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Limiting stresses and elastic properties of biological material under axial and radial compression as related to their handling and containerization

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Abstract

This is a report on the evaluation of elastic properties of UTC tomato fruit to determine the maximum contact pressure, contact stresses and elastic modului relevant to design of transportation system of the biomaterial. A universal compression test rig developed at the Department of Industrial and Production Engineering of the Nnamdi Azikiwe University, Awka, Nigeria was used to test the biomaterial properties under axial and radial loading condition to ascertain the engineering stress-strain, true stress-strain, isotropic and anisotropic condition of the material under investigation. The elastic properties evaluated under longitudinal(axial) and transverse loading were found to be approximately the same, giving the elastic modulus and Poisson's ratio for engineering stress-strain as 0.1628MPa and 0.2563 respectively while the transverse loading gave 0.2158 and 0.2596 respectively. The Hertz's maximum contact pressure was evaluated as 0.063MPa at contact radius of 0.01m, while the principal Hertzian stresses were equally evaluated and the maximum shearing stress of 0.3Pmax = 0.02281MPa while maximum principal stress was found to be -0.0736MPa. Above all the study found that within the elastic limit the material biomechanical properties are isotropic giving approximate elastic modulus of about 0.2MPa and Poisson's ratio of 0.3 and the shear modulus of 0.06479MPa-0.0857MPa. Other properties evaluated are the ultimate compressive strength which was found within the range 14.595KPa-16.7731KPa, fracture limit found within the range 12.3250KPa - 14.3940KPa, while the bioyield point was found to be within the range 8.7961KPa-9.4666KPa. The designers of transportation for tomato should therefore ensure that the maximum contact stresses between the tomato and container does not exceed the maximum contact pressure and the maximum shear stress evaluated in this study.

Keywords: UTC tomato; elastic properties; compression; tomato; sphericity; hertzian stresses; principal stress

1. Introduction

Fruit and vegetables are highly susceptible to mechanical damage during harvesting, handling, transportation and storage. The damage causes them to rot quickly, reduces quality and increases loss (Xiaoyu and Wei, 1998). In order to minimise mechanical damage the handling and transportation stresses must be kept under a certain value, it therefore became necessary that during design and optimization of machine for handling, cleaning, transporting, and storing, the physical attributes of improved UTC tomato variety and their relationships must be known (Mirzaee et al., 2008; Amin et al., 2011. Studies related to this paper are due to Taheri-Garavand et al., 2009, Blewett et al., 2000, Thiagu et al., 1993, Gonzalez et al 1998 ,Wang et al. 2006, Jizhan et al., 2008. Other studies on tomatoes are also available Ozarslan, 2002; Aydin et al., 2002; Guner, 2003; Dursun and Guner, 2003; Calısır and Aydın, 2004. The aim of this study is to determine the physical properties, and mechanical behavior such as rupture force, rupture energy, Poisson's ratio and elastic modulus under compression loading of improved UTC variety tomato fruits.

2. Theoretical relations relevant to study

The following relations necessary for the computation of the mechanical and physical properties of tomato material are found in Benham and Warnock (1981), Beleyaev (1979).

$$\mu = \frac{Transverse\ strain}{Axial\ Strain} = \frac{\left\{\frac{(A_i - A_0)}{A_0}\right\}}{Axial\ Strain} \qquad (1)$$

$$E \equiv \frac{(FL_0)}{A_0 \Delta L} \qquad (2)$$

$$\varphi = \frac{\left(D_L D_{T\,max} D_{T\,min}\right)^{\frac{1}{3}}}{D_L} \quad (3)$$

$$D = \sqrt{AB} \quad (4)$$

$$G = \frac{E}{2(1+\mu)} \quad (5)$$

$$\sigma = \frac{F}{A} \quad (6)$$

where F is applied force (N), A is area of section (m^2) and σ is the stress (in N/m^2). φ = sphericity of material, G =shear modulus, D = equivalent diameter of sphere, μ = Poisson's ratio,

Contact stresses relations are evaluated in line with the experimental procedures of Ma and Ravi-Chandar(2000) such that when the moving platen $d_1 = \infty$ (having flat surface) and the test piece d_2 (having curved surfaces) are pressed together during transverse loading with a force of magnitude F as shown in figure 2. Hertz contact stresses relations presented by Shigley and Mischke (2001) are

$$a = \sqrt[3]{\frac{3F}{8}\frac{(1-\mu_1^2)/E_1 + (1-\mu_1^2)/E_2}{1/d_1 + 1/d_2}} \quad (7)$$

$$P_{max} = \frac{3F}{2\pi a^2} \quad (8)$$

where a is the contact radius, P_{max} is the maximum pressure on the material surface and the principal stresses are related as

$$\sigma_x = \sigma_y = -P_{max}\left[\left(1 - \frac{z}{a}\tan^{-1}\frac{1}{\frac{z}{a}}\right)(1+\mu) - \frac{1}{2\left(1+\frac{z^2}{a^2}\right)}\right] \quad (9)$$

$$\sigma_z = \frac{-P_{max}}{1+\frac{z^2}{a^2}} \quad (10)$$

and z is permitted to take values as $0 \le z \le 3a$ and F is the elastic force on the material measured at the proportionality limit.

3. Material and methods

The improved UTC tomatoes variety was used for all experiments in this study. The light red samples were obtained from the regular Ose Market in Onitsha Anambra state, eastern Nigeria. This is because the stiffness of tomatoes at the light red stage is larger than red stage and the tomatoes at this ripe stage are convenient for storage and transportation (Kiyohide et al., 1991).

The first step of this experimentation is to determine the approximate shape of the tomato by computing the sphericity of the tomato. All the tests were conducted using a compressive test rig (Ihueze et al., 2011); in measurement of physical properties, three orthogonal diameters of tomato (Fig. 1b) was measured, tomatoes were divided into two groups and labelled, and each sample mass was taken using a triple beam balance (Precision: 0.02 g) before experiment. In each experiment, firstly, the transverse diameter D_T (Perpendicular to the axis) and D_L (along the axis) of intact tomatoes was measured with a vernier calliper (Precision: 0.01 mm). Then equivalent diameter D (for transverse loading) values were calculated using Eqs. 1 and 2. (Tudor and Thomas, 2004; Zhiguo et al, 2010). Subsequently, the original cross-sectional area through which the force is applied A_0 and final cross-sectional area A_i were computed. The sphericity is a shape index of fruit, which indicates the difference between the actual shape of fruit and the sphere (Zue, 1994). Deformation energy (E_d) was also determined directly from the graph by measuring the area under the force–deformation curves.

3.1. Compression experiment

In order to determine the mechanical properties of tomatoes in compressive tests, a compressive test rig was used Fig. 1a. A typical stress–strain curve for compressed tomato was established using measured test values. After measuring the initial length and width of the tomato, it was compressed until deformation occurred on the fruit body Fig. 2. The Poisson's ratio(μ) of the tomato was calculated (Mohsenin, 1980) after measuring the final diameter and length after deformation. The modulus of elasticity, E (Pa) of the test tomato was also determined.

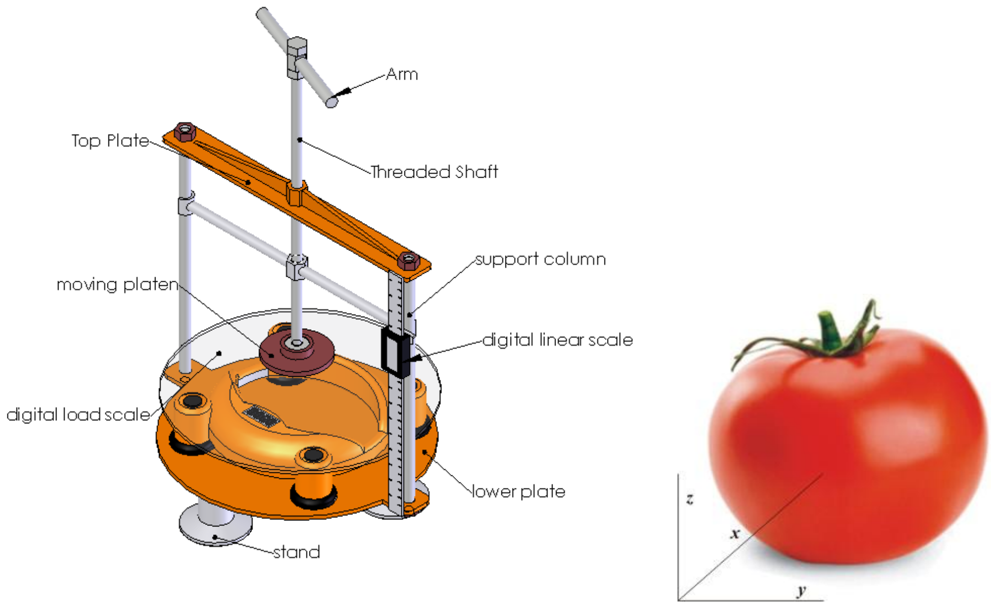
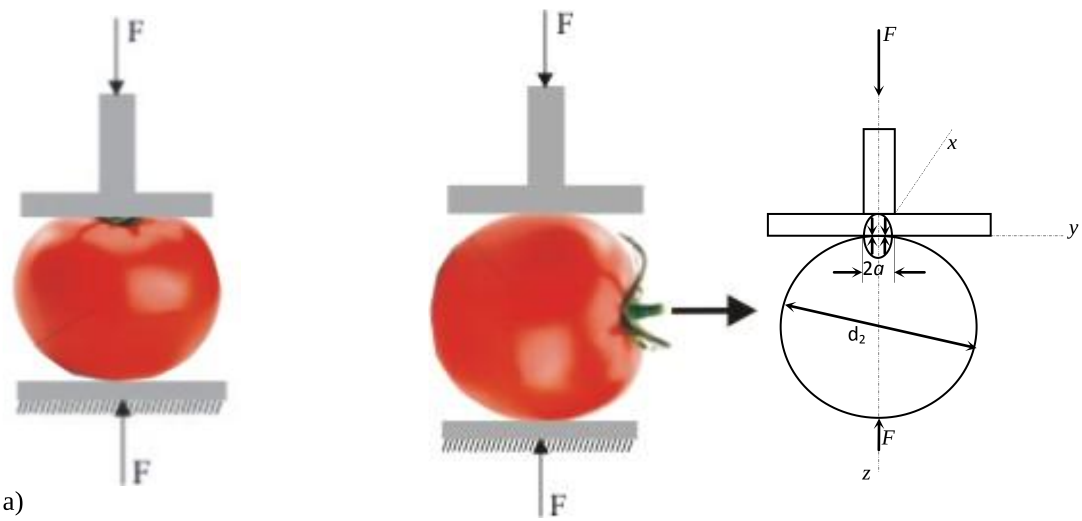


Fig. 1a. Compression test rig (Ihueze et al., 2011); b. Three orthogonal directions of tomato.

4. Experimental and computed results



a)

b)

Fig. 2. Depiction of specimen loading, a. Depiction of axially loaded specimen, b. Depiction of radially loaded specimen.

4.1. Axial compression

The results of this section are exhibited in tables 1 and 2.

Table 1
Engineering property results under axial compression

Sample	Engineering properties							
	Elastic Modulus (MPa)	Poisson's Ratio μ	Yield Strength S_y (Pa)	Ultimate Strength S_u (Pa)	Fracture Strength S_f (Pa)	Mass (Kg)	Sphericity φ	Bulk Modulus G (MPa)
Average for samples	0.1628	0.2563	9466.645	14595.16	14393.97	55.2	1.1407936	0.06479

4.2. Radial compression

The results of this section is in tables 2 and 3

Table 2
Results of radial Compression experiment on improved UTC tomato variety

Major DIM (D_L)	Minor DIM (D_T)	Force (N)	Displa-cement (M)	Cross sectional area (M^2)	Stress (N/M^2)	Axial strain (ΔMJ/MJ)	Transv strain (ΔMN/MN)	True stress	Area Ratio $[A_I-A_O]/A_O$
0.049	0.049	0	0	0.001886	0	0	0	0	7.68823E-06
0.047	0.049	16	0.002	0.001816	8808.68	0.040816	0.004082	8808.68	0.036908696
0.0465	0.0498	16	0.0025	0.001819	8796.127	0.05102	0.016327	8796.127	0.035534279
0.0458	0.0499	17	0.0032	0.001795	9469.711	0.065306	0.018367	9469.711	0.048145594
0.045	0.05	19	0.004	0.001767	10750.41	0.081633	0.020408	10750.41	0.062897667
0.044	0.0505	22	0.005	0.001745	12604.7	0.102041	0.030612	12604.7	0.074559385
0.042	0.0506	28	0.007	0.001669	16773.05	0.142857	0.032653	16773.05	0.11487561
0.041	0.051	22	0.008	0.001642	13394.38	0.163265	0.040816	13394.38	0.129119565
39.5	52.3	20	0.0095	0.001623	12324.95	0.193878	0.067347	12324.95	0.139594287

Table 3
Engineering property results under radial compression

Sample	Engineering properties							
	Elastic Modulus (MPa)	Poisson's Ratio μ	S_y (Pa)	S_u (Pa)	S_f (Pa)	Mass (Kg)	Sphericity φ	Bulk Modulus G (MPa)
Average for samples	0.2158	0.259649	8796.127	16773.05	12324.95	43.5	1.0219631	0.08566

4.3. Considerations for contact stresses for radial loading

The evaluated contact stresses are as in table 4 and the Magnitude of the stress components below the surface as a function of the maximum pressure is shown in fig. 3.

Table 4
Hertzian stresses tabulations

z/a	σ_x (MPa)	σ_z (MPa)	τ_{max} (MPa)	Stress/P_{max} (MPa)	σ_z/P_{max} (MPa)	τ_{max}/P_{max} (MPa)
0	-0.058898155	-0.073622694	0.007362269	-0.8	-1	0.1
0.5	-0.013278098	-0.058898155	0.022810028	-0.180353333	-0.8	0.309823333
1	-0.002133761	-0.036811347	0.017338793	-0.028982388	-0.5	0.235508806
1.5	3.32208E-05	-0.022653137	0.011343179	0.000451231	-0.307692308	0.154071769
2	0.000403731	-0.014724539	0.007564135	0.005483783	-0.2	0.102741892
2.5	0.000413115	-0.010154854	0.005283985	0.005611243	-0.137931034	0.071771139
3	0.000355389	-0.007362269	0.003858829	0.004827162	-0.1	0.052413581

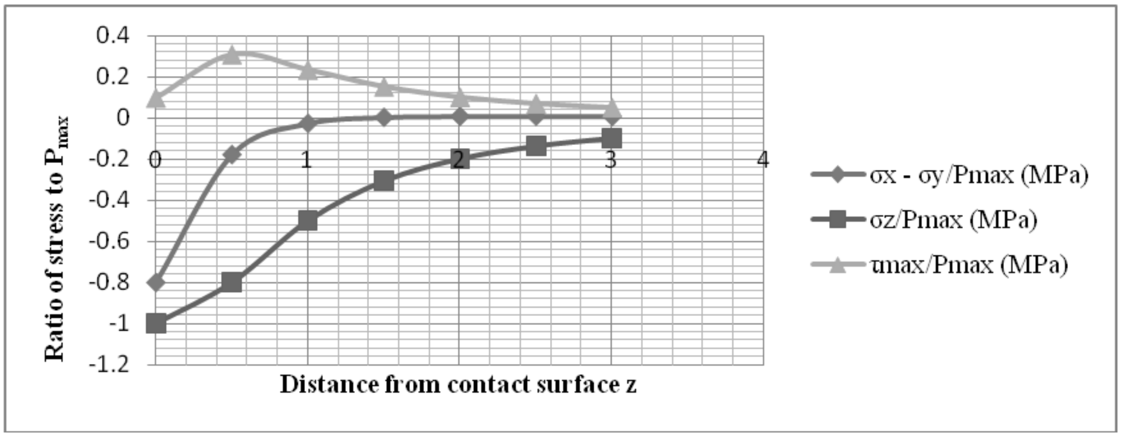


Fig. 3. Magnitude of the stress components below the surface as a function of the maximum pressure.

5. Discussion

The biomechanical properties of the tomato investigated are found in tables 2 and 5 for axial and radial loading respectively. The similarity of the values of the two tables shows that the tomato material is isotropic. This made it possible for Hertz method of contact stresses to be applied.

The elastic modulus of the improved UTC tomato verity used for the study was calculated to be 0.2MPa and the Poissons ratio is 0.3. In fig. 3, the maximum shear stress is slightly below the surface and is approximately 0.3Pmax. The chart is based on a Poisson's ratio of 0.3 for which all the normal stresses are all compressive stresses. The obtained results of the determined physical and mechanical properties of improved UTC tomato verity are shown in Tables 2 and 5. The appearance of this variety of tomato was very close to sphere because of evaluated sphericity value of 1.1407936.

Figure 3 shows that the maximum shear stress occurs slightly below the contact surface and is approximately 0.3Pmax and that the normal stresses are all compressive. It is however the opinion of many authorities that this shear stress is responsible for the surface fatigue failure of contacting elements. The explanation is that a crack originates at the point of maximum shear stress below the surface and progresses to the surface. Also found from the graphics of figure 5 is that that the minimum of the principal stresses stresses is attained at a distance z = 3a so that from table the minimum values of the principal stresses are $\sigma_z = -0.007, \sigma_y = -0.00, \tau_{xz} = 0.004$ and the maximum shearing stress is recorded as 0.02281MPa at a distance 0.5a below the surface.

Computed contact stress distributions between the moving platen and the tomato specimen and also that between the tomato specimen and the machine base were continuous and relatively uniform across the contact patch (Table 6). Except for lightly-loaded instants near the extrema of the load range, the contact patch stayed relatively consistently located on the surface as indicated by the almost uniform contact radius of 0.01m. Maximum computed principal stresses at various directions are for x = -0.0589, for y =-0.0589, for z = -0.0736 and are computed with equations (7-10). Above all tables 2 and 5, show that within the elastic limit the material biomechanical properties are isotropic giving elastic modulus of about 0.2MPa and Poissons ratio of 0.3 and the shear modulus of 0.06479MPa-0.0857MPa. Other properties evaluated are the ultimate compressive strength which was found within the range 14.595KPa-16.7731KPa, fracture limit found within the range 12.3250KPa - 14.3940KPa, while the bioyield point was found to be within the range 8.7961KPa-9.4666KPa.

6. Conclusion

Deformation behaviour and physicomechanical properties of improved UTC tomato variety have been discussed in detail. The experimentation has helped to determine the behaviour of tomato biological material when mechanically damaged during handing, transportation and storage for application in design of applicable equipments.

Above all the study found that within the elastic limit the material biomechanical properties are isotropic giving approximate elastic modulus of about 0.2MPa and Poisson's ratio of 0.3 and the shear modulus of 0.06479MPa-0.0857MPa. Other properties evaluated are the ultimate compressive strength which was found within the range 14.595KPa-16.7731KPa, fracture limit found within the range 12.3250KPa - 14.3940KPa, while the bioyield point was found to be within the range 8.7961KPa-9.4666KPa.

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