EFFECT OF DEFICIT IRRIGATION ON THE ELASTIC PROPERTIES OF TOMATO FRUITS

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ABSTRACT

The aim of this research work was to determine the physical and elastic properties of tomato fruits (Lycopersicon esculentum) cv under four water regimes (ET_{100}, ET_{90}, ET_{80} and ET_{70} of water requirements) to develop a technique that can predict the packing height to protect fruits from mechanical damage. The physical properties of tomato include mass, volume, dimensions, bulk density, soild density and geometric mean diameter. The elastic properties of tomato fruit include Young's modulus of elasticity (E), firmness coefficient (FC), bioyield stress (σb), bioyield strain (εb), rupture stress (σr), rupture strain (εr) and rupture energy (RE). The results showed that the different water regimes have a significant effect on physical and elasticity properties. The values of E, FC, σb and RE were increased with decreasing water level, while, σr was increased with increasing water level. Accordingly, the maximum heights of packing box were 177.4, 353.6, 456.5 and 526.4 mm for ET_{100}, ET_{90}, ET_{80} and ET_{70}, respectively.

Keywords: *Tomato, deficit irrigation, elasticity, modulus, bioyield, rupture, and stress.*

INTRODUCTION

Tomatoes (*Lycopersicon esculentum Mill.*) are commercially important vegetable worldwide, with an annual production of more than 120 million tons in the world. Tomato is mainly cultivated in Egypt followed by China, United States, Turkey and India, where tomato production in Egypt about 8.5 million tons (***FAO, 2010***). Packaging becomes very vital in the trading process for fruits. Packaging and its associated problems therefore affect the quality of fresh produce. During packaging, there is a static mechanical load in the lower fruit layers of tomato bulk due to filling tomatoes over each other, which leads to high mechanical load and damage of tomato fruit (mechanical damage).

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The major cause of mechanical damage (bruising) is impact. Impact sensitivity of fruits and vegetables is defined as having components, namely bruise threshold and bruise resistance (***Bajema and Hyde, 1998***). Bruising in fruits and vegetables occurs when the produce rubs against each other, packaging containers, parts of processing equipment and the tree (***Altisent, 1991***).

Knowledge of the physical properties of tomato fruit is necessary for the design of post harvesting equipment such as cleaning, sorting, grading, kernel removing, and packing. The importance of dimensions is in determining the aperture size of machines, particularly in separation of materials as discussed by ***Mohsenin (1986)***. These dimensions can be used in designing machine components and parameters.

Grading fruit, based on weight, reduces packing and handling costs and also provides suitable packing patterns (***Khoshnam et al., 2007***).

Ghonimy and Kassem. (2011) reported that there are significant differences between different production zones of date fruits for each of fruit mass, flesh mass, fruit volume, fruit moisture content, fruit dimensions, flesh thickness, fruit projected area and elasticity of fruits.

Fecete (1994) found that the coefficient of elasticity for tomato and apple can be used to characterize the fruit firmness. ***Cenkowski et al. (1995)*** studied the effect of moisture sorption hysteresis on the mechanical behaviour of canola and showed that the modulus of elasticity of the product brought into equilibrium through adsorption was higher than that of the one obtained through desorption at the same moisture content. The other products whose mechanical properties have been studied include kiwi fruit ***(Abbott and Massie, 1995),*** apples ***(Abbott and Lu, 1996)*** and sea buckthorn berries ***(Khazaei and Mann, 2004)***. ***Anazodo and Chikwendu (1983)*** developed equations for the calculation of the Poisson’s ratio and elastic modulus of circular bodies subjected to radial compression and ***Dinrifo and Faborode (1993)*** applied the Hertz’s theory of contact stresses to cocoa pod deformation. ***Anazodo and Norris (1981)*** noted that the modulus of elasticity, crushing strength and modulus of toughness of corncob all decreased with moisture content.

The aim of this research was to investigate some physical and elastic properties of tomato fruits under different water deficit to develop a technique that can predict the packing height to protect fruits from mechanical damage.

MATERIALS AND METHODS

1. Location, plant materials and sample preparation

The experiments were conducted in October 2011 and 2012 of the experimental farm of the Irrigation Unit, Agricultural Engineering Department, Faculty of Agriculture, Cairo University. Some chemical and physical characteristics of the experimental field soil are shown in Table (1). Also, Table (2) shows some physical analyses of irrigation water used in the experiment. The soil and water samples were tested in Soil Science Department – Faculty of Agriculture – Cairo University.

Table (1): Some physical and chemical analyses of soil samples.

Soil depth (cm)	**Texture**	**Bulk density ($g\ cm^{-3}$)**	**pH**	**EC_e ($dS\ m^{-1}$)**	**$HCO3^-$ meq/l**
0 – 20	SCL*	1.29	7.74	2.43	1.0
20 – 40	SCL	1.31	7.69	1.92	0.9
40 - 60	SCL	1.33	7.81	1.78	0.8

Soil depth (cm)	**CL^- meq/l**	**SO_4^{--} meq/l**	**Ca^{++} meq/l**	**K^+ meq/l**	**Mg^{++} meq/l**	**Na^+ meq/l**
0 – 20	3.6	19.84	7.8	1.14	6.4	9.1
20 – 40	3.0	15.9	5.6	0.82	5.4	7.9
40 - 60	3.2	13.62	4.0	0.82	5.0	7.8

* SCL: silty clay loam

Table (2): Some chemical and physical analyses of water sample.

p^H	7.20	Ca^{++}, meq/l	3.60	K^+, meq/l	0.18
EC, ds/m	0.83	Mg^{++}, meq/l	2.60	SAR	0.51
Cl^-, meq/l	1.00	Na^+, meq/l	0.90	T.S.S*	0.00
HCO^-_3, meq/l	5.00	SO^{--}_4, meq/l	1.28		

* T.S.S = Total Suspended Solids in irrigation water

The tomato (El-Odds E448) variety (*Lycopersicon esculentum*) was used in this study, which is planted at a spacing of 0.5 × 1.2 m within and between rows. The research focused on the tomato light red stage of maturity, which is at this stage more solid and convenient for storage and transportation (***Allende et al., 2004; Lien et al., 2009***).

The fruits in this experiment were hand harvested at the light red ripening stage according to US Department of Agriculture (USDA) standards (***USDA, 1991***). Extremely large or small tomatoes were excluded. After careful transportation to the laboratory, the tomatoes were inspected again to ensure that they were uniform, non-damaged and not attacked by worms. In addition, the measurements were conducted within 48 hours.

Physical and mechanical properties of tomato fruits were determined at four water regimes. For each treatment, 100 tomato fruits were selected.

2. Experimental design and treatments

The tomatoes were arranged in a completely randomized experiment design with three replicates. Four irrigation treatments were applied (ET_1: 1 time potential crop evapotranspiration (ET_c), ET_2: 0.9 ET_c, ET_3: 0.8 ET_c and 0.7 ET_c, ET_4). Fertilizers consisted of 84 kg/fed actual N (as ammonium sulphate), 95.8 kg/fed K_2O, 300.3 and kg/fed P_2O_5. Plants were transplanted in a single plot. The Plot consists of 5 rows (20 x 6 m). Irrigation water was delivered via a trickle system. The emitters used in the trickle irrigation system were with flow rate of 4 l/h, the emitters were spaced at 50 cm with polyethylene tubes (16 mm in external diameter with 20 m in length).

3. Measurements

3.1. Crop irrigation water requirement

The FAO Penman–Monteith method (***Allen et al., 1998***) was used to calculate the reference evapotranspiration ET_o in the CROPWAT Program. Crop water requirements (ET_c) over the growing season were determined from ET_o according to the following equation using crop coefficient K_c:

$$ET_c = K_c\, ET_o \qquad \ldots\ldots (1)$$

Where ET_c is the crop water requirement, K_c is the crop coefficient and ET_o is the reference evapotranspiration. Since there was no rainfall during the experimental period, net irrigation requirement was taken to be equal to ET_c.

The total amounts (average two seasons) of irrigation water applied (from transplantation to harvest) in the irrigation levels in this study were 1635 mm per season in ET_1, 1471 mm in ET_2, 1308 mm in ET_3 and 1144 mm in ET_4. The water requirement was determined for different months based on crop growth stages and climatic data.

3.2. Some physical parameters of tomato fruit

The tomato fruits were harvested during harvesting stages and divided into four groups (treatments) after being labeled. One hundred tomatoes were taken from each group and the following measurements were determined for each fruit; the tomato size, in terms of the three principal axial dimensions that is (in mm), the longitudinal height L_c (the height between the upper contact point and lower contact point uncompressed), the maximum transverse diameter L_{max}, and minimum transverse diameter L_{min}. All dimensions of tomatoes were measured by Vernier calliper to an accuracy of 0.01 mm. The mass of tomato was determined using a digital balance with an accuracy of 0.01 g. Tomato volumes were measured by the water displacement method. Tomatoes were weighed in air and allowed to float in water. Fruits were lowered with a needle into a beaker containing water and the mass of fruit in the water was recorded.

$$\text{Volume (cm}^3\text{)} = \frac{\text{Displaced water (g)}}{\text{Water specific mass (g/cm}^3\text{)}} \qquad \dots (2)$$

The solid density is defined as the ratio of mass of the sample to its true volume (***Mohsenin, 1986; Joshi et al., 1993***)

$$\rho_s = \frac{M}{V_C} \qquad \dots\dots (3)$$

Where; ρ_s is the solid density (g/cm^3) and V_c is the volume of cage that contains the samples (cm^3).

The moisture content was determined for tomato using AOAC procedures (***AOAC, 1995***) where the samples were dried at 70^{o}C for 48 hours.

3.3. Some mechanical parameters of tomato fruit

3.3.1. Compression test

The parallel-plate compressive test was carried out to determine the mechanical properties using a universal testing machine (Instron-1000 N). Individual tomato fruits were uniaxilly compressed at a cross-head speed of 0.5 mm/s to a total deformation 10 mm. A plate (diameter 7.5 cm) compressed a tomato flesh slab placed on a mounted fixed table. The contact surfaces were oriented parallel to the compression surfaces during loading (Fig. 1). A random 10 fruits sample of each cultivar at each red ripening stage was taken for compression tests. All experiments were carried out at room temperature (23 ^{o}C).

The contact area between the parallel-plate disk surface and each tested fruit surface was determined experimentally. The plunger disk surface was covered with a white paper, followed by gently pressing the horizontally oriented upper longitudinal fruit surface in an ink stamp, and then allowing the plunger to contact the fruit surface. The resulting contact area traced on the white paper was scanned, and specially developed software that accurately estimates the scanned surface area was used to determine the contact area.

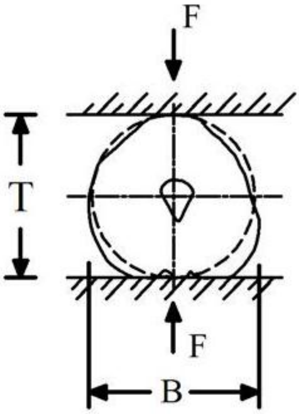


Figure (1): Tomato fruit loaded between the two parallel plates

3.3.2. Elastic property of tomato fruit

A typical force-deformation curve (***Mohsenin 1986***) is shown in figure (2). As it is shown, the force-deformation curve exhibited two peak points. The first peak corresponds to the yield point at which damage was initiated. The second peak corresponds to the maximum compressive force.

For stress-strain tests, the following mechanical properties were calculated; the modulus of elasticity (E), firmness coefficient (*FC*), bioyield stress (σb), bioyield strain (εb), rupture stress (σr), rupture strain (εr) and rupture energy toughness (*RE*).

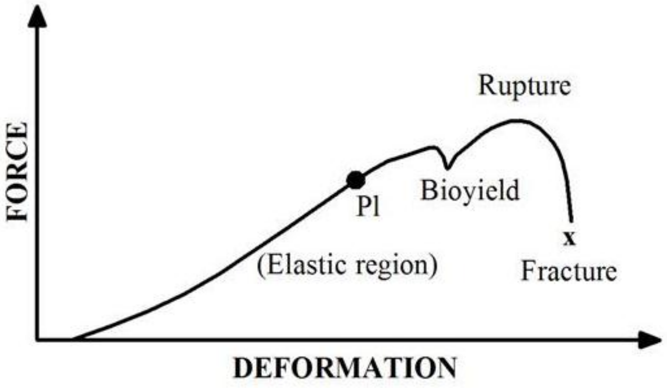


Figure (2): A typical force-deformation plot for agricultural materials (***Mohsenin 1986***).

The Young's modulus of elasticity is a good measure of the elasticity of ideal materials. The behavior of ideal materials is described by the Hooke's law and the model of which is a spring without damper.

The Young's modulus of elasticity (*E*) for compressive stress is expressed by following equation:

$$E = \frac{\sigma}{\varepsilon} \qquad \ldots\ldots (4)$$

Where; *E* is Young's modulus of elasticity, kPa; σ is compressive stress, kPa; and ε is the strain, mm/mm.

The strain was calculated by dividing the deformation of the fruit by the initial fruit average thickness.

$$\varepsilon = \frac{\Delta l}{l} \qquad \ldots\ldots (5)$$

Where; Δl is the variation in the thickness (deformation), mm; and l is the original thickness, mm.

The average stress was calculated by dividing the force on one fruit by the projected area of the fruit as follows:

$$\sigma = \frac{F}{A_p} \qquad \ldots\ldots (6)$$

Where; F is the force on one fruit, N; and A_p is the contact area of tomato fruit, mm^2.

Firmness coefficient (*FC*) is calculated as the average slope of force – deformation curve from zero to point of rupture or failure (***Shafiee et al., 2008***). *FC* was calculated by applying the following equation:

$$FC = \frac{F}{\Delta l} \qquad \ldots\ldots (7)$$

Toughness (*RE*) or mechanical energy or work required for rupture was determined by calculating the area under the force – deformation curve from the following equation (***Braga et al., 1999***):

$$RE = \frac{F_r \; D_r}{2} \qquad \ldots\ldots (8)$$

Where; *RE* is the toughness, J, F_r is the rupture force, N, and D_r is the deformation at rupture point, m.

The area was measured by using a computer software program (AutoCAD 2012), then, to relate the rupture energy to tomato fruit volume, it was divided it by tomato fruit volume.

4. Determination of the height of packing box

In bins or shipping containers, only a portion of the surfaces of individual fruits, vegetables, grains and seeds are in contact. If the force acting at a point can be determined, then the area of contact and the maximum stress at the point of contact can be estimated using the contact stress theory. The forces at points of contact can be estimated using the approach described by ***Ross and Isaacs (1961)***. This requires several assumptions. The fruits are assumed to be spherical with a uniform diameter D_g. Their contact is assumed to be in elastic, which has the following two implications: a- The fruits do not deform appreciably and therefore the distance between fruits does not change. b- The inter fruit forces act at the points of contact. The particles are assumed to be arranged in the rhombic stacking model shown in Figure (3).

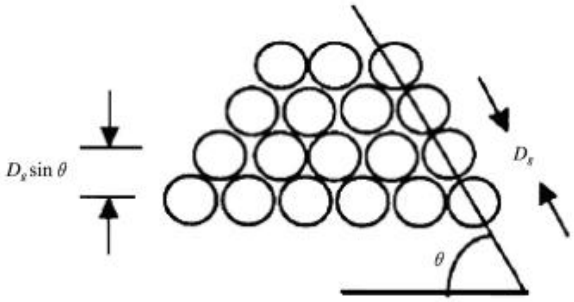


Figure (3): Rhombic stacking model for fruits.

The individual fruits are in contact along a line which makes an angle θ with the horizontal. In this model, the angle θ is dependent on N, the number of fruits per unit volume, and D_g, the characteristic diameter of the fruits. These three variables are related by the following Equation (***Stroshine, 1998***):

$$N = \frac{1}{4D_g^3 \cos^2\theta \sin\theta} \qquad \text{...... (9)}$$

Number of fruits per unit volume (N) is obtained from ratio of bulk density to mass of each fruit multiplied by its unit volume.

The maximum static force occurs in the last layer of fruits (Figure 4). There are four forces acting from above on the fruit in contact with the floor (Figure 5). They will sum to the following equation (***Stroshine, 1998***):

$$F_{\max} = n \times w \qquad \text{...... (10)}$$

Where; F_{max} is the maximum allowable force on fruit in the last layer (at bioyield stress), N and w is the fruit weight, N.

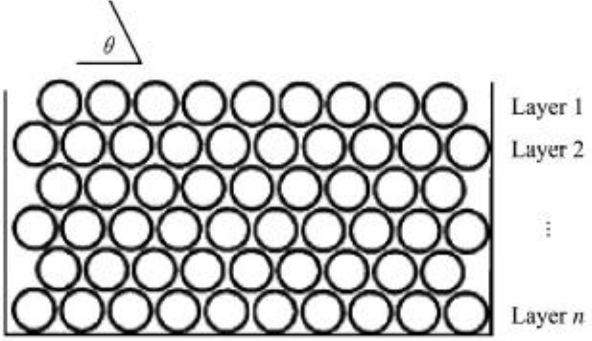


Figure (4): Diagram of stack of samples having n layers and confined by a vertical.

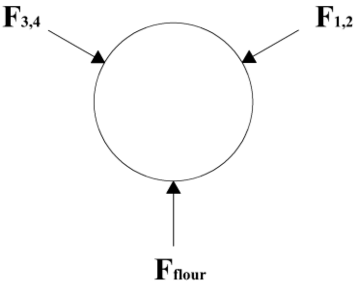


Figure (5): Static forces on the last layer of fruit.

Angle of the fruit and number of layers are calculated from last two equations. Thus, box height is calculated from the following equation (***Stroshine, 1998***):

$$h = nD_g \sin\theta \qquad \text{...... (11)}$$

Where; *h* is the height of box, (without mechanical damage), mm, D_g is the geometric mean diameter, mm; *n* is the number of layers and θ is the angle of contact line with horizontal, deg.

5. Determination of the contact stress

Heinrich Hertz (***Shigley et al., 2008***) proposed a solution for contact stress in two elastic isotropic bodies, such as the case of two spheres (hemispherical contact) of the same material touching each other and attempted to find the magnitude of the maximum pressure. Figure (6) shows two spheres of diameters d_1 and d_2. The area of contact is a hemispherical of radius ***b***, and the pressure distribution within the contact area of each sphere is hemispherical.

The radius b is given by the following equation (***Shigley et al., 2008***):

$$b = \sqrt[3]{\frac{3F}{8}\frac{(1-\mu_1^2)/E_1 + (1-\mu_2^2)/E_2}{1/d_1 + 1/d_2}} \qquad \text{...... (12)}$$

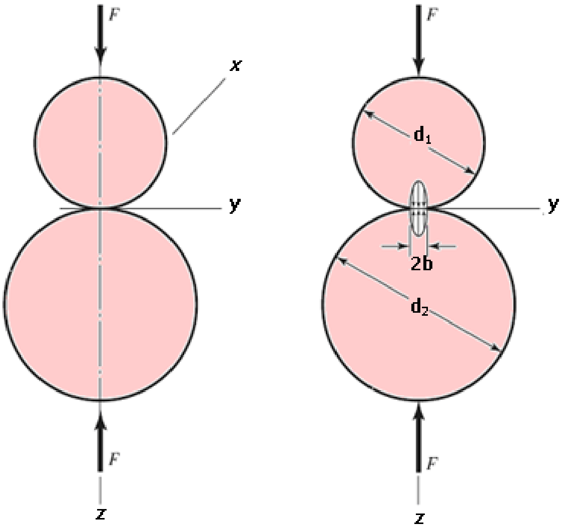
Where; *b* is the radius of contact, mm, *F* is the acting force on the two spheres, N, E_1 and E_2 are the modulus of elasticity for spheres (1) and (2), MPa, μ_1 and μ_2 are the Poisson ratio for spheres (1) and (2), dimensionless; and d_1, d_2 are the diameter for spheres (1) and (2), mm.

In this study, *E*, μ and d are same parameters for first and second sphere (tomato), therefore the last equation becomes as following;

$$b = \sqrt[3]{\frac{3D_g F(1-\mu^2)}{2E}} \qquad \text{...... (13)}$$

The maximum pressure (P_{max}, Pa) is called the Hertz (compressive) stress which occurs at the center of the contact area; it is given by following equation (***Shigley et al., 2008***):

$$p_{\max} = \frac{3F}{2\pi b^2} \qquad \text{...... (14)}$$



(a) **(b)**

Figure (6): Contact of two spheres: (a) Two spheres held in contact by forces. (b) Contact stress has a hemispherical distribution across contact zone diameter (2a).

6. Statistical analysis

Statistical analysis was carried out using a randomized complete block procedure of the M Stat-c statistical package. LSD and Duncan multiple range comparison were used to identify means that were different at probabilities of 5 % or less (***Snedecor and Cochran 1976***).

RESULTS AND DISCUSSIONS

1. Physical properties of tomato fruit

A summary of the descriptive statistics of the various physical dimensions is shown in Table (3). Table (3) shows the average values of fruit mass, fruit volume, bulk density, fruit length, fruit diameter and fruit thickness. Minimum values of the mass, length, width, thickness, and volume were 88.9 g, 44.6 mm, 54 mm, 51.9 mm, and 87.5cm^3 found with ET_4, while the minimum value of solid density (0.969 g/cm^3) was found with ET_3. The maximum values of the mass, length, width, thickness, and volume were 116.7 g, 50.7 mm, 62.1, 59.9 mm, and 118 cm^3, found with ET_1 but the maximum value of solid density (1.028 g/cm^3) was found with ET_2.

The results show that the mass of tomatoes decreased by decreasing crop water requirements. Same results trend was found for the length, width, thickness and volume. The reason for these results is due to water stress decreasing the above-mentioned measurements.

2. Mechanical properties of tomato fruit

In a bid to mechanize the various unit operations involved in the postharvest processing of tomato, information and data on the behavior of these strength properties as a function of moisture content is needed. These data when fully used will not only save energy but will promote the design and development of effective and efficient process machines.

The mechanical properties of tomato fruit at different water deficit included modulus of elasticity (E), firmness coefficient (FC), bioyield stress (σb), bioyield strain (εb), rupture stress (σr), rupture strain (εr), and rupture energy (RE) as shown in table (3).

Figure (7) shows the stress-strain curve of tomato fruit at four water regimes. It is clear that, before the point called proportional limit (P_l). Generally, the elastic limit is the limit beyond which the tomato will no longer go back to its original shape when the load is removed, or it is the maximum stress that may be developed such that there is no permanent setting when the load is entirely removed. For the four water regimes, the statistical analysis (at 5% level) showed significant differences for most elasticity properties of tomato fruits.

The elastic limits were 95.9, 220.6, 294.4 and 402.1 kPa for ET_{100}, ET_{90}, ET_{80} and ET_{70}, respectively. The results showed that the elastic limit increased with decreasing water level. The reason may be due to decreasing water content and increasing structural tissues in tomato fruit.

Table (3): Physical and mechanical properties of the tomato fruits (average two seasons).

Properties	ET_{100}	ET_{90}	ET_{80}	ET_{70}
	Physical properties			
Fruit mass, g	116.7A	101.3AB	93.0BC	88.9C
Fruit volume, cm^3	118A	99.5B	96.0B	87.5C
Solid density, g/cm	0.989B	1.028A	0.969BC	1.015A
Bulk density, g/cm	0.619C	0.681AB	0.687A	0.694A
Fruit length, mm	50.7A	47.3B	47.1BC	44.6C
Fruit diameter, mm	62.1A	59.7AB	57.9B	54.0C
Fruit thickness, mm	59.9A	58.7A	55.9B	51.9C
	Mechanical properties			
Firmness Coeff., N/mm	1.32CD	2.73C	3.44B	4.33A
Modulus of elasticity, kPa	95.9D	220.6C	294.4B	402.1A
Bioyield stress, kPa	7.2D	15.4BC	20B	27A
Rupture stress, kPa	11.7C	16.1BC	19.1AB	23.2A
Rupture energy, kJ	104.5D	137.8B	151.8AB	157.5A

(a) Mean values with different letters are significantly different (< 5% level).

Possible bruising damage by falling impact was inspected by visual inspection and mechanical analysis. Tomato samples of various deficit irrigation levels were randomly selected for the compression test. Figure (7) shows the force–deformation responses of different ET levels under the compression test. The bioyield points of tomato at different water regimes were 5, 9, 11 and 13 N for ET_{100}, ET_{90}, ET_{80} and ET_{70}, respectively.

2.1. Modulus of elasticity (*E*)

Young's modulus is a measure of how easily the tomato can be ruptured. The effects of this fundamental strength property as a function of water regimes (Otherwise, called moisture content in tomato) are shown in Table (3). It is clear that the modulus of elasticity (E) decreased with increasing water level. The Young's modulus of elasticity (E) for tomato fruits were 95.9,220.6, 294.4 and 402.1 kPa for ET_{100}, ET_{90}, ET_{80} and $ET_{70,}$ respectively.

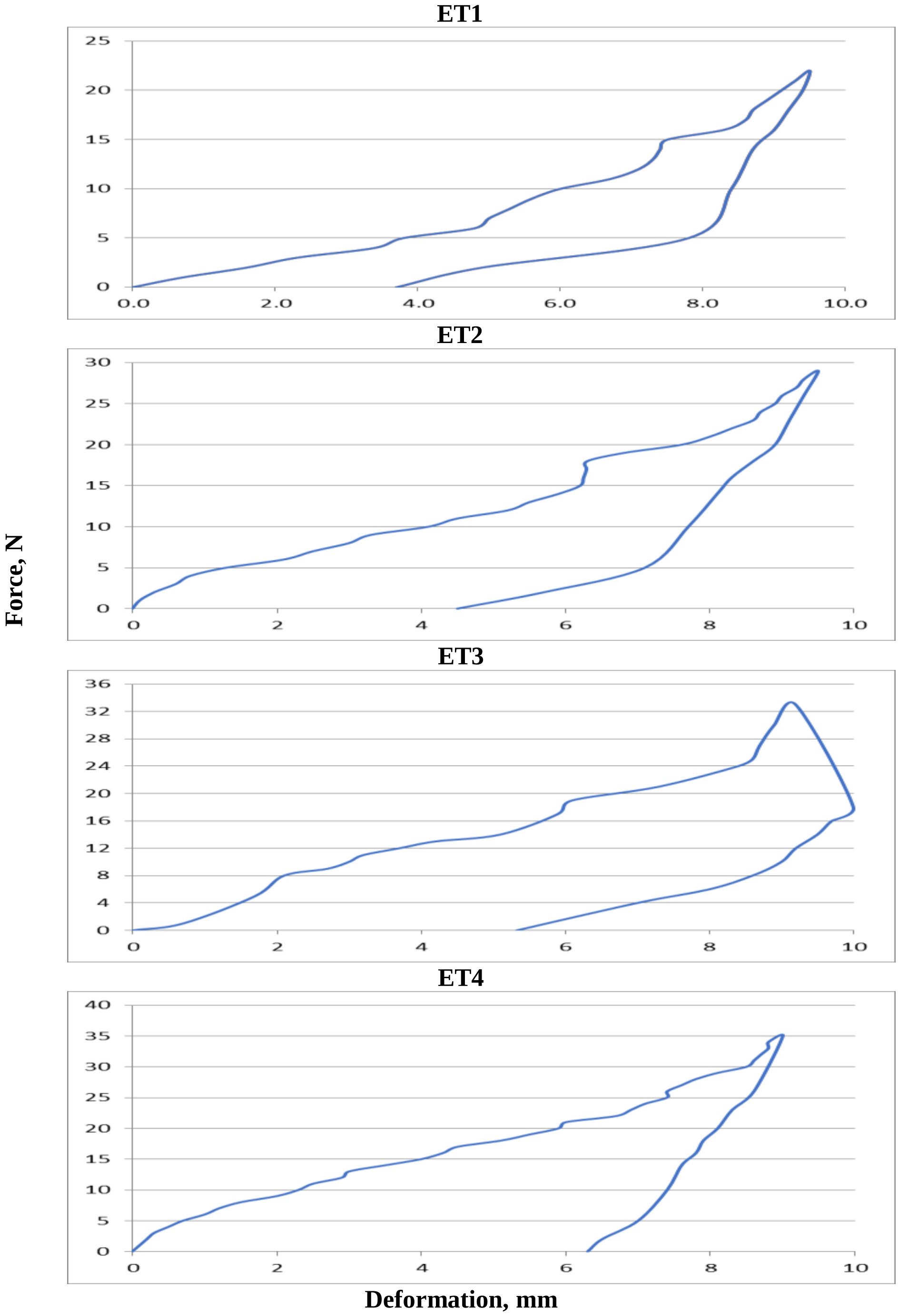


Figure (7): Typical force-deformation curve of tomato samples in the parallel plate compression test under four water regimes.

Generally, moisture content has a negative effect on the firmness of tomato. Average values of firmness were 1.32, 2.73, 3.44 and 4.33 N/mm^2 for water regimes of ET_{100}, ET_{90}, ET_{80} and ET_{70}, respectively. This decline in resistance of the tomato to applied load as a result of moisture increase could be used to conserve force. These results are consistent with that of ***Burubai et al (2008)***.

2.2. Bioyield stress *(σb)*

The average values of bioyield stress *(σb)* for tomato fruits at different water regimes are shown in Table (3). It is clear that the bioyield stress *(σb)* decreased with increasing water level.

The bioyield stress *(σb)* for tomato fruits were 7.2, 15.4, 20 and 27 kPa for ET_{100}, ET_{90}, ET_{80} and ET_{70} respectively.

2.3. Bioyield strain (*εb)*

The average values of bioyield strain (*εb)* for tomato fruits at different water regimes are shown in Table (3). It is clear that the bioyield strain (*εb)* increased with increasing water level.

The bioyield strain *(εb)* for tomato fruits were 0.075, 0.07, 0.068 and 0.067 mm/mm for ET_{100}, ET_{90}, ET_{80} and $ET_{70,}$ respectively.

2.4. Rupture stress (*σr)*

The average values of rupture stress (*σr*) for tomato fruits at different water regimes are shown in Table (3). It is clear that the rupture stress (*σr*) decreased with increasing water level.

The *σr* for tomato fruits were 11.7,16.1, 19.1 and 23.2 kPa for ET_{100}, ET_{90}, ET_{80} and ET_{70} respectively.

2.5. Rupture strain (*εr)*

From the calculated results of rupture strain for tomato fruits at different ripening stages with different varieties, as shown in Table (3), it can be found that the rupture strain decreased with increasing water level.
The rupture strain (*εr)* for tomato fruits were 0.148, 0.133, 0.130 and 0.130 mm/mm for ET_{100}, ET_{90}, ET_{80} and $ET_{70,}$ respectively.

The results showed that the rupture strain of tomato increased with increasing water level.

2.6. Rupture energy (*RE*)

The average values of rupture energy (*RE*) for tomato fruits at different water level are shown in table (3). It is clear that, the rupture energy (*RE*) decreased with increasing water level.

The rupture strain (εr) for tomato fruits were 104.5, 137.8, 151.8 and 157.5 mm/mm for ET_{100}, ET_{90}, ET_{80} and $ET_{70,}$ respectively.

The results showed that the rupture strain of tomato decreased with increasing water level.

For the four water regimes, the statistical analysis (at 5% level) showed significant differences for all mechanical properties of tomato fruits.

In general, the mechanical properties of tomato fruit are influenced by water regimes. As concluded from the results of the present study, each of E, FC, σb and RE decreased with increasing water level while, σr was increased with increasing water level. The physical and mechanical properties of tomato fruit under four water regimes are important in designing machine used for harvesting and post-harvest handling of tomatoes.

3. Predicting the height of packing box

In order to get optimum (prediction) of the height of packing box the following procedure was applied.

Applying equations (10) and (11) considering the following assumption:

$d_1 = d_2$ = fruit thickness.

$E_1 = E_2$= Modulus of elasticity for tomato fruit.

$\mu_1 = \mu_2$ = Poisson ratio of tomato fruit (the absolute value of the transverse strain to the corresponding axial strain resulting from uniformly distributed axial stress below the proportional limit of the material, it was measured $\approx$ 0.4.

l = Fruit length.

P_{max} = Bioyield stress of tomato fruit.

Substitute equation (10) in equation (11) use try and error method to calculate the maximum allowable force (F_{max}) for the four water regimes, the values of n, and H_{act} can be calculated as shown in table (4).

Table (4): Estimated parameters to calculate the maximum height of box for tomatoes.

Properties	ET_{100}	ET_{90}	ET_{80}	ET_{70}
θ, deg.	32.9	32.9	33	33
n	9.4	14.8	18.3	22.5
h_{th}, mm	266.0	530.4	684.8	789.6
h, mm	177.4	353.6	456.5	526.4

Therefore, the maximum heights of packing box which does not result in mechanical damage were 177.4, 353.6, 456.5 and 526.4 mm for ET_{100}, ET_{90}, ET_{80} and ET_{70}, respectively.

CONCLUSION

The obtained results of physical and mechanical properties of the tomato fruit under four water regimes can be summarized as follows:

1. There were significant differences between ripening stages of tomato fruits for most physical properties.
2. There were significant differences between ripening stages of tomato fruits for mechanical properties.
3. For different water regimes, the values of E and FC decreased with decreasing water level, while, σb, σr and RE were increased with decreasing water level
4. The maximum heights of packing box are 390.2, 589.3, 705.5 and 809.8 mm for ET_{100}, ET_{90}, ET_{80} and ET_{70}, respectively.

REFERENCES

Abbott, J. A. and D. R. Massie. 1995. Non-destructive dynamic force/deformation measurement of kiwifruit firmness (Actinidia Delicious). Trans. ASAE, 38(6): 1809 – 1812.

Abbott, J. A. and R. Lu. 1996. Anistropic mechanical properties of apples. Trans. ASAE, 39(4): 1451 – 1459.

Allen, R.G.; L.S. Pereira; D. Raes and M. Smith, 1998. Crop evapotranspiration. Guidelines for computing crop water requirements. FAO irrigation and Drainage. Paper No. 56, FAO, Rome, Italy, pp: 300.

Allende, A., M. Desmet, E. Vanstreels, 2004. Micromechanical and geometrical properties of tomato skin related to differences in puncture injury susceptibility. Postharvest Biol. Technol., 34: 131-141.

Altisent, M.R. 1991. Damage mechanisms in the handling of fruits: Progress in agricultural physics and engineering. John Matthew (Ed.), Commonwealth Agricultural Bureaux (CAB) International, Willingford, UK, pp. 231-255.

Anazodo, U. G. N. and E. R. Norris. 1981. Effects of genetic and cultural practices on the mechanical properties of corncobs. J. Agr. Eng. Res., 26: 97 – 107.

Anazodo, U. G. N. and S. C. Chikwendu. 1983. Poisson's ratio and elastic modulus of radially compressive biomaterials – I: small deformation approximation. Transactions of the ASAE, 26(3): 923 – 929.

AOAC. 1995. Official methods of analysis (16th ed.). Association of Official Analytical Chemists. Wash., DC.

Arab Agricultural Statistics Yearbook. 2009. Plant production. Part 3. Vol. 29.

Bajema, R. W. and G. M. Hyde. 1998. Instrumented pendulum for impact characterization of whole fruit and vegetable specimens, Trans ASAE, 41(5), 1399-405.

Braga, G. C., Couto, S. M., Hara, T., and Neto, J. T. P. A. 1999. Mechanical behaviour of macadamia nut under compression loading. J. Ag. Eng. Res., 72: 239–245.

Burubai, W., E. Amula, R.M. Davies, G. Etekpe. And S.P. Daworiye, 2008. Determination of Poisson's ratio and elastic modulus of African nutmeg (Monodora myristica). International Agrophysics J., 22: 99-102.

Cenkowski, S., Q. Zhang and W.J. Crerar. 1995. Effect of sorption hysteresis on the mechanical behaviour of canola. Transactions of the ASAE, 38(5): 1455 – 1460.

Dinrifo, R. R. and M. A. Faborode. 1993. Application of Hertz's theory of contact stresses to cocoa pod deformation. J. Ag. Eng. and Tec., 1: 63 – 73.

FAO 2010. Food and Agriculture Organization of the United Nations. http://www.faostat.fao.org. 16Aug. 2012.

Fecete, A. 1994. Elasticity characteristics of fruits. International Agrophysics, 8(3): 411- 414.

Ghonimy, M. I., and M. A. Kassem. 2011. The elasticity characteristics of palm date. Misr, J. Ag. Eng., 28 (2): 386 – 400.

Joshi, D.C.; S.K. Das and R.K. Mukherjee. 1993. Physical properties of pumpkin seeds. Agric. Eng. 54: 219–229.

Khazaei, J. and D. D. Mann. 2004. Effects of temperature and loading characteristics on mechanical and stress relaxation properties of sea buckthorn berries, Part 1: Compression tests. Ag. Eng. I. Ejournal, Manuscript FP 03 011, http//cigr-ejournal.tamu.edu/html/Volume 6, April.

Khoshnam, F., A. Tabatabaeefar, M. Ghasemi Varnamkhasti and A. Borghei. 2007. Mass modeling of pomegranate (Punica granatum L.) fruit with some physical characteristics. Scientia Horticulturae 114: 1, 21-26.

Lien, C.C., C.Y. Ay, C.H. Ting, 2009. Non-destructive impact test for assessment of tomato maturity. J. Food Eng., 91(3): 402-407.

Mohsenin, N. N. 1986. Physical properties of plant and animal materials, 2nd ed. Gordon and Breach Sc. Publishers

Myhara, R. M., Karkalas, J., and M. S. Taylor. 1999. The composition of maturing Omani dates. Journal of the Science and Food Agriculture, 79, 1–6.

Ross, I. J. and G. W. Isaacs. 1961. Forces acting in stacks of granular materials (Part I). Transactions of ASAE, 4(1): 92-96.

Shafiee, S., A. M. Motlagh, A. R. Didar and S. Minaee. 2008. Investigation the effect of skin on mechanical behaviour of apple. J. Food Tec., 6(2): 86 -91.

Shigley, J. E., C. R. Mischke, C. R. and R. G. Budynas. 2008. Mechanical engineering design. MC Graw-Hill, Singapore.

Snedecor, G. A. and W. G. Cochran. 1976. Statistical Method. Iowa State Univ. Press, Ames.

Stroshine R. 1998. Physical Properties of Agricultural Material and Food Products. Dept. of Agricultural Engineering Purdue Univ. Press, West Lafayette. New York, USA, pp. 28

USDA 1991. United States Standards for Grades of Fresh Tomatoes. http://www.ams.usda.gov/standards/tomatfrh.pdf. 3 Jul. 2012.

الملخص العربي

تأثير النقص المائي للري على خواص المرونة لثمار الطماطم

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يهدف هذا البحث الي تقدير الخواص الطبيعية وخواص المرونة لثمار الطماطم (El-Odds E448) تحت اربع مستويات مياه مختلفة (١٠٠% - ٩٠% - ٨٠% - ٧٠% من الاحتياجات المائية) نظراً لان تقدير هذه الخواص لها تأثير هام فى عمليات حصاد وتصنيع وتداول ثمار الطماطم.

وقد تم تقدير كل من الخواص البعدية للثمرة، والوزن، والحجم، والكثافة الظاهرية للثمار، والكثافة الحقيقية، وايضاً خواص المرونة للثمرة مثل معامل يانج للمرونة ومعامل الصلابة وإجهاد الخضوع الحيوى وانفعال الخضوع الحيوى وإجهاد التحطم وانفعال التحطم والطاقة اللازمة للتحطيم.

و قد بينت الدراسة ما يلي:

١. توجد فروق معنوية علي معظم الخصائص الطبيعية تحت مستويات المياه المختلفة.
٢. توجد فروق معنوية علي الخصائص الميكانيكية تحت مستويات المياه المختلفة: معامل يانج للمرونة ومعامل الصلابة وإجهاد الخضوع الحيوى وانفعال الخضوع الحيوى وإجهاد التحطم وانفعال التحطم والطاقة اللازمة للتحطيم.
٣. وجد ان خواص معامل يانج للمرونة ومعامل الصلابة وإجهاد الخضوع الحيوى وإجهاد التحطم والطاقة اللازمة للتحطيم تقل مع نقص مستوى المياه.
٤. يزداد معامل يانج للمرونة بنقص مستوى المياه المضاف ٩٥.٩ – ٢٢٠.٦ – ٢٩٤.٤ – ٤٠٢.١ كيلوباسكال عند $ET_{70} – ET_{80} – ET_{90} – ET_{100}$ على التوالي.
٥. . يزداد معامل الصلابة بنقص مستوى المياه المضاف ١.٣٢ – ٢.٧٣ – ٣.٤٤ – ٤.٣٣ نيوتن/مم عند $ET_{70} – ET_{80} – ET_{90} – ET_{100}$ على التوالي.
٦. يزداد إجهاد الخضوع الحيوى بنقص مستوى المياه المضاف ٧.٢ – ١٥.٤ – ٢٠ – ٢٧ كيلوباسكال عند $ET_{70} – ET_{80} – ET_{90} – ET_{100}$ على التوالي.
٧. كانت قيم إجهاد التحطم لثمار الطماطم ١١.٧ – ١٦.١ – ١٩.١ – ٢٣.٢ كيلوباسكال عند $ET_{70} – ET_{80} – ET_{90} – ET_{100}$ على التوالي.
٨. كانت قيم الطاقة اللازمة للتحطيم لثمار الطماطم ١٠٤.٥ – ١٣٧.٨ – ١٥١.٨ – ١٥٧.٥ كيلو جول/م^{٣} عند $ET_{70} – ET_{80} – ET_{90} – ET_{100}$ على التوالي.
٩. أقصى ارتفاع مأمون للعبوات كانت ١٧٧.٤، ٣٥٣.٦، ٤٥٦.٥، ٥٢٦.٤ مم عند ET_{100} – $ET_{70} – ET_{80} – ET_{90}$ على التوالي.

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