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POSTHARVEST IMPACT BRUISING OF APPLE AS RELATED TO THE MODULUS OF ELASTICITY

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Abstract. The moduli of elasticity of fruit (E'_p and E'_7) calculated from the maximum force reading (F_p) and from the average flesh force reading at 7 mm depth (F_7) were used to predict bruise volume of apple during storage. The relationship between the measured bruised volume (*MBV*) and the predicted bruise volume based on E'_p (PBV_p) was linear with coefficient of proportionality (K_p) of 4.61 and coefficient of correlation (R) of 0.928 while the relationship between the measured bruise volume (*MBV*) and the predicted bruise volume based on E'_7 (PBV_7) was linear with K_7 of 2.37 and R of 0.903. K_p linearly correlated to the average of E'_p with R value of 0.974 and K_7 linearly correlated to the average of E'_7 with R value of 0.986. The values of E' as well as K drastically decreased during two months storage time and were then relatively constant for longer storage time. Utilising E'_p Hertz's theory was underestimated 23.37 % while employing E'_7 it was overestimated 36.66 % in predicting postharvest bruising of Golden Delicious apple.

Keywords: apple, modulus of elasticity, predicted bruise volume, measured bruise volume

INTRODUCTION

Numerous operations during postharvest handling, packaging and distribution may subject apples to impact loading. During impact four phases may be identified. At the beginning of impact, quasi-elastic deformation takes place and will completely cease on unloading. Plastic deformation then initiates, when the mean pressure exceeds the dynamic yield stress of the material and a part of deformation remains after the load has been removed. The deformation continues and fully plastic deformation sets in, during which the mean pressure drops to below the dynamic yield stress. Finally, the elastic stresses and deformations conserved in the material terminate during unloading and the plastic deformations remain permanently, which is usually observed as bruising.

The need to understand what factors influence bruising due to impact has brought some researchers to develop theoretical methods to analyse impact phenomena [9,11,17], while other researchers have established instrumentation for measuring impact parameters and related them to bruising [1,2,5,7,8,13,14].

Fruit firmness in the form of Magness-Taylor force reading has been co-operated to predict impact bruising. Employing Hertz's theory, Siyami *et al.* [20] have used the Magness-Taylor force (11.1 mm probe's diameter) together with apple weight, drop height and apple diameter to predict the bruise diameter created using an impact table. Sober *et al.* [21] have applied the same method within the simulated packing line impacts.

Because the fruit firmness changes with the progress of ripening, the impact response and corresponding bruising may vary with postharvest time. Unfortunately, there is still a doubt about this variation. As an illustration, Klein [12] noted that bruise volume decreased with storage time whereas Brusewitz and Bartsch [1] indicated that the change in bruise volume per unit change in total impact energy increased with storage time. On the other hand, Holt and Schoorl [10] noted that bruise volume per energy absorbed tended to remain constant during 18 weeks storage at 2 °C.

Since there exist different probe diameters normally used, which may influence the results, in our study we intended to use the modulus of elasticity of fruit rather than the force readings such as Magness-Taylor, together with drop height, apple mass and apple volume, to predict bruise volume. The aims were to establish the relation between the predicted bruise volume and the measured one, and to investigate the changes of this relation during storage time.

Bruise prediction model

If a fruit impacting on a rigid surface is considered as one cycle impact, from Hertz's theory the severity of impact can be expressed in the form of dimensionless relative damage volume [19] as:

$$\frac{\Delta V}{V} = K\left(H\gamma\,\frac{(1-\nu)^2}{E}\right)^n \tag{1}$$

where ΔV - bruise volume (m^3), V fruit volume (m^3), K - coefficient of proportionality equal inverse of acceleration, (s^2 m^{-1}), H - drop height (m), γ - density of fruit (kg m^{-3}), E - modulus of elasticity of fruit (Pa), ν - Poisson ratio, $n = \frac{4}{5}$.

This relation gives the calculated bruise volume:

$$\Delta V = K\frac{M}{\gamma}\left(H\gamma\,\frac{(1-\nu^2)}{E}\right)^{\frac{4}{5}} \tag{2}$$

where M - mass of fruit (kg), or more simply $\Delta V = K\,PBV$ where PBV - predicted bruise volume. According to Hertz's theory the value of K should be 3.74 [19].

Within the above relation, if the drop heights are kept constant and the fruits having uniform size are used, the value of calculated bruise volume mainly depends on the modulus of elasticity.

MATERIAL AND METHODS

Golden Delicious apples from the same grade were utilised in the experiments. Fruit were manually harvested from the experimental orchard, INRA Avignon, France in 05.09.1995, and then cool stored at 2 °C and 95 % humidity. A sample of 20 apples was used for every experiment. The first experiment was done five days after harvest and every month a sample with the same size was randomly taken for the next experiments. We followed the fruit for five months storage time. Before testing the fruit was exposed to ambient temperature (20 °C) for 24 h. The fruit was weighed and its density was determined by weighing it in water. Physical data of the fruit used for every experiment are presented in Table 1. The fruits were then subjected to impact and penetrometer test.

Table 1. Physical data of fruit used in the experiments

Experiment (storage time)	No. of fruit	Mass (kg)	Diameter (m)	Density (kg/m^3)
I (5 days)	20	0.1936 ± 0.0097	0.0771 ± 0.0018	789 ± 90
II (35 days)	20	0.1901 ± 0.0093	0.0774 ± 0.0014	782 ± 11
III (66 days)	20	0.1922 ± 0.0086	0.0771 ± 0.0019	783 ± 10
IV (97 days)	20	0.1880 ± 0.0094	0.0772 ± 0.0021	781 ± 10
V (127 days)	20	0.1883 ± 0.0087	0.0769 ± 0.0016	778 ± 10
VI (160 days)	20	0.1873 ± 0.0093	0.0762 ± 0.0016	781 ± 11

Impact test

Figure 1 illustrates the impact apparatus used in the experiments. This apparatus mainly consists of a stand, an impact surface made of aluminium plate installed on a concrete block, a vacuum pump and a sliding metal bar mounted at the stand. During operation the fruit was held by the vacuum pump and the drop height was fixed by the metal bar and adjusting the fruit position. The fruit was then released without initial speed and let to strike against the impact surface on its cheek. The fruit was caught by hand just after striking to avoid a second impact. For marking the bruise, the impact surface was smeared with blue inks made of liquid paraffin and colour powder. The bruise was measured by sectioning through its centre 24 h after impact. Each fruit was dropped from 5, 15, 25 and 35 cm on different equatorial parts.

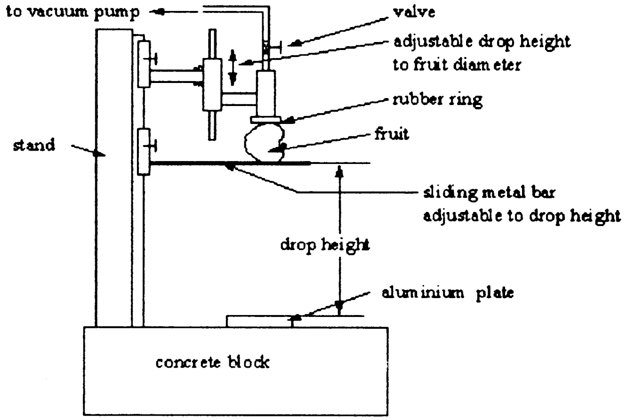

Fig. 1. Impact apparatus used in the experiments.

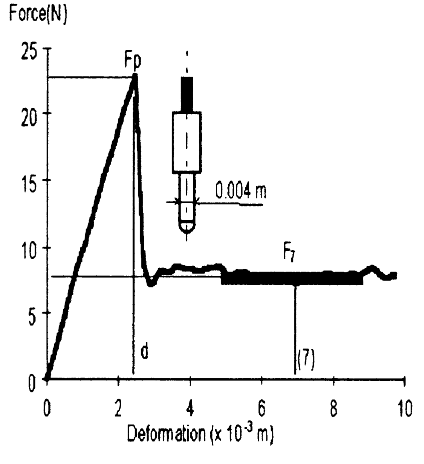

Fig. 2. Graphical perfomance of penetrometer test showing probe dimension. F_p is the maximum or skin plus flesh failure force and F_7 is the average force between 5 and 9 mm depth.

Penetrometer test

Using the procedure developed in the laboratory, a multi-purpose penetrometer described in detail by Duprat *et al.* [6] was used to measure the fruit firmness. The apparatus was equipped with a probe having 4 mm diameter and hemispherical tip. This system has a precision of 0.01 mm in deformation and 0.01 N in force. The rate of penetration used in the experiments was 20 cm/min. Graphical performance of this system of measurement is presented in Fig. 2. The penetration was done near (about 10 mm from) the bruise and every bruise had its local force reading. The skin failure maximum force (*Fp*) and the average force at 7 mm depth (F_7) were used to calculate the modulus of elasticity.

Definition of parameters

Apple can be assumed as a sphere and elastic body without too much error [3,15,16], even though naturally it is a fruit having spherical shape and viscoelastic behaviour. The radius of this sphere (apple) can be approximated by:

$$R=\left(\frac{3M}{4\pi\gamma}\right)^{\frac{1}{3}} \tag{3}$$

where R - apple radius (m), M - apple mass (kg), γ - apple density (kg m^{-3}).

Bruise volume

A typical cross-section of the bruise showing parameters used in bruise volume determination is depicted in Fig. 3. The bruise above the contact plane is equivalent to the volume of a spherical segment [18] and can be calculated from:

$$V_1=\frac{\pi}{3}h^2(3R-h) \tag{4}$$

where h - depth of crushed zone equal to $R-\left(R^2-a^2\right)^{\frac{1}{2}}$ (m), a = bruise diameter (m).

Similarly, the volume of bruise below the contact plane is given by:

$$V_2=\frac{\pi}{3}p^2(3R_1-p)$$

or

$$V_2=\frac{\pi}{6}p(3a^2+p^2) \tag{5}$$

where p - bruise depth (m), R_1 - radius of the bruising zone equal to $\dfrac{(a^2+p^2)}{2p}$ (m).

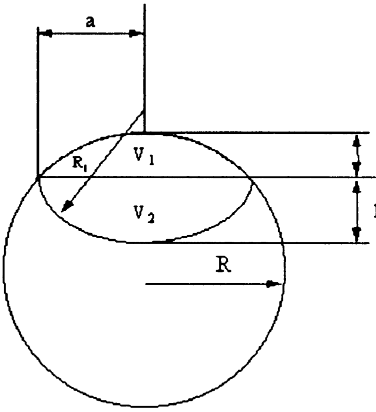

Fig. 3. Bruise section showing parameters used in bruise volume detemination.

Thus, the total bruise volume V is the total volume of V_1 and V_2 named measured bruise volume (MBV):

$$MBV=V_1+V_2\,.$$

Modulus of elasticity

From Fig. 2, the modulus of elasticity of fruit, based on Fp and F_7, can be calculated according to Hertz's theory [4] as follows:

$$E_p=\frac{3F_p(1-\nu^2)}{4r^{\frac{1}{2}}d^{\frac{3}{2}}} \tag{6}$$

$$E_7=\frac{3F_7(1-\nu^2)}{4r^{\frac{1}{2}}d^{\frac{3}{2}}} \tag{7}$$

where E_p - modulus of elasticity of fruit calculated basing on F_p (Pa), E_7 - modulus of elasticity of fruit calculated basing on F_7 (Pa), F_p - maximum skin plus flesh force (N), F_7 - force reading at 7 mm depth (N), d - deformation (m), r - radius of probe (m). The value of ν used in the calculation was 0.3.

Final predicting equation

Substituting Eqs(6) and (7) in Eq.(2) produces final predicting equations as follows:

$$\Delta V_p=K_p\frac{M}{\gamma}\left(H\gamma\frac{1}{E_p'}\right)^{\frac{4}{5}} \tag{8}$$

or

$$PBV_p=\frac{\Delta V_p}{K_p}$$

where $E'_p = \dfrac{E_p}{(1-\nu^2)}$

$$\Delta V_7 = K_7 \frac{M}{\gamma}\left(H\gamma \frac{1}{E'_7}\right)^{\frac{4}{5}} \qquad (9)$$

or

$$PBV_7 = \frac{\Delta V_7}{K_7}$$

where $E'_7 = \dfrac{E_7}{(1-\nu^2)}$.

RESULTS AND DISCUSSION

Models of elasticity variability

The averages of E'_p and E'_7 and their standard deviations for every experiment are given in Table 2.

This table shows that the apples had a very high variation in modulus of elasticity (standard deviation of 9.66 - 13.55 % for E'_p and 17.04 - 27.46 % for E'_7), though they were physically uniform (Table 1). However, this variability should not produce significant errors in the bruise prediction since the individual value of the modulus of elasticity for each bruise was used in calculation rather than the average values.

Measured bruise volume vs. predicted bruise volume

Figures 4 and 5 present the calculated bruise volumes divided by K (PBV or predicted bruise volume), based on E'_p and E'_7, plotted against the measured bruise volumes (MBV) using total data (480 points). The measured bruise volumes linearly correlated to the predicted bruise volumes based on E'_p (PBV_p) with coefficient of correlation (R) value of 0.928, while the measured bruise volumes also linearly correlated to the predicted bruise volumes based on E'_7 (PBV_7) with R value of 0.903. Comparing the K value given by Hertz's theory (3.74), the K value produced by the first relationship was greater (4.61) whereas the K value produced by the second relationship was smaller (2.37). It means that utilising E'_p Hertz's theory was underestimated 23.37 %, whereas employing E'_7 Hertz's theory was overestimated 36.66 % in predicting postharvest bruise volume.

Changes of E and K during storage time

With the progress of ripening the modulus of elasticity varied. Figure 6 presents the averages E'_p and E'_7 and their standard deviations for every experiment plotted against storage time. This figure shows that both E'_p and E'_7 decreased drastically during two months storage time and were then relatively constant for longer storage time.

Because of these changes the values of K were also changed. This can be observed when the predicted bruise volumes were plotted against the measured bruise volumes for every experiment as given in Table 3.

Based on the above table, it can be noted that using E'_7 Hertz theory predicted almost correctly (with K_7 of 3.48 or an error of 6.95 %) the bruise volumes when the fruit was still fresh (5 days in the storage). It was then overestimated for longer storage time.

Table 2. The average modulus of elasticity (E'_p and E'_7) of fruit and its standard deviation for every experiment

Experiment (storage time)	No. of fruit	E'_p (MPa)	Standard deviation (MPa)	E'_7 (MPa)	Standard deviation (MPa)
I (5 days)	20	3.14	0.30	1.95	0.33
II (35 days)	20	2.78	0.38	1.43	0.33
III (66 days)	20	2.50	0.33	1.09	0.28
IV (97 days)	20	2.36	0.27	1.10	0.30
V (127 days)	20	2.25	0.27	1.03	0.23
VI (160 days)	20	2.19	0.28	1.04	0.24

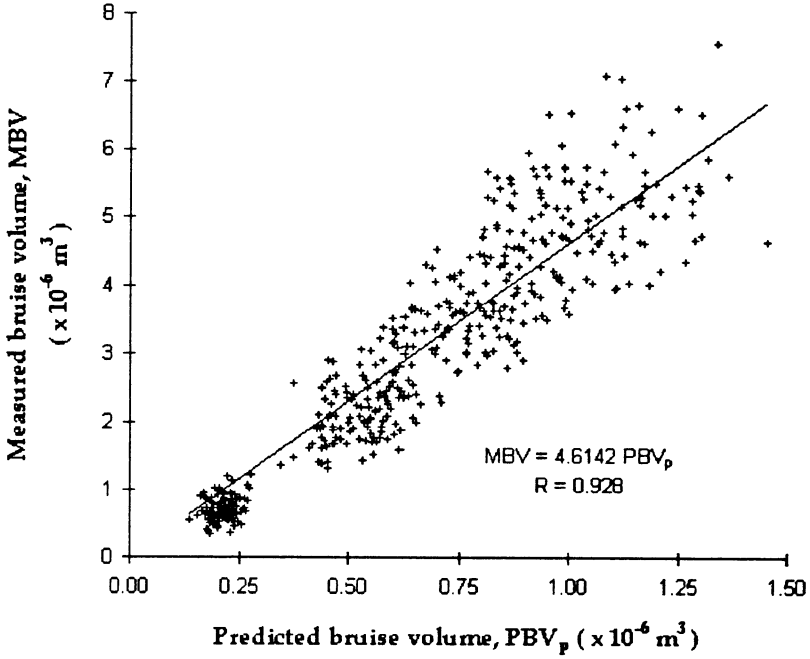

Fig. 4. Measured bruise volume plotted against predicted bruise volume based on (PBV_p) for total data (480 points).

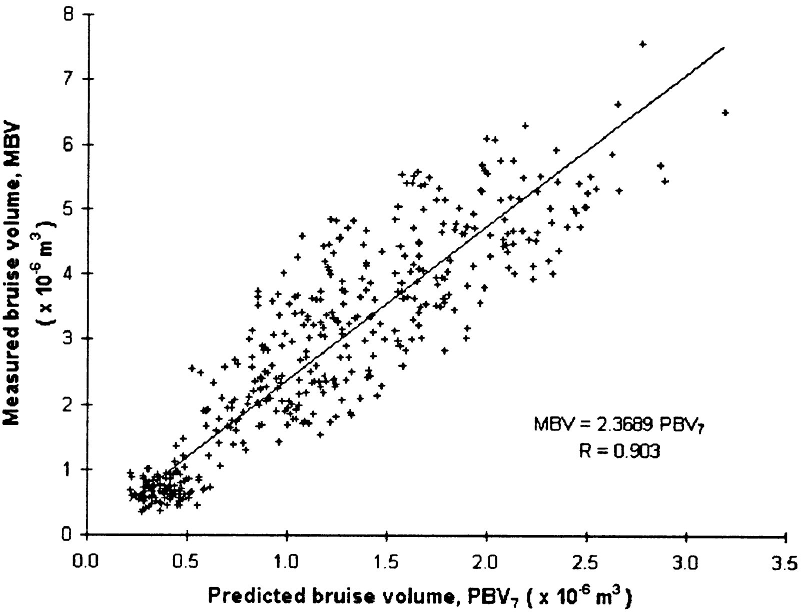

Fig. 5. Measured bruise volume plotted against predicted bruise volume based on (PBV_7) for total data (480 points).

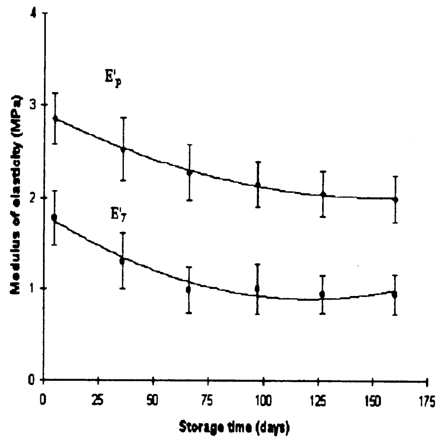

Fig. 6. Averages of the modulus of elasticity and their standard deviations plotted against storage time.

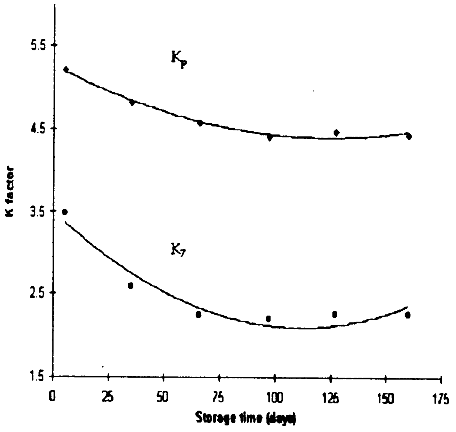

Fig. 7. K factors plotted against storage time.

Table 3. The relationship betwen the predicted bruise volumes (*MBV*) and the measured bruise volumes (*PBV*) for every experiment

Experiment (storage time)	No. of fruit	Equation based of E'_p $MBV = K_p PBV_p$	R value	Equation based of E'_7 $MBV = K_7 PBV_7$	R value
I (5 days)	20	$K_p = 5.21$	0.945	$K_7 = 3.48$	0.934
II (35 days)	20	$K_p = 4.82$	0.923	$K_7 = 2.60$	0.904
III (66 days)	20	$K_p = 4.58$	0.926	$K_7 = 2.25$	0.906
IV (97 days)	20	$K_p = 4.49$	0.953	$K_7 = 2.20$	0.915
V (127 days)	20	$K_p = 4.48$	0.847	$K_7 = 2.27$	0.921
VI (160 days)	20	$K_p = 4.44$	0.916	$K_7 = 2.26$	0.900

MBV - measured bruise volume and *PBV* - predicted bruise volume.

On the other hand, using Hertz's theory was underestimated along the storage time. The changes of K_p and K_7 during storage time followed the same patterns as and as presented graphically in Fig. 7.

K factor vs. modulus of elasticity

Figure 8 depicts the linear relationship between K_p and the averages of E'_p, while Fig. 9 shows the linear relationship between K_7 and E'_7. The first relationship produced R value of 0.974 and the second relationship resulted in R value of 0.986. It can be shown that the values of K decreased when the values of E' decreased. So the change in K mainly represented the change of E'.

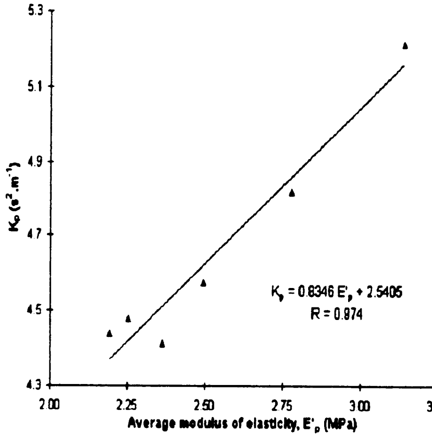

Fig. 8. Relationship between K_p and average modulus of elasticity, E'_p.

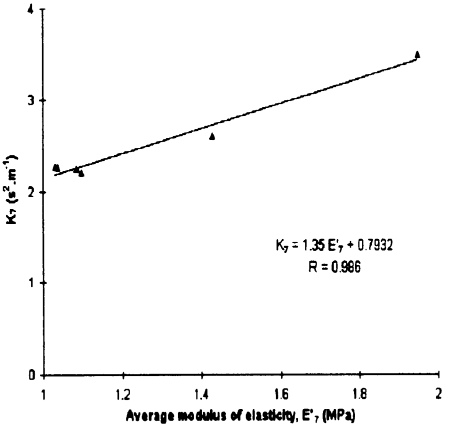

Fig. 9. Relationship between K_p and average modulus of elasticity, E'_7.

CONCLUSIONS

The predicted bruise volumes based mainly on the moduli of elasticity of fruit linearly correlated with the measured bruise volumes. The relationship between the measured bruise volume and the predicted bruise volume based on E'_p (*PBVp*) was linear with coefficient of proportionality (K_p) of 4.61 and coefficient of correlation (R) of 0.928, while the relationship between the measured bruise volume and the predicted bruise volume based on E'_7 (PBV_7) was linear with K_7 of 2.37 and R of 0.903. K_p linearly correlated to the average of E'_7 with R value of 0.974 and K_7 linearly correlated to the average of E'_7 with R value of 0.986. The values of E' as well as K drastically decreased during two months storage time and were then relatively constant for longer storage time. Utilising E'_p Hertz's theory was underestimated 23.37 %, while employing E'_7 it was overestimated 36.66 % in predicting postharvest bruising of Golden Delicious apple.

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