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Monitoring post-harvest quality of *Granny Smith* apple under simulated shelf-life conditions: destructive, non-destructive and analytical measurements

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Summary The purpose of this research was to use destructive and non-destructive measurement methods to evaluate *Granny Smith* apple quality changes under room storage conditions (20°C, 65% relative humidity) and to relate it to internal structure changes as observed using light microscopy. The *Granny Smith* apple firmness was non-destructively measured with forced vibration and acoustic impulse techniques. At the determined time intervals, compression and tensile tests were carried out to determine apple flesh mechanical properties. The cell-wall rupture was examined with light microscopy. The pH value, internal air space (IAS), soluble solids concentration (SSC), colour changes and weight losses of the apples were also monitored during storage. Apple firmness measured with forced vibration correlated well with the impulse test. The acoustic impulse measurement had less deviation compared with the vibration test. The pH value and IAS increased during storage at room temperature. The *Granny Smith* apple has a long storage life and the criteria for the mealiness are suggested from compression and tensile tests.

Keywords Acoustic impulse, cell rupture, firmness, mealiness, texture.

Introduction

The *Granny Smith* apple was originally discovered in Australia and spread slowly to other countries in Europe. *Granny Smith* apples are mostly imported from Australia, New Zealand, South Africa and Chile, although France and Italy are also important suppliers (Desmond O'Rourke, 1986). The *Granny Smith* apple is considered a firm apple and has a relatively long storage life which is advantageous for the market.

Apple quality after harvest has been studied quite extensively. Holt & Schoorl (1984) reported the mechanical properties and texture of *Granny Smith*, *Delicious* and *Jonathan* apples during cool storage. They found a good correlation between sensory evaluation, ultimate tensile strength and fracture resistance. The effect of water loss on apples in cool storage was studied by Hatfield & Knee (1988). The apple texture can be determined either by destructive methods or by non-destructive methods. The non-destructive resonant measurement of apple firmness has been reported by many researchers (Abbott *et al.*, 1968; Finney, 1970; Yong & Bilanski, 1979; Van Woensel *et al.*, 1988; Armstrong *et al.*, 1990; Chen & De Baerdemaeker, 1993; Liljedahl & Abbott, 1994). Abbott & Liljedahl (1994) found that the apple resonant frequencies and stiffness factor were most highly correlated with compression slope than with the area under force deformation curves and maximum force. However, apple texture development under shelf-life conditions has had only limited attention.

Besides firmness, mealiness is another important parameter for apple texture evaluation. Mealiness

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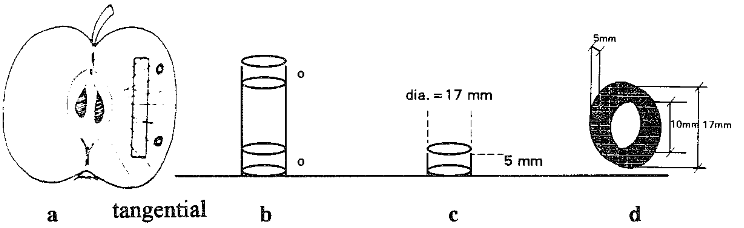


Figure 1 The sample preparation. **a.** tangential cut cylindrical samples from apple. ○ indicates outer parts of the cylinder. **b.** cylinders from the apple. **c.** samples for compression test. **d.** samples for tensile test.

in apples is described as the breakdown of flesh into small pieces in the mouth, which tend to be dry (Harker & Hallett, 1992). Harker & Sutherland (1993) studied mealy texture development in nectarines during storage. They observed that the presence or absence of juice on the fracture surface after the tensile test was the main difference between non-mealy and mealy nectarines. Although mealy texture of apples has been studied by some authors (Harker & Hallett, 1992; Khan & Vincent, 1993), little is known whether mealiness can be determined by mechanical methods.

The main objectives of this research were to: (1) investigate *Granny Smith* apple texture development destructively and non-destructively under simulated shelf-life conditions; (2) observe the relation between micro-structure and mechanical properties; and (3) suggest instrumental measurement criteria for *Granny Smith* apple mealiness.

Materials and methods

Granny Smith apples imported from South Africa were purchased from a local supermarket. The size (diameter) was between 70 and 80 mm. The apples were immediately stored under 20°C, 65% RH conditions throughout the entire experiment. The experiment started 1 day later.

A total of 83 apples were tested in the experiment. Fifteen apples were subjected to impulse response and random vibration non-destructive measurements during the storage. The other apples were numbered and randomly grouped with 4 apples in each group. Every 3 days, one group of apples was taken out of storage and subjected to compression and tensile tests.

Destructive measurements

The tests were carried out with a Universal Testing Machine System (UTS Testsysteme GmbH, Germany). The samples were made as shown in Fig. 1. The apple flesh was cut with a cylindrical cutter. The apple core was carefully avoided and the outer parts of the cylinders were used. Sample cylinders were between 40 and 50 mm long depending on the apple size. The compression test was carried out by compressing a cylindrical sample between two parallel plates with the compression rate of 50 mm min^{-1}. The maximum deformation was 80% of the sample height. The tensile test (Fig. 2) was carried out using ring-shaped samples subjected to radial loading as described by Verlinden & De Baerdemaeker (1994). This type of test avoids clamping problems of the apple specimen as well as damage to the sample texture. The tensile test device consists of two half ring shaped cylinders over which the ring shaped sample can slide. During the test, the moving crosshead moves at the test speed and the ring shaped sample deforms and eventually breaks. The force-deformation curve was recorded. A typ-

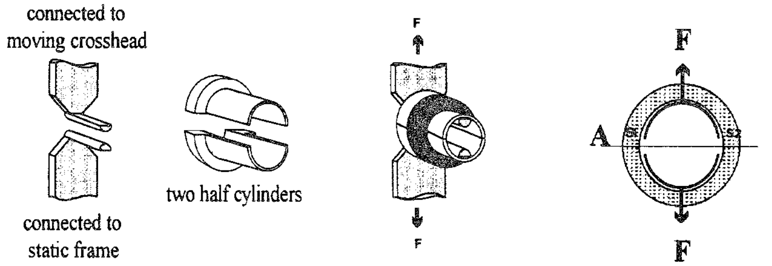
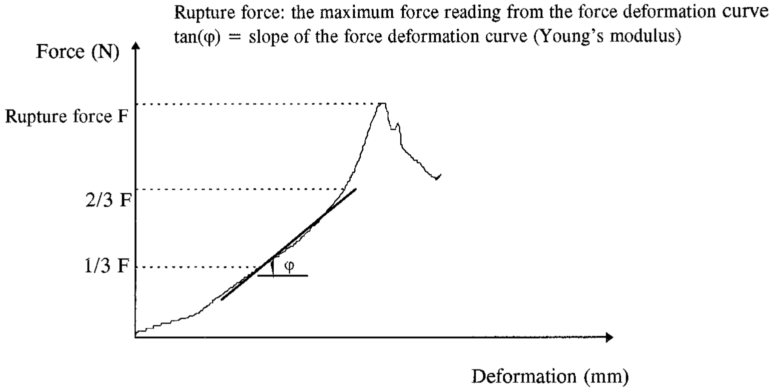


Figure 2 The tensile measurement set up.



Rupture force: the maximum force reading from the force deformation curve
tan(φ) = slope of the force deformation curve (Young's modulus)

Figure 3 A typical force-deformation curve during tensile test.

ical force-deformation curve can be seen in Fig. 3. It is assumed that the deformation ϵ is the same in both 'loop' sides since the material in both sides is the same. The tensile stress can be calculated by dividing the measured force F by the sum of the cross-sections S_1 and S_2 of each 'loop'.

$$\sigma = \frac{F}{S_1 + S_2} \tag{1}$$

Non-destructive measurements

Apple firmness was determined by acoustic impulse response technique and forced random vibration test on the intact apples. The set up of acoustic impulse response measurement was the same as used by Chen & De Baerdemaeker (1993). During the test, the acoustic response signal was amplified and sent to a HP 35665A dynamic signal analyser (Hewlett-Packard Company, WA, USA). The peak in the frequency spectrum corresponding to the spherical mode shape of apple was recorded. The apple firmness was indicated by the stiffness factor which is calculated as $f^2M^{2/3}$ (f: first peak frequency, Hz; M: apple mass, g). To reduce the apple-shape effect, the f was represented by the three average resonance frequencies measured at three marked locations separated about 120° around the equator.

Because of the air between the apple and microphone, the damping during impact measurement cannot be correctly determined. The widely used random vibration measurement was applied to determine the apple vibration frequency and damping ratio. The vibration excitation and the data analysis method are illustrated in Fig. 4. The intact apple was fixed horizontally with two-sided tape on a round plate mounted on a force transducer which was connected to a vibrator. A random signal with a bandwidth of 1600 Hz was generated in the analyser and fed to a power amplifier to drive the vibrator. A small accelerometer (PCB QUARTZ, series 303A03 PCB Piezotronics INC, NY, USA; frequency range 1–10000Hz ±5%, mass = 1.9 g) was held firmly with clay on the top of the apple opposite to the vibrator. The HP 35665A dynamic signal analyser detected both the force and acceleration signals. The second resonant frequency was used here since the first peak frequency was shown by Yong & Bilanski (1979), Van Woensel *et al.* (1988) and Kimmel *et al.* (1992) to correspond to the apple movement as a vertical rigid body mode with a local deformation at the supporting area. The second resonant frequency is related to the elastic properties of the fruit. The damping is calculated as:

$$\text{damping d} = R/\sqrt{(R^2 + I^2)}, \tag{2}$$

where: R = real part of the complex pole pair corresponding to the resonance;
I = imaginary part of the complex pole pair corresponding to the resonance.

The results were the average of three measurements on the marks around the equator.

Colour

A commercial 'colour chart' (colour chart suggested by the research committee on storage (Belgium)) scaled from 1 (background colour deep green) to 8 (yellow, ripe) was used to evaluate the colour of apples following the storage.

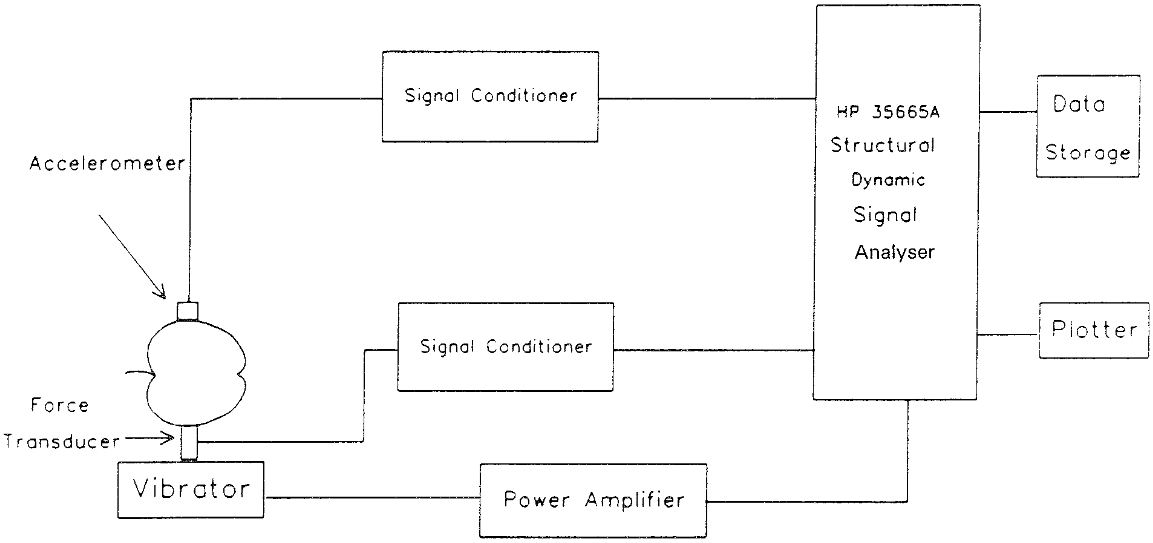


Figure 4 Schematic representation of forced random vibration measurement.

Weight loss

The numbered apples were weighed at the beginning of the experiment and the weight loss was followed during the whole experiment.

pH value

pH value of the apple juice was determined after destructive measurement at 20°C with a pH meter (ORION, model 250 A, USA).

Internal air space (IAS)

The specific gravity (SG) of apple was determined by weighing a beaker containing 760 mL water (W1). The beaker was reweighed with an apple floating in the water (W2), and then weighed again (W3) with the apple submerged below the surface of the water by three fine needles. The apple specific gravity was calculated from: (W2-W1)/(W3-W1). This method is the same as that of Hatfield & Knee (1988). The specific gravity of apple juice was the average of estimations using a pycnometer. The internal air space of whole fruit was calculated from eqn 3.

$$\text{IAS}(\%) = \left(1 - \frac{\text{SG fruit}}{\text{SG juice}}\right) \times 100\% \qquad (3)$$

Soluble solid content (SSC)

Apple juice expressed during compression was collected directly into a hand-operated refractometer (0% to 85%; Zeiss, Germany) to measure SSC.

Cell wall rupture

The samples after the tensile test were kept in a solution consisting 10 mL of commercial formol (36% formaldehyde), 5 mL of acetic acid (100%), 85 mL of ethanol (94%), and then examined through a microscope. After being washed and dehydrated, 4–5 mm of the broken zone of each ring sample was cut with a razor blade across the whole ring thickness. Slices 70 μm thick were cut in ice sections from the inner diameter of the sample to the outer diameter and investigated with a video analysis system (VIDAS, Contron Image Analysis, Cambridge, UK) connected to the light microscope. The breaks at cell wall and middle lamella levels were observed. The number of counted cells per sample varied between 60 and 90 according to the rupture angle. The observed cell wall rupture or cell separation was expressed as percentages of observed cells.

Results and discussion

Instrumental measurement results

The compression rupture force decreased during storage as shown in Fig. 5. The rupture force

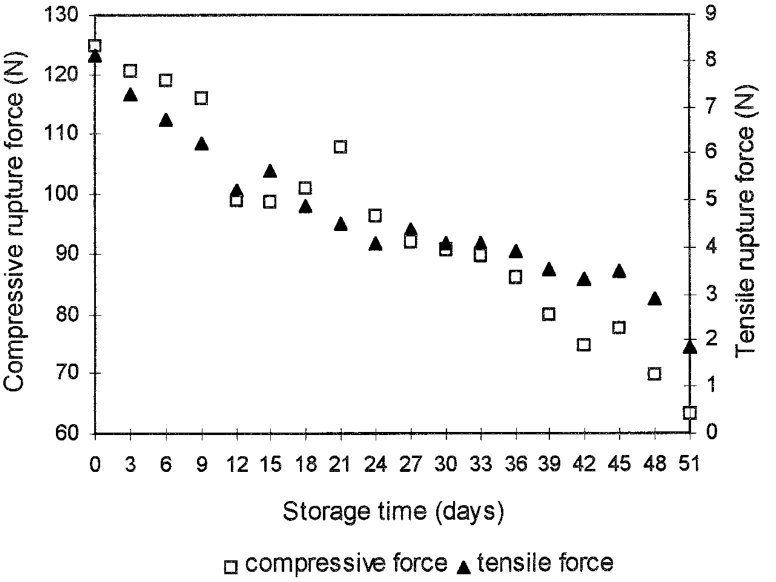


Figure 5 Compression and tensile rupture force changes during storage.

declined from 125 N for fresh fruit to about 60 N after 51 days of shelf-life. This rupture force changed linearly with time under the experimental conditions:

$$F_c = 122.56 - 1.09 \times T \quad (R^2 = 0.88) \quad (4)$$

where F_c is the compressive rupture force, T is storage time in days.

The tensile test is believed to be a good method to evaluate apple texture (Holt & Schoorl, 1984). The tensile rupture force as a function of shelf-life can be seen from Fig. 5. The tensile force tended to level out after 25 days of storage. This may indicate that *Granny Smith* apples are completely ripened after about 3 weeks storage. If the storage time is longer, the *Granny Smith* apple may lose its good taste and a soft, mealy texture may develop.

The stiffness factors measured by the non-destructive acoustic impulse resonance technique are shown in Fig. 6. The *Granny Smith* apples continuously lost their firmness

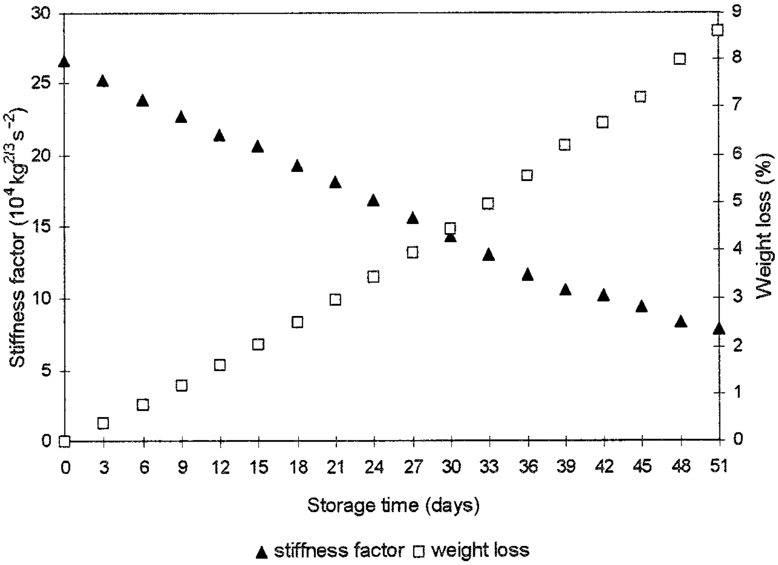


Figure 6 Stiffness factor and water loss during storage.

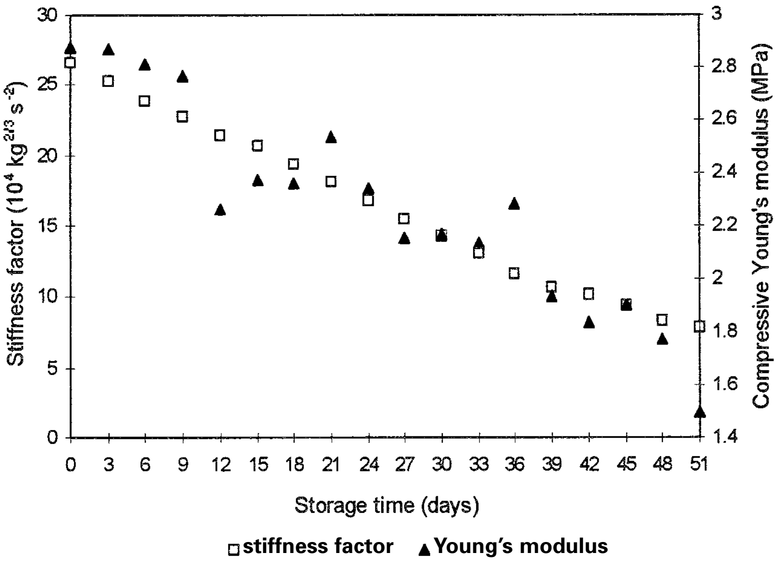


Figure 7 Stiffness factor and compressive Young's modulus changes during storage.

and the stiffness factor decreased linearly with the storage time as expressed by the linear regression equation:

$$S = 26.11 - 0.37 \times T \quad (R^2 = 0.76) \qquad (5)$$

The weight loss is negatively correlated with the apple firmness, correlation coefficient −0.83. It is commonly accepted that a weight loss of 5% will result in significant wilting, softening, shrivelling and a poor, mealy taste (Hatfield & Knee, 1988). This happened after 1 month under the given shelf-life conditions. A stiffness factor of about 13 × 10^4 kg$^{2/3}$s^{-2} can be considered as a texture indicator in determining the *Granny Smith* apple shelf-life. Below this stiffness point, the water loss is high which may result in a soft, dry texture.

The correlation between compressive Young's modulus and stiffness factor is good as can be seen in Fig. 7 and Table 1. This indicates that apple firmness can be measured by destructive or non-destructive acoustic response methods. Water loss (Table 1) is negatively correlated with the compressive Young's modulus and the stiffness factors measured by impulse or vibration measurements. The apple damping ratio is positively correlated with water loss and negatively correlated with Young's modulus and stiffness factors, confirming the findings of Chen *et al.* (1992).

Table 1 Correlation matrix of the *Granny Smith* apple

	W_{loss}	E_{comp}	S_{imp}	S_{vib}	f_{imp}	f_{vib}	d
W_{loss}	1.00	−0.66	−0.86	−0.88	−0.83	−0.90	0.81
E_{comp}		1.00	0.83	0.82	0.85	0.84	−0.75
S_{imp}			1.00	0.94	0.97	0.92	−0.88
S_{vib}				1.00	0.90	0.97	−0.91
f_{imp}					1.00	0.93	−0.88
f_{vib}						1.00	−0.93
d							1.00

W_{loss}: water loss;
E_{comp}: Young's modulus of compression;
S_{imp} : stiffness factor of acoustic impulse response measurement;
S_{vib} : stiffness factor of forced random vibration measurement;
f_{imp} : first peak frequency in impulse test;
f_{vib} : second peak frequency in forced random vibration test;
d : damping ratio.

Comparison of the two non-destructive measurement techniques

The acoustic impulse response and the forced vibration measurement results are shown in Fig. 8. The damping was determined only with the vibration technique. Each value in Fig. 8 is the average measurement on 3 points around the equator of 15 apples.

The correlation between $_{\text{fimp}}$ and f_{vib} is 0.93. It is also clear that there is a systematic difference between the two measurement techniques. The frequency measured by the vibration technique was lower than that measured by the acoustic impulse technique. The good correlation between frequency and stiffness factor indicates that these two measurement techniques are interchangeable by means of frequency measurement.

On the other hand, the accuracy of the two techniques is not the same. The measurement error of the two techniques was evaluated in this study. The measurement deviation was calculated as the average deviation of the error (STD) of each measurement point in Fig. 8. The deviations are 5.00%, 6.18%, 1.03% for f_{vib}, damping, and $_{\text{fimp}}$, respectively. We can conclude that the measurement deviation is lowest in the acoustic impulse response technique. The deviation in acoustic impulse response is mainly caused by the apple shape (Chen & De Baerdemaeker, 1993). The deviation in forced vibration tests is caused not only by apple shape but also by the contact clay, unclear mode, and the additional weight of the accelerometer. Chen *et al.* (1992) also indicated that the acoustic impulse response technique appears to be more efficient and reliable.

The damping ratio is negatively correlated with stiffness factor. The higher apple firmness corresponds to its low damping. It is noticed from Fig. 8 that the damping ratio increased more rapidly after 30 days of storage. This means that apple absorbs more energy as it becomes softer. The damping increase slowed down after 43 days indicating the apple's residual texture had almost been reached. The damping ratio may be considered as an important indicator of apple texture.

Texture development of *Granny Smith* apple

The SSC and colour changes of the *Granny Smith* apple during storage are shown in Fig. 9. The soluble solids content increased during the first 10 days of storage and thereafter stabilized around 11.6% for the rest of the experiment. The background colour became yellow and the colour score increased from 2 to 7 during the experiment.

The pH value increased almost linearly with storage (Fig. 10) and IAS also increased during the storage. Other researchers (Hatfield & Knee, 1988; Vincent, 1989; Harker & Hallett, 1992) have demonstrated that large internal air spaces are associated with poor apple texture and it may be considered as symptomatic of mealiness. From a previous study (unpublished data) it was found

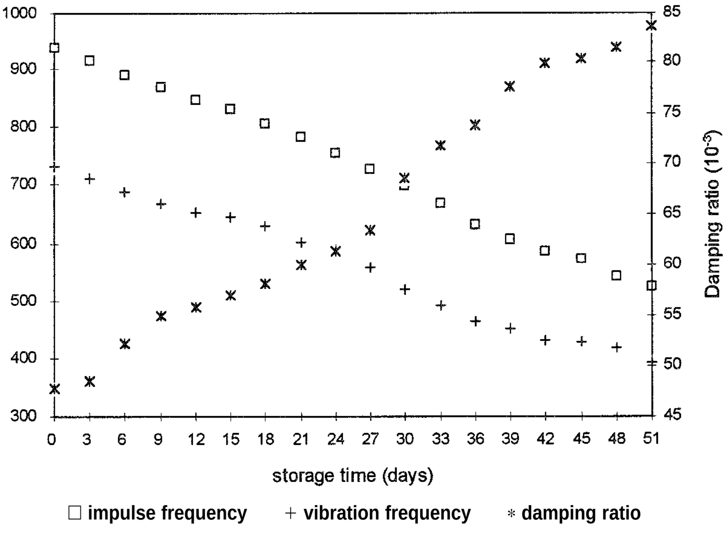


Figure 8 Impulse response frequency, forced vibration resonic frequency and damping ratio changes during storage.

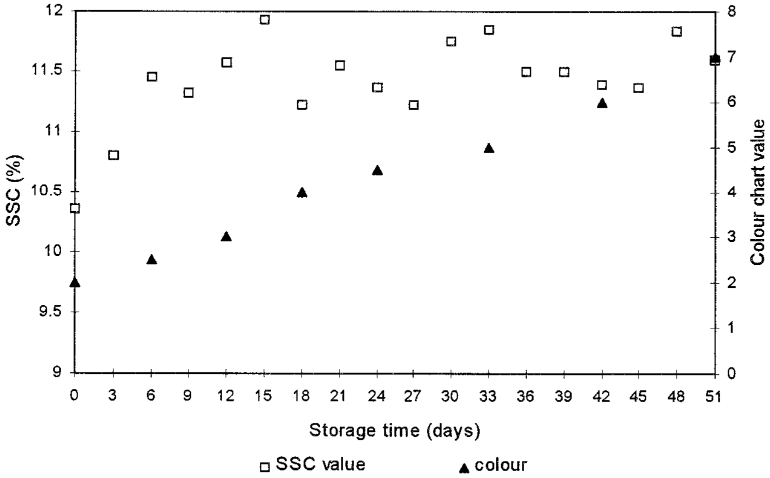


Figure 9 SSC and colour changes during storage.

that the apple *Elstar Jonagold* tended to taste mealy as the IAS increased more than 20%. This was also the case for the *Granny Smith* apple which tasted mealy at IAS around 20%. The large internal air space in the ripened apple may be caused by a degradation of the middle lamella and indicates the reduction of cell adhesion. The cells probably expand slightly and become rounded as the apple ripened, which increases internal air space and reduces the cell contact areas. Thus, the cell-to-cell adhesion decreased but cell-wall strength was maintained. The individual cells are easy to separate but difficult to rupture (Harker & Hallett, 1992).

More cell wall rupture was observed for fresh *Granny Smith* apples (Fig. 11). As the apple storage time progressed, cell rupture decreased and cell separation along the middle lamella increased. This observation was consistent with what Harker & Hallett (1992) found. Cell separation increased rapidly after 40 days of storage which indicates individual cells become difficult to rupture and the apple becomes mealy. This is because of the breakdown of pectin in the weak intercellular lamellae.

Most (>80%) *Granny Smith* apples were judged mealy (by a taster) after about 45 days of shelf-life. If we consider the rupture stresses at

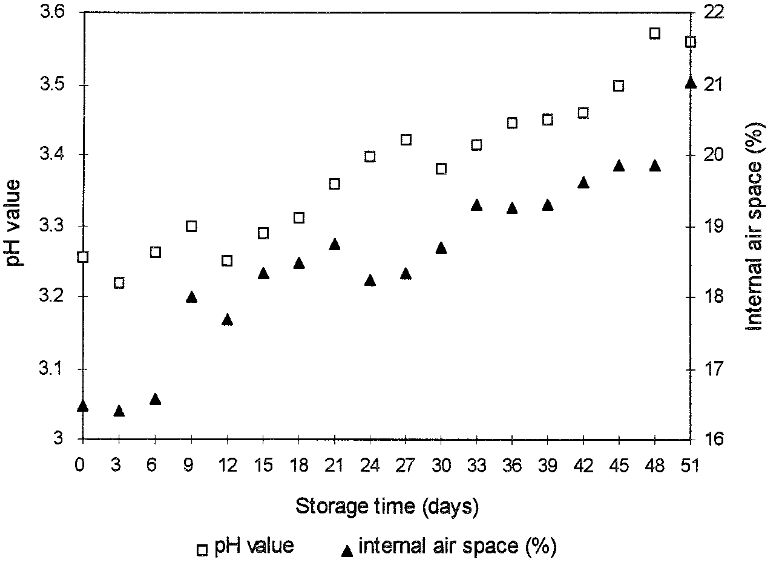


Figure 10 pH value and internal air space changes during storage.

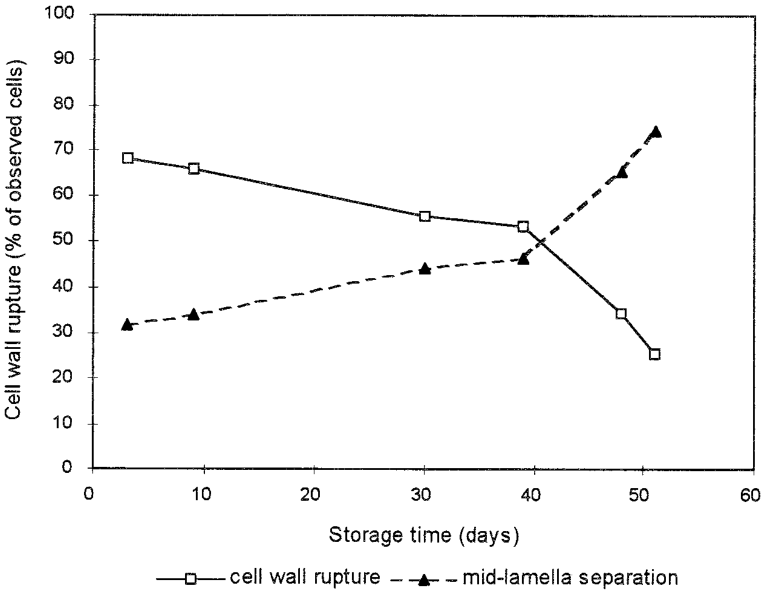


Figure 11 Observation of cell-wall breaks (%) during storage.

this time as the criteria, it is suggested that rupture stresses of 0.31 MPa and 0.086 MPa are critical stresses of mealiness for compression and tensile tests, respectively. Based on a previous study (unpublished data), *Granny Smith* apples during long-time cold storage (2°C, 10 months) will develop physiological disorders and mealiness. The mealiness developed during long-time cold storage is similar to that under shelf-life. The compression and tensile rupture force was below 70 N and 3 N, respectively, as the *Granny Smith* apple became soft and mealy under these experimental conditions.

Conclusions

Different measurement methods have been applied to study *Granny Smith* apple texture during shelf-life. The destructive and non-destructive indicators correlated well. Of the non-destructive methods, the acoustic impulse technique seems superior to the random vibration test because of its efficiency and less variation. Apple mealy texture is associated with the high internal air space. Microscopy observations indicated that the mealiness of apple relates to the separation of cells rather than the extent of tissue rupture. Tensile and compression tests may not conclusively indicate the degree of mealiness but may possibly indicate if apple is mealy or not as the apple flesh strength falls below a certain level. Future work needs to be carried out to correlate sensory (panel) tests with the mechanical and micro-structural measurements to clarify the criteria for apple mealy texture.

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