Journal of Food Engineering 103 (2011) 308–316

Contents lists available at ScienceDirect

Journal of Food Engineering

journal homepage: www.elsevier.com/locate/jfoodeng

Assessment of the mechanical properties of Tarocco orange fruit under parallel plate compression

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ARTICLE INFO

Article history:
Received 23 March 2010
Received in revised form 25 October 2010
Accepted 31 October 2010
Available online 11 November 2010

Keywords:
Bounding box
Effective contact area
Elliptic Fourier Analysis
Engineering strain
Image analysis
Modulus of deformability
Tarocco orange fruit
Parallel plate compression test

ABSTRACT

In this work the mechanical compressive properties of orange fruits of the Tarocco variety were assessed using a Universal Testing Machine, equipped with upper and lower plates made of transparent graduated Plexiglas® and three cameras positioned along the axis lines *x*, *y* and *z*. By submitting each fruit to different engineering strains (ε_z) along the *z*-axis in the range of 3–21% of the initial fruit height, the momentary contact area of each fruit under testing was precisely determined by approximating its outline to a polygon and reconstructing it via the Elliptic Fourier Analysis, or an ellipse inscribed in a bounding box. Both estimates yielded no statistically significant difference and varied linearly with ε_z. Their prediction using the ASABE Standard Method (2008), or assuming no variation in the volume of the fruit undergoing compression, resulted be under- or over-estimated by 45% or 19%, respectively. Use of image analysis allowed the apparent Poisson's ratio and modulus of deformability (E_O) of the whole orange fruit to be estimated as equal to 0.16 ± 0.09 and 353 ± 3 kPa, respectively.

By assimilating the orange fruit to a deformable membrane (*flavedo*) filled with an internal incompressible juice, it was possible to estimate the compressive stress acting on the equatorial horizontal cross-section of the epicarp only and thus estimate the apparent modulus of elasticity of the orange peel (=375 ± 33 kPa), and a burst pressure of 533 ± 103 kPa at a rupture strain ε_{zR} of 0.30 ± 0.03 for rind thicknesses ranging from 0.8 to 4.0 mm.

1. Introduction

The assessment of the rheometrical and textural characteristics of citrus cultivars appears to be crucial for their selection and commercialization, since they affect the 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 fruit resistance to squeezing generally results in persistent deformations, especially after long-term shipping.

Presently, fruit firmness evaluation is carried out manually via the so called Magness–Taylor (MT) test (Shmulevich et al., 2003), that uses a hand-held penetrometer, also known as *fruit pressure tester* (Magness and Taylor, 1925), and 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).

Among the fruit testers used, it is worthy citing the Durofel instrument (Agro-Technologie, Tarascon, France), and Analogue/Digital Firmness Meter (DFM) (Commonwealth Scientific and Industrial Research Organisation, CSIRO, Clayton South, Australia) (Barreiro et al., 2004).

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.

Similarly, other techniques based on visible (VIS) or near-infrared spectroscopy (NIRS), impaction or acoustic impulse resonance frequency (AIF) have so far exhibited inaccurate results (García-Ramos et al., 2005; Ruiz-Altisent and Ortiz-Canavate, 2005). In particular, it is worth citing their use in combination with non-destructive flesh colour readings (Valero et al., 2003), as successfully tested to determine the optimum harvest date and quality characteristics of apple (Menesatti et al., 2009; Zude et al., 2006) or mandarin (Hernández Gómez et al., 2006) fruit, respectively, or with artificial neural network software to predict kiwifruit firmness (Ragni et al., 2010).

Nowadays, just two non-destructive on-line high-speed systems have been developed and commercialised to test the firmness of individual fruits by resorting to the so called *impact methods*, coping with the free fall of the fruit over a force (piezoelectric) sensor or vice versa. In particular, the *Intelligent*

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doi:10.1016/j.jfoodeng.2010.10.029

Nomenclature

A_j	generic contact area of the fruit submitted to parallel plate compression test (m^2)
A_F	equatorial cross-section of the orange peel (m^2)
a_j	generic semi-major axis of the contact area (m)
a_V	radius of the upper equivalent spherical segment (m)
b_j	generic semi-minor axis of the contact area (m)
C_F	circumference of the elliptic rind (m)
D_j	fruit diameter along the generic *j*-axis (m)
D_e	diameter of the equivalent sphere (m)
E_j	modulus of deformability (Pa)
F_z	compression force applied along the *z*-axis (N)
f	degrees of freedom
H	sample height (m)
h	semi-deformation applied along the *z*-axis (m)
k	empirical constant in Eq. (17) (Pa)
n	number of Fourier harmonics used to fit the contact area outline
p	parameter defined by Eq. (7) (m^2)
q	parameter defined by Eq. (8) (m^3)
r^2	coefficient of determination
R_V	radius of the lower equivalent spherical segment (m)
t_j	orange rind thickness in the generic j position (mm)
$t_{\alpha,f}$	one-sided Student *t*-test
V	sample volume (m^3)
V_T	cross-head speed ($mm\ s^{-1}$)
x	generic coordinate along the *x*-axis (m)
y	generic coordinate along the *y*-axis (m)
Z	parameter defined by Eq. (6) (m)

Greek symbols

α	confidence level
Δ	parameter defined by Eq. (9) (m^3)
Δx	sample deformation along the *x*-axis (m)
Δy	sample deformation along the *y*-axis (m)
Δz	sample deformation along the *z*-axis (m)
ε_j	engineering strain along the generic *j*-axis (dimensionless)
μ_j	apparent Poisson's ratio (dimensionless)
σ_z	engineering stress along the *z*-axis ($=F_z/A_j$, Pa)

Subscripts

ASM	referred to the ASABE Standard Method
BB	referred to the bounding box
C	referred to the capsule model
EFA	referred to the Elliptic Fourier Analysis
F	referred to flavedo
max	maximum
min	minimum
O	referred to the whole orange fruit
o	initial
R	referred to fruit rupture
S	referred to the fruit sample
V	referred to the hypothesis of constant sample volume
x	referred to axis *x*
y	referred to axis *y*
z	referred to axis *z*

Firmness Detector (iFD, Greefa, Trich, NL) consists of a wheel equipped with piezoelectric sensors with a maximum capability of 12 fruit pieces per second per lane (www.greefa.nl). Alternatively, the *Sinclair Internal Quality-Firmness Tester* (SIQFT, Sinclair Systems International, Fresno, CA, USA) uses several heads, each one capable of injecting compressed air over a piezoelectric element placed on the tip of a bellow (Harrison, 2003; Howarth et al., 2003). Despite such a system has been successfully applied to grade several fruits (Howarth et al., 2003; Valero et al., 2003), its application for citrus fruit sorting is still undocumented.

All these methods are based on empirical knowledge or statistical relationship between physical (optical, mechanical) fruit properties and texture.

Thus, there is an urgent need for novel tests capable of assessing the mechanical properties of citrus fruit in a rapid, objective and reproducible way (Menesatti et al., 2008), mainly in the case of blood oranges their higher softness with respect to blond ones being frequently the primary cause for the entire fruit stock rejection in the emerging markets of Japan, North America and Australia. To this end, Sicilian orange fruit exporters are searching for more appropriate sorting rules to supply the domestic or international market with softer or stiffer fruits, respectively (Menesatti et al., 2009).

The main aim of this work was to submit orange fruit of Tarocco variety to conventional parallel plate compression tests while assessing precisely the contact area of the fruit under squeezing at different deformation levels via two different visual methods, in order to convert the typical force–deformation curves into true stress–strain relationships, as an attempt to assess the real mechanical properties of Tarocco orange fruit and to develop more efficient on-line non-destructive sorting rules.

2. Materials and methods

2.1. Raw material

Blood orange fruits of the same Tarocco variety (*cv.* Arcimusa) with about a spherical shape were selected by the CRA-ACM experimental farm Palazzelli (Lentini, Siracusa, Italy) in the 2009 harvest season.

To account for the variations due to orange fruit shape, size, age and cellular structure, any of the mechanical tests performed was replicated 20 times as suggested by ASABE Standards (2008).

2.2. Mechanical tests and image acquisition

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 $2.08 \times 10^{-4}\ mm\ s^{-1}$; 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 upper and lower plates made of transparent graduated Plexiglas® GS 233 (Röhm GmbH, Darmstadt, Germany) to determine precisely the contact area of each fruit under testing (Fig. 1a). The modulus of elasticity (3.3 GPa) and Poisson's ratio (0.37) of such a material were extracted from the manufacture product description (Ref. No. 211-April, 1st, 2004).

Three cameras, one of which being an AVT Camera Guppy (Allied Vision Technologies, Stadtroda, Germany) and the other two LifeCams VX-6000 (Microsoft Corporation, Redmond, WA, USA),