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Adaptation of current silage towers Vítkovice for grain crops treatment and storage

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ABSTRACT: The project objective was to use current silage towers Vítkovice for grain crops treatment and storage. In the project are presented results of measurements within the food grain crops treatment through intensive aeration in towers of unit storing capacity 750 tons. For these towers was suggested and verified the air-ventilation network of distributing and aerating channels. For the proper aeration there were used the medium-pressure fans (for each tower 2 aerating fans) being able to ensure a minimum 20 m^3 of air per 1 ton of stored grain within 1 hour. The highest attention was paid to the principal parameter – the output air speed from the stored grain layer at its intensive aeration. From the measured figures it resulted, that the average air output speed from the stored grain layer along the tower perimeter is 0.101 m/s, average air output speed in the tower centre, i.e. on the top of the pouring conus of height 1.8 m, is 0.027 m/s. It is evident from the measured values, that air output speed from the layer of stored grain in tower of unit storing capacity 750 tons is sufficient, therefore risk of the proof condensation layer creation and the stored grain deterioration is minimal.

Keywords: silage tower; grain crops; storage

For maintenance of biological and chemical properties of stored grain it is necessary to create a complex of premises to prevent the stored grain quality to decrease or to be deteriorated.

The project of the Research Institute of Agricultural Engineering in Prague 6-Ruzyně (RIAE) implemented an adaptation of current silage towers Vítkovice for treatment and storage of the food grain crops at the Agricultural joint stock company PODCHOTUCÍ, KŘINEC. The aim of the project was to utilize current silage towers Vítkovice for treatment and storage of food grain crops.

The food grain crops treatment and storage has its own specific problems, mainly the necessity to respect all requirements for healthy nourishment different from treatment and storage of all other grain crops. At present the treatment of stored grain in containers is solved by active aeration at considerable unequality of the air output speed through the stored grain layer. Then some parts of the stored grain in storage space are "overdried", some reach standard moisture content and some parts have their moisture content higher than is the CSN Standard regulation. For the active aeration are often used unfavourable ventilators which do not comply with the requested parameters, i.e. air volume and requested pressure. Therefore, the food grain crops treatment and storage demand significant care and the harvest must be performed at the full ripeness and the grain treatment should be approached by intensive aeration of the stored grain.

DESCRIPTION OF THE ADAPTATION

On the basis of the previous experiences and analysis of the present state, RIAE has suggested the ventilation system built-in to the footing plate for the silage towers Vítkovice, type OH 09132. The tower diameter is 8.57 m, height 20.1 m.

The current silage towers adapted for treatment and storage of grain crops have undergone the statistical testing to find out conditions for storage of grain in total volume of the tower with respect to the strength and stable resistance of the tower casing. According to the statical assessment the current silage towers Vítkovice, type OH 09132 (brown line) may be loaded and unloaded through centre and thus their maximum capacity 750 tons of stored grain is fully utilized.

The proper adaptation is based on the construction of the aerating channels placed on the current footing plate inside the tower. The concrete consumption per 1 tower is about 25 m^3. Each tower is fitted by two medium-pressure aerating fans enabling to supply min. 20 m^3/h of air per 1 hour related to 1 ton of stored grain. The main distributing channels of dimensions 0.5 × 0.5 m are covered by the wooden boards, the aerating channels are covered by special aerating sieves.

The results presented in this paper were acquired within the solution of the Research project of the Ministry of Agriculture of the CR No. 7068.

The aerating channels dimensions are 0.25 × 0.30 m, spacing between the aerating channels is 0.6 m.

The footing plate of each tower is divided by technological channel into two ideal halves. The technological channel dimensions are 0.7 × 0.5 m. The channel is covered by wooden boards with output holes for the grain discharging from the tower.

For the stored grain aeration are used the medium-pressure ventilators RSH-500 of the following parameters:

$V_v = 9{,}000$ m^3/h
$\Delta p_c = 2{,}000$ Pa
$P = 7.5$ kW

where: V_v – air volume,
Δp_c – overpressure,
P – input.

The intensive aeration of the stored grain is optimized by automated system operating the aerating ventilators in dependence upon the relative humidity of air charged by ventilators and stored grain temperature.

The maximum drying effect occurred in the moment when air of relative humidity up to 70% is being used for aeration and stored grain temperature does not exceed 30°C.

The automated regulation of the aerating ventilators needs following demands of the stored grain.

Adjusted values:

- maximum relative air humidity 70%
- maximum stored grain temperature 30°C.

1. The aerating ventilator switches on – when the stored grain temperature is higher than 30°C even when the relative air humidity exceeds 70%.

2. The aerating ventilator switches off – when the relative air humidity is above 70% and stored grain temperature is bellow 30°C.

3. The aerating ventilator switches on – when the relative air humidity is lower than 70% and stored grain temperature is lower than 30°C, in that case occurs the maximum drying effect.

4. The aerating ventilator switches on – when the relative air humidity is lower than 70% and stored grain temperature is higher than 30°C.

The stored grain temperature in the tower is indicated by the silotherms when the arrangement of individual sensors is such as to involve thermally whole cross section of the stored grain layer.

It corresponds with requirement for perfect and lossless air distribution in order for the grain to be regularly exposed to the air flow effects in the storage place and when spaces creation is prevented, where the air cannot reach the stored grain.

The long-time results of the investigation in practice proved, that the automated regulation of the aerating ventilators provides an optimal process of the grain aeration and thus decreases the power consumption by about 2 kW/h.

The aerating channels arrangements in the footing plate is presented in Fig. 1.

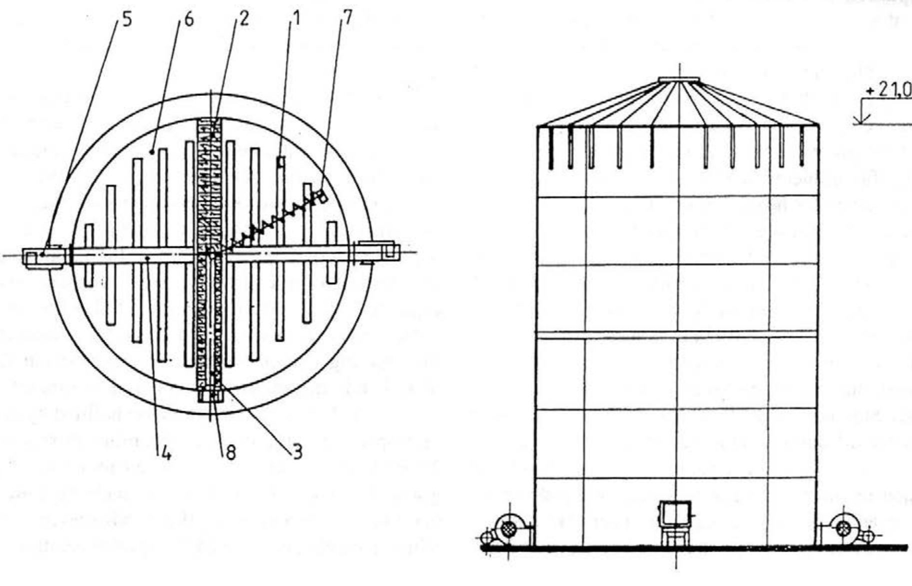

Fig. 1. Current silage tower Vítkovice – diameter 8.57 m – aeration
1 – aerating channels, 2 – technological channel, 3 – closure, 4 – distributing channel, 5 – aerating ventilator, 6 – increased bottom, 7 – unloading auger conveyer, 8 – belt conveyer

METHOD

The task of the investigation was to suggest and to verify grain treatment and storage by intensive aeration in adapted current silage towers Vítkovice of diameter 8.57 m and unit storing capacity 750 tons.

The adapted footing plate with suggested aerating channels was tested from point of view of ventilation system. The air output speed from the stored grain layer was measured by the vane anemometer. For precise recording of the air output speed from the stored grain layer a special trunkated pyramid-shaped equipment was produced, preventing the ambient air penetration. The base of this equipment is 1 × 1 m large. The air output speed from the stored grain layer inside the tower was measured in the four concentric circles, on each circle were provided ten measurements. The measured values were averaged. These measurements are the basic criterion for projecting the optimal air-ventilating network of the aerating channels. The stored grain temperature in the tower was indicated by the rope resistent thermometers suspended on the tower roof structure. The stored grain moisture content in tower was controlled by the moisture meter HE-50 directly at the working site.

RESULTS

The measurements of the ventilating system were focused to the air output speed investigation from the stored grain layer in the tower during intensive aeration.

The measurements were performed under following conditions:

- Stored grain weight (food wheat Hana) 720 tons
- Average moisture content (food wheat Hana) 14.9%
- Relative air humidity 61%
- Air temperature 24°C.

The air output speed from the stored grain layer was measured by the AIRFLOW anemometer. For precise

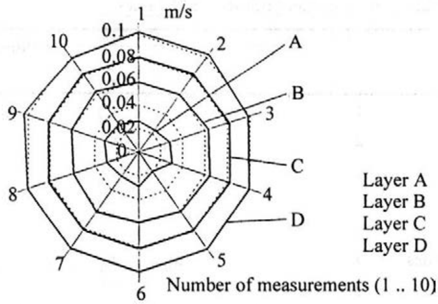

Fig. 2. Course of the air output speed in dependence upon the measuring points – food wheat Hana (Z.A.S. Křinec)

recording of the air output speed from the stored grain layer was used special trunkated pyramid shaped equipment preventing the ambient air penetration.

The air output speed from the stored grain layer inside the tower was measured according to the determined methodics in four concentric circles, 10 measurements was performed within each circle.

- Point A – concentric circle, diameter 2 m
- Point B – concentric circle, diameter 4 m
- Point C – concentric circle, diameter 6 m
- Point D – along the tower perimeter, i.e. diameter 8.57 m

The measured values are presented in Table 1.

The air output speed results from the stored grain layer were evaluated by the statistical methods of the dispersion analysis.

Considering two factors – *A* and *B* simultaneously effecting a certain statistical sign *X*.

Factor *A* has *m* levels $A_1, A_2 \dots A_m$ (by this factor all the observations may be assorted into *m* groups). The measured values are arranged according to Table 2.

The processed results of the air output speed from the stored grain layer in the tower are summarized in Table 3.

Table 1. Air output speed from stored grain layer in tower of unit storing capacity 750 tons (food wheat Hana)

Number of measurements	Air output speed (m/s) within individual grain layer points A	B	C	D	Average values (m/s)
1	0.026	0.059	0.083	0.102	0.068
2	0.027	0.060	0.082	0.103	0.068
3	0.028	0.063	0.082	0.098	0.068
4	0.026	0.064	0.084	0.099	0.068
5	0.025	0.061	0.082	0.100	0.067
6	0.029	0.059	0.082	0.101	0.067
7	0.028	0.062	0.081	0.100	0.067
8	0.025	0.059	0.083	0.101	0.067
9	0.027	0.061	0.084	0.104	0.069
10	0.029	0.063	0.083	0.098	0.068
Average values	0.027	0.061	0.083	0.101	0.068

Table 2. Arrangement of measured values

		Columns							Line sum	Line mean
		1	2		j		n		x_{i}	x'_{i}
	1	x_{11}	x_{12}	. . .	x_{1j}	. . .	x_{1n}		$x_{1\cdot}$	$x'_{1\cdot}$
	2	x_{21}	x_{22}	. . .	x_{2j}	. . .	x_{2n}		$x_{2\cdot}$	$x'_{2\cdot}$
	.									
	.									
	.									
Lines	i	x_{i1}	x_{i2}	. . .	x_{ij}	. . .	x_{in}		$x_{i\cdot}$	$x'_{i\cdot}$
	.									
	.									
	.									
	m	x_{m1}	x_{m2}	. . .	x_{mj}	. . .	x_{mn}		$x_{m\cdot}$	$x'_{m\cdot}$
Column sum x_{j}		$x_{.1}$	$x_{..2}$	. . .	$x_{.j}$	. . .	$x_{.n}$			
Column mean x'_{j}		$x'_{.1}$	$x'_{.2}$	. . .	$x'_{.j}$	. . .	$x'_{.n}$		$x_{..} = \sum_{i=1}^{m} x_{i.} = \sum_{j=1}^{n} x_{j}$	

Total mean $x'_{..} = \dfrac{x_{..}}{m\,.\,n} = \dfrac{1}{m\,.\,n}\sum_{i=1}^{m} x_{i.} = \dfrac{1}{m\,.\,n}\sum_{j=1}^{n} x_{j}$

From the measured values obtained by the dispersion analysis (double assortment, Tables 2 and 3) results a very significant difference between columns caused by the conus created during grain loading.

A considerable unequality of the air output speed from the stored grain layer is caused by the conus creating during the loading of tower. The rise of that conus above other layer is 1,500–2,000 mm, where the air

Table 3. Dispersion analysis at double assortment with one observance in each subclass

Dispersion analysis (double assortment)			
Variability	Sum of squares	Degree of freedom	Dispersion
Between lines	0.00	9	0.00
Between columns	0.03	3	0.01
Residual	0.00	27	0.00
Total	0.03	39	
Lines influence		Test criterion 0.53	
		No significant difference between lines	
Columns influence		Test criterion 3349.46	
		Highly significant difference between columns	
		Zero hypothesis probability is lower than 1%	

The contrast significance test between columns				
Columns		Difference	Criterion	Difference character
1	2	–0.03	27.99	Highly significant difference
1	3	–0.06	45.52	Highly significant difference
1	4	–0.07	60.20	Highly significant difference
2	3	–0.02	17.53	Highly significant difference
2	4	–0.04	32.21	Highly significant difference
3	4	–0.02	14.68	Highly significant difference
End of calculation				

Table 4. Processed results of air output speed from stored grain layer in tower of unit storing capacity 750 tons

Variability	Sum of squares	Degree of freedom	Dispersion	Testing criterion F
Between lines	$S_1 = \frac{1}{n} \sum_{i=1}^{m} x^2_{i.} - C$	$m - 1$	$s^2_1 = \frac{S_1}{m-1}$	$F_1 = \frac{s^2_1}{s^2_r}$
Between columns	$S_2 = \frac{1}{m} \sum_{j=1}^{n} x^2_{.j} - C$	$n - 1$	$s^2_2 = \frac{S_2}{n-1}$	$F_2 = \frac{s^2_2}{s^2_r}$
Residual	$S_r = S - S_1 - S_2$	$(m - 1)(n - 1)$	$s^2_r = \frac{S_r}{(m-1)(n-1)}$	
Total	$S = \sum_{i=1}^{m} \sum_{j=1}^{n} x^2_{ij} - C$	$mn - 1$		

where: $C = \frac{x^2..}{m \cdot n}$

n – set extent,
m – number of groups,
x – general independent variable.

output speed is lowest (0.025 m/s), but sufficient for prevention of the tight condensation layer creation.

THE STORED GRAIN TEMPERATURE AND HUMIDITY

The stored grain temperature was indicated by the rope resistant thermometers suspended on the roof construction of each tower. These thermometers are a part of the automatics controlling the aerating ventilators in dependence upon the air relative humidity suctioned by the ventilators and stored grain temperature. In each tower are located three rope thermometers (silotherms) arranged in four measuring points to cover thermally whole cross section of the stored grain layer in tower. The stored grain temperature was investigated in tower loaded by the food wheat Hana. The temperature was controlled and registered three times every day always at 7.00, 13.00 and 18.00 o'clock. The investigated period lasted from 6. 8. 1999 to 19. 10. 1999. From the measured values there were determined average temperatures and their courses within 6. 8.–7. 9. are presented in graphs in Fig. 3 in dependence on the time of storage. The ambient air temperature course investigated always at 7.00 and 18.00 o'clock is always presented in graph of Fig. 3.

It resulted from the measured values, that the stored grain temperature fluctuation in the tower is caused by the ambient air temperature and own respiration of the stored grain. The stored grain is a living material, its respiration and especially moisture produces an excessive amount of heat. There exists a basic dependence between humidity, stored grain temperature and appropriate time of storing, which is indirectly proportional to the grain moisture content and temperature.

The average moisture content of food wheat stored in the tower was 14.9%. The samples were taken every day at 7.00 and 18.00 o'clock from the bottom and upper parts of the stored grain. From the measured values were determined average daily figures of the stored grain moisture content. Average values of the reduced m.c. of the stored grain at intensive aeration (stored grain was aerated 1–1.5 hours daily due to its conditionning) in dependence upon the storing time are evident from Fig. 5.

The found dependence has a non-linear character and its course may be expressed by the polynomic function of second order:

– upper layer
$y_1 = 0.0004\,x^2 - 0.0687\,x + 14.971$
$I_{yx} = 0.9147$
– bottom layer
$y_2 = 0.0004\,x^2 - 0.0849\,x + 14.968$
$I_{yx} = 0.9232.$

For the both relationships the correlation index I_{xy} was determined which proved that in both cases exist very strong correlation dependences of precise truthfulness.

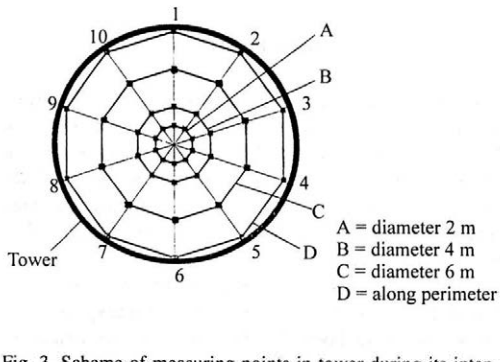

Fig. 3. Scheme of measuring points in tower during its intensive aeration

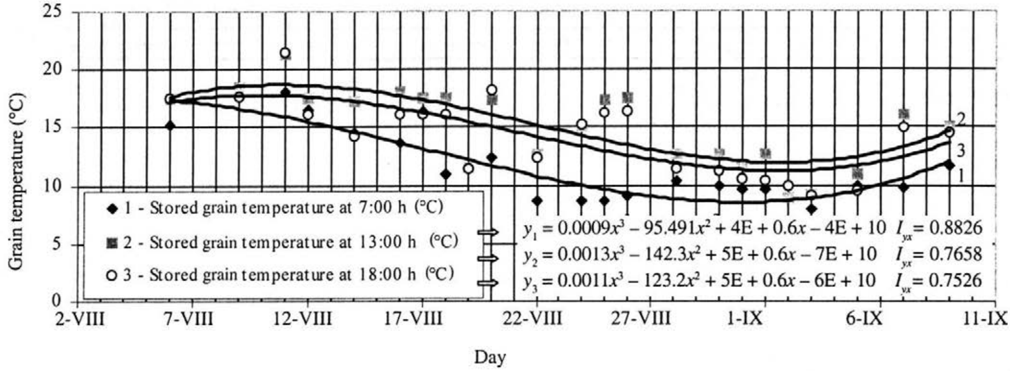

Fig. 4. Stored grain temperature (food wheat Hana)

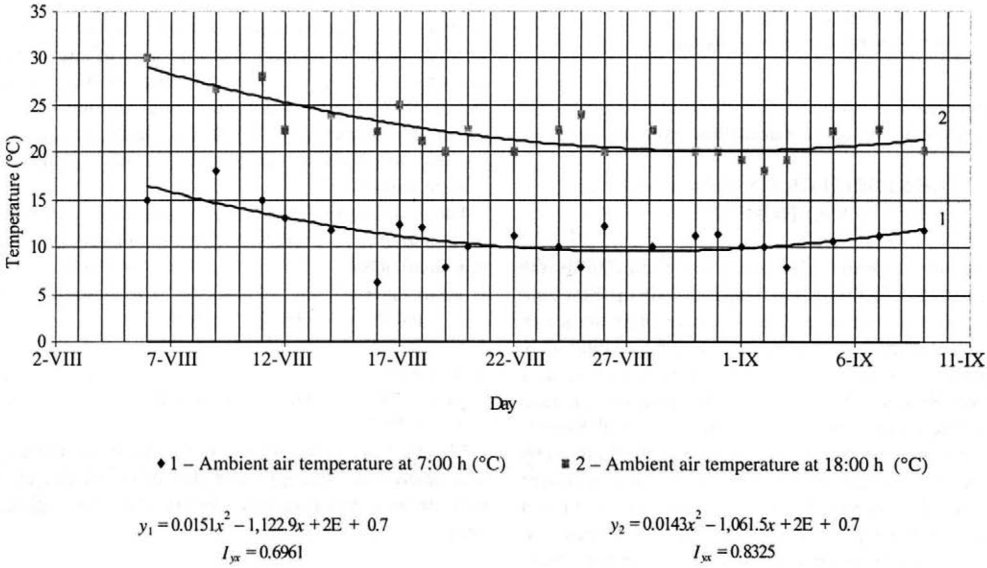

Fig. 5. Ambient air temperature

DISCUSSION

The obtained results show, that the food grain crops treatment for rational nourishment in adapted towers Vítkovice, type OH 09132 by means of the intensive aeration fully corresponds with the Standard ČSN 46 1000 – 2 requirements. In that standard are presented requirements for initial raw material (wheat) before its final processing.

The basic criterion of the intensive aeration of the stored grain in storage site is the air output speed from the stored grain layer. It resulted from the measured values, that the air output speed is sufficient, thus there is no risk of the tight condensation layer aeration.

For the intensive aeration is necessary to use medium-pressure ventilators which are able to ensure a sufficient air volume, i.e. min. 20 m^3/h per 1 ton of stored grain and overpressure min. 1,500 Pa.

The measured values proved, that a cosiderable difference of the air output speed from the stored grain in tower is between the columns (Table 2) caused by the conus originated during the grain loading into tower. Between individual measured values within the same concentric circle does not exists any significant difference, i.e. the air-ventilating distributing system is optimal.

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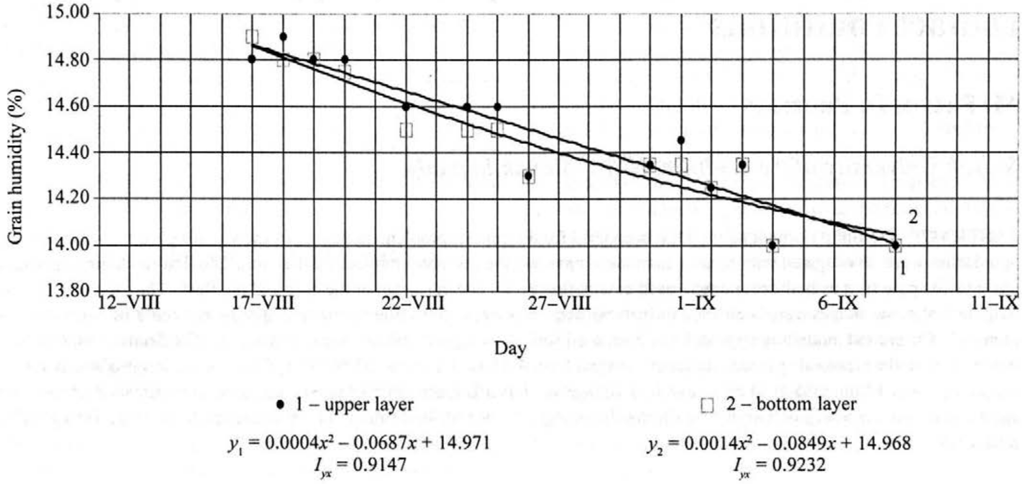

Fig. 6. Grain humidity (food wheat Hana)

Adaptace silážních věží typu Vítkovice pro ošetření a skladování zrnin

ABSTRAKT: Cílem řešení bylo využít stávající silážní věže typu Vítkovice pro ošetřování a skladování zrnin. V práci jsou uvedeny výsledky měření při ošetřování potravinářských zrnin intenzivním provzdušňováním ve věžích o jednotkové skladovací kapacitě 750 t. Pro tyto věže byla navržena a ověřena vzduchoventilační síť rozvodných a provzdušňovacích kanálků. K vlastnímu provzdušňování byly použity středotlaké ventilátory (na každou věž dva provzdušňovací ventilátory), které jsou schopny zajistit min. 20 m³ vzduchu na 1 tunu uskladněného zrna za 1 hodinu. Největší pozornost byla věnována hlavnímu parametru – výstupní rychlosti vzduchu z vrstvy uskladněného zrna při jeho intenzivním provzdušňování. Z naměřených hodnot vyplývá, že průměrná výstupní rychlost vzduchu z vrstvy uskladněného zrna po obvodu věže je 0,101 m/s, průměrná výstupní rychlost vzduchu uprostřed věže, tedy na vrcholu násypného kužele, jehož výška byla 1,8 m, je 0,027 m/s. Z naměřených hodnot vyplývá, že výstupní rychlost vzduchu z vrstvy uskladněného zrna ve věži o jednotkové skladovací kapacitě 750 t je dostatečná, takže nehrozí nebezpečí vzniku neprodyšné kondenzační vrstvy a tím znehodnocení uskladněného zrna.

Klíčová slova: silážní věž; zrniny; skladování

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Modelling of the frequency response of apples during contact conditions

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ABSTRACT: The finite element method has been used for the contact problem modelling of the vibrating fruit. Two modelling approaches were investigated with respect to mode shapes and the resonant frequency extraction. The first modelling approach considered apple fruit as body with empty seed cavity, the second one consisted of the core and the flesh. The torsional and the longitudinal mode shapes have been used for natural frequency evaluation. Both modelling approaches could be considered as identical. The second modelling approach has been used for following the firmness index evaluation. The firmness index determinated using the torsional resonant frequency ranged from 4.51 $10^4/kg^{2/3}/s^2$ to 55.86 $10^4/kg^{2/3}/s^2$, for the longitudinal resonant frequency ranged from 6.85 $10^4/kg^{2/3}/s^2$ to 84.75 $10^4/kg^{2/3}/s^2$. Laser Doppler interferometry was used as verification experiment for the resonant frequency determination during the storage. Values of the firmness index decreased from 23.91 $10^4/kg^{2/3}/s^2$ to 8.91 $10^4/kg^{2/3}/s^2$.

Keywords: apples; finite element method; firmness; contact

Increasing demand for a quality evaluation motivates the developement of the acceptable non-destructive test methods. The quality evaluation of the fruits is largely based on their physical properties assessment. Thus certain physical factors depose an important quality indicators such as degree of maturity, predicted shelf life, the optimum harvest day, the postharvest treatment, etc. There are particular methods for measurements of the selected physical properties. These methods are based on the measurement of the acoustic response (LILJEDAHL, ABBOTT 1994; DUPRAT et al. 1997), compress tests (MIZRACH et al. 1992), ultrasonic response (UPCHURCH et al. 1987), analysis of near infrared spectrum (LAMMERTYN et al. 1998), nuclear magnetic resonance (CHEN P. et al. 1989) and RTG and gamma radiation (CHEN, SUN 1991).

Generally, firmness is one of the most important factors characterizing physiological degree of maturation. Usually, firmness could be determined by the force and the corresponding deformation using destructive or non-destructive methods (STEIMETZ et al. 1996), or the non-destructive accoustic resonance tests (ARMSTRONG et al. 1997). During the past three decades, a huge effort has been made in the acoustic non-destructive firmness sensing. Acoustic and mechanical impulse have been used as an excitation so far. Based on these methods, the resonance frequency is measured in the defined frequency range for the material properties determination. The study of the response at the sonic excitation impulse shown an effects of the density, the weight and the resonant frequency at the fruit firmness (ABBOTT, LILJEDAHL 1994). An investigation of the mechanical impulse effects suggests change in the overall frequency response due to the location of the transducer, fixation and the size (CHEN P. et al. 1992).

Considering the complex physical problem of the vibrating fruit's frequency response, the numerical simulation gives a suitable solving techniques for this purpose. The finite element method (FEM) was successfully used for the mode shape determination of the vibrating fruit (CHEN H. et al. 1996; LU, ABBOTT 1997).

The objectives of the presented work are:

– to compare two different modelling approaches considering the contact problem,

– to determinate the firmness index for both finite element models considering different masses of the fruits,

– to compare the firmness indexes gained from numerical simulation and laser Doppler interferometry with respect to the storage period and different masses of the fruits.

MATERIALS AND METHODS

TESTED APPLES

Four groups consisting of selected apples of variety Gala were subjected for the resonant frequency measurements during the five months each three weeks. Apples were selected according to the condition of the similar size and shape. Samples were picked from the same part of the tree. Apples were stored in controlled atmosphere

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(N_2 78–96%, CO_2 3%, O_2 1%) at 0°C. A humidity in storage tank ranged between 90–95%. The terms of the measurements are presented in the Table:

1	2	3	4	5	6
29.9.1999	20.10.1999	10.11.1999	1.12.1999	23.12.1999	14.1.2000

An ambient temperature ranged between 18°C and 22°C during the measurements.

LASER DOPPLER INTERFEROMETRY

Laser Doppler interferometry could be classified as non-destructive method assigned for velocity and displacement detection of the vibrating object (POLYTEC 1998). The low power He-Ne laser is used as a source of the coherent light. The beam leaving the source is splitted by the lens assembly into an object beam and a reference beam. The object beam focused at surface of the vibrating object induced by Doppler shift is backscattered and consequently intefers with the reference beam. Interference occurs in the straight direction, two coherent waves have the same phase in time. The frequency difference between the object beam and the reference beam causes an intensive modulation of the light. Decoded modulation gives velocity and displacement values. The whole facility consists in an optic interferometric probe and an electronic control unit. The electronic control unit demodulates the signal outgoing from the optical head of the interferometric probe and creates an analog voltage output signal which is proportional to velocity and displacement of the vibrating surface. The quality of output signal is determinated by linearity, accuracy, resolution and dynamic range. Doppler frequency shift induced by vibrating object modulates 40 MHz carrier signal generated in Bragg cell. Using velocity decoding, the information is gained from the frequency modulated signal containing changes of the frequency and generates the velocity output.

The information containing displacement of the vibrating object is given by the phase of Doppler signal which directly relates to displacement. The physical operating principle is given in the work (BROZMAN, KUBÍK 2000). The tested apple was stem suspended and subjected to sinusoidal acoustic signal in the frequency range from 200 Hz to 2,000 Hz. Low frequency generator was used as source of acoustic signal in the given frequency range. Amplified signal was sent into a speaker. A distance between the speaker and apple was set at 2–5 cm. The laser beam was focused at the lower part of the tested fruit at the opposite point of apple with respect to the excitation. The distance between the laser optical head and vibrating fruit was set at 17 cm. Software facility of Doppler vibrometer allowed recording of the resonant frequencies during vibration. Each resonant peak was recorded into data file. Recorded values of the resonant frequency contained information about absolute displacement during vibration. Thus, the frequency spectrum of the vibrating fruit was obtained.

THE FINITE ELEMENT SIMULATION

The finite element method was used for the modal response and the contact problem simulation. The finite element software LUSAS (FEA Ltd., Forge House, 66 High Street, Kingston Upon Thames, Surrey, KT1 1HN, United Kingdom) was used for this purpose. Performed modal analysis determinated the deformed shapes (modal shapes) of the structure at the natural frequency. Modal analysis is a technique for solving the reduced number of n unknown global displacements. Each structure may be considered as a combination of the finite number of elements with infinite number of the degree of freedom. Behavior of this complex system may be approximated by the finite number of equations. This number defines the dimensions of analysed problem, stiffness matrices, mass matrices, theoretical number of the resonant frequencies and modal shapes. The equation of the motion for structure with multiply degree of freedom can be written as follows:

$$[M]\{x\} + [C]\{\dot{x}\} + [K]\{x\} = \{F\} \qquad (1)$$

where: $[M]$ – thee mass matrix,
$[C]$ – the damping matrix,
$[K]$ – the stiffness matrix,
$\{F\}$ – the external force vector,
$\{x\}$ – the displacement vector.

For natural frequency analysis, the damping matrix and the external force vector is set to zero. Poles, the resonant frequencies, damping factors, residuals may be considered as modal parameters. There is a possibility to deduce these parameters from dynamic experiments. Solution of the frequency response using acceleration $\{\ddot{x}\} = -\lambda_i \{x\}$ and consequently eigenvalue $\lambda_i = \omega_i^2$ leads to:

$$([K] - \omega^2 [M])\{\Phi_i\} = 0 \qquad (2)$$

where ω represents the circular frequency. Nodal displacement vector $\{x\}$ can be written as the sum of orthogonal eigenvectors Φ_i as follows:

$$\{x\} = y_1\Phi_1 + y_2\Phi_2 + \ldots + y_n\Phi_n = [\Phi]\{Y\} \qquad (3)$$

where: $[\Phi]$ – the eigenvector matrix,
y – the factor to vectors so that their sum equals $\{x\}$.

The matrix $[\Phi]$ contains m eigenvectors for the equation of the system (2). Using (3) this equation can be written as follows:

$$[M][\Phi]\{\ddot{Y}\} + [K][\Phi]\{Y\} = 0 \qquad (4)$$

During the finite element simulation, the contact behavior was modelled. For this purpose, slidelines were used to model the contact. Each slideline comprises two surfaces, the master surface and the slave surface (FEA Ltd. 1999). However for three dimensional slideline surfaces the assignment of the master and the slave surface is irrelevant, so this assignment was neglected. Considering numerical simulation during the eigenvalue extraction the sliding option was used. This assigned option allowed to model a mutual contact interaction between apple and steel plate in the three dimensional space with respect to the constant contact conditions. The slideline option is based numerically on the penalty function method. This algorithm allows an interaction of surfaces upon contact and imposes interaction forces to prevent penetration. A penalty constraint is introduced between the penetrating node of the finite element and the element of surface to be penetrated. The algorithm has symmetrical nature, the contact surface nodes are considered in determining the presence of the contact. In addition, the method is quite simple.

For numerical simulation, two three-dimensional finite element models were created. The first modelling approach considered only material properties of the flesh (Model 1). The core was not modelled. The second approach considered the core for numerical simulation (Model 2). In both cases, apple was modelled with H/D ratio 0.8. H represent the mean value of the apple height and D means the equator diameter. The whole apple was considered as an elastic body with isotropic material properties. For both models, Young's modulus varied in the range from 2 MPa to 20 MPa with 2 MPa increment. Assigned value of Poisson's ratio was considered as 0.3, the mass density was determinated by value of 880 kg/m^3. Steel plate was modelled as isotropic rigid body, assigned value of Young's modulus was set at 210 MPa, the mass density was 7,800 kg/m^3, Poisson's ratio was determinated by value of 0.3.

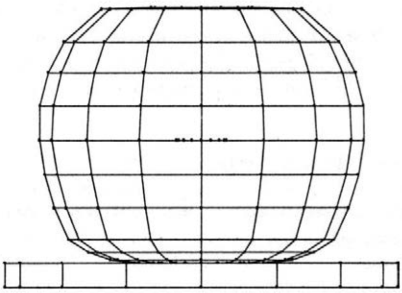


Fig. 1. Modelled contact problem describing mutual interaction between apple and plate

An influence of the both modelling approaches and the contact conditions was studied during the finite element simulation. The frequency response of the whole configuration was evaluated by mode shapes and corresponding resonant frequencies. The first 20 modes were extracted and investigated.

A specified number of the eigenvalues and the corresponding eigenvectors was solved using subspace iteration. This technique starts the solving procedure by establishing the number of starting iteration vectors with respect to the required eigenvalues and the convergence considerations. The following procedure is a projection of these vectors into subspace consequently solved using Jacobi iteration. The eigenvalues and the eigenvectors are approximated from the iteration vectors. The eigenvectors of this reduced problem are then transformed into the full new form containing iteration vectors. The process continues since the convergence is achieved. The all process of solution is completed by calculating the error estimates. This value gives the notion about the precision of the eigenvalue and the eigenvector evaluating. The specific error ε is given by:

$$\varepsilon_i = \frac{\left\| [K]\{\Phi_i\} - \lambda_i [M]\{\Phi_i\} \right\|_2}{\left\| [K]\{\Phi_i\} \right\|_2} \qquad (5)$$

where: $\{\Phi_i\}$, λ_i represents the eigenvector and eigenvalue of the solution.

THE FIRMNESS INDEX DETERMINATION

Generally, firmness was determinated according to following equation (COOKE, RAND 1973):

$$FI = f^2 m^{\frac{2}{3}} \qquad (6)$$

where: f – the resonant frequency,

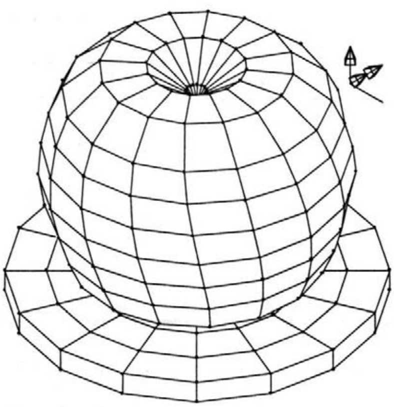
m – the mass of the fruit.

Two different notations are used in the presented work. In the following we use the experimental firmness index determined by laser Doppler interferometry as FI_{exp} and the theoretical firmness index determined by FEM as FI_{theor}. The torsional resonant frequency and the longitudinal resonant frequency from the finite element modelling were used for the firmness index determination as well as the resonant frequencies gained from laser Doppler interferometry. The mass of the fruit ranged from 0.16 kg to 0.22 kg with 0.02 kg increment.

RESULTS AND DISCUSSION

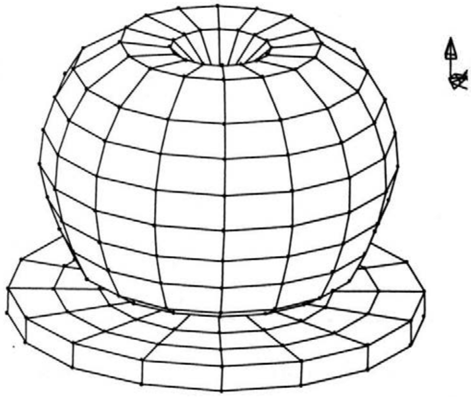
RESULTS OF THE FINITE ELEMENT MODELLING

The results of the finite element modelling represent mode shapes and the corresponding resonant frequencies. The torsional mode shape and the longitudinal mode shape were detected with the corresponding torsional resonant frequency and the longitudinal resonant frequency for both models (Fig. 2). Rigid body mode shapes were detected in the frequency range from 140.54 Hz to 345.23 Hz. These types of mode shapes were not taken into account because they can not be detected by dynamic tests. For both modelling approaches, the torsional resonant frequency was detected in the range from 391.49 Hz to 1,238.01 Hz. The longitudinal resonant frequency varied from 482.24 Hz to 1,524.88 Hz. The small differences were observed in the dependency between assigned Young's modulus and determined resonance frequencies. The values of the torsional resonant frequency ranged from 391.494 Hz to 1,238.01 Hz for Model 1 and from



a

Fig. 2a. The torsional mode shape



b

Fig. 2b. The longitudinal mode shape

391.465 Hz to 1,237.9 Hz for Model 2. The values of the longitudinal resonant frequency ranged from 482.235 Hz to 1,524.88 Hz for Model 1 and from 476.75 Hz to 1,507.37 Hz for Model 2. It could be stated that the used modelled approaches make no difference in the terms of gained relationship between Young's modulus and the resonance frequency. Model assuming material properties of the core (second modelling approach – Model 2) was used in the following firmness index determination. This approach is to be likely modelling the real situation. The coefficients of determination and the polynomial coefficients for both the finite element models are presented in Table 1. The regression equation has the following form: $Y = a + bx + cx^2 + dx^3$.

Values of the torsional resonant frequency are smaller than values of the longitudinal resonant frequency for both modelled approaches. This shift in order of mode shape is in coincidence with the previous findings (CHEN, DE BAERDEMAEKER 1993). The extracted resonant frequencies from the finite element modelling were used for the firmness index determination using equation (6).

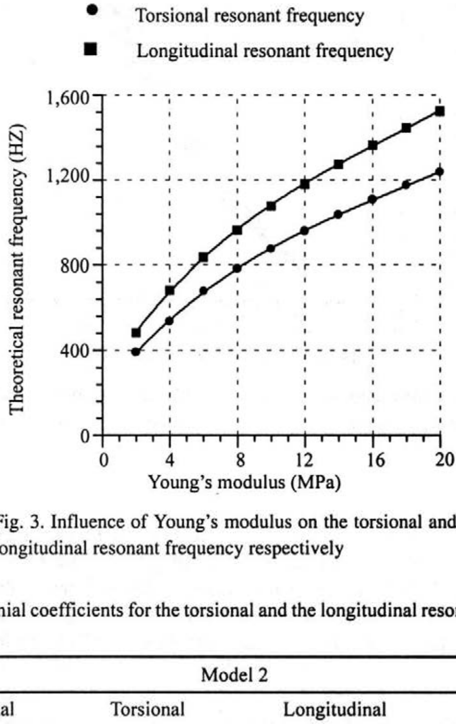


Fig. 3. Influence of Young's modulus on the torsional and the longitudinal resonant frequency respectively

Table 1. Values of the coefficients of determination and the polynomial coefficients for the torsional and the longitudinal resonant frequency for both modelling approaches

	Model 1		Model 2	
Coefficient of determination	Torsional	Longitudinal	Torsional	Longitudinal
Degree 0	0	0	0	0
Degree 1	0.978483	0.978464	0.978057	0.978479
Degree 2	0.998304	0.998302	0.998594	0.998304
Degree 3	0.999819	0.999818	0.999844	0.999819
Polynomial coefficient	Torsional	Longitudinal	Torsional	Longitudinal
a	219.036	266.76	214.248	269.829
b	95.5124	116.323	94.7915	117.659
c	–3.67767	–4.48011	–3.5104	–4.53071
d	0.072824	0.088717	0.0667212	0.0897176

Table 2. Values of the coefficients of determination and polynomial coefficients for torsional resonant frequency corresponding to torsional mode shape for Model 2. Regression function: $Y = a + bx + cx^2$

Coefficient of determination	m = 0.16 kg	m = 0.18 kg	m = 0.20 kg	m = 0.22 kg
Degree 0	0	0	0	0
Degree 1	0.97865	0.97865	0.97865	0.97865
Degree 2	1	1	1	1
Polynomial coefficient	m = 0.16 kg	m = 0.18 kg	m = 0.20 kg	m = 0.22 kg
a	–2.39E-006	5.84E-006	–2.39E-006	–3.75E-006
b	7.57E-009	–1.92E-008	7.56E-009	1.28E-008
c	2.95E-005	3.19E-005	2.95E-005	3.64E-005

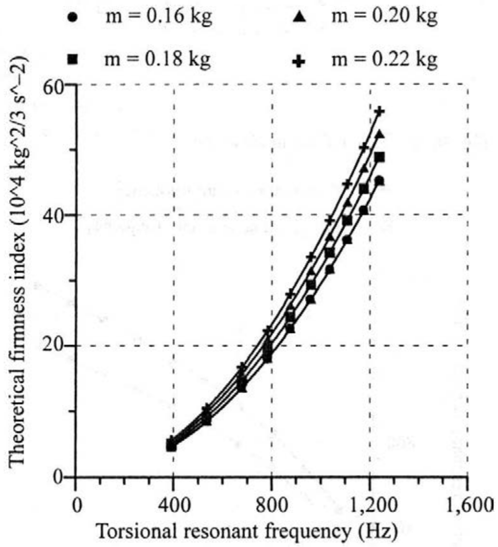


Fig. 4. Dependency of the firmness index on the torsional resonant frequency for different masses, Model 2, torsional mode shape

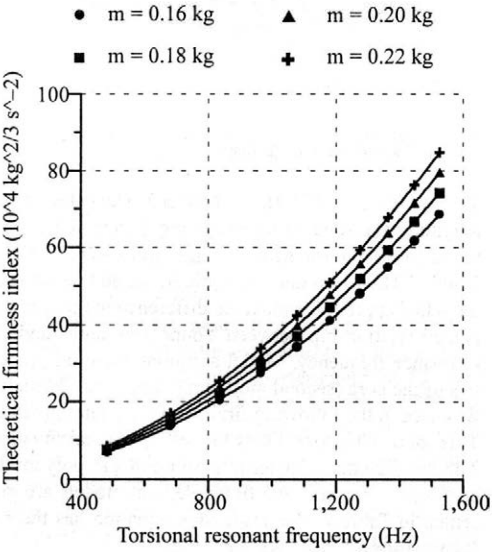


Fig. 5. Relationship between the longitudinal resonant frequency and the firmness index for different masses, Model 2, longitudinal mode shape

The firmness index was calculated for different values of the mass. This dependency is presented in the Figs. 4 and 5. Differences in the values of the firmness index gained by the finite element simulation using Young's modulus of the model which equals to 2 MPa is for the torsional resonant frequency 1.07 10^4/kg$^{2/3}$/s^2, for the longitudinal resonant frequency 1.62 10^4/kg$^{2/3}$/s^2. On the contrary, using assigned 20 MPa Young's modulus causes 10.69 10^4/kg$^{2/3}$/s^2 and 16.22 10^4/kg$^{2/3}$/s^2 change for the torsional and for the longitudinal resonant frequency re-

Table 3. Values of the coefficients of determination and the polynomial coefficients for the longitudinal resonant frequency corresponding to longitudinal mode shape for Model 2. Regression function: $Y = a + bx + cx^2$

Coefficient of determination	m = 0.16 kg	m = 0.18 kg	m = 0.20 kg	m = 0.22 kg
Degree 0	0	0	0	0
Degree 1	0.97848	0.97848	0.97848	0.97848
Degree 2	1	1	1	1
Polynomial coefficient	m = 0.16 kg	m = 0.18 kg	m = 0.20 kg	m = 0.22 kg
Degree 0	–1.05E-005	9.84E-006	1.37E-005	9.26E-006
Degree 1	–2.35E-008	–2.21E-008	–3.15E-008	–2.01E-008
Degree 2	2.95E-005	3.18E-005	3.42E-005	3.64E-005

Table 4. Values of the coefficients of determination and the polynomial coefficients for the firmness index calculated from the results of laser Doppler interferometry. Regression function: $Y = a + bx + cx^2$

Coefficient of deterimation	m = 0.16 kg	m = 0.18 kg	m = 0.20 kg	m = 0.22 kg
Degree 0	0	0	0	0
Degree 1	0.996704	0.996704	0.996704	0.996704
Degree 2	1	1	1	1
Polynomial coefficient	**m = 0.16 kg**	**m = 0.18 kg**	**m = 0.20 kg**	**m = 0.22 kg**
a	2.99E-005	–1.26E-005	–8.33E-005	2.99E-005
b	–8.59E-008	3.352E-008	2.47E-007	–8.59E-008
c	2.94E-005	3.18E-005	3.42E-005	2.94E-005

spectively. Polynomial of degree 2 was used for the curve fitting in both cases.

RESULTS OF LASER DOPPLER INTERFEROMETRY

The results gained from laser Doppler interferometry were used for the firmness index dependency construction.

Values of the resonant frequency decreased during the storage period. The constructed values of the firmness index depended on the mass values. The influence of the mass at overall firmness index is presented in the Figs. 6 and 7. Increase in values of the resonant frequency causes an increase in the firmness index values (Fig. 6). The polynomial fit of degree 2 $Y = a + bx + cx^2$ was used for the curve fittings. A gradual fall in the firmness index values was observed during the storage period for all masses of the fruit (Fig. 7). The dependency between the firmness index and storage period is described by exponential function in the form: $y = Ae^{-0.05x}$ according to the best value of the R^2. Values of the exponential coefficients are presented in Table 5 along with the coefficients of determination. The larger variation of the firmness index may be seen in the earlier stages of the storage with respect to changes in the mass. At the beginning of the storage, the difference in the firmness index values was 4.58 $10^4/kg^{2/3}/s^2$, lately after 15 weeks this difference was 2.11 $10^4/kg^{2/3}/s^2$.

CONCLUSION

The finite element modelling was used for numerical simulation of the apples frequency response during contact conditions. Two different modelling approaches were considered. No significant differences were observed between the first and the second modelling approach. The

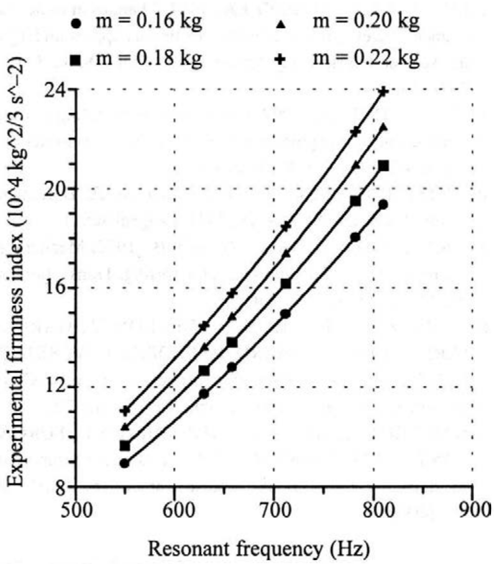


Fig. 6. Dependency between the firmness index and resonant frequency

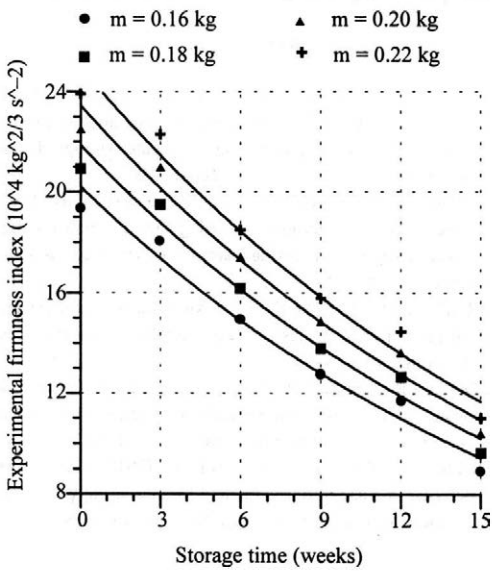


Fig. 7. Relationship between the firmness index and storage time for Gala variety

Table 5. Values of the coefficients of determination and the exponential coefficients for the firmness index of variety Gala, regression function $y = Ae^{-0.05x}$

m	0.16 kg	0.18 kg	0.20 kg	0.22 kg
A	20.2011	21.8511	23.441	24.9786
R^2	0.974685	0.974685	0.974685	0.974685

values of the torsional resonant frequency ranged from 391.494 Hz to 1,238.01 Hz for Model 1 and from 391.465 Hz to 1,237.9 Hz for Model 2. The values of the longitudinal resonant frequency ranged from 482.235 Hz to 1,524.88 Hz for Model 1 and from 476.75 Hz to 1,507.37 Hz for Model 2. There was not observed any direct difference in the values of the resonant frequencies for both modelling approaches. The finite element model considering the core was used in the following the firmness index calculation. Calculated firmness indexes FI_{theor} using different masses varied from 4.51 10^4/kg$^{2/3}$/s^2 to 55.86 10^4/kg$^{2/3}$/s^2 and from 6.85 10^4/kg$^{2/3}$/s^2 to 84.75 10^4/kg$^{2/3}$/s^2 for torsional resonant frequencies and longitudinal resonant frequencies respectively. The values of the FI_{theor} for torsional resonant frequencies are lower than values of the FI_{theor} for longitudinal resonant frequency. As verification experiment, laser Doppler interferometry was used. The values of the resonant frequencies decreased during the storage period. At the beginning of laser Doppler interferometry, the difference in the firmness index values was 4.58 10^4/kg$^{2/3}$/s^2, later after 15 weeks this difference was 2.11 10^4/kg$^{2/3}$/s^2 for the given mass variation. The firmness index FI_{exp} varied from 23.91 10^4/kg$^{2/3}$/s^2 to 8.91 10^4/kg$^{2/3}$/s^2 during the storage period for used values of the mass.

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Modelovanie frekvenčnej odozvy jabĺk počas podmienok kontaktu

ABSTRAKT: V práci sa použila metóda konečných prvkov na modelovanie kontaktného problému vibrujúceho ovocia. Skúmali sa dva modelovacie prístupy, a to vzhľadom na modálne tvary a prislúchajúce rezonančné frekvencie. Prvý modelovací prístup uvažoval plod jablone ako plod s prázdnym jadrom, druhý prístup uvažoval model jablka, ktorý pozostával z dužiny a jadra. Pre ohodnotenie rezonančných frekvencií sa uvažovali torzné a pozdĺžne modálne tvary. Na základe týchto výsledkov je možné tieto dva prístupy považovať za totožné. Pre výpočet koeficientu tvrdosti sa uvažoval druhý modelovací prístup. Pre torznú rezonančnú frekvenciu sa koeficient tvrdosti pohyboval v rozsahu od 4,51 $10^4/kg^{2/3}/s^2$ do 55,86 $10^4/kg^{2/3}/s^2$, pre pozdĺžnu rezonančnú frekvenciu od 6,85 $10^4/kg^{2/3}/s^2$ do 84,75 $10^4/kg^{2/3}/s^2$. Ako verifikačný experiment sa použila laserová Dopplerovská vibrometria. Hodnoty koeficientu tvrdosti počas skladovania klesali z 23,91 $10^4/kg^{2/3}/s^2$ na 8,91 $10^4/kg^{2/3}/s^2$.

Kľúčové slová: jablká; metóda konečných prvkov; tvrdosť; kontakt

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REVIEW

Static mechanics and texture of fruits and vegetables

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ABSTRACT: Mechanical properties of fruits and vegetables form very important information on their quality. They pre-determine product usability as food for direct consuming as well as raw product for further processing. The quality aspect of mechanical properties is known as texture, originally determined by sensory panel test. Modern texture studies are based on objective instrumental test that give the exact and more complex information about the tested product. Most frequent traditional texture parameter is firmness, having its instrumental form since 1920s. This review describes the basic static tests that are used for determination of the texture of horticultural products. Application of different methods is used in relation to susceptibility to mechanical damage and static and impact bruising, and water induced surface cracking. Special properties of different products are analyses from point of view of the products' maturity and ripening. It is shown that for every product the special property for testing its mechanical properties has to be found.

Keywords: fruit; vegetable, firmness; texture; Young's modulus, bioyield; strength; cracking; bruising; berries; maturity; ripening

The mechanical properties of fruits and vegetables have been used in a number of applications. Mohsenin (1970) lists eight applications of mechanical properties: characterisation of the material; optimum time to harvest; optimum method of detachment; separation from undesirable materials; mechanical processing; texture, quality evaluation and control; damage in collection, handling and first group storage. These applications can be concentrated into two groups; firstly, for characterisation of the product including evaluation of its quality, and, secondly, for determining possible mechanical damage to the product, and methods of processing it mechanically. It is clear that determination of product properties can be applied, not only in the sphere of horticulture but also in the sphere of product processing.

Production of fruits and vegetables is a very complicated process, but – like the production of other plant products – it has four basic stages: the cultivation, harvesting, storage and product processing. The first two stages are controlled by farmers, while the other two are usually managed by processing companies or by distributors. Most of the products are sent to market immedi-

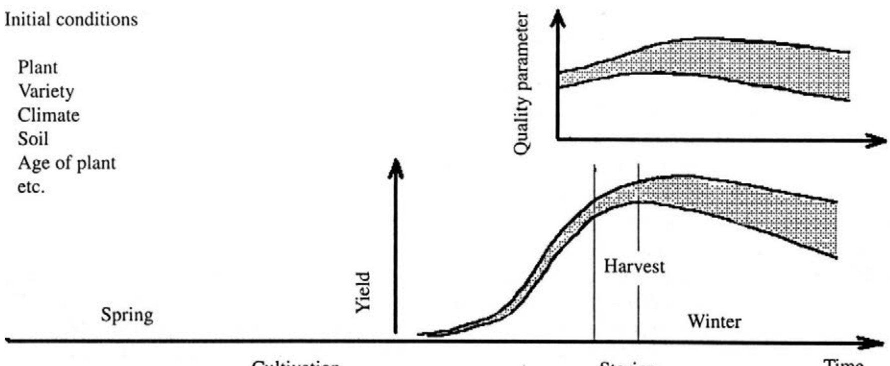


Fig. 1. Time development of plant production represented by yield production and one representative quality parameter. The grey area expresses possible variations of the yield and the quality of production dependent on initial conditions and modifications used in cultivation, harvesting and storage of the product

ately after harvest or after controlled storage. All the parameters of the production system determine the yield and also the product quality, as shown in Fig. 1. Product quality is represented by one hypothetical quality parameter; every real product system is characterised by many different quality parameters of various origins. The grey areas in Fig. 1 represent possible yields and quality values depending on the initial parameters, methods and parameters of cultivation (fertilising, spraying, water supply, etc.), time and methods of harvesting, and time and parameters of storage. Yields depend not only on the crop production potential but also on losses in all stages of production. Like the yields, the quality of the product also depends on the parameters of the production system. Every optimisation process of the production system (including product quality) consists in finding optimal alternatives of production parameters.

Product quality has to be determined by reliable objective tests. These include mechanical tests. Most mechanical tests involve determining the relation between contact mechanical force and changes caused in the dimensions and shape of the product – i.e., product deformation. This relation can be rationalised by the mechanical properties of the product. The mechanical tests described in this chapter are limited to the area of quasi-static deformations (JOHNSON 1985), i.e., to deformations performed at strain rates well below the term $\Delta\varepsilon v/l$, where $\Delta\varepsilon$ is the change in the strain, v is the sound velocity in the body, and l is its dimension. However, the actual strain rate has to be high enough to induce non-zero stress fields in the tested body. Biological mechanisms controlling the mechanical stresses in products are outside the scope of this chapter. Most of the tests under consideration were performed **at** constant deformation rates of 0.01–5 mm/s.

PHYSICAL BASIS OF MECHANICAL TESTING

Quasi-static compression tests form a group of many different kinds of tests with many different modifications. The common basis of all of the tests is the deformation curve obtained at constant deformation rate (Fig. 2) with four important characteristic parts: i) the initial (pre-Hookean or pre-Hertzian) part, ii) the quasi-elastic Hookean or Hertzian part, iii) the bioyield part, and iv) the irreversible deformations after the yield area. The lower yield point (see Fig. 2) is not observed in every deformation test, but it is typical for some types of tests (see e.g. the penetration test). A special role is played by the proportional limit or Hertzian limit (see Fig. 2), the points dividing the deformation curve into two parts: the lower deformations (so called quasi-elastic deformations) and the higher deformations (so called inelastic deformations). Tests performed at deformations less than PL (HL) are usually referred to as non-destructive, while tests which lead to higher deformations are referred to as destructive tests.

MECHANICAL TESTS

Mechanical tests can be classified in various ways, as follows:

– classification according to methods of loading
  – homogeneous tests (some most frequent modifications are displayed in Fig. 3). The formulas between stress and strain given in this figure can be applied only in the Hookean area, well below the proportional limit,
  – non-homogeneous tests (some more frequent modifications of tests of this type are given in Fig. 4).

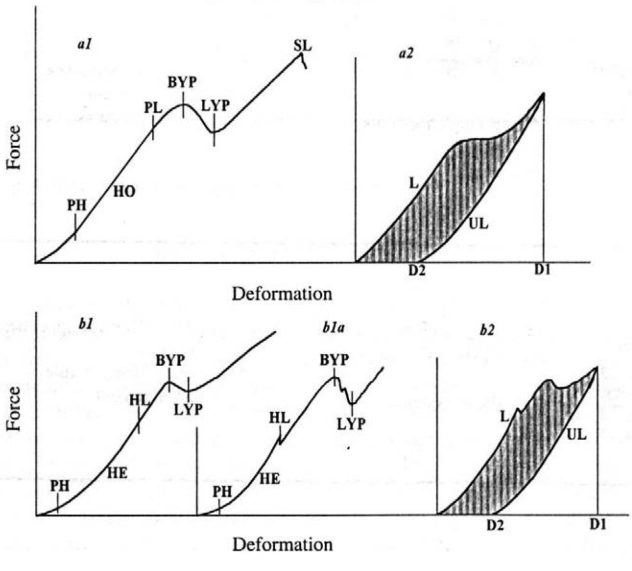


Fig. 2. The main characteristics of quasi-static deformation tests that can be determined directly from the deformation curves. a – pure tension, compression and shear tests and penetration of a cylindrical indentor with a flat tip; b – penetration of a cylindrical indentor with a spherical tip and compression of a round product between two plates (b1a is some modification of the compression curve b1). Simple compression test: PH – pre-Hookean area (a1) or pre-Hertzian area (b1 and b1a), HO – Hookean area, HE – Hertzian area, PL – proportional limit (a1), HL – Hertzian limit (b1 and b1a), BYP – bioyield point (also UYP – upper yield point), LYP – lower yield point, SL – strength limit (only for pure compression). The loading/unloading test (a2,b2): L – loading curve, UL – unloading curve, D1 – loading defomation, D2 – inelastic deformation, the filled area is the absorbed and/or dissipated energy

As in homogeneous deformations, the formula of this figure can be used only for elastic solutions (the deformation has to be lower than the proportional and/or Hertzian limits – see Fig. 2);

- classification according to intensity of loading
  - non-destructive testing – no damage to the tested product can be observed even after storage,
  - tests leading to bruising – tests that activate the enzyme browning of the loaded part of the product,
  - tests leading to damage – some part of the tested product is mechanically damaged.

Tests leading to bruising and/or damage are usually referred to as destructive tests

- classification according to time order of the test
  - loading tests with a constant deformation rate performed up to the defined level followed by quick unloading (*simple deformation test,* see Fig. 2, b1 and b1a),
  - loading tests with a constant deformation rate up to the defined level followed by controlled unloading at the same deformation rate (so called *loading/unloading tests,* see Fig. 2, a2 and b2),
  - loading tests up to the defined deformation level usually higher than PL or HL, followed by time analysis of stress (so called *relaxation tests*),
  - loading tests up to the defined stress level usually higher than PL or HL, followed by time analysis of deformation (so called *creep tests*).

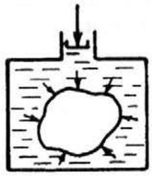
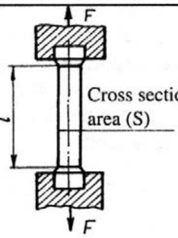
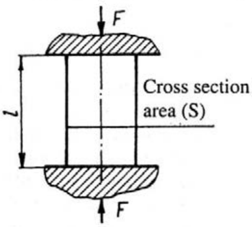
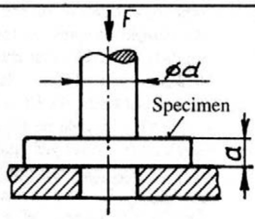
Type	Scheme	Relations	Notes
a. Hydrostatic compression		$\Delta p = -K \frac{\Delta V}{V}$ K – Bulk modulus p – pressure V – volume $K = \frac{E}{3(1-2\nu)}$	Tests of specimens and also whole products
b. Tension		$\varepsilon = \frac{\Delta l}{l} = \frac{F}{SE} = \frac{\sigma}{E}$ E – Young's modulus ε – strain σ – stress	Tests of specimens and some parts of the products
c. Compression		$\varepsilon = \frac{\Delta l}{l} = \frac{F}{SE} = \frac{\sigma}{E}$ E – Young's modulus ε – strain σ – stress	Tests of specimens and some parts of the products
d. Shear		$\gamma = \frac{F}{\pi G d a} = \frac{\tau}{G}$ G – shear modulus	Test of special specimens only; one of the possible arrangements

Fig. 3. Basic types of homogeneous deformation

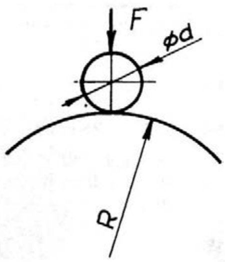
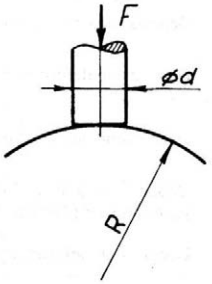
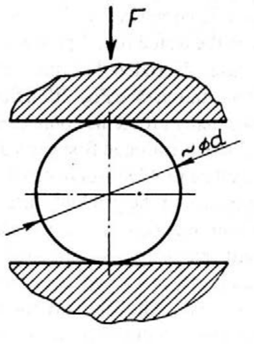
Type	Scheme	Relations	Notes
a. Indentor with spherical tip		$\bar{a}=\sqrt[3]{\frac{3F}{2E_Ax}}$; $x=\frac{2}{R}+\frac{4}{d}$ $\sigma_M=\frac{1}{\pi}\sqrt[3]{\frac{3FE_A^2x^2}{2}}$; $D=\frac{1}{2}\sqrt[3]{\frac{9F^2x}{4E_A^2}}$; $E_A=\frac{E}{(1-\nu^2)}$; $E_A=\frac{3}{4}F\sqrt{\frac{x}{2D^3}}$ $\bar{a}$ – radius of contact area σ_M – maximum normal stress D – penetration depth ν – Poisson's ratio	Tests of specimens and surface parts of various products (of radius R) E_A – apparent modulus
b. Spherical indentor with flat tip		$p(r)=\frac{F}{\pi d\sqrt{d^2/4-r^2}}$ $D=\frac{F}{E_Ad}$; $E_A=\frac{F}{Dd}$ p – tip pressure r – radial coordinate D – penetration depth ν – Poisson's ratio	Tests of specimens and surface parts of various products $d/2 << R$
c. Compression between two plates		$\bar{a}=\sqrt[3]{\frac{3FR}{4E_A}}$ $\sigma_M=\frac{1}{\pi}\sqrt[3]{\frac{6FE_A^2}{R^2}}$ $D=\sqrt[3]{\frac{9F^2}{2RE_A^2}}$ $E_A=\frac{3F}{\sqrt{2RD^3}}$ $R = d/2$ D – deformation of the product, see also type a	Deformation of whole products of spherical shape (of diameter d)

Fig. 4. Basic types of non-homogeneous deformations

TEST PARAMETERS

It is very difficult to describe simply the whole package of methods usually used for evaluation of all the quasi-static tests. This is why the procedures used for evaluation of stress relaxation and/or creep tests will not be described here. The deformation curves that can be obtained in simple and loading/unloading compression tests are briefly reviewed in Fig. 2. Fig. 2a (2a1 and 2a2) represents the typical deformation curves with linear (Hookean) quasi-elastic part of deformation, while Fig. 2b (2b1, 2b1a and 2b2) contains the compression curves with the power (Hertzian) quasi-elastic part of deformation. Both parts of quasi-elastic deformation are preceded by some part of irregular pre-Hookean and or pre-Hertzian deformations that are more frequent and expressive for deformation of flaccid agricultural products. This non-linear part of the deformation curve can easily be distinguished from the linear Hookean part in case a. The same operation is more difficult in case b, where the initial irregular part is non-linear, like as the Hertzian part. Moreover, the measured force increases very slowly with increasing small deformation in this case, so that it is very

Table 1. Basic parameters of mechanical tests

Parameter	Definition	Unit	Notes
Young's modulus (E)	Measure of slope of elastic part of deformation curve (Fig. 3)	(MPa)	Measure of consistency in texture profile analysis (TPA)
Apparent modulus of elasticity (E_A)	Measure of slope of elastic part of deformation curve in inhomogeneous tests (Fig. 4)	(MPa)	
Bioyield stress (BSS)	Stress corresponding to Bioyield point in Fig. 2	(MPa)	In TPA, BSS is denoted as fracturability (Fr)
Bioyield strain (BSN)	Strain corresponding to Bioyield point in Fig. 2	(–)	In Simplified TPA (BLAHOVEC et al. 1999a,b) BSN is denoted as initial elasticity (IE)
Strength (SSS)	Stress at point of rupture (strength limit in Fig. 2)	(MPa)	
Strain at strength limit (SSN)	Strain at point of rupture (strength limit in Fig. 2)	(–)	
Degree of elasticity (DE)	DE = (D1–D2)/D1 – see Figs. 2a2 and 2b2	(–)	Depends on deformation extent
Total work of loading (W_T)	Proportional to the area under the loading curve (L) in Figs. 2a2 and 2b2	(J)	Depends on deformation extent
Energy released (W_U)	Energy released during specimen unloading – proportional to the area under the unloading curve (UL) in Figs. 2a2 and 2b2	(J)	Depends on deformation extent
Energy absorbed (E_A)	$W_T - W_U$	(J)	Depends on deformation extent Also referred to as energy dissipated
Relative absorbed energy	E_A/W_T	(–)	Depends on deformation extent

difficult to determine exactly the initial points of the deformation curve.

Elastic theory can be used for describing of the quasi-elastic parts of the deformation curves (see also Figs. 3 and 4). This can be formulated for small deformation (i.e., for strain values lower than appr. 5%) in the following forms:

$$d\sigma = E\, d\varepsilon \quad (1)$$

for pure compression and tension, and similarly for the other cases in Fig. 3 (here E is Young's modulus of elasticity, σ – normal stress and ε – strain),

$$dF = E_A d^2\, d\varepsilon' \quad (2)$$

for penetration of the cylindrical indentor with a flat tip in the so called Boussinesq problem – see Fig. 4b (ε' – ratio of penetration depth to the diameter of the tip d),

$$dF = E_A d^2 \varepsilon''^{1/2}\, d\varepsilon''/2 \quad (3)$$

for penetration of a cylindrical indentor with a spherical tip in the so called Hertz problem – see Fig. 4a (ε'' – ratio of the penetration depth to the radius of the testing sphere – $d/2$) and

$$dF = E_A\, d^2 \varepsilon'''^{1/2}\, d\varepsilon'''/2 \quad (4)$$

for compression of a round product between two rigid plates – a special case of the Hertz problem – see Fig. 4c – (ε''' – ratio of compression deformation to the mean diameter d of the tested round product).

In many cases, Hertzian deformations are analysed in energy representation (see Fig. 2b2). Such a type of analysis excludes many problems connected with interpretation of the above mentioned first parts of the deformation curves, as well as problems connected with the inhomogeneous character of the product surfaces.

In most homogeneous tests, information about the strength limit can also be obtained (SL in Fig. 1a1), but in penetration tests (e.g., Fig. 2b1) only information on yield point is given. The bioyield point in this case contains information on the strength of the tested product. Similar problems also have to be solved in the deformation of compression specimens of large diameter and low height.

INTERPRETATION OF RESULTS

Several tens of different parameters can be defined and evaluated from deformation curves obtained under different experimental arrangements, different deformation and time regimes and product samplings. The most important of them are defined and characterised in Table 1. Some others, not so frequent, will be briefly described later in the text directly in relation to applications.

COMPOSITION AND STRUCTURE OF PRODUCTS

Every product can be classified under the source plant, divided into species, subspecies and/or varieties. More

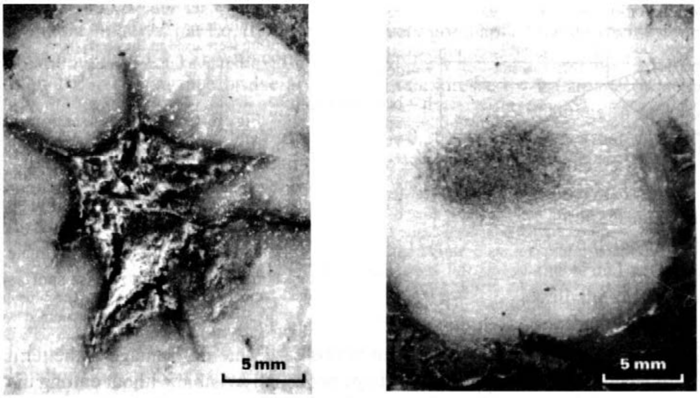


Fig. 5. Examples of internal mechanical damage (of potato tuber) initiated by external force: internal cracking (on the left) and internal bruising – black spot (on the right) – NOBLE (1985)

important in our case is the classification of fruits and vegetables into groups according to their appearance and use. These groupings are not very accurate but are very useful for our purpose. Consideration will be given to four categories of vegetable tissues, based on their appearance: roots, stems, leaves, and fruits. Various other categorisations of the products can be used (berries, bulbs, tubers, etc.) depending on country, weather conditions, culture, etc.

Fruit and vegetables consist mainly of parenchyma tissue with big cells (dimensions are given in tenths of a millimetre) of thin cell wall and very high water content (70–99% mostly concentrated in big vacuoles of the cells). These edible plant parts are characterised as flesh (apple flesh, vegetable flesh, etc.). The flesh parts are soft and juicy and their mechanical properties are turgor dependent. The parenchyma also contains air, concentrated in the inter-cellular space. The volume concentration of the air pre-determines the flesh density and other properties. The air concentration in the flesh is very variable: while the potato tuber contains less than 2 volume per cent of air, the apple fruit contains nearly 20% (CALBO, SOMMER 1987) or more (VINCENT 1990). Most products are covered by skin (epidermis – the thickness is usually given in tenths of mm), and contain some small supporting parts; the mechanical properties are then: Young's modulus 0.1–10 MPa and strength 0.1–3 MPa (BLAHOVEC 1988). The mechanical properties of the parenchyma, cover and supporting parts of the products move in very wide limits, and this variation forms the basis of the texture variability. There are further sources of fruit and vegetable variability: colour, composition, dimension, and other parts of the products as seeds, such as stones, and shells.

Table 2. Classification of mechanical damage in fruits and vegetables

Initiation Location/Character of damage	External	Internal
Surface/Macroscopic	breakage crushing splitting	surface cracks
Surface/Microscopic	peeling	surface micro-cracks
Internal/Macroscopic	cracking	
Internal/Microscopic	crushing, bruising	

Table 3. Evaluation methods used to classify surface mechanical damage

Type of product	Evaluation method
Table products	Two degrees: perfect and damaged
Products used for storage	Several degrees: based on extent of the heaviest damage (damage depth is a critical parameter in many cases – e.g., potatoes 3–5 mm)
Products for direct use (cooking and processing)	Several degrees: based on relative losses of product during the process (e.g., relative volume losses for potato)

Fruit and vegetable parenchyma has to be classified as non-homogeneous. Every product contains a vascular ring formed by firmer sclerenchyma cells (for potatoes, see VAN ES, HARTMAN 1981). Moreover, chemical composition, dry matter content and mechanical properties vary greatly in different parts of the product parenchyma (HUFF 1971). Most fruits and vegetables are strongly non-homogeneous products with strong anisotropy patterns; the periphery of fruits consists of radial flattened or spherical cells with spherical intercellular spaces. Towards the interior the cells increase in size and are radially elongated, organised into radial columns (e.g., apples – KHAN, VINCENT 1990).

Tissue firmness has its source in the cell walls and their carbohydrate cellulose, hemi-cellulose including pectic substances (VAN BUREN 1979), where crude fibre content plays a very important role (BLAHOVEC 1988).

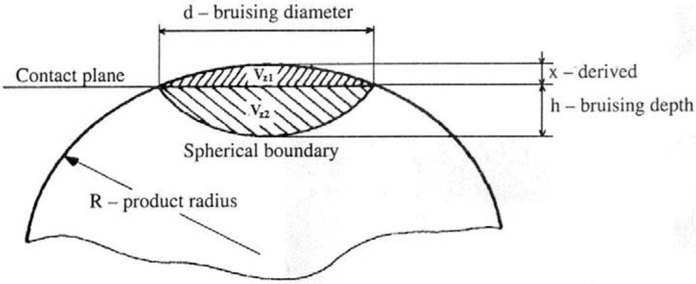


Fig. 6. Central cross-section of the surface bruise spot, located directly under the product skin. Two spherical parts determined by maximum spot diameter (d) and spot depth (h) approximate the volume of the bruise spot

SUSCEPTIBILITY TO DAMAGE AND BRUISING

Two different classes are usually distinguished for mechanical damage of vegetable and fruits (for potato tubers, see MCRAE 1985): external damage and internal damage (Table 2). External damage is damage visible without cutting the product open. The product skin is usually broken in this case. Internal damage is the term applied to damage not usually visible without cutting the product open, and comprises bruising and various forms of internal destruction (crushing and various forms of internal cracking). Bruising is usually understood as a change of the tissue properties, especially the tissue colour in some part of the tuber as a result of pressure or impact action. Bruising is not accompanied by any form of macroscopic separation of any parts of the tissue one from another. Bruising is the most frequent damage in the case of fruits. Tissue bruising can be directly observed as dark spots, but some incubation time in defined conditions is necessary for them to become observable. Internal cracks and black spot representing bruising of potato tubers are displayed in Fig. 5. The extent of the damage is usually expressed in terms of its volume (for potatoes, see MCRAE 1985). Various methods are used to classify surface damage extent (Table 3). Mechanical damage has a source either in external contact forces or in internal stresses (Table 2) due to inhomogeneous growth or rapid turgor changes. Most bruise spots have their origin in contact of the product with another solid body, either in static or dynamic (impact) loading. In this case the surface bruises are formed and they are located directly under the product skin (Fig. 6).

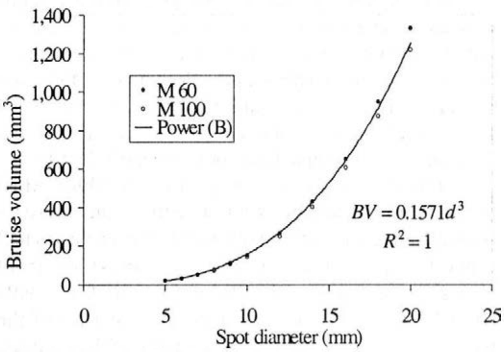


Fig. 7. Bruise volume plotted against spot diameter. Mohsenin's formula (Eq. (5)) was used for fruits of two diameters: 60 mm (M 60) and 100 mm (M 100). The simple equation (6) (BARREIRO 1999) was also plotted in this figure. In all cases the empirical relation $h = 0.3d$ was respected

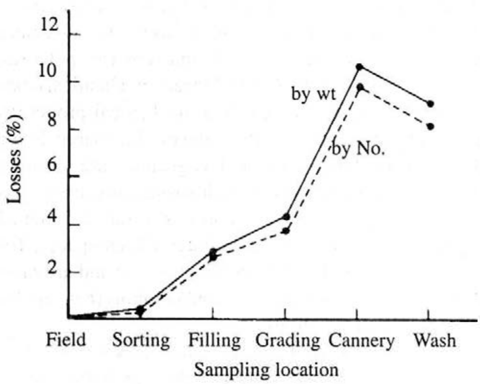


Fig. 8. Season total damage losses (broken fruits) in bulk loads of tomatoes at various sampling locations (O'BRIEN 1974)

The volume of the surface bruise spots – the so called bruise volume – can be estimated from the diameter and depth of the bruise spot, as was given by MOHSENIN (1970), see Fig. 6. The total volume BV of the bruise is given by the sum of the two spherical parts V_{z1} and V_{z2} from Fig. 6:

$$BV = \frac{\pi}{24}\left[3d^2(x+h) + 4h^3 + 4x^3\right] \tag{5}$$

where $x = R\left(1-\sqrt{1-\frac{d^2}{4R^2}}\right)$. The parameters R, d and h are determined directly from the cross section of the bruise spot after its formation in suitable temperature conditions. The ratio of h to d is approximately constant for a wide range of test conditions (for apples of different varieties and $V = 2$–$3\ cm^3$: $h/d = 0.30 \pm 0.04$ – BLAHOVEC et al. 1991).

BARREIRO (1999) gave a simpler formula for bruise volume:

$BV = \pi d^2 h/6$ (6)

Figure 7 shows that Eq. (6) represents a very good approximation of Eq. (5), with computed differences lower than 10%. The surface bruise area (SBA) is expressed as:

$SBA = \pi d^2/4 = 3\ BV/2h \approx 5\ BV/d$ (for $h \approx 0.3d$) (7)

For $h \approx 0.3d$ the bruise volume can also be approximated by $\pi d^3/20 \approx 0.1571 d^3$ (see Fig. 7).

THE EXTENT OF LOSSES DUE TO MECHANICAL DAMAGE

Mechanical damage to fruit and vegetable is cumulative (see Fig. 8) and can occur each time that they are handled. Fig. 1 shows the increase of product yield and/or quality in the time of growth and ripening. However, the same figure contains information on yield losses and/or quality decrease in the period of harvesting and storage. One of the most important causes of production deterioration is mechanical damage. It is a major problem in Europe, North America and in other developed countries, where mechanical damage leads to direct losses, secondary infections during storage and increased labour costs during grading and processing (MCRAE 1985; HUGHES et al. 1985; NOBLE 1985; KAMPP, NISSEN 1990, etc.). In the case of potatoes, total losses due to mechanical damage are about 30–40% when mechanical harvesting, sorting, and handling are used. STUDMAN (1995) shows that apple-downgrading losses by bruising can be as high as 50% in some cases.

TESTING OF SUSCEPTIBILITY TO MECHANICAL DAMAGE

The extent of product damage is very variable even for the same mechanical operation made in different conditions. Variety, temperature, water content, specific gravity, degree of maturity, etc., are the main but not the only factors playing some role in product mechanical damage (MCRAE 1985; CHOWDHURY et al. 1991; WOUTERS et al. 1985).

Various methods can be used to determine the susceptibility of real samples to mechanical damage. They can be divided into two groups: direct and indirect methods. Direct methods are based on defined damage of some representative tubers of the sample. This part of the test can be performed by various procedures, working step by step with simple products or using complex procedures for the whole sample. It is very important to use a damage procedure similar to that leading to product damage in real conditions. The test goes on to analyse the extent of damage to all the products used in the test (Table 3). Direct determination of the damage extent is usually a very difficult and time-consuming operation.

Indirect methods of testing damage susceptibility involve determining of some characteristic parameters of the tested product. These parameters have to correlate with the susceptibility and/or resistance of the product to mechanical damage. Indirect testing is usually based on repeating well-defined objective mechanical tests of simple products. Mechanical tests can usually be performed much more quickly than all the operations involved in the above-mentioned direct methods, and they provide very clear and well-defined numerical results as a basis for standard statistics. The main problem of indirect methods concerns in good correlation between the obtained test parameters and the damage extent observed in real conditions. Earlier attempts at indirect testing used simple parameters (Young's modulus, stress at strength limit, strain at strength limit) of quasi-static deformation tests (e.g., HUFF 1971). However, these parameters fail to incorporate other important circumstances of the process controlling product damage, such as product shape, dimensions, density, impact rate, non-elasticity of the product, etc. Table 4 shows possible ways of modifying of the simple parameters (I_1 and I_2) in the case of homogeneous elastic spherical products during their deformation between two plates and during their fall onto a planar rigid plate. The most frequent type of external product damage is impact damage. This is why dynamic impact tests are used in studies of product susceptibility to damage, e.g., for potatoes (GRAY, HUGHES 1978; GALL et al. 1967; GRANT, HUGHES 1985; HUGHES et al. 1985; NOBLE 1985; CHEN, YAZDANI 1991; DELWICHE, SARIG 1991, etc.).

A further group of indirect methods used for determining of product susceptibility to mechanical damage consists in analysing the energy necessary for producing a unit area of crack. These methods exist in various modifications – based on theory of fracture and generally the energy balance in the deformed products (HOLT, SCHOORL 1983, 1984; SCHOORL, HOLT 1983a,b; VIN-

Table 4. Damage susceptibility of spherical products expressed by characteristic mechanical parameters (based on the Hertz contact theory)

Characteristics	Quasi-static loading (Compression between two rigid plates)	Dynamic loading (Product falling onto a rigid plate)
Characteristic process parameter	maximum compression force without damage $F_{max} = \pi^3 r^2 I_1/6$ where r is radius of fruit	maximum height of falling without damage $h_{max} = \pi^4 I_2/(80\rho g)$ where ρ is product density
Characteristic material parameter (see Table 1 and Fig. 4)	$I_1 = BSS^3/E_A^2$	$I_2 = BSS^5/E_A^4$

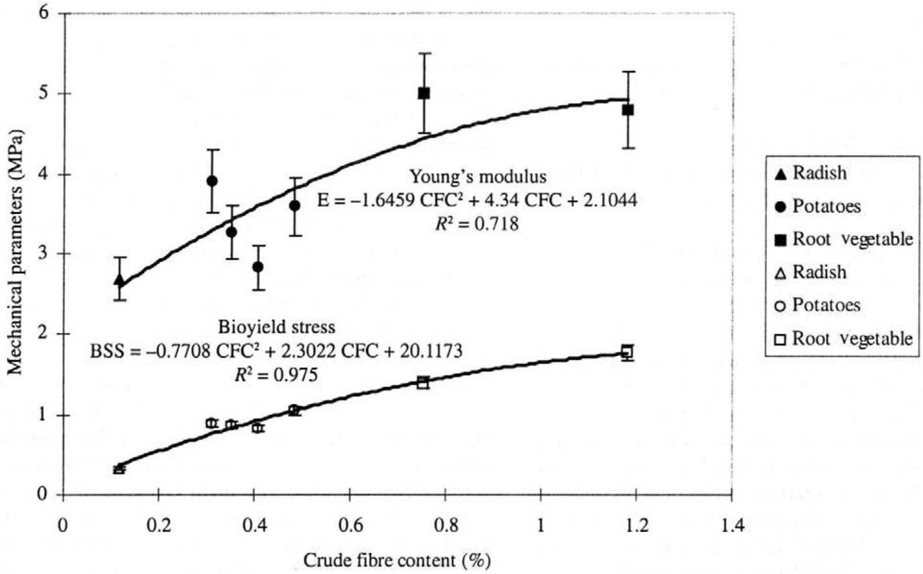


Fig. 9. Young's modulus and bioyield stress plotted against crude fibre content in several vegetable products (root vegetables are represented by carrots and red beet). The bars at experimental points determine the standard error for 30 repetitions (BLAHOVEC et al. 1984)

CENT 1990). Susceptibility to external damage is given by fracture toughness (in J/m²).

In the case of bruising, SCHOORL and HOLT (1983a) were inspired by fracture toughness. They defined two quantities similar to fracture toughness; both as the ratio of the bruise extent to energy consumption. They are bruise resistance coefficient (BRC) as the ratio of bruise volume (BV) and the corresponding relative absorbed energy (see Table 1), and bruise sensitivity (BS) as the ratio of bruise volume and the corresponding total work

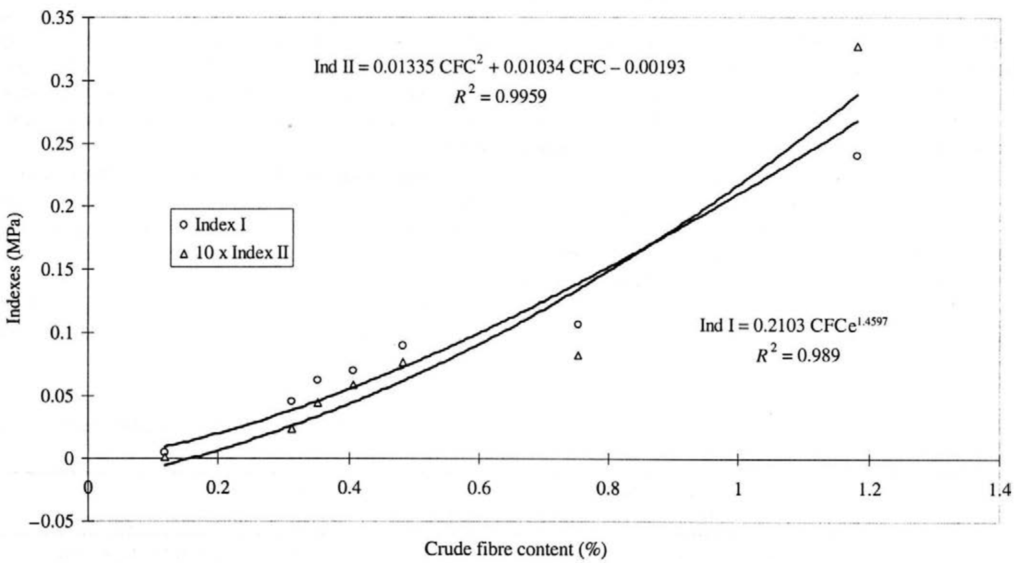


Fig. 10. Indices I and II (for definitions see Table 4) plotted against crude fibre content in vegetable flesh. The indices were computed using the experimental data from Fig. 9 (simple points) or their approximations by quadratic polynomials in this figure (full lines)

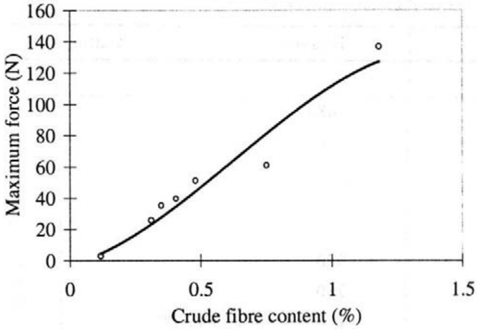


Fig. 11. Maximum force at which the bioyield stress is not overcome in the sphere deformed between two rigid plates (diameter of the sphere: 50 mm, Poisson's ratio 0.49). The simple points correspond to separate data from Fig. 9, the full line corresponds to approximations by quadratic polynomials

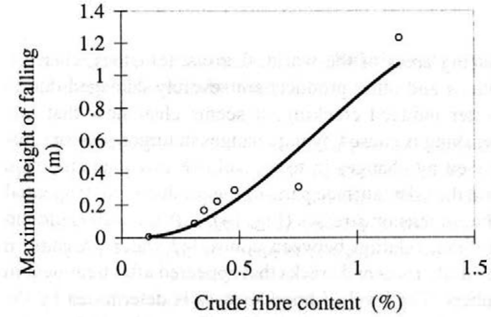


Fig. 12. Maximum height of fall of an elastic sphere (density corresponds approximately to a potato – 1,100 kg/m³, Poisson's ratio 0.49) on to a rigid plate for which the bioyield stress is not overcome. Simple points correspond to separate data from Fig. 9, and the full line corresponds to approximations by quadratic polynomials

of loading (Table 1). Similarly as in the case of fracture toughness, BRC and BS, too, can be determined in many different mechanical tests in which a bruise is formed and the energy necessary for its formation is registered.

SUSCEPTIBILITY TO EXTERNAL MECHANICAL DAMAGE

The mechanical parameters of fruits and vegetables depend on the cell arrangement in the tissue, especially on cell dimension and cell wall structure. Some part of this variation can be expressed by crude fibre content (BLAHOVEC 1988). Fig. 9 contains Young's modulus and bioyield stress plotted against crude fibre content, and the obtained curves can be understood as the main source of differences in the mechanical parameters of different products and/or plants. Further sources of variation (turgor pressure, content and quality of the other components

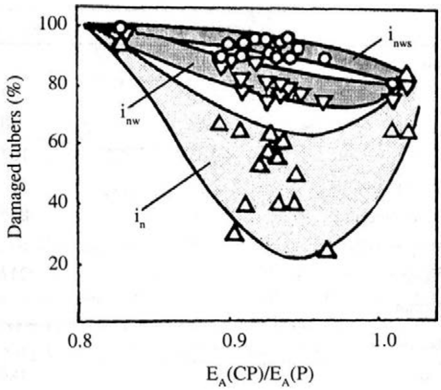


Fig. 13. Degree of damage of potato tubers in a harvesting test plotted against the ratio of apparent moduli of elasticity of central parenchyma (E_A(CP)) and pith (tuber centre – E_A (P)). The degree of damage is expressed as parts of the harvested tubers that are determined after harvesting. Three different levels were used: undamaged tubers (i_n), undamaged and slightly damaged tubers – only the skin is damaged (i_{nw}), and tubers with a damage depth lower than 5 mm (i_{nws}). Based on tests of 17 different potato varieties in 1988 (BLAHOVEC 1990 – unpublished)

– e.g., starch in the case of potato, pectin in cell wall lamella, etc.) play a secondary role that can increase in individual cases. In practical terms, this means that products with a higher content of crude fibre are harder and stiffer. Increasing crude fibre content also leads to higher values of both Indexes I and II defined in Table 4 (see Fig. 10), and to lower susceptibility to damage as is clear from Figs. 11 and 12. Especially in the case of a sphere falling on to a hard plate, the role of crude fibre is very important; a tenfold increase in crude fibre content leads to more than one hundred times greater height of safe fall. This crude calculation is strongly limited by the simplicity of the model.

This simplification consists not only in our reduction of the composition problem to crude fibre content only, but also in the elasticity and homogeneity of the model product and its spherical shape. The product skin plays a particularly important role in the study of external damage to real fruit. The tougher the product skin, the higher the loading that can be applied the product without it being damaged. The role played by product structure in susceptibility to external mechanical damage is illustrated in Fig. 13. Susceptibility to mechanical damage is represented by parts of potato tubers damaged up to a specified level. These values are plotted against the ratio of apparent moduli of elasticity determined for two different parts of a potato tuber: the central parenchyma and the pith. Both of these parts are located near the centre of the tuber, and a penetration test (see Fig. 4b) was used for studying them (BLAHOVEC 1990, unpublished). Fig. 13 shows that a difference of less than 20% between the apparent moduli of the two parts of the tuber led to very

Table 5. Brittle toughness of parenchyma from apple and potato (VINCENT 1990) – all values in J/m²

Variety	Compression	Wedge opening	Tension	Cutting
Apples				
Cox's Orange Pipkin	62.13	72.4	68.6	
Bramley	60.94	50.5	46.3	
Gloster	269.4	164		
Rock Pipkin	762.5			
Norfolk Beefing	972.0	856		
Granny Smith			350	
Delicious		211.6	250	
Jonathan			250	
Potatoes				
Record	376.0	389.0		
Bintje	541.0			200
Maris Piper	473.0	332.5		
Portland Dell	539.0			

major differences of damage level in the harvester test. No other parameter among more than 20 used in this case correlated with the damage level better than the above-mentioned ratio. Indexes I and II (Table 4), crude fibre content, starch content, etc., were among those parameters.

The degree of damage is very variable for one type of product (Fig. 13), and similar variation can also be observed for one variety cultivated in similar conditions. It can be concluded that, in relation to mechanical damage, fruits and vegetables are not well defined materials. Variation can also be observed in mechanical parameters (Figs. 9–12). Brittle toughness also has a similar character, as is clear from Table 5, where selected values for brittle toughness of apples and potatoes are given. The values for apples and potatoes overlap, even if the values for apples move in wider limits (50–1,000 J/m²) than for potatoes (200–550 J/m²).

WATER INDUCED SURFACE CRACKING

Water induced surface cracking is a serious problem limiting production of fruits and vegetables in many producing areas of the world. Carrots, tomatoes, cherries, plums and other products are severely damaged due to water induced cracking. It seems clear now that this cracking is caused by big changes in turgor pressure followed by changes in tissue volume that loads the skin and the other surface parts of the product with tangential (hoop) tension stresses (Fig. 14). LIPPERT (1995) found a direct relation between controlled water pressure in kohlrabi roots and cracks that appeared after treatment in tubers. The level of hoop stresses is determined by the properties of the product skin. The mechanical properties of the skin usually differ from the properties of the internal parts of the same products. This rule is illustrated in Table 6, where moduli of elasticity and strength parameters of tomatoes are given. The lower the ratio E_f/E_s, the higher is the stress concentration in the fruit skin. After skin cracking, stress concentrates near the crack tip and the crack grows.

Water induced cracking is a very complicated dynamic process. The probability of crack formation depends on several different sub-processes. The first of these is the state of the product before its contact with water. The main role is played by the water potential in the product.

Table 6. Mechanical properties of tomato fruit tissues (BLAHOVEC et al. 1980)

Variety	Flesh tissue		Skin		E_f/E_s	BSS/SSS
	E_f (MPa)	BSS (MPa)	E_s (MPa)	SSS (MPa)		
Intermek	0.37	0.09	26.4	2.55	0.014	0.035
Nova	0.55	0.12	–	–	–	–
Nuova AT 30	0.75	0.18	23.3	2.16	0.032	0.083
ONT 743	0.44	0.16	36.1	2.80	0.012	0.057
Tanzimech	0.52	0.14	28.1	2.47	0.019	0.057
V 714	0.33	0.09	22.9	2.08	0.014	0.043
VF 65	1.18	0.33	26.2	2.08	0.045	0.158
Vrbičanské	0.36	0.08	70.2	5.67	0.005	0.014

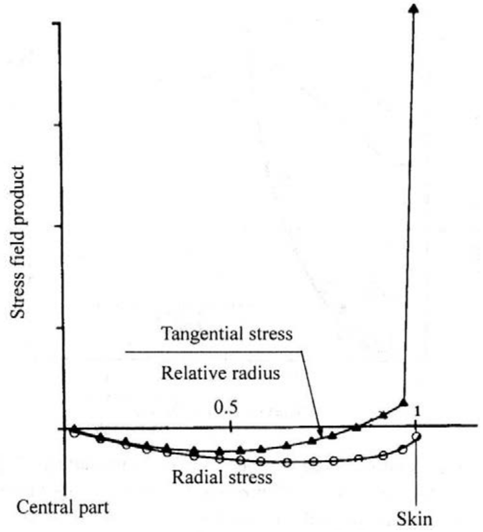


Fig. 14. Tentative stress distribution in a spherical product caused by its internal expansion forming

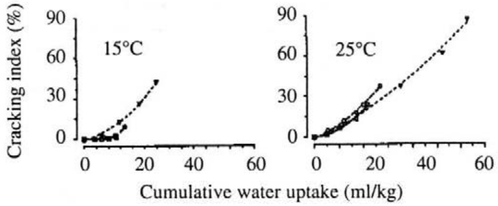


Fig. 16. Cracking index (100% corresponds to the highest degree of cracking) of cherry fruits plotted against cumulative distilled water uptake into immersed fruits (ml of water per kg of fruits) at 15°C (left) and 25°C (right). Three varieties were tested: Sam, Ulster and Van – CLINE et al. (1995)

Fig. 15 shows the relative volume of two product samples soaked in manitol-water solutions of different concentrations. This figure shows that the volume of the product samples dehydrated by soaking in solutions of high manitol concentration can increase after coming into contact with water by more than 40% (potato tubers). The higher the dehydration of the product, the higher is the increase of its volume after coming into contact with water. The stress state in the product depends on the turgor pressure, which is in direct relation to the osmotic potential of the cellular sap. A special role is also played by the intercellular free space, in which single cells can expand minimising the volume changes of the product (see Fig. 15 and compare the data obtained for apples, with about 25% of intercellular space with the data obtained for potato tubers, with about 2% of intercellular space). It can be concluded that the water potential of the product tissue and the mechanical properties of the cel-

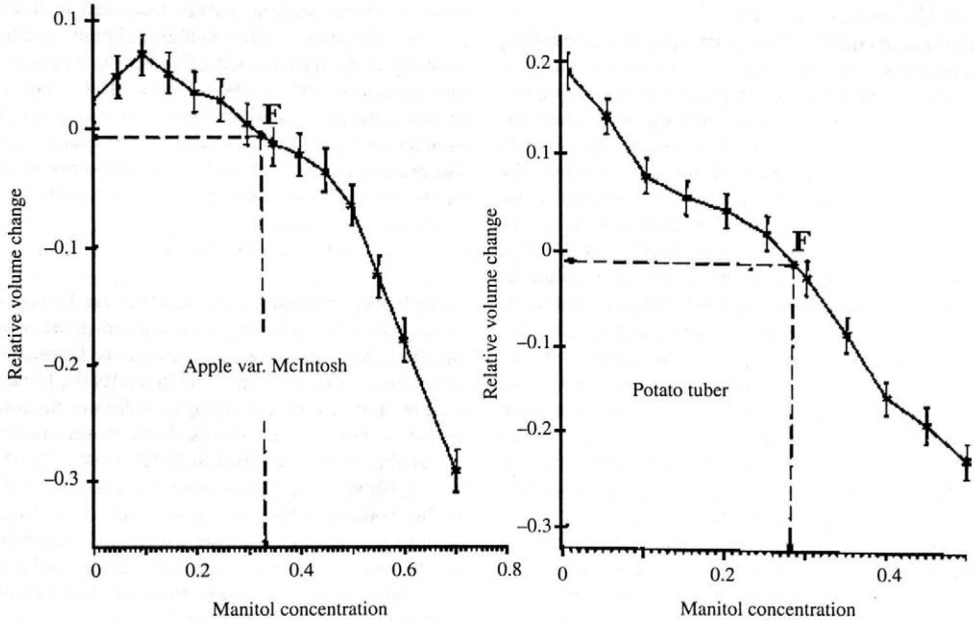


Fig. 15. Relative volume change of samples soaked in a manitol solution of various concentrations (apples on the left side and potato tubers on the right side). Points F denote unsoaked samples (after LIN, PITT 1986)

Table 7. Fruit characteristics of 20 cherry varieties tested over 4 years in Danish conditions (CHRISTENSEN 1995)

Variety	Fruit mass (g)	Cracking index (%)	Firmness*
Karešova	7.6	50	2
Ranna Cherna Edra	6.7	36	2
Adrian	7.2	4	4
Merpet	8.3	83	2
Kristin	8.2	41	4
Viscount	8.0	51	4
Starking	9.1	61	4
Stella	8.9	51	4
Van	7.9	68	5
Oktavia	8.9	45	4
Merton Marvel	7.6	47	4
Viola	9.0	53	4
Kozerska	9.4	36	4
Sunburst	11.9	57	3
Lapins	9.7	37	4
Uriase di Bistra	10.1	28	3
Merla	6.7	34	4
Boambe de Cotnari	9.1	48	5
Bianca di Verona	7.4	34	5
Flamengo Srim	7.1	16	5

*1 – very soft, 5 – very firm

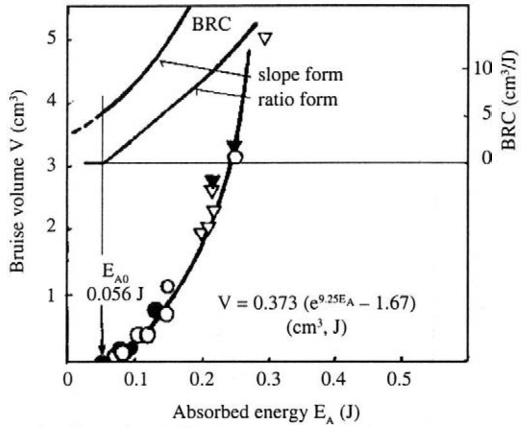


Fig. 17. Bruise volume of spots observed on the surface of apples after quasi-static compression between two rigid plates (maximum relative deformation was 8%) in different stages of cold storage plotted against the absorbed energy. Varieties: Golden Delicious (circles) and Spartan (triangles). The bruise resistance coefficient in two different forms (slope and ratio) is plotted with a separate scale

lular walls and intercellular space in co-operation predetermine the extent of free tissue expansion after it comes into contact with water.

The second important sub-process playing a controlling role in product cracking is transport of water into the product tissue. This is a very complex process with various modifications for different products and/or different watering conditions. In the case of stone fruits, rainwater can also be transported into the fruits through their skin. The quicker the transport of the water to the product cells, the quicker is the product expansion and the more severe the product cracking can be. Skin permeability plays a very important role in this case. The role of water uptake in cherry cracking was studied by CLINE et al. (1995), and it was shown that varieties with slower water uptake (Ulster and Sam) are more resistant to cracking than the variety Van, which has at least two times quicker water uptake than Ulster and Sam (Fig. 16). It is evident from the study by CLINE et al. (1995) that variety differences in cracking of cherries are closely associated with the indirect effects that the fruit's osmotic potential and skin permeability have on the rates of water accumulation.

The last important sub-process controlling cracking of the product is proper loading of the product surface. We have seen that the existence of the product skin or other less deformable surface layers is the source of tensile stress concentration on the product surface. However, the skin – similarly like as the other biological tissues – is not ideal elastic solid: it flows and the stresses concentrated in it relaxes in time. The higher the rate of the stress relaxation in tissues near the product surface, the higher is the resistance of the product to water induced surface cracking.

Water induced cracking of various products depends on many different special properties of the products (dimension, shape, position on its surface, etc.), methods of product cultivation and also methods of protection (e.g., spraying of cherry trees with Ca and Cu sprays in the time prior to ripening – BROWN et al. 1995). For most products, the most important effect for minimising water-induced cracking is the selection of a suitable variety. The primary role of the variety in the resistance of cherries to water induced cracking is shown in Table 7.

BRUISING

The bruise resistance coefficient (BRC) and bruise sensitivity (BS), the generally accepted indicators of fruit susceptibility to bruising, were determined for many different fruits and also for potatoes in the 1980s. The influence of storage time and storage conditions, the role of season, variety and methods of cultivation were also studied at that time (e.g., BRUSEWITZ, BARTSCH 1989; KAMP, NISSEN 1990). The main characteristic of these studies is the high level of the observed bruise volume. Big bruise spots are easily detectable, and their volume can be determined more precisely than the volume of small bruise spots, which are however more important from practical point of view. Both the above mentioned research groups (BRUSEWITZ, BARTSCH 1989; KAMP, NISSEN 1990) presented the relations between the impact absorbed energy (or total work of loading) and the

Table 8. Bruise resistance of selected products

Product specification	Energy (mJ)			
	Absorbed energy		Total work of loading	
Product	E_{A0} *	E_{A500} **	W_{T0} *	W_{T500} **
Apples				
Golden Delicious (BLAHOVEC et al. 1997)	≈ 60	≈ 110	97	198.4
Spartan (BLAHOVEC et al. 1997)	≈ 26	≈ 75		
Static and dynamic loading (HOLT, SCHOORL 1984)		36–70		
Paula Red & McIntosh dynamic loading (BRUSEWITZ, BARTSCH 1989)		45–88		≈ 70
7 varieties dynamic loading (KAMPP, NISSEN 1990)		21–83		
Idared – long stored (BRUSEWITZ, BARTSCH 1989)		100–300		
Cherries				
Kordia (BLAHOVEC et al. 1995)	1.55	8.6	4.0	10.3
Sam (BLAHOVEC et al. 1995)		7.0	6.0	8.1
Bananas				
Musa AAB Group (KAJUNA et al. 1997)	≈ 20	≈ 250	74	370
Potatoes				
(PARKE 1963)	130	301		

* The highest values without any bruising pattern
** The values corresponding to bruise volume 500 mm^3

bruise volume of apples in the general linear form. However, the constant term of the linear equation differed for different varieties, seasons and store conditions, being stochastically positive and negative. These data were the first indications of the non-constant character of BRC and BS. The non-linear and off-zero character of the relation between bruise volume and energy parameters (E_A and W_T) was shown for apples by BLAHOVEC et al. (1997). It is clear that the traditional parameters BRC and BS (see also Fig. 17) can be understood as only a very crude estimation of the relation between BV and energy parameters. Especially for low-level bruising, BRC and BS should be re-defined rather as functions in the form of derivatives to dependence V–E_A or V–W_T (slope form – see Fig. 17).

For easy quantification of susceptibility to bruising at low-level loading, it is necessary to determine at least two characteristic points on the curves BV–E_A or BV–W_T. The first of these are very important initial points corresponding to the maximum energy values for which no bruising is observed. These values can be obtained by extrapolation of the corresponding BV–E_A or BV–W_T curves to V = 0; they are denoted as E_{Ao} (see Fig. 17) and W_{To}, respectively. The ratio E_{Ao}/W_{To} was determined as 0.52 for apples and cherries (BLAHOVEC 1999). The second point represents a low-level value of BV that can be determined easily and reliably by direct analysis of the bruise spot. This value is 500 mm^3, and the corresponding energies are denoted as E_{A500} and W_{T500}. Some values of E_{A0}, E_{A500}, W_{T0}, and W_{T500} are given in Table 8.

These two points (for zero BV and BV 500 mm^3) can serve as a basis for estimation of other data by linear interpolation and/or extrapolation – e.g., for E_A in the following form:

$$E_{AV} = E_{A0} + (E_{A500} - E_{A0})\,BV/500 \quad (J, mm^3) \qquad (8)$$

where BV is the bruise volume at estimated absorbed energy E_{AV}. When the energy value for a bruise of defined diameter (d) or defined surface bruise (SBA) is found, the equality presented near Eq. (7) helps to modify Eq. (8) as:

$$E_{Ad} = E_{A0} + 0.0003142(E_{A500} - E_{A0})\,d^3 \quad (J, mm) \qquad (8a)$$

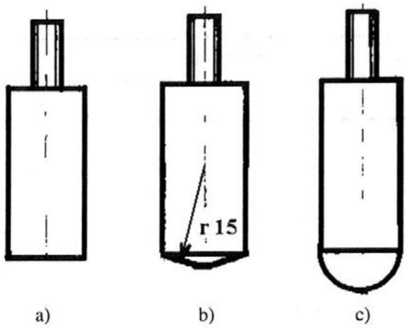
$$E_{AS} = E_{A0} + 0.0004514(E_{A500} - E_{A0})\,SBA^{3/2} \quad (J, mm^2) \qquad (8b)$$

Equation (8a) is important for estimating the energy parameters for pome fruits for which the EC standard limit is a by diameter of 10 mm. For stone fruits, EC standards give a bruise limit in the form of SBA (50 mm^2) so that Eq. (8b) forms a suitable basis for calculation of the corresponding energies.

For apples, BRC decreases with increasing time of storage, while the opposite trend was observed for BS (BRUSEWITZ et al. 1989). Detailed analysis of E_{A0}, E_{A500}, W_{T0}, and W_{T500} for stored apples shows that all the parameters decrease slowly during storage. This means that the probability of low-level bruising of apples rather increases during storage.

PRODUCT QUALITY

Several scientists, grouped in the early 1960s at General Foods Corporation in Tarrytown (New York State, USA), came with a new idea (SZCZESNIAK 1963; SZCZESNIAK et al. 1963; KRAMER 1963) to replace at least some operations of the classical sensory panel tests that were traditionally used for determining of food quality by objective instrumental determination of a system of parameters termed as the texture profile. This idea was lat-



Variety	Landsberg		Starking	
Type	skin off	skin intact	skin off	skin intact
Flat tip a)	0.082⁺	0.177	0.112	0.128
Magness-Taylor b)	0.084⁺	0.122	0.092	0.191
Spherical c)	0.098⁺	0.153	0.155	0.348⁺

Fig. 18. Maximum mean pressure on tips of cylindrical indentors of different types used for puncture tests of apples with skin (skin intact) or with removed skin (skin off) – see also Fig. 4. This parameter is referred to also as firmness. The penetration depth was about 14 mm, and the diameter of the indentors was 11.28 mm (WILKUS 1980). ⁺ in this case the maximum force was measured as the second maximum at penetrations higher than 10 mm

er developed into a special test known as **Texture Profile Analysis (TPA)** – see BOURNE (1978).

A quick assessment of tissue firmness has played a traditional role in testing fruits and vegetables since the beginning of the 20th century. Tests of this type are based on thrusting special indentors into the flesh according to a pre-fixed programme. As regards the experimental procedure, the tests may be roughly divided as follows (MOHSENIN 1970; BOURNE 1966; see Fig. 4):

1. **Puncture tests**, where the maximum force required for pushing the indentor into the product is measured. This type of destructive test is characterised by the force-sensor working on the pre-determined penetration depth.

2. **Deformation tests**, in which the resulting product deformation is measured in a test with a constant force acting in a pre-determined time period. The test is characterised by a distance-measuring instrument, a pre-determined constant level of force, and it excludes a higher level of destructive penetration of the tested product.

3. **Penetration test**, which is based on measuring the depth of destructive penetration of an indentor in a product under a constant force in a given time. A distance-measuring instrument is used for measurement at a pre-determined penetration depth reached under a constant predetermined force.

The famous Magness-Taylor test (MAGNESS, TAYLOR 1925) is a puncture test. A metal cylinder with a spherical tip and a diameter of 5/16 or 7/16 inch is pushed into the tested product up to a depth of 5/16 inch (i.e. approximately 8 and 11 mm in diameter, and 8 mm in depth),

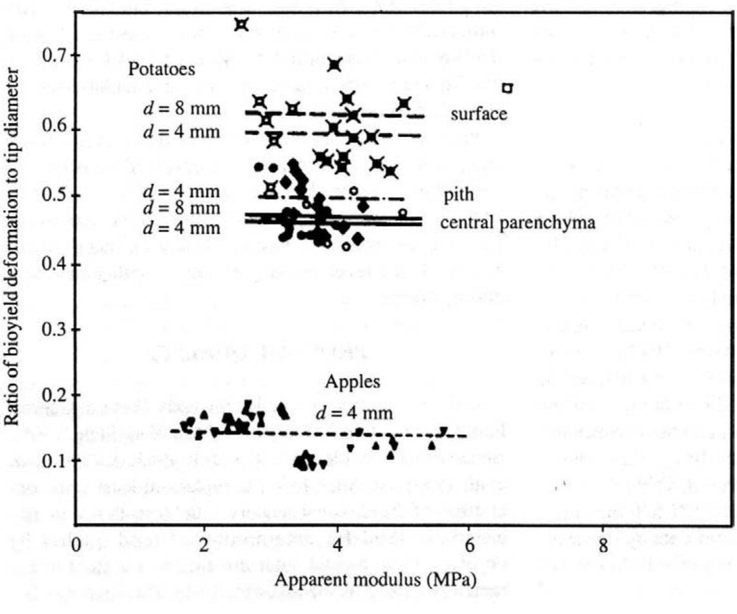


Fig. 19. Ratio of bioyield deformation (in mm) divided by tip diameter (in mm) obtained in deformation tests of potatoes and apples. The universal testing machine with constant deformation rate 0.167 mm/s was used; tips of the cylindrical indentors were flat

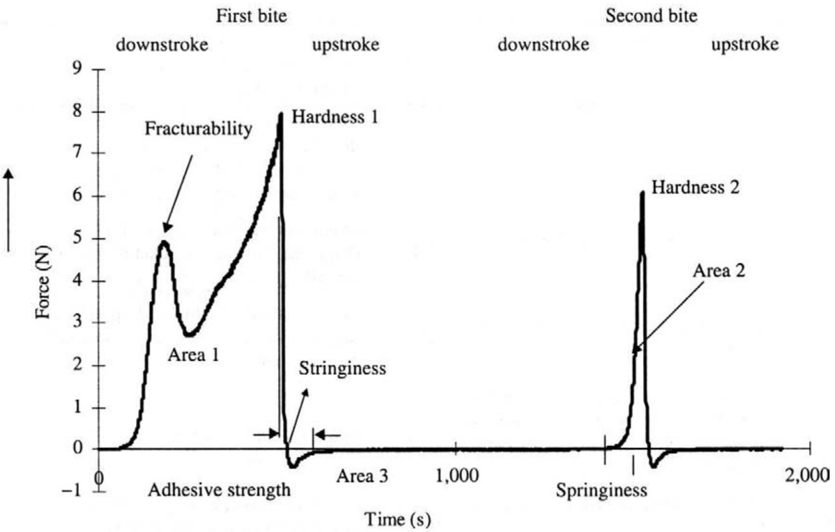


Fig. 20. Scheme of TPA test. The measured force is plotted against the test time. The TPA test is divided into two bites. The forces at characteristic points determine fracturability, hardness (determined as hardness 1) and adhesive force (maximum negative force in the upstroke of the first bite). The deformations determine stringiness and springiness (deformation time multiplied by deformation speed must be added) and the energies serve as measures of deformation works (area 1 and 2) or of stringiness (area 3). Areas 1–3 also have to be multiplied by deformation speed

and the maximum force in this process is measured. The corresponding mean pressure on the tip serves as an alternative result of the test. The obtained values are known as the firmness of the tested product. The Magness-Taylor test – and the other simple pressure tests – served as the sole means for investigation the mechanical properties of fruits up to the beginning of the 1960s.

The surface parts of fruits and vegetables are generally in-homogeneous, and one of the main advantages of the puncture test consists in its destructive character, which

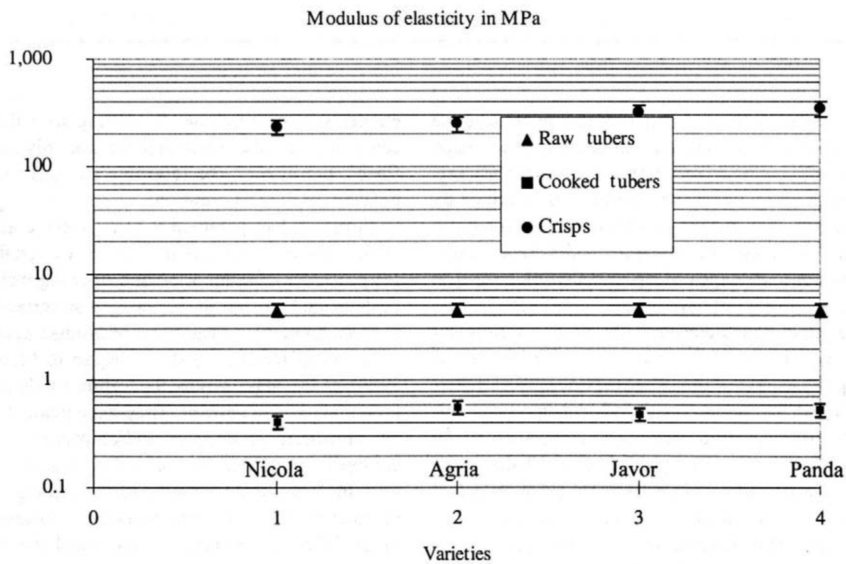


Fig. 21. Young's modulus of raw and cooked central parts of tubers of four potato varieties. The values of Young's modulus of fried planar slices – potato crisps – as determined in a flexure test are also included in this figure. Standard errors of the measured values are also denoted

Table 9. Definition of TPA parameters (see Fig. 20)

TPA parameter	Original definition (BOURNE 1978) Method of determination	Unit	Modified definition (BLAHOVEC et al. 1999a,b) Method of determination	Unit
Young's modulus (E)	(–)		Slope of the first linear part of the downstroke of the first bite, divided by strain rate and cross section and multiplied by height of specimen	(MPa)
Hardness (Ha)	Maximum force during first bite (Hardness 1 in Fig. 1)	(N)	Maximum stress during first bite (hardness 1 in Fig.1 divided by sample cross-section)	(MPa)
Fracturability (Fr)	Force at the first major drop in force curve	(N)	Strength at the first major drop in force (original value divided curve by sample cross-section)	(MPa)
Cohesiveness (Co)	The ratio of area 2 to area 1 (see Fig. 1); area 2 – work done during downstroke in the second bite, area 1 – the same in the first stroke	(–)	The same (not modified)	(–)
Springiness (Spr)	Active deformation length in second bite	(mm)	Active deformation length in second bite divided by the specimen height	(–)
Gumminess (Gu)	Ha × Co	(N)	Ha × Co	(MPa)
Chewiness (Ch)	Gu × Spr = Ha × Co × Spr	(N/mm)	Gu × Spr = Ha × Co × Spr	(MPa)
Stringiness (Str)	Distance specimen extends in the first bite upstroke before it breaks away from the compression plate	(mm)	Ratio of the same distance to initial specimen height	(–)
Adhesiveness (Adh)	Work done for overcoming the adhesion forces in the first bite (area 3 in Fig.1 multiplied by strain rate)	(N/mm)	Ratio of the same quantity and sample cross-section	(J/m²)
Adhesive force modified	Maximum negative force in upstroke of the first bite	(N)	Ratio of the same quantity and sample cross-section	(kPa)
Adhesive strength				
Ads				

makes it possible to test not only the surface but also the sub-surface parts of the tested products. The exact shape of the indentor tip plays a very important role in this case, as shown in Fig. 18, where the firmness determined by a puncture test with indentors of various tip shapes is given. The role of the skin in the test – different for different varieties and shapes of tip – is also illustrated in this figure. In the case of homogeneous products the first part of the puncture is determined by a quasi-elastic solution of the problem: by Eq. (2) in case of the flat tip (a) and by Eq. (3) in case of the spherical tip (c). The differences obtained for indentors of different tip shapes increase with increasing deformation, and they also depend on the structure of the tested product. Fig. 19 shows the variations in the position of the bioyield point on deformation curves; bioyield was observed at deformations of ≈ 0.2d in apples, and deformations ≈ d in the surface parts of potatoes. Firmness should be determined in non-elastic deformations higher than the bioyield point and this is why the puncture depth has to be higher than the indentor diameter. The non-elastic behaviour of fruits and vegetables is very important for testing fruit firmness, because the measured force depends not only on the elastic forces, but also on the relaxable stresses generally dependent on the test duration.

Firmness-like parameters usually serve as indicators of time induced changes in fruits and vegetables. There are processes of maturation and ripening that can easily be detected by firmness. Firmness also serves as the simplest parameter for evaluation of product quality.

Universal testing machines began to be used in the 1960s as the main means for testing foods and agricultural materials in general. They have made it possible to deform different samples and/or products in tension, compression or bending, and the parameters obtained from the tests have been used for describing of the product quality (FINNEY 1969; JINDAL, TECHASENA 1985). Many different parameters of the tests have been termed as firmness. Some of the tests have been simplified and computerised so that they can be used in field conditions (MIZRACH et al. 1992; TAKAO, OHMORI 1994), like the Magness-Taylor test.

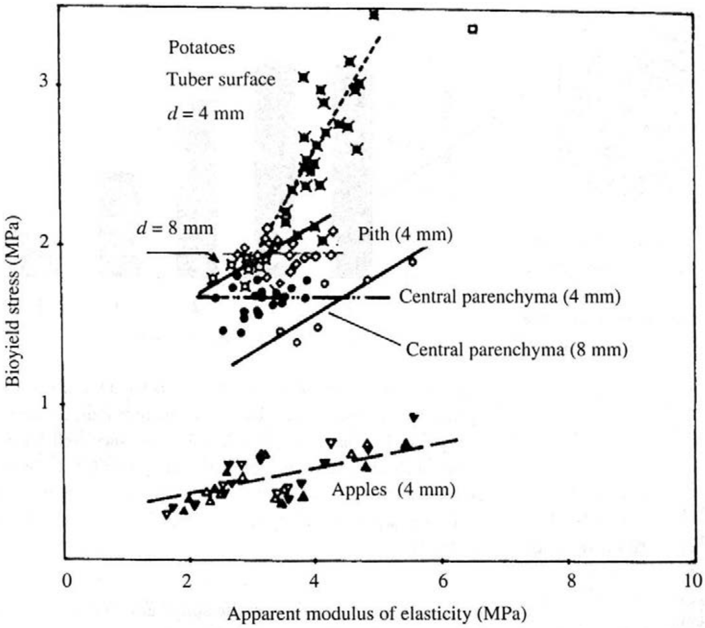


Fig. 22. Bioyield stress plotted against apparent modulus. Both the parameters were obtained in penetration tests (Fig. 4b) of potatoes and apples at a constant deformation rate (0.167 mm/s)

TPA begins with the preparation of product specimens in the form of plan-parallel plates of constant cross-section. They are about 10 mm in height, with a cross section of a few cm^2. Every specimen is deformed repeatedly between two plates in compression. The deformation rate at loading is the same as at unloading. This process is described by the force plot in Fig. 20. The downstroke of the first bite is followed by an upstroke to the initial position after some predetermined deformation (usually 75%). When the deformation plate returns to the initial position the process is repeated once more in the second bite. The TPA texture parameters are evaluated from the data plotted in Fig. 20; Table 9 shows how to do this. The original definitions of the TPA parameters were modified to be less sensitive to possible modifications of the experimental procedure.

The quality of fruits and vegetables is very variable. Standard deviations about 20% are very frequently obtained for instrumentally determined texture parameters even for carefully prepared samples of one variety from which non-standard products were excluded before measurement. And in many cases this 20% deviation represents the level of differences between different degrees of quality. Fig. 21 contains the values of Young's modulus of four very different potato varieties that were obtained in raw state, cooking state and after frying. We can see that cooking potato tubers leads to values of Young's modulus approximately ten times lower than in the raw state. Frying, on the other hand, causes an increase in this parameter to values many tens of times higher than in the raw state. However, differences between varieties of the same product are comparable with the above mentioned variation level. In practical terms, this determination of product quality is a very difficult problem that needs to be based on repeated experiments on many specimens.

SOFT TISSUES

The Magness-Taylor test, either in its original form or in various modified instrumental forms, is still the most frequently-used method for firmness determination of soft products. The larger diameter of the indentor that is used in the test, the greater the depth of the product that is analysed. Fig. 22 demonstrates this fact on results obtained in a penetration test on potatoes and apples. The firmness – expressed here as bioyield stress – of apples is much lower at the same apparent modulus than the firmness of potatoes. This means that the difference in mechanical properties of the surface and subsurface parts is lower in potato tubers than in apple fruit. The main sources of this behaviour are apple fruit anisotropy (KHAN, VINCENT 1990 – see also Fig. 23), cell shape and dimension, existence and anisotropy of large intercellular spaces.

Potato tubers are also not homogeneous bodies, and this is why different values of bioyield stress were obtained for pith, central parenchyma and surface of the tubers (Fig. 22). The main source of higher firmness of sub-surface parts of potato tubers is the vascular ring, located a few millimetres under the tuber surface. Fig. 24 shows that the firmness measured at the tuber surface is always higher than the firmness of the central parenchyma.

The non-homogeneous character of the tested products limits their firmness to the role of a comparative and test-

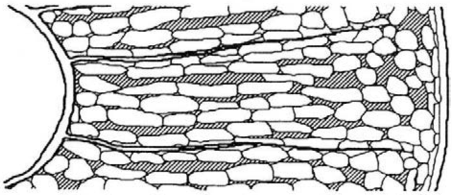


Fig. 23. A diagrammatic representation of a radial cut section through the apple cortex showing the changes in size, orientation and aspect ratio of cells and intercellular spaces throughout the depth of the cortex. The Radial vascular strands are represented by dark lines, and the intercellular spaces by shaded areas (KHAN, VINCENT 1990)

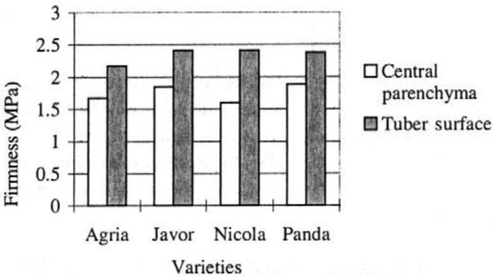


Fig. 24. Bioyield stress (firmness) obtained in a penetration test (Fig. 4b, see also Fig. 22) of four potato varieties (Agria, Javor, Nicola and Panda). Deformation rate 0.167 mm/s, indentor diameter 8 mm

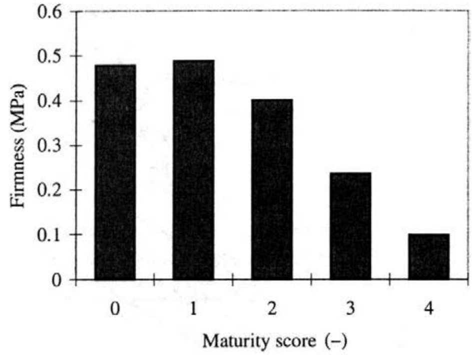


Fig. 25. Tomato firmness (indentor diameter 0.8 mm) plotted against the maturity score – based on tomato colour: 0 – immature green, 1 – mature green (jelly-like substance well formed in the lucules and seeds are not easily cut by a knife), 2 – breaker (first appearance of external pink colour), 3 – light pink, 4 – dark pink, variety: Early Pack (arranged under CHEN, STUDER 1977)

dependent parameter. This means that we can compare only the values obtained at the same parts of the same products in tests with the same loading procedure and the same shape and the same diameter of the indentor. It also means that all firmness data should be accompanied by complex information on the shape and diameter of the indentor and further details of the test.

Firmness is a very important indicator of product maturity. Fig. 25 contains mean values of firmness for different maturity levels of tomato fruits. This figure shows that immature fruits have very stable firmness, which starts to decrease with appearance of pink colour on the fruit surface. When a tomato matures its firmness decreases to values representing only about 20% of its initial firmness.

Fruit softening usually continues during ripening. Fig. 26 shows how the firmness of apple and pear flesh develop during ripening at room temperature. The decrease in firmness can be approximated by exponential or power function in both cases, but the fall is much steeper for pear flesh than for apple flesh. In the final

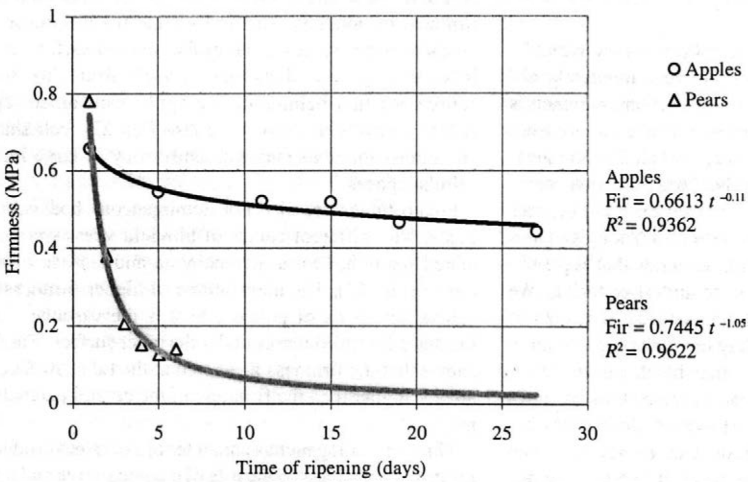


Fig. 26. Firmness (Fir) of apple and pear flesh plotted against ripening time (arranged after WAN et al. 1992). Temperature of ripening 21°C, diameter of indentor with round tip 7.9 mm, penetration depth 7.9 mm, deformation rate 50.8 mm per min, tests of fruit halves after removing the skin, varieties: Red Delicious (apple) and D'Anjou (pear)

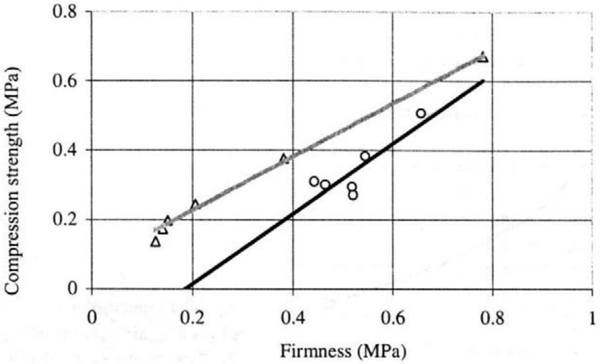


Fig. 27. Compression strength of apple and pear flesh plotted against their firmness. Arranged from data of WAN et al. (1992) – the firmness values are also plotted in Fig. 26. The compression strength was determined in tests of cylindrical specimens of 20 mm in diameter and 20 mm in length, and the deformation rate was 50.8 mm per min

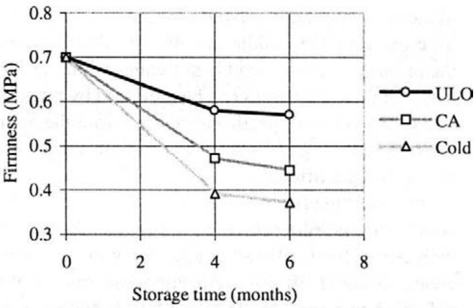


Fig. 28. Flesh firmness of apples stored in various conditions at 1°C (SIDDIQUI et al. 1996). Variety: Golden Delicious, Chatillon penetrometer – indentor diameter 11 mm, ULO – ultra-low oxygen content (3% CO_2, 1% O_2), CA – controlled atmosphere (3% CO_2, 3% O_2), Cold – cold store only

ripe state, the firmness of apple flesh is greater than the firmness of pear flesh. Most of the variance observed in flesh firmness is connected with changes in flesh strength. Fig. 27 shows the relation between the firmness values given in Fig. 26 and the compression strength of the same flesh tested in parallel compression tests. This figure shows that, for each of the fruits, the relation between compression strength and firmness can be approximated by a linear equation that is tighter in the case of pears. The differences between the linear equations for the two fleshes can be understood as indications of differences in the anatomy of the two products. Relations similar to those in Fig. 26 were also obtained by TU et al. (1997) for the Cox's Orange Pippin apples variety: approximately linear relations between firmness (Magness-Taylor test with diameter 11 mm) and compression strength were observed, and a similar relation was also observed for firmness and tensile strength.

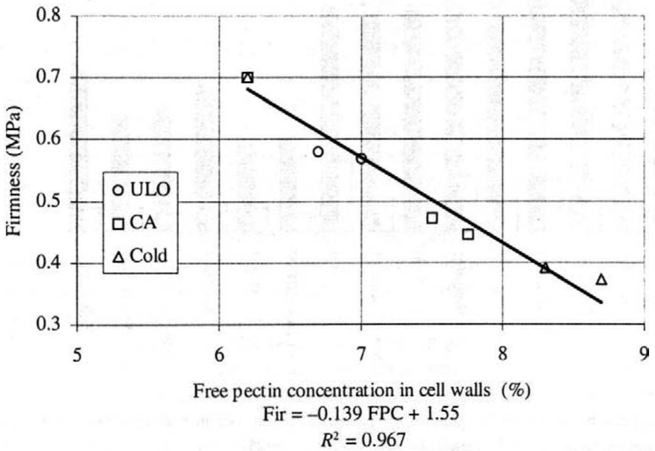


Fig. 29. Flesh firmness from Fig. 28 plotted against free pectin concentration in cell walls (FPC) – arranged from data of SIDDIQUI et al. (1996), for symbols see Fig. 28

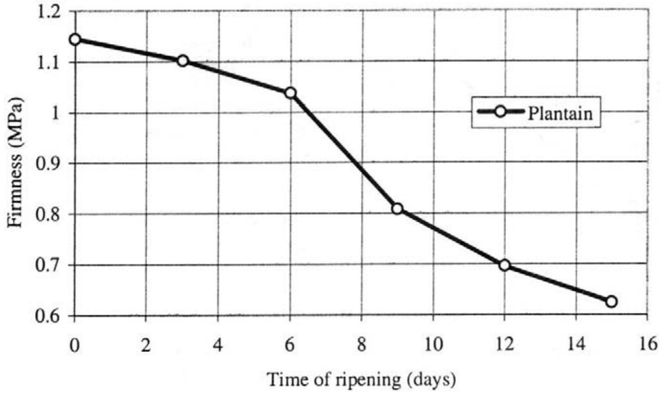


Fig. 30. Firmness of whole plantain fruits plotted against time of ripening at 21–24°C. Cultivar AGBAGBA, indentor diameter 7.9 mm (ASOEGVU 1996)

Reduction of firmness plays a very important role as an indicator of fruit quality during storage. It is a very sensitive function of storage conditions. Fig. 28 shows the results of firmness measurement of apple flesh for Golden Delicious apples after long time storage in three different conditions. These results show that the softening process is slower in a controlled atmosphere store than in a cold store. In ultra-low oxygen conditions, the softening is even slower than in a CA store.

The lower the store temperature the lower is the product softening. The lower the oxygen content, the lower is the product softening (SHARPLES, JOHNSON 1987). It was emphasised by HOFF (1973) that cell wall composition is important in determining fruit and vegetable texture. Other factors, such as cell anatomy and its water relations, remain largely unaffected in products stored under high humidity. In addition, the main parameter determining product texture, fibre or cellulose content (see Fig. 9), remains basically unchanged. However, the liberation and degradation of the main binder component of the cell wall, water-soluble pectic substances, followed by erosion of the middle lamella and disintegration of the primary cell wall, lead to softening of the flesh products. All these processes can be indicated by transformation of the cell wall pectic substances from the bound to the free state. Fig. 29 shows a very tight linear relation between apple firmness and content of free cell wall pectin in experiments with storing apples in very different conditions, as were presented in Fig. 28. The higher the increase of free cell wall pectin, the greater is the decrease of apple firmness. An important role in product softening is played by ACC oxidasa (l-aminocyclopropane-l-carboxylic acid) with its product ethylene (CHEN et al. 1997).

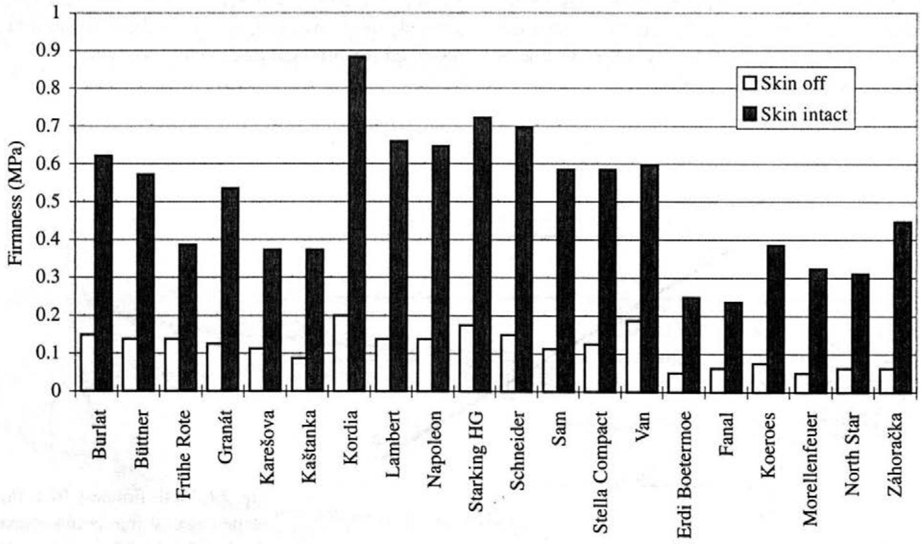


Fig. 31. Bioyield of cherries in harvesting maturity as measured by penetration of a cylindrical indentor of diameter 3.2 mm with a flat tip into skin intact and skin off fruit – deformation rate 0.83 mm/s (BLAHOVEC et al. 1995)

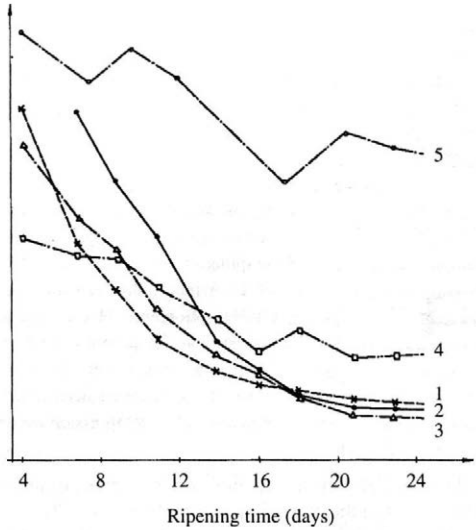


Fig. 32. TPA parameters and firmness of pear flesh stored at 21°C plotted against time of storage (time of ripening) – BOURNE (1968). Abbreviations: 1 – firmness (Magness-Taylor test), 2 – hardness (see Table 9), 3 – brittleness, 4 – elasticity, 5 – cohesiveness (see Table 9), the texture parameters are plotted in relative form

Pre-storage treatments at elevated temperatures (higher than 35°C) inhibit the ripening of various fruits. Keeping apples at 38°C for 4–6 days before storage can retard or inhibit fruit softening. BEN SHALOM et al. (1996) obtained about 10% higher firmness for Anna apples pretreated for 4 days at 38°C and then stored for two months at 0°C, in comparison with the same apples without pretreatment. This effect is usually discussed as a result of inhibition of solubility of the carbonate soluble pectin fraction caused by thermal pre-treatment. Pre-storage irradiation is another pre-storage treatment influences the storage softening process. YU et al. (1996) showed that electron beam pre-storage irradiation (dose 0–2 kGy) of strawberries causes a 15–20% decrease of their firmness after 8 day storage at 2°C, in comparison to strawberries stored in the same conditions without the pre-treatment. At least part of this effect can be explained by variations of the oxalate-soluble pectin content.

Flesh softening can be detected even by puncture tests with skin intact. Fig. 30 contains results of puncture tests of whole plantain fruits ripened at room temperature (21–24°C). The observed decrease of firmness is high enough for estimation of the flesh softening during the ripening time. Generally, the differences between product firmness as determined with skin (skin intact) and as determined without skin (skin off) should not be overlooked. Especially for soft products the skin plays a very important role. Fig. 31 contains the results of a puncture test of sweet and sour cherries in both the above mentioned states (skin off and skin intact), and in many cases (e.g., for Kordia variety) the differences between the two values represent more than 3/4 of the firmness with skin intact. This means that in such a case more than 75% of the fruit firmness, i.e., also its stability in relation to the external forces applied by the indentor, consists in its skin. In the case of sour cherry variety Záhoračka, it is 86%! However, this ratio is meaningful as an indicator of the role played by skin when the results of tests were obtained by indentors of different diameter. BOURNE (1966) showed that penetration strength force is given by superposition of the compression part proportional to the tip area (as a quadratic function of the tip diameter) and shear part proportional to the tip perimeter (as a linear function of the tip diameter). During the penetration test the fruit skin is deformed mainly in shear, but the fruit flesh is deformed mainly in compression. This means that every decrease of the tip diameter leads to an increasing role of the skin in the penetration strength of the complex product. The lower the tip diameter, the worse is the expression of the compression strength of the complex product with skin by mean contact pressure on the tip (e.g., the high firmness values of tomatoes tested by an indentor with a diameter of 0.45 mm – RUIZ-ALTISENT et al. 1980).

Product softening during the ripening process can also be detected by TPA parameters as was originally shown by BOURNE (1966) (Fig. 32). TPA parameters can also be used to study the cooking processes in potatoes and other vegetables (e.g., BLAHOVEC et al. 1999a,b). The two processes, ripening and cooking, have similar effects on the TPA parameters: they decrease with increasing time of the effect.

BERRY LIKE FRUITS

The soft fruits discussed above, which have skin much firmer than flesh, i.e., cherries, tomatoes, ripe kiwi, etc.

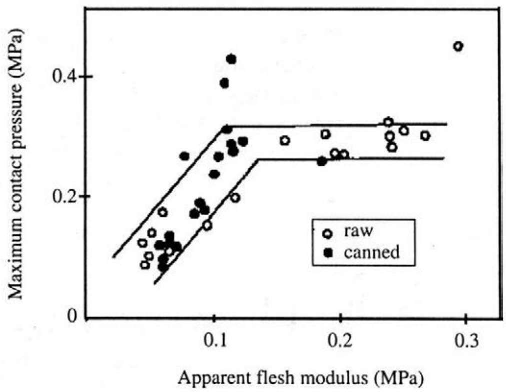


Fig. 33. Maximum contact pressure in raw and canned cherries during compression between two rigid plates plotted against apparent modulus of elasticity of flesh as determined by a puncture test of the skinned fruits (BLAHOVEC et al. 1995). The maximum contact pressure was determined in point of inflexion of the compression curves – near Hertzian limit in Fig 2b1

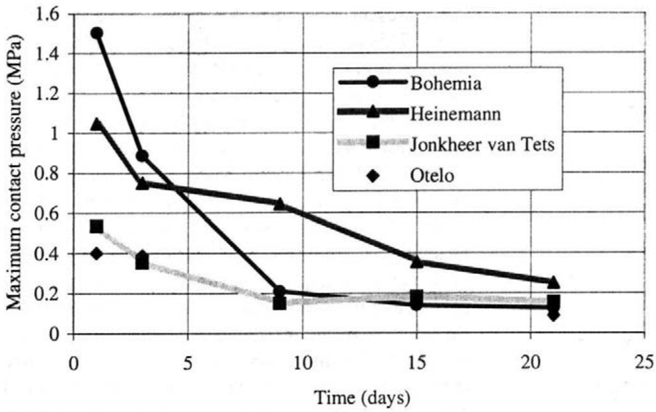


Fig. 34. Maximum contact pressure in currant fruits plotted against time of sampling (1 corresponds to 16th June 1992). Arranged data of BAREŠ et al. (1994) – Bohemia, Heinemann and Jonkheer van Tets are red varieties, and Otelo is a black variety. Maximum contact pressures were determined at rupture point of compression curves

behave similarly to an elastic balloon filled with a quasi-liquid. These products can be included in a special class of soft horticultural products referred to as berry-like fruits. Firmness testing has some limits in this case, and more special testing methods and testers have to be used (PATTEN, PATTERSON 1985; BERNSTEIN, LUSTIG 1985; LUSTIG, BERNSTEIN 1987). The methods are based on a simple compression test of a spherical product between two plates (Fig. 4c). BERNSTEIN and LUSTIG (1985) defined berry firmness as the mean pressure in the contact area. This parameter was expressed as a sum of the three components: turgor pressure, the stress due to the increase of skin tension of the compressed fruit, and the stress due to the structural stiffness of the flesh. Practical realisation of their conception involves measuring both the force and the contact area, simultaneously. They developed a special firmness tester for juicy fruits (LUSTIG, BERNSTEIN 1987) which is useful for this purpose.

Bernstein and Lustig firmness can be replaced by maximum contact pressure p_0, defined by the Hertz contact theory (JOHNSON 1985), expressed as:

$$p_0 = \frac{6F}{\pi d^2 (D/d)} \qquad (9)$$

where the symbols defined in Fig. 4c are used. According to the Hertz contact theory, p_0 increases with increasing $(D/d)^{1/2}$, but in the case of berry-like fruits it varies at higher deformations only very little (BAREŠ et al. 1994).

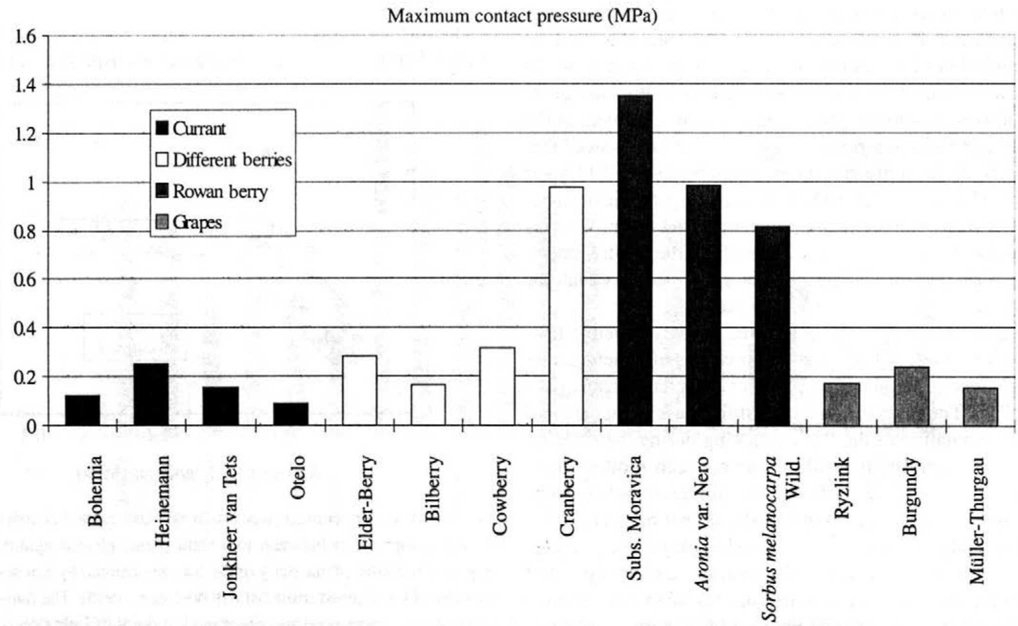


Fig. 35. Maximum contact pressure of various matured berry-like fruits. Arranged data of BAREŠ et al. (1994)

It seems to be a very good firmness parameter for soft berry-like fruits. Fig. 33 contains some values obtained for cherries (raw and canned, including sour cherries) plotted against the apparent modulus of elasticity of the cherry flesh. A good relation was observed between these parameters for cherries with very soft flesh. For raw cherries with harder flesh (apparent modulus higher than appr. 0.13 MPa), the inflexion point moves to lower deformation values and p_0 is rather constant (0.25–0.3 MPa).

Maximum contact pressure (MCP) is very good means for determining the degree of maturity of berry-like fruits. Fig. 34 contains maximum contact pressures determined at rupture points of currant fruits compressed (deformation rate 0.5 mm/min) between two rigid plates; they are plotted against time of sampling. All the results decrease with increasing time of sampling. A very quick decrease of MCP is observed in the Bohemia variety, while a very slow decrease is detected for the very late variety Heinemann. The early varieties Jonkheer van Tets (red variety) and Otelo (black variety) decrease very slowly and similarly, because they were tested at a higher stage of maturity. The dynamics of increasing maturity can be well described by MCP. The rupture point is usually observed at relative compression 0.4, and the highest values of relative compression were detected at the beginning of the mature state, i.e., at the beginning of the MCP plateau.

Maximum contact pressures of various berry-like fruits was in the matured state are plotted in Fig. 35. This figure shows that the most berry-like fruits in this state have MCP lower than 0.3 MPa (see also Fig. 33 for cherries). Only cranberries and various varieties of Rowan berry are larger (0.8–1.4 MPa). These different values of MCP cannot be explained only by the thickness of the fruit skin. BAREŠ et al. (1994) observed thicker skin not only for Rowan berries (0.1–0.134 mm) but also for grapes (0.115–0.150 mm) and black currant (about 0.1 mm). In order to explain these, it is necessary to take into consideration the structure of the fruit fleshes.

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Statické vlastnosti a textura ovoce a zeleniny

ABSTRAKT: Mechanické vlastnosti ovoce a zeleniny představují velmi důležitou informaci o jejich kvalitě. Předurčují použitelnost produktu buď jako potravu k přímé spotřebě, nebo jako surovinu pro další zpracování. Kvalitativní aspekt mechanických vlastností je znám jako textura, která byla původně určována degustační komisí. Moderní studie textury jsou založeny na objektivních instrumentálních testech dávajících přesné a komplexnější informace o testovaných produktech. Nejčastější tradiční texturní parametr je firmness (v českém jazyce není stejný ekvivalentní pojem, nejblíže se anglickému originálu blíží tvrdost), která má instrumentální ekvivalent již od dvacátých let 20. století. Tento přehled popisuje základní statické testy používané ke studiu textury zahradnických produktů. Různé metody jsou použity ve vztahu ke stanovení náchylnosti k mechanickému poškození a vzniku statických a dynamických otlaků a povrchového praskání produktů v důsledku změn vlhkosti. Speciální vlastnosti různých produktů jsou analyzovány z hlediska jejich zralosti a dozrávání. Pro každý produkt je uvedena speciální vlastnost vhodná k testování jeho mechanických vlastností.

Klíčová slova: ovoce; zelenina; tvrdost; textura; modul pružnosti; biologická mez makrodeformace; pevnost; praskání; otlačení; bobule; zralost; dozrávání

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