatoes are indications of mechanical strength of the tomatoes to withstand compressive loading. They determine the mode of mechanical response of the fruit leading to rupture of the fruit under compressive loading. The primary load of concern in tomato packaging for transportation is a compression load. Thus, the effects of long-term compressive loading on tomatoes are of primary importance. Resistance of tomato fruit to break under compressive loading is of importance to tomato transporters especially when transporting by road in open trucks. The approach of studying force-deformation behavior of fruit and vegetables in their natural state [8] is justified for tomato on the ground that the fruit is usually subjected to compression, in its natural forms.

The present work aims at studying the mechanical responses of packaged Roma tomatoes to compressive loading leading to the break point. It investigates the effects of ripeness stage, effects of vibration and packaging containers on strength parameters at break.

2. MATERIALS AND METHODS

2.1 Experimental plant material

Hand-harvested tomatoes of the Roma variety, without defects, were obtained for this experiment from a local market farm in Ilorin suburb. The fruits were sorted into three stages of ripeness indicated as unripe, half-ripe and full-ripe. The unripe tomatoes consisted of fruit at the mature green/breaker (or green pink) stage, being the first point of skin colour change from green to about 30% pink. The half-ripe stage consisted of 30-70% pink to red skin while the ripe (or table ripe) stage consisted of 70-100% red skin but still firm. The designated ripeness stages are respectively equivalent to colour levels 2, 4 and 6 on tomato colour chart of McGlasson et al. [9]. The maturity stages also correspond to skin colour levels depicted as 1, 5 and 9 on the tomato colour chart of the Organisation de Coooperation et de Development Economiques, Paris [10].

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

Harvested fruits were transported to the Engineering Material Testing Laboratory of the National Center for Agricultural Mechanization (NCAM), Ilorin. Wholesome fruits were sorted for reasonable uniformity in shape and size of 2.5 to 3.0cm.

2.2 Packaging containers

Tomatoes were packed into two packaging containers, plastic crate and raffia woven basket. The plastic crate is a nest/stack type (manufactured by Shongai Packaging Industries Ltd) that has been previously recommended by the Nigerian Stored Products Research Institute (NSPRI) for packaging tomatoes for road transportation [11. It is similar to the one described by Thompson [10]. The crate had a holding capacity of 25kg and external dimensions of 60cm x 40cm x 30cm high (with filling height of 25cm). The basket, which is the type extensively used in road transportation of tomatoes in Nigeria, was 30cm deep and 43cm in diameter and was capable of holding 20kg of tomato fruit.

2.3 Vibration treatment

The packaged tomatoes were vibrated in their respective containers (plastic crate and raffia basket) using a laboratory mechanical vibrator, a Gallenhamn Orbital Shaker (App. No 9B 3742 E), The filled containers were carried on the vibrator's platform, fitted internally with oscillating cams that vibrated the platform, thereby 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 respectively, by setting the operating speed at 200 or 400 rev/min for duration of 60 minutes.

2.4 Compression test

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.

Compression tests were conducted with the Testometric Universal Testing Machine (UTM), (manufactured by Testometric Co. Ltd. UK), shown in Fig. 1, with a force exerting capacity of 50kN. It was installed in the Engineering Material Testing Laboratory of the National Center for Agricultural Mechanization (NCAM), Ilorin. Each 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 [5]. The electronic computing unit of the UTM was set to measure selected strength parameters (load, deformation and stress) at break of the compressed tomatoes. Measured values and force-deformation plots were obtained directly from data sheets generated with the aid of a PC.

2.5 Statistical Analysis

Data collected from compression test were subjected to statistical analysis using randomized complete block design based on a 3^2x2 factorial experiment. Statistical analysis was carried out using the 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

Fig. 2 shows a typical compression load-deformation curve generated for a strength parameter at break of the compressed tomatoes. The curves generally had sharp peaks following the elastic deformation at the end of each compression just as observed in our previous work [3]. Similar observation was made by Bourne [12] with Instron generated curves which show sharp peaks at the end of each compression, rather than rounded peaks obtained from the General Foods Texturometer. sharp peaks following the elastic deformation at the end of each compression Fellows [13], in assessing idealized and typical load-deformation curves for different foods, attributed the observed behavior in compression to soft, weak brittle materials. He particularly remarked that the point of maximum force or rupture could also occur at bioyield point. This, thus, explains why break (or rupture) point may not be distinguishable from bioyield point in curves such as that in Fig. 1.

3.2 Statistical Analysis

Tables 1 to 3 show the results of analysis of variance (ANOVA) of the compression tests for determination of load, deformation and stress at break, respectively, each Table showing the effects of ripeness, vibration and container. Vibration level and stage of ripeness had significant effects on load, deformation and stress at break (P=0.001). The effects of container type were significant (P=0 001) on deformation and stress at break. The analysis also indicated that the two-factor interactions vibration*container and vibration*ripeness were significant (at P=0.001 and P=0.005, respectively) on stress at break. All two-factor interactions had no significant effects on deformation at break. However, the F-value of vibration*container interaction (2,348) was higher than that of vibration*ripeness (1,802), hence, more important than the ripeness*container and vibration*container interactions. Interactive effects between the three subject factors (ripeness*container*vibration) were not significant for all strength parameters at break.

3.3 Effects of stage of ripeness

The statistical analysis of variance means and differences among the three stages of ripeness tested during the compression testing is presented in Table 4. Load at break as well as stress at break of Roma tomato reduced with advancing stage of ripeness as well as level of vibration. This indicates a decrease in the resistance of the fruit to compression loading. Break (in form of cracking, splitting or cleavage failure) is a normal stress phenomenon involving the tearing apart of tissues due to the presence of tensile (often induced) stresses [4].

Like in the test of the parameters at bioyield [3], a reduction in load and stress at break was observed with advancing stage of ripeness of tomato fruit (Table 4). This is most probably due to the reduction of turgor in tomatoes that accompanies ripening as reported by De Belie et al., [14]. Higher turgor tends to make the cell more brittle when such tissues are subjected to compression, leading to failure at a lower force [15]. This is supported by Garcia et al. [16] who observed that mechanical stresses were higher in the tissues of turgid fruit.

Pitt [17] relates the externally applied stress to the cell wall stress it induces in vegetative tissues. With energy absorption, the internal features by which the tissue resists an applied load include the structural aspect of the cell wall, cell contents, cementing agents, such as pectic substances, and the relationship of structure of turgor pressure and tissue rigidity. The author explained that failure of the cellular conglomerate is initiated by either the tension failure of the cell walls or the failure of the intercellular bonds. These two modes of structural failure vary among different commodities and normally change as the tissue ripens. The dominant mode of failure is apparently determined by the relative strength of these two structural features. The mode of failure may change as the tissue ripens. Thus, perhaps, mechanical damage results in immediate loss in cell wall only in the riper fruit of tomato as reported by Schouten et al. [18].

The observed increase in deformation at break with advancing stage of ripeness of tomato fruits (Table 4) indicates that compression force will inflict greater damage on tomatoes at advancing stages of ripeness. This can be explained by observation of previous workers [19] that, during ripening, cellulose and hemicellulose of normal tomatoes decreased; while mannose and glucose contents decreased greatly between mature green and pink stages of ripeness. The results obtained therefore agree with the findings of Olorunda & Tung [20] that fruit maturity influences the susceptibility to mechanical injury, with ripe tomatoes being more susceptible.

The observed characteristics of the ripeness response of stress at break can also be related to ripening-related changes of the mechanical properties of the cuticular membrane. The presence of a transition in the cutin matrix of the isolated tomato fruit cuticular membrane is lowered when ripeness increased and is hardly apparent when isolated cuticular membrane samples are totally ripe [21]. With an increase in plasticizer content in the totally ripe samples, the plasticizing effect can be described in terms of lowering the fracture strength, elastic modulus, and viscosity of the biopolymer-water mixtures.

3.4 Effects of vibration Level

The present study involves experimental simulation of vibration encountered by packaged tomatoes at varying levels during road transportation. Table 4 shows the statistical analysis of variance of means and differences among the three levels of vibration tested during the compression testing. Load and stress at break of Roma tomato reduced significantly (P=0.001) with advancing level of vibration. However, a reduction in deformation at break by 17.4% was recorded upon the application of low-vibration to fruits while an overall increase of 13.5% in deformation was caused by subsequent application of high-vibration.

The reduction in deformation at break with initial application of vibration (at low level) can be attributed to the reduction of the interspaces' (void) volumes within the bulk, which is associated with compaction during vibration. The fractions of voids that were available for reduction by the compressive force become smaller in the vibrated fruits than in non-vibrated fruits. This offered a resistance to pressure application during the subsequent compression process, thereby restricting downward movement and limiting the summation of the bulk deformation recorded in the vibrated fruits. On the other hand, the measured deformation (or deflection) in non-vibrated fruit was driven, in part, by the existence of interspaces' volumes within the bulk. The larger amount of these interspaces' volumes was, however, removed during the initial application of low-vibration. The effect of vibration will be greater with or even limited to the low-level vibration when the initially large void volume would have been greatly reduced or removed. The observed reversal of effect with an overall increase (of 13.5%) in deformation which occurred upon application of high-vibration may be due to structural disintegration of the fruit cuticle. The cuticle was noted by Shahbazi et al. [22] as being sensitive to higher frequency vibration. According to Matas et al. [21] these characteristics of the vibration response of deformation can be related to the presence of a transition in the cutin matrix of the isolated tomato fruit cuticular membrane. It is on this basis that the workers noted that tomato fruit skin plays an integral role in the regulation of tomato fruit strength. Imparted vibration received in the packaging containers rendered the fruit susceptible to mechanical deformation during compression. Tomatoes subjected to excessive vibration , as in this work,will easily be inflicted with mechanical damage, judged by the low maximum load and stress at break recorded for the treated fruit. This result is in agreement with the reports of Idah et al. [23], which relate severity of compression damage in fruits to the level of vibration (and the stage of ripeness). Shahbazi et al. [22] particularly noted that damage to watermelon increased as vibration frequency (and duration) of the truck during watermelon transportation increased close to 7.5. Similar trends of effects of vibration frequency were obtained in the current study on Roma tomato. As the non-vibrated fruits had the least deformation after compression, it is advised that packaged tomatoes should not be subjected to excessive vibration in the course of road transportation. The results of this study therefore point to the importance of using well maintained vehicles and roads when considering transportation of packaged tomatoes by road. Berardinelli et al. [24] had earlier noted that vibrations imparted to fruit during transportation are influenced by road roughness and some characteristics of the truck such as the suspension and the number of axles.

3.5 Effects of container types

The effects of container were significant (P=0.00) on deformation and stress at break point during the compression testing (Tables 1 to 3). Load at breaks was persistently lower in basket than in crate, regardless of the stage of ripeness. Container is interacted with vibration and together determined the intensity of compression damage inflicted on the packaged fruits.

4 Conclusion

The work investigated the modes of deformation leading to break point (rupture) in Roma tomatoes under compression force similar to that induced inside packages during road transportation. Compression tests of the packaged tomatoes were performed for the measurement of strength parameters at break to study the effects of ripeness stage, vibration and packaging containers.

The major findings showed that **s**tage of fruit ripeness and level of encountered vibration significantly affected all the strength parameters of Roma tomatoes: namely: load, deformation, stress and energy at break; while container type affected only deformation and stress.

The results indicated that tomatoes packaged at advanced stages of ripeness were more susceptible to compression stress due to reduced breaking resistance. In addition, increased level of vibration resulted in reduced resistance to rupture.

Data obtained herein concerning the strength parameters increase substantially our knowledge about the properties of tomato affecting mechanical damage in the packaged fruit. These conclusions indicate that mechanical damage encountered in tomato packages during transportation can be substantially reduced by harvesting the fruits to be transported at the earlier stage of maturity. Control over the various sources of vibration to the packaged fruits, such as type of vehicle, road conditions and container arrangement will also reduce compression related damage during road transportation.

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TABLE 1.

STATISTICAL ANALYSIS OF RESULTS FOR LOAD AT BREAK OF ROMA TOMATO FRUITS

Source	Type III Sum of Squares	Df	Mean Square	F	Sig.
Corrected Model	6643078.737[a]	11	603916.249	9.768	.000
Intercept	67169948.6	1	67169948.61	1086.384	.000
Vibration	2597556.344	2	1298778.172	21.006	.000
Container	234201.680	1	234201.680	3.788	.058
Ripeness	2142138.690	2	1071069.345	17.323	.000
Vibration*Container	273223.090	2	136611.545	2.210	.122
Vibration*Ripeness	331617.482	4	82904.370	1.341	.271
Container*Ripeness	.000	0			
Vibration*Container*Ripeness	.000	0			
Error	2596814.642	42	61828.920		
Total	78409397.7	54			
Corrected Total	9239893.379	53			

a. R Squared = .719 (Adjusted R Squared = .645)

TABLE 2.

STATISTICAL ANALYSIS OF RESULTS FOR DEFORMATION AT BREAK OF ROMA TOMATO FRUITS

Source	Type III Sum of Squares	Df	Mean Square	F	Sig.
Corrected Model	6671.976[a]	11	606.543	4.822	.000
Intercept	130042.525	1	130042.525	1033.872	.000
Vibration	2125.742	2	1062.871	8.450	.001
Container	2158.267	1	2158.267	17.159	.000
Ripeness	3573.410	2	1786.705	14.205	.000
Vibration*Container	590.664	2	295.332	2.348	.108
Vibration*Ripeness	906.835	4	226.709	1.802	.146
Container*Ripeness	.000	0			
Vibration*Container*Ripeness	.000	0			
Error	5282.843	42	125.782		
Total	144067.129	54			
Corrected Total	11954.819	53			

a. R Squared = .558 (Adjusted R Squared = .442)

TABLE 3.
STATISTICAL ANALYSIS OF RESULTS FOR STRESS AT BREAK OF ROMA TOMATO FRUIT

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	1.419E-04[a]	11	1.290E-05	8.707	.000
Intercept	3.426E-03	1	3.426E-03	2312.242	.000
Vibration	5.066E-05	2	2.533E-05	17.098	.000
Container	3.931E-05	1	3.931E-05	26.534	.000
Ripeness	5.448E-05	2	2.724E-05	18.387	.000
Vibration*Container	2.396E-05	2	1.198E-05	8.088	.001
Vibration*Ripeness	3.019E-05	4	7.548E-06	5.095	.002
Container*Ripeness	.000	0			
Vibration*Container*Ripeness	.000	0			
Error	6.222.E-05	42	1.481E-06		
Total	3.752E-03	54			
Corrected Total	2.041E-04	53			

[a] R Squared = .695 (Adjusted R Squared = .615)

TABLE 4.
STATISTICAL ANALYSIS OF VARIANCE MEANS AND RIPENESS STAGES.

Strength parameter	Stage of ripeness		
	Unripe	Half-ripe	Full-ripe
Load at break (N)	1450.339a	1077.965b	858.022 b
Deformation at break (mm)	42.724a	50.456b	55.208b
Stress at break (N/mm^2)	8.856e-03a	7.489e-03a	7.972e-03a

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

TABLE 5.
STATISTICAL ANALYSIS OF VARIANCE MEANS AND VIBRATION LEVELS

Strength parameter	Level of vibration		
	Non-vibrated	Low-vibration	High-vibration
Load at break (N)	1407.438a	1070.292b	877.242c
Deformation at break (mm)	50.361a	41.614b	57.153c
Stress at break (N/mm^2)	9.008E-03a	8.388E-03ab	6,548E-03b

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

TABLE 6.

STATISTICAL ANALYSIS FOR VARIABLE MEANS AND CONTAINER TYPE

Strength parameter	Type of container	
	Crate	Basket
Load at break (N)	1211.619a	1025.028a
Deformation at break (mm)	52.065a	47.357b
Stress at break (N/mm²)	7.433E-03a	8.469E-03a

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

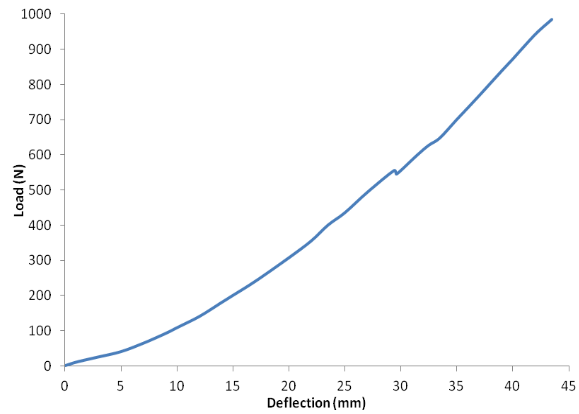

Fig. 2. Load-deformation curve for vibrated ripe tomatoes packaged in basket

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