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Compression Testing of Orange Fruits

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In this work the compressive properties of orange fruits of the Tarocco variety were assessed using a Universal Testing Machine, equipped with a transparent graduated Plexiglas plate to determine precisely the momentary cross-sectional area of the fruits submitted to different engineering strains (ε_E) in the range of 2 to 25% of the initial fruit height. Despite quite an accurate reconstruction of such contact areas between the compression plates and the specimen undergoing compression, this procedure is still cumbersome. By calculating the compression stress (σ_F) acting on the equatorial horizontal cross-section of the fruit epicarp only, typical concave upward σ_F-vs.-ε_E relationships may be easily obtained by assessing simply the flavedo thickness immediately after fruit rupture.

1. Introduction

Rheometrical and textural characteristics are crucial in the selection of citrus cultivars since they affect consumer choice (Steenkamp, 1997). In fact, exported stocks are normally checked for the presence of defects, appearance and fruit firmness (USDA, 2003). In particular, low resistances to fruit squeezing generally result in persistent deformations after long-term shipping, thus causing frequently the rejection of the entire stock. Presently, fruit firmness evaluation is carried out manually via the so called Magness-Taylor test (MT) (Shmulevich et al, 2003), using a hand-held penetrometer, also known as *fruit pressure tester*, which gives a direct measure of the peak force at rupture. Such a force has been used as an index of maturity and firmness for several different crops, especially apples (DeLong et al, 2000), where a loss of fruit firmness can be time-monitored by measuring the force required to puncture the fruit surface. In citrus fruits the relationship between puncture force and firmness is however concealed by the differences in the tissue types directly under the puncture probe. Moreover, such tests are generally inadequate for fruit sorting and should be replaced with another one capable of assessing the mechanical properties of citrus fruits in a more objective and reproducible way (Menesatti et al., 2008). Even the ASAE standard method recommended to determine the resistance to mechanical injury of food materials of convex shape (ASABE Standards, 2007) appears to be muddled, since it relies upon the determination of the radii of curvature of the convex surfaces of any sample at the points of contact with the upper and lower plates, as well as the Poisson's ratio of the food material under testing.

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The main aim of this work was to submit orange fruits of Tarocco variety to conventional uniaxial compressive tests by using a Universal Testing Machine (UTM) equipped with a transparent graduated Plexiglas plate to determine precisely the momentary semi-axes of the elliptical cross-sectional area of the fruits under squeezing at different deformation levels and up to rupture.

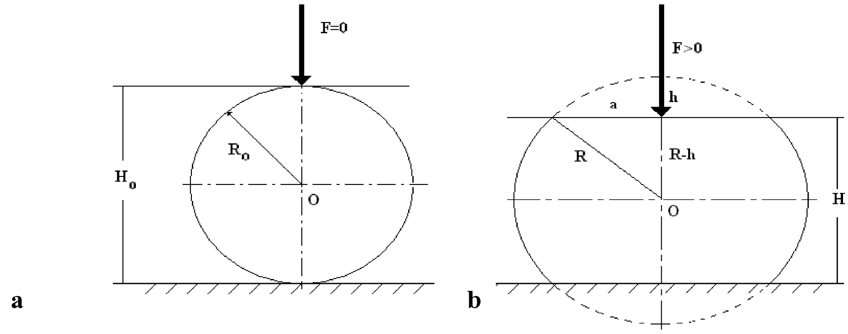

Figure 1 *Schematic drawing of the changes in the volumetric shape of a spherical orange fruit with an average radius R_0 at the beginning (**a**) and during compression testing (**b**) by applying a force (F).*

2. Materials and Methods

Citrus fruits of the same Tarocco variety with about a spherical shape were selected.
All mechanical tests were performed using a column table-top digital dynamometer, Zwick 1.0 Universal Testing Machine (Zwick/Roell Testing System, Kennesaw, GA, USA) having the following characteristics: deformation resolution of 0.2265 μm; position repetition accuracy of ±2 μm; speed range of 0.1-30 mm s^{-1}; speed accuracy of $2.08x10^{-4}$ mm s^{-1}; force range of 0.2-1000 N; force accuracy of 2 N. The software (testXpert®) was used to acquire whole force-deformation curves. The UTM was equipped with a transparent graduated Plexiglas plate to determine precisely the momentary semi-axes of the elliptical cross-sectional area of the fruits squeezed via quasi-static compression tests as a function of the instantaneous engineering strain ($\varepsilon_E=\Delta H/H_0$), where H_0 and H(t) are the initial instantaneous heights of each orange fruit tested while $\Delta H[=H_0-H(t)]$ is the deformation applied.
By using a constant cross-head speeds (V_T) of 15 mm s^{-1}, several orange fruits were submitted to compression-decompression tests for ε_E ranging from 2 to 25% and to compression tests up to rupture. Any of these tests was replicated five times. Test results mean values are given together with the corresponding standard deviations.

3. Results and Discussion

Orange fruits are quite complex multi-domain systems, that consist of a rind with coloured epicarp and hypoderm (*flavedo*) with numerous external oil vesicles; a white spongy mesocarp (*albedo*); a variable number of segments, loosely united with each other; the rind, filled with club-shaped juice vesicles (*emergencies*); and eventually seeds (Tressler and Joslyn, 1961). Any test involving fruit compression between two rigid plates while measuring simultaneously the displacement of the plates and the compression force is hard to interpret in terms of the citrus fruits intrinsic mechanical properties and is often used to measure a bursting force only. To attempt to determine such properties, the area (A) of the fruit exposed to the compression force F(t), as well as its permanent deformation (ε_P), was determined so as to identify the most appropriate way to construct stress-strain relationships for orange fruits.

3.1 Estimation of sample compressed area

When a orange fruit is positioned between two horizontal rigid plates, one of which being stationary and the other one moving at a constant speed V_T, and then submitted to uniaxial compression tests, its original almost spherical shape with an average radius R_0 is axisymmetrically squeezed in the upper and lower polar regions. As shown in Fig. 1, the compressed sphere may be approximately assimilated to two symmetrical spherical segments of two circular bases of radii R and a, respectively. By assuming that the overall volume of the citrus fruit as such (with an initial height H_0=2R_0) or deformed to an instantaneous height H (=H_0-2h, h being the semi-deformation imposed) is about constant and equal to the initial one (V_0=4/3 π R_0^3):

$$\frac{4}{3}\pi R_0^3 = \frac{1}{3}\pi\ (R - h)[3R^2 + 3a^2 + (R - h)^2] \qquad (1)$$

it is possible to estimate the instantaneous radii R and a of the two circular bases of the equivalent spherical segments as follows:

$$R = z - p/(3z) \qquad (2)$$

$$a^2 = h\,(2R - h) \qquad (3)$$

with

$$z = \sqrt[3]{\frac{-q \pm \Delta}{2}}\ ; \quad p = -(3/2)\,h^2; \quad q = ½\,h^3 - R_0^3; \quad \Delta^2 = q^2 + 4p^3/27 \qquad (4)$$

Thus, for any compressive engineering strain (ε_E) imposed the instantaneous cross-sectional area (A) of the deformed sample becomes:

$$A = \pi a^2 \qquad (5)$$

Figure 2 compares the observed cross-sectional area (A) as a function of the strain (ε_E) imposed for two classes of orange fruits having different original average radii (R_0) of 34±2 mm (closed symbols) and 43±1 mm (open symbols). The continuous and broken lines plotted in Fig. 2 were calculated using eq.s (2)-(5) and enabled the observed A values to be reconstructed with an average percentage error of 16%. By applying the conventional procedure (ASABE Standards, 2007), the predicted values of A were found to be underestimated by 67 to 26% as ε_E was increased from 2 to 25%.Thus, Eq.s (2)-(5) will be used to estimate the construct the compressive stress (σ_E)-vs.-strain (ε_E)- curves of oranges fruits under squeezing.

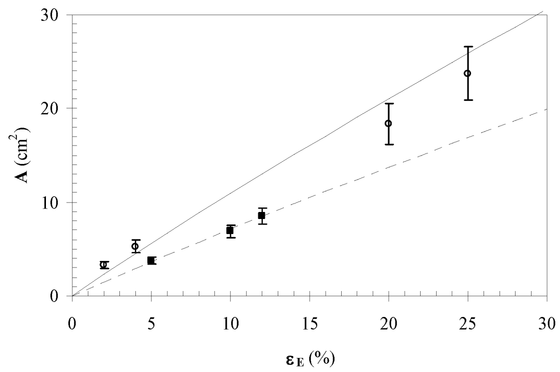

Figure 2 *Effect of the engineering strain (ε_E) on the observed cross-sectional area (A) of citrus fruits of different radii (R_0) submitted to uniaxial compression testing at a*

crosshead speed of 15 mm s^{-1}: ■, - - -, R_0=34±2 mm;, O ——, R_0=43±1 mm. The continuous and broken lines were estimated as reported in the text.

3.2 Compression-Decompression Testing

To measure the permanent deformation of orange fruits with average initial radius (R_0) of 42±1 mm, several tests were performed using a constant cross-head speed of 15 mm s^{-1}. After applying an engineering strain in the range of 2-25%, the compression force was then released and each specimen was allowed to reassume its initial shape for as long as 60 s before determining newly its height (H_0') and mass (M_0'). As ε_E was increased up to 25%, the amount of oil and air squeezed out ($\Delta M = M_0 - M_0'$) was found to be negligible, being in average (0.002±0.001)% of the original fruit mass (M_0). On the contrary, the permanent deformation ($\Delta H = H_0 - H_0'$) tended to increase almost linearly up to (6.5±0.4)% of the initial fruit height, as shown in Fig. 3.

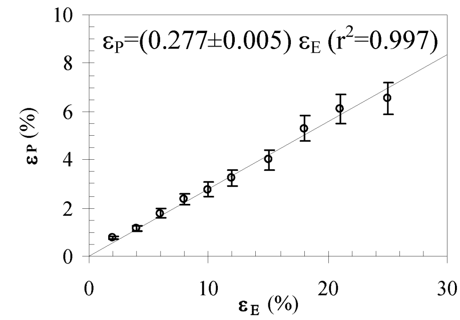

Figure 3 *Effect of the engineering strain applied (ε_E) on the permanent deformation strain (ε_p) of orange fruits (R_0=42±1 mm) during compression-decompression tests performed at a crosshead speed (V_t) of 15 mm s^{-1}. The continuous line was calculated by using the least squares regression equation given in the figure.*

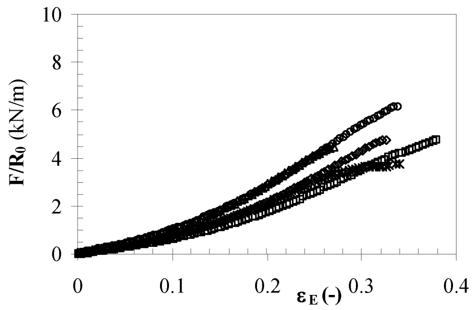

Figure 4 *Specific compressive load (F/R_0) against engineering strain (ε_E) for 5 orange fruits (R_0=41.8±0.2 mm) submitted to uniaxial compression testing up to rupture using a crosshead speed of 15 mm s^{-1}.*

3.3 Compression Testing

To study preliminarily the mechanical behaviour of the orange fruits examined, they were roughly assimilated to deformable membranes (*flavedo*) filled with an internal incompressible liquid. Thus, as suggested by Carin *et al* (2003), the compression curves up to rupture, obtained for 5 orange fruits with approximately the same size (R_0=41.8±0.2 mm), variety and maturity, were compared by plotting the force per unit radius (F/R_0) against ε_E (Fig. 4). For all the specimens tested, fruit failure initiated at the equator and propagated towards the axis of symmetry with burst occurring for ε_{ER}=(33±4)%.

By assuming that the compression force impinged on the equatorial horizontal cross-section of the epicarp ($A_{F0} = 2\ \pi\ R_0\ s_0$, where s_0 is its initial rind thickness), it was possible to obtain a rough measure of the compressive stress for the orange external rind only ($\sigma_F = F/A_{F0}$). By varying s_0 for any of the fruits tested in the range of 0.95-1.5 mm, it was possible to superimpose all the resulting σ_F-vs-ε_E curves, thus obtaining a unique concave upward relationship. This was described by the following polynomial model for it was able not only to reconstruct the experimental non-linear stress-strain relationships up to the break point with coefficients of determination (r^2) greater than 0.999, but also to estimate an apparent modulus of elasticity for flavedo (E_F=680±21 kPa) as ε_E tended to zero:

$$\sigma_F = E_F\, \varepsilon_E + k\, (\varepsilon_E)^2 \qquad (6)$$

where k (=4005±71 kPa) is an empirical constant that represents a measure of the upward deviation from linearity or material densification capability. For k tending to zero, eq. (6) reduces to Hooke's law.

Alternatively, for the overall fruit tested their compression F-vs-ε_E curves were converted into engineering stress(σ_E)-strain relationships (Fig. 5), by referring the instantaneous F values to the resultant cross-sectional area (A) of the fruits undergoing compression, as estimated via eq.s (2)-(5).

Owing to the uncertainty in the estimation of A, especially at strains smaller than 2-4%, the engineering stresses for any specimen assayed resulted to be overestimated and decreasing as ε_E was increasing from 0 to 3-4%. For greater strains up to about 8%, σ_E appeared to be practically constant with values ranging from 22±2 kPa to 36±3 kPa depending on the specimens tested. As ε_E was further increased from 8-10 to 22-27%, σ_E exhibited quite a linear increasing trend. Beyond such strains, the growth in σ_E declined till burst occurred at ε_{ER}=(33±4)%.

To account for the patterns shown in Fig. 5, it was guessed the following. As the vertical deformation of citrus fruits progressed, the incompressible orange juice reacted by exerting a growing hydrostatic pressure on the internal surface of flavedo, that made the fruit expand laterally. Until the area dilatation change was of the pure linear elastic type, the increase in F and A might compensate one another, thus leading to an almost constant compressive stress (Fig. 5). Beyond the linear elasticity, further citrus fruit squeezing makes σ_E promptly increase up to the rupture values shown in Fig. 5. The linear region in the σ_E-vs.-ε_E curves enabled the apparent modulus of elasticity (E_O) of the orange fruit to be estimated, this ranging from 121±1 kPa to 195±2 kPa depending on the specific fruit tested. Obviously, E_O was different from the above apparent elasticity modulus (E_F), that was related to the equatorial cross-section area of the only flavedo.

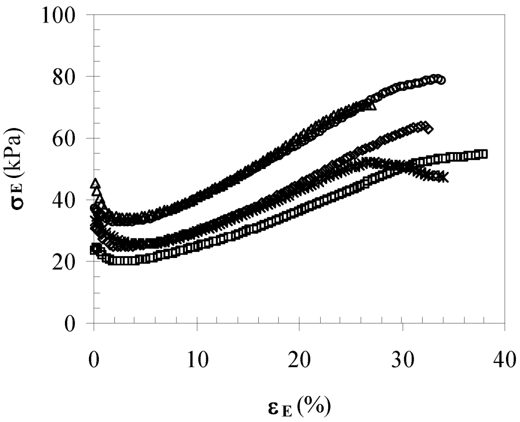

Figure 5 *Compressive engineering stress (σ_E)-strain (ε_E) relationships for 5 orange fruits (R_0=41.8±0.2 mm) submitted to uniaxial compression testing up to rupture using a crosshead speed of 15 mm s^{-1}.*

By applying the conventional procedure (ASABE Standards, 2007), the predicted values of the apparent modulus of elasticity (E_{ASAE}) were found to be negatively correlated to ε_E in the range examined here. Its average value (505±159 kPa) was 2.5 to 4 times greater than the above E_O values, that were estimated on the basis of a more accurate assessment of the contact areas between the compression plates and the specimen.

4. Conclusions

The real engineering stress-strain relationships for orange fruits submitted to uniaxial compression testing can be hardly extracted from typical force-deformation curves. The accurate assessment of the contact areas between the compression plates and the specimen during its compression may help, but it cannot be recommended as a routine procedure. On the contrary, by assimilating the orange fruits to deformable membranes filled with an internal incompressible liquid and plotting the compression stress (σ_F) acting on the equatorial horizontal cross-section of the epicarp (A_{F0}), it would be possible to yield typical concave upward σ_F-vs.-ε_E relationships by assessing the flavedo thickness immediately after fruit rupture.
Further tests will be performed to substantiate such preliminary findings.

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