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Non-destructive, mechanical method for measurement of plums' firmness

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A b s t r a c t. A method was developed based on the measurement of the apparent modulus of the elasticity of plums, using a cylindrical probe and a force of 1 N. This method is extremely sensitive and is fully non-destructive. The measurements are taken using an Instron Universal Testing Machine. The results obtained correlate very well with other objective quality indices and sensory tests. The method was verified on several plum cultivars. This method is suitable in estimating the different grades at which any particular fruit has ripened by the day of picking and during storage and may be used to establish the firmness of the plums from the point of view of the consumer. It was found that fruit of the Dąbrowicka, Amerf and Valjevka varieties should have – at the consumption stage of maturity – an apparent modulus of elasticity ranging from 0.100 to 0.250 MPa (optimum at 0.150 MPa), when measured using a 6 mm probe and when recalculated using a 4 mm probe, respectively 0.071–0.217 MPa (optimum at 0.120 MPa).

K e y w o r d s: modulus of elasticity, ripeness, sensory assessment, quality

INTRODUCTION

The mechanical properties of materials are important from the point of view of a material's susceptibility to damage and the influence of various external factors during harvest, transport, storage and processing (Szot and Stępniewski, 1999). Although many methods were proposed for measuring plum firmness, no recommendable uniform method exists to estimate plum firmness and ripeness. Most methods described in the literature are destructive and they differ widely making any comparison of the results impossible. The most popular are those based on the 'puncture' test. Bourne (1979b) used a standard Magness-Taylor pressure tester equipped with an 11 mm diameter probe. Gur (1986), Robertson *et al*. (1992) and Crisosto *et al*. (1993) used an 8 mm diameter probe, whereas Valero *et al*. (2002) used a probe with a diameter of 5 mm. Other methods applied were based on measuring fruit compression under a load (Komandi, 1988; Ben and Gaweda, 1992). Crouch and Griessel (1996) proposed a tensiometric dynamometer to measure the firmness of the stone fruit; this measures the firmness of the external and internal layer of the mesocarp. According to Crisosto (1994) modern technologies such as near infrared, magnetic resonance, light transmittance and acoustic methods will allow the development of an ideal, reliable, non-destructive method that might be used to estimate the firmness of plums and other fruit. This opinion was confirmed by the experiments conducted by Onda *et al*. (1994), Muramatsu *et al*. (1996) and Abu-Khafal and Bennedsen (2001). Some non-destructive methods are available as on-line prototypes for testing fruit and vegetables (Shmulevich, 2001), but such equipment is not common and is expensive.

The simplest method of measurement of plum is investigation of their elasticity properties. Umeda and Namikawa (1994) concluded that the physical property of a plant should be described on the basis of its cell structure and that a single cell wall is an isotropic elastic membrane and that under compression the cell is changed from spherical to ellipsoid in shape. Nowadays, elasticity can easily be determined both in laboratories, using Instron or Zwick Machines, and in orchards with hand held instruments (Fekete and Felföldi, 1994). Although elasticity properties are quite often used in comparative experiments as an indicator of the changes in fruit ripeness (Fekete, 1994; Blahovec, 2001; Valero *et al*., 2002) usually there is no further information on the relation between the parameters determined and other quality features restricting the usefulness of the results obtained. In horticultural practice, researchers and growers lack a simple, easily accessible and unified method that would be useful to assess the physical state of fruits such as the plum.

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The purpose of the experiments presented was to develop a non-destructive, mechanical method suitable to estimate the degree of the ripeness of plums on a laboratory scale. It was assumed that the method should be highly sensitive in application and the results obtained should correlate accurately with other parameters characterizing fruit ripeness and sensory tests.

MATERIALS AND METHODS

The parameters of the non-destructive method based on the measurement of the apparent modulus of elasticity were checked in several experiments using plums of the Dąbrowicka, Amerf and Valjevka cultivars. Fruit of the Dąbrowicka cultivar was investigated over three seasons, whereas fruit of the Amerf and Valjevka cultivars were investigated over two seasons and always on the day of commercial picking in the experimental orchards of the Research Institute of Pomology in Skierniewice. The fruit used to investigate the method was initially sorted into classes based on a subjective appraisal of its ripeness.

The apparent modulus of the elasticity of the fruit was measured by the same operator in all tests using an Instron machine, model 4303, and a 10 N load cell. The measurement parameters were as follows: cross-head speed 50 mm min^{-1}, force up to 1.0 N. The relation between the force applied and fruit deformation was recorded at a frequency of 10 times per second. Force was applied to the side of the fruit where the flesh was thickest (places for measurement were marked with permanent ink). Different probes were used: a cylindrical probe with a diameter of 4 mm with a flat tip, a cylindrical probe with a diameter of 6 mm with a flat tip and a flat probe with a surface exceeding that of the fruit measured. During measuring, the fruit was placed in a standard concave support and held by hand to secure its position. The apparent Young modulus was determined by the Instron computer programme (Series IX) as a tangent (slope) of force (N) – deformation (dL/L) curve obtained during compression of a single plum up to 1N force and calculated for a linear range between 0.25–1.0 N.

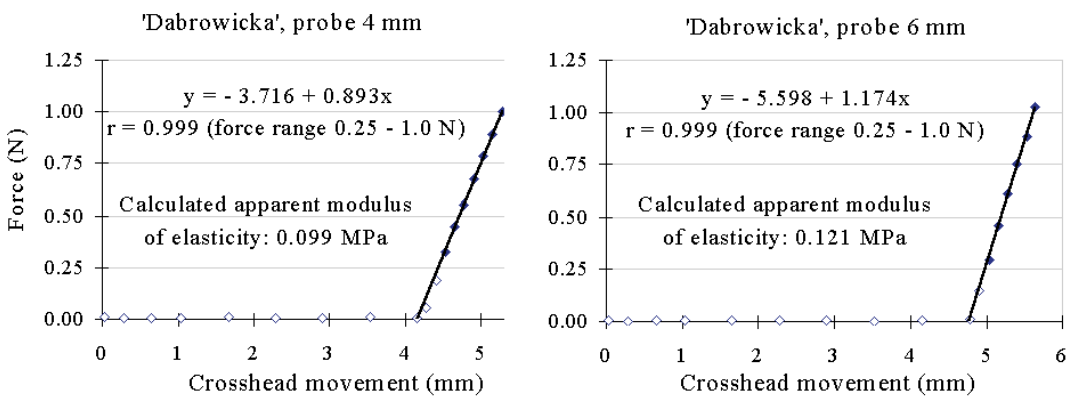
An example of the data recorded for the relation between stress and strain for the two cylindrical probes is given in Fig. 1. Because practically all data points were located on a straight line irrespective of whether a probe diameter of 4 mm or 6 mm was used, the correlation coefficient in both cases was 0.999.

In addition to the apparent modulus of elasticity, other ripeness indices were measured: flesh colour, soluble solids, acidity and in some experiments, the coefficient of elasticity. Measurement of flesh colour was made using a Hunter Mini Scan model MS-4500L tristimulus colorimeter. L, a and b values were measured for a sample of 30 fruits in each combination.

Soluble solids were evaluated with a refractometer, separately for each fruit in combination at a temperature of 20°C. Titratable acidity was determined in a homogenized sample and the results are expressed in % of malic acid.

In sensory tests, the following characteristics were determined: the colour and firmness of the flesh, the sweetness and sourness, the flavour and the degree and acceptability of ripeness. Each combination was evaluated by 10 testers using the ANALSENS NT (LABNT) computerized system for data collection developed at the Polish Academy of Science.

The coefficient of elasticity was measured using a pseudo, non-destructive, hand held penetrometer developed by Fekete (referred to hereinafter as the hand-held instrument). The coefficient was calculated based on the stress/strain relation when a probe with a diameter of 4 mm was pressed into the fruit to a depth of 0.15 mm. The values of the coefficient of elasticity are expressed in MPa mm^{-1}.



Experiment on the verification of the usefulness of the apparent modulus of elasticity and the effect of the diameter of the cylindrical probe

For this experiment, 10 plums were selected. These differed widely in the degree of ripeness. Each fruit was pressed ten times with a force of 1 N at the same place using a probe with a diameter of 6 mm and then on the other side ten times with a probe with a diameter of 4 mm. The second batch of fruit was treated in a similar manner, except that initially, a probe with a diameter of 4 mm was used and then one with a diameter of 6 mm.

Comparison with other objective and subjective criteria of the usefulness of the apparent modulus of elasticity

In this experiment fruit was separated into maturity classes based on sensory judgement. The following were distinguished: consumption maturity (C), hard (H), and those under ripe (U). For 30 fruits in each class the apparent modulus of elasticity was measured using cylindrical probes with diameters of 4 and 6 mm and in addition a flat probe. The soluble solids, flesh colour and acidity (on a combined sample) in the fruit of each class were also measured. The fruit was also subjected to sensory tests.

Experiment on the relation between the apparent modulus of elasticity and the sensory characteristics of the fruit

Fruit of three cultivars (each picked in the second season) were divided into ten ripeness classes differing in the apparent modulus of elasticity by 0.025 MPa. The firmness of the plums in each class was determined as the average of the modulus of elasticity value for ten fruits selected randomly from each class. Plums of each class were subjected to sensory trials and checked for soluble solids and acidity. Regressions were calculated between the apparent modulus of elasticity and the results of sensory tests for each cultivar.

Experiments on the practical usefulness of the method of the apparent modulus of elasticity

The usefulness of the method was checked in two experiments. In the first experiment, fruit from the whole tree was divided into several classes – differing in the apparent modulus of elasticity by 0.05 MPa – in order to check the uniformity of the degree of ripeness. The classes were designated as:

very over ripe	< 0.100 MPa
over ripe	0.101–0.150 MPa
ripe	0.151–0.200 MPa
hard	0.201–0.250 MPa
slightly unripe	0.251–0.300 MPa
unripe	>301 MPa

Mechanical testing of stored fruit

In the experiment on stored fruit, the fruit was initially sorted into four ripeness classes differing by 0.05 MPa. The plums were numbered. This allowed the changes in the apparent modulus of elasticity of the same fruit to be investigated directly after picking and both during and after cold storage. Different batches of fruit divided into classes were either stored at 20°C for sixteen days or for ten days at 0°C initially and then at 20°C for the next six days.

Tests by hand-held instrument

Fruits of the cultivars investigated were divided into classes differing by 0.025 MPa based on the apparent modulus of elasticity. Ten fruits from each class were selected, numbered and on each of them, the apparent modulus of elasticity was measured along with the coefficient of elasticity, using a hand-held instrument. For each cultivar, the correlation coefficient was calculated between both methods on the individual results and on the averages for the classes.

RESULTS AND DISCUSSION

Experiment to verify the usefulness of the apparent modulus of elasticity and the effect of the cylindrical probe diameter

The results obtained indicate that only in a few cases did the V% exceed values of 10%. There was no difference in the repeatability of results of the experiment whether the probe with a diameter of 4 mm was used or whether the probe with a diameter of 6 mm was used. On the contrary rather large differences were found in the minimum and maximum values. It is clear that measurement techniques require standardization. While being measured, the fruit should be stable (in the experiments conducted, it was held in one hand) and the test should be conducted on the same area on the surface of the fruit. It was found that the values obtained depended very much on where the measurements were taken. This is understandable taking into consideration the anatomy of the plum and the fact that fruit does not ripen evenly which is also evident by the color of the skin and the flesh. Therefore if a limited quantity of fruit is available, or if it is necessary to obtain precise results, it may be justified to take the same plum's measurements twice, once on each site. The data obtained shows that even if a measurement is taken twenty times at the same place with the same probe there is no damage to the flesh. The successive averages for a series of measurements obtained for the same fruit batch are very much the same. It was found that the values of the modulus of elasticity depended on the diameter of the probe used; both probe methods have the same degree of precision but not the same accuracy ($p = 0.01$) and the results should be re-calculated according to the formula given in Fig. 2.

Comparison of the usefulness of the apparent modulus of elasticity with other objective and subjective criteria

The experiment showed (Tables 1–3) that the flat probe was the least suitable. The modulus of elasticity established using the probe with a diameter of 6 mm was closer to that using the flat probe than it was by using the probe with a diameter of 4 mm. Use of the latter probe facilitated significant differentiation of the batches of fruit investigated which was not the case for either the flat probe or the cylindrical probe with the diameter of 6 mm. It may be anticipated that the probe with the diameter of 4 mm afforded full and instantaneous contact with the surface of the fruit when using minimum pressure. A probe with a diameter of 6 mm was used in all the experiments reported in this paper because they were conducted simultaneously with the verification of the method.

Fruit colour

In Table 2 the results are reported for the objective quality indices. For one cultivar different parameters are evidently more important than others. For Dąbrowicka a good criterion of ripeness is flesh lightness L and an excellent criterion was the proportion between a/b. Statistical differences between the combinations were also found for the content of soluble solids and the proportion of soluble solids to acidity. For the Amerf variety of plum, flesh lightness L was not such a useful index of maturity (no statistical differences between the treatments). On the contrary, the a and b values and their derivatives allowed the significant differences between the under ripe fruit and the two other classes to be distinguished. There was a significant difference in

ripeness: (C) consumption maturity, (H) hard, (U) under-ripe.

T a b l e 2. The objective maturity indices of plums on the day of picking

Cultivar	Degree of plums ripeness *	Flesh colour **				Soluble solids (%)	Acidity/sol. solids
		L	a	b	a/b		
Dąbrowicka	C	48.9 a	17.2 b	39.5 a	0.438 c	16.9 c	16.3 c
	H	55.7 b	18.4 b	49.1 c	0.376 b	15.8 b	13.3 b
	U	58.6 c	12.9 a	45.0 b	0.286 a	14.9 a	11.5 a
Amerf	C	67.6 a	4.72 b	42.2 b	0.111 b	13.1 b	18.6 b
	H	67.5 a	3.93 b	43.1 b	0.089 b	12.2 a	17.8 b
	U	68.8 a	0.72 a	40.6 a	0.017 a	11.8 a	16.1 a

T a b l e 3. The subjective indices of maturity in plums for investigated fruit classes

Cultivar	Degree of plums ripeness*	Sensory test (points)				
		Flesh firmness	Flesh colour	Sweet taste	Sour taste	Degree of ripeness
Dąbrowicka	C	5.2 a	5.9 b	5.6 a	4.4 a	5.3 b
	H	5.7 a	5.3 ab	5.0 a	5.3 a	4.8 ab
	U	6.6 b	4.5 a	4.9 a	5.4 a	4.2 a
Amerf	C	5.9 a	4.8 b	4.6 a	3.0 a	5.0 b
	H	6.6 ab	4.0 ab	4.1 a	3.7 a	3.8 ab
	U	7.2 b	3.0 a	3.8 a	4.0 a	3.4 a

For explanations see Table 1.

the content of soluble solids in the plums at the consumption stage of maturity and in the other two classes. None of the objective quality indices could differentiate the classes of maturity in both cultivars. In the sensory test (Table 3) the testers can distinguish class C (for both cultivars) from the other two classes in respect of flesh firmness, flesh colour and the degree of ripeness. As far a sweetness is concerned, there was a tendency towards higher scores for class C compared to classes H and U and a reverse tendency in respect of sour of taste.

Experiment on the relation between the apparent modulus of elasticity and the sensory characteristics of fruit

It was found that in most cases there is a good correlation between the apparent modulus of elasticity and the intensity of the components of fruit texture (Table 4). The linear correlation coefficients for all cultivars were greater than 0.800. For Dąbrowicka the apparent modulus of elasticity correlates quite well with flavour appraisal and the preference for ripeness. Data presented on Figs 3a and b shows the range of the modulus of elasticity most preferred by the testers. Considering that flavour scores should be above six points on a ten point scale, the respective values for the modulus of elasticity may be read from the curves. Most preferred were the plums when their modulus of elasticity was about 0.150 MPa, but also acceptable were those within the range 0.070–0.250 MPa. For Amerf and Valjevka cultivars highly acceptable ranges could not be established. The Valjevka plum variety was considered acceptable over a broad range of the apparent modulus of elasticity. The Amerf cultivar obtained lower scores for flavour even when acceptable considering the degree of ripeness. This may be a result of the lower content of soluble solids (below 12.8%) and the lower acidity (0.80% as malic acid) compared to the other cultivars investigated. In all cultivars, when the apparent modulus of elasticity was higher than 0.250 MPa, the fruit scored below six points in respect of ripeness and flavour. Therefore, the value of 0.250 MPa was considered acceptability limit.

Experiments on the practical usefulness of the method of the apparent modulus of elasticity

In the first experiment, the results obtained allowed comparisons to be made of the cultivars which had been investigated for uniformity in the degree of ripeness of the fruit on the day of picking. An example of the distribution of the apparent modulus of elasticity is given on Fig. 4. In the first season, the distribution of results obtained for the Dąbrowicka variety resembled normal distribution. In those classes between 0.100 and 0.300 MPa, were about 80% of the results. In the second season, the fruit ripened irregularly due to rain and a strong infestation by fruit fly (most soft fruit had larvae). In the third season commercial picking was started too early. As shown on the graph almost 50% of the fruit was classified as unripe. The data distribution obtained

T a b l e 4. The coefficients of correlation between the apparent modulus of elasticity and sensory scores

Cultivar	Flesh colour	Flesh firmness	Sweet taste	Sour taste	Degree of ripeness	Preference for plum ripeness	Overall taste acceptance
Dąbrowicka (1st seas.)	**0.902**	**0.935**	**0.852**	**0.853**	**0.874**	**0.922** *	**0.925** *
Dąbrowicka (2nd seas.)	**0.880**	**0.943**	**0.956**	**0.932**	**0.961**	**0.932** *	**0.972** *
Amerf	**0.816**	**0.835**	0.453	**0.563**	**0.831**	**0.774** *	**0.582** *
Valjevka	0.377	**0.957**	**0.556**	0.077	**0.906**	**0.576**	0.359 *

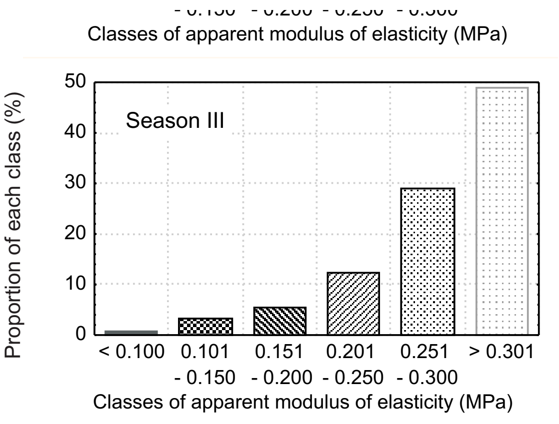
Numbers given in bold are statistically significant at p 0.05, *coefficient of correlation determined for square polynomial regression.

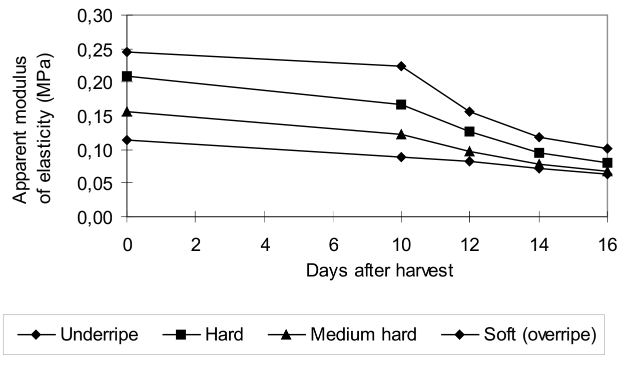
Fig. 3. Relations between the apparent modulus of elasticity of the Dąbrowicka cultivar (measured up to 1N load with 6 mm dia. probe) and ripeness preference: 0 – undesirable, 10 – highly desirable (a) or flavour judgement (b) during sensory tests: 0 – unpalatable, 10 – very tasty.

for the cultivars investigated shows that the season has a very strong effect on the uniformity of ripening of a particular cultivar and that genetic factors also have a strong effect on ripening characteristics. For example, data for the Amerf cultivar was quite evenly distributed between the classes investigated over successive seasons.

Mechanical testing of stored fruit

In the storage experiment, the apparent modulus of elasticity changes in the plums was related to the temperature during storage and the initial degree of the ripeness of the fruit (Fig. 5). During the storage of the plums at room temperature, the values of the apparent modulus of elasticity decreased depending on initial value. The rate of any softening was high for unripe fruit but much lower for over ripe fruit. Plums are of a group which softens fast during ripening. The firmness of the fruit when fully mature does not exceed 22% of its firmness just before ripening. (Bourne, 1979). The data obtained confirms the results of Streif (1989) and Ben and Gaweda (1992) – obtained using other





methods, who found high degree of firmness changes once plums have been picked.

The results obtained show that the apparent modulus of elasticity may be useful in comparing cultivars in respect of uniformity of ripeness and for monitoring the changes which occur during the storage of plums.

Tests by hand-held instrument

Results for individual fruits are presented in Fig. 6. For all the cultivars investigated, the correlation coefficients calculated from average values were above 0.950 and for calculations from individual results they were above 0.880 (in both cases statistically significant at p 0.05). It was also found that there is an effect of a cultivar on regression coefficients b of the regression formula. For the cultivars investigated, we also proved that there is a significant correlation (p 0.05) between the coefficient of elasticity and the firmness or degree of ripeness when determined by the sensory method (r ranged from 0.767 to 0.950). Therefore we conclude that both methods may be used interchangeably and the results might be recalculated for particular cultivars according to the formulas given in Fig. 6. The advantage of the hand-held instrument is such that it may be used in field conditions.

CONCLUSIONS

1. A non-destructive method for the measurement of the degree of ripeness of plums was developed based on the measurement of the apparent modulus of elasticity.

2. It was found that plums at the consumption stage of maturity should have a modulus of elasticity between 0.100–0.250 MPa and that the optimum of ripeness is at 0.150 MPa (probe diameter 6 mm).

3. The method developed allows information to be obtained on the variability of elasticity (maturity) within the tree on the day of picking and during storage.

4. The measurement of the apparent modulus of elasticity may be substituted by the measurement of the coefficient of elasticity using a hand-held instrument.

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