Fresh and processed apple products: vacuum infiltration, texture and quality

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Abstract

Apple slice texture and quality is affected by a diverse array of preharvest, postharvest and processing factors. The study described in this thesis had two primary objectives:

1) to investigate factors that influence the effectiveness of the vacuum infiltration process and thereby identify ways to enhance infiltration in difficult-to-infiltrate fruit.
2) to ascertain the effects of a range of pre- and post- harvest factors including cultivar, temperature, edible surface coatings and calcium treatments on fresh and processed apple texture and quality.

Vacuum infiltration is used to replace the 8-36% of tissue volume made up by occluded gases in the commercial production of solid-pack canned apple slices. This removal: reduces textural degradation caused by thermal expansion of these gases; prevents can corrosion and off-flavour development caused by residual oxygen; and ensures that relative density of the tissue is increased sufficiently to achieve prescribed can fill weights. Vacuum infiltration is often incomplete for fruit produced in cold growing seasons and also with immature fruit. In this study, level of infiltration achieved in apple slices was affected by pre-condition of the tissue (eg. maturity, porosity, whole fruit density) and by variables that relate directly to the vacuum infiltration process (eg. vacuum time, absorption time, solution temperature). Infiltration was enhanced in fruit taken from later harvests and in fruit pre-stored for a short period at 20 °C. Key aspects of the vacuum infiltration process were investigated and the relationships between vacuum time, absorption time, and slice relative density were characterised. Reduced vacuum levels were detrimental to liquid impregnation. To maximise infiltration in 'Braeburn' fruit required: high vacuum levels (preferably > 95 kPa), vacuum times of approx 2 min, and absorption times $\geq$ 6 min. Infiltration was enhanced by heating the infiltrating solution.

The texture and quality of solid-pack canned apple slices is to a large extent determined by the quality of the raw product. 'Braeburn', 'Fuji' and 'Granny Smith' apples varied quite markedly in terms of textural quality, storage potential, tolerance of ambient temperatures and ultimately in their response to processing. In general, fresh and processed apple texture declined with increasing fresh fruit storage temperature and duration. Application of edible surface coatings enhanced texture and reduced free-juice content of canned slices. The level of benefit achieved varied considerably with cultivar and storage temperature and, to a more limited extent, grower line and coating concentration. Calcium application during the pre- or post-harvest phases had little effect on processed slice texture, but in some cases free-juice volume was reduced. The interrelationships between the variables under study are discussed and a conceptual model presented that describes the effects of key postharvest variables on fresh and processed fruit texture.

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a	radius of twist tester blade (m)
a_o	radius of twist tester spindle
A	fruit surface area (m^2)
A^{punch}	area of punch/penetrometer probe
ACP	anaerobic compensation point
ANOVA	analysis of variance
ATP	adenosine triphosphate
b	width of twist tester blade
BC	background colour
BKra	maximum force as measured by Kramer shear cell (blanched fruit slices; N)
c, d, g, h, i, j, k, l, m, n, o, q, s, u, v	parameters for linear and non-linear equations
C	chroma
CA	controlled atmosphere storage
CI	confidence interval
CMC	carboxymethylcellulose, sodium salt
cont	control
CV	coefficient of variation
HD	harvest date
Δp_j	difference in partial pressure of gas j between internal and external atmospheres (Pa)
Δp_{H_2O}	water vapour pressure difference between fruit and surrounding airstream
Δp_{O_2}	difference in partial pressure of oxygen between internal and external atmospheres (Pa)
$\Delta\rho_{rel}^{slice}$	change in relative density of an apple slice after infiltration
DOI	degree of infiltration (%)
DPen	firmness as measured by drill-mounted penetrometer (N)
ε	cortical tissue porosity ($m^3.m^{-3}$)
ε^a	cortical tissue porosity estimated using infiltration ($m^3.m^{-3}$)
ε^b	cortical tissue porosity estimated from initial relative density of tissue and juice ($m^3.m^{-3}$)
ε_e	effective porosity
EP	extinction point
Eq(s).	equation(s)
f	resonance frequency
f	fruit firmness
F	bioyield point
FCP	free choice profiling
Fig(s).	figure(s)
FKra	maximum force as measured by Kramer shear cell (fresh fruit slices; N)
FT	fermentation threshold
g	gravity constant 9.8 $m.s^{-2}$

θ	angle of rotation (°)
HDM	hydrodynamic mechanism
IAS	intercellular air space
IPen	firmness as measured by Instron operated penetrometer (N)
K_c	commodity compression coefficient
K_{FT}	firmness temperature coefficient (%/°C)
K_s	commodity shear coefficient
L	lightness
LO	low oxygen storage
LOI	level of infiltration
LOL	lower oxygen limit (kPa)
LOL^i	internal lower oxygen limit (kPa)
LTLT	low temperature long time blanch treatment
m_T	moment
M	mass
M^{fruit}	fruit mass (kg)
M^{app}	apparent mass of non-infiltrated slice in air (kg)
MA	modified atmosphere storage
M_i^{app}	apparent mass of infiltrated slice submerged in water (kg)
M_n^{app}	apparent mass of non-infiltrated slice submerged in water (kg)
M_w^{app}	apparent mass of slice submerged in water (kg)
NS	not significant
P	probability or level of significance of a statistical test
P^{punch}	perimeter of punch
PD	permanent deformation (mm)
pH	concentration of hydrogen ions in a solution
p_{atm}	atmospheric pressure
p_c	capillary pressure
p_j^e	partial pressure of gas j in the external atmosphere (Pa)
p^e_{O2}	external partial pressure of oxygen (kPa)
p^i_{CO2}	internal partial pressure of carbon dioxide (kPa)
p_j^i	partial pressure of gas j in the internal atmosphere (Pa)
p^i_{O2}	internal partial pressure of oxygen (kPa)
p_r	reduced capillary pressure
p_{vac}	pressure during vacuum treatment
P'_{H2O}	fruit skin permeance to water vapour ($mol.s^{-1}.m^{-2}.Pa^{-1}$)
P_j	permeability to gas j ($mol.s^{-1}.m.m^{-2}.Pa^{-1}$)
P'_j	permeance to gas j ($mol.s^{-1}.m^{-2}.Pa^{-1}$)
P'^{skin}_{O2}	fruit skin permeance to oxygen ($mol.s^{-1}.m^{-2}.Pa^{-1}$)
P'^{coat}_{O2}	coating permeance to oxygen ($mol.s^{-1}.m^{-2}.Pa^{-1}$)
PCA	principal component analysis
PGA	polygalacturonic acid
PE	pectinesterase
PG	polygalacturonase
PI	prediction interval
PKra	maximum force as measured by Kramer shear cell (processed fruit slices, N)
σ	crush strength (Pa)

Q_{10}	temperature coefficient (=[rate of O_2 uptake at (T+10°C)]/[rate of O_2 uptake at T])
QDA	quantitative descriptive analysis
R	apparent compression ratio
r	actual compression ratio
r^2	square of the correlation coefficient (r) or the proportion of total variation in y that can be explained by the independent variable x
r^T_{O2}	specific rate of transfer of O_2 at temperature T ($mol.s^{-1}$)
RH	relative humidity
RG 1	rhamnogalacturonan 1
RQ	respiratory quotient
RQB	respiratory quotient breakpoint
ρ_{H2O}	density of water ($kg.m^{-3}$)
ρ^{fruit}_{rel}	density of whole fruit relative to water
ρ^{juice}_{rel}	density of juice relative to water
$\rho^{slice}_{rel,\ init}$	density of an uninfiltrated slice relative to water
ρ^{slice}_{rel}	density of a slice relative to water
SE	standard error
SED	standard error of the difference between means
SEM	standard error of the mean
SI	starch index
SPE	sucrose polyester formulation
SS	total soluble solids content (%, ° Brix)
t	time
T	temperature (°C)
TBio	twist test bioyield (kPa)
TCA	tricarboxylic acid cycle or Krebs cycle
TMax	twist test maximum crush strength (kPa)
TPA	texture profile analysis
V	volume
V_h	volume of submerged portion of hook (m^3)
V_s	volume of slice (m^3)
WVP	water vapour pressure
WVPD	water vapour pressure deficit
XET	xyloglucan endotranslycosylase
x	volumetric fraction of liquid
x_v	volume fraction of pore occupied by liquid
WSP	water-soluble polyuronides
Z	distance of the centre of mass of the rod from the axis of rotation

Chapter 1

General Introduction

Apples are a significant economic contributor to the New Zealand market, with apple exports in the 1995 season earning New Zealand $482 million (Bollard, 1996). Of those apples not exported fresh, a significant proportion are made into processed apple products. Worldwide, c. one third of the commercial apple crop is processed (Fisher and Kitson, 1991). In 1995, $13.1 million of canned apple products were exported from New Zealand (Bollard, 1996). Apples are converted into a diverse range of canned, dehydrated, frozen and liquid processed products. Canned apple products include applesauce, solid-pack pie slices, pie filling, spiced apple rings, baked apples and canned apple pieces in syrup (Fisher and Kitson, 1991). The work described in this thesis has focused on a single apple product: solid-pack pie slices. This product is used primarily by the catering industry and as such has to withstand further processing in the form of pie and strudel manufacture. Apples used for solid-pack production should be firm, retain their shape, produce little free juice, exhibit a strong characteristic apple flavour and produce slices of a uniform bright colour (yellow-white; J. Wattie Foods, personal communication, 1992; Luh *et al.*, 1986). Of these quality attributes, texture and free juice content are of primary concern to processors. Soft textureless slices are undesirable as they do not withstand further processing, whilst hard, rubbery slices are also unsuitable. Texture consistency is also important in an industry that demands uniform product. Pie / strudel manufacturers and other re-processors require a product with minimal free juice so that their finished product quality is not adversely affected. Solid-pack slice quality is affected by: 1) the quality of the unprocessed apples and 2) the way in which the unprocessed flesh responds to the canning process.

The ultimate quality of processed apple slices is affected by a range of preharvest (or production), postharvest and processing factors. Cultivars vary considerably in terms of fresh fruit texture (Paoletti *et al.*, 1993), storage potential (Mohr, 1989) and processing characteristics (Reeve and Leinbach, 1953; McLellan *et al.*, 1984a).

Many preharvest factors including fruit maturity, mineral nutrition, soil quality, irrigation management, rootstock selection, tree management (pruning, bending and girdling of branches) and environmental conditions may influence both fresh and processed fruit texture and quality. During the postharvest phase inappropriate handling or storage conditions may result in excessive waste and low or variable product quality. Storage temperature, RH, duration, internal partial pressures of oxygen ($p^i_{O_2}$, kPa) and carbon dioxide ($p^i_{CO_2}$) and other physiologically important gases are just some of the postharvest factors that may directly or indirectly affect fresh and processed fruit quality. The processing phase comprises a number of individual operations, each of which has the potential to influence final product texture and overall quality. Vacuum infiltration is the procedure used by processors to remove occluded gases from the tissue. Removal of these gases is necessary to: increase tissue relative density and hence ensure prescribed can fill weight is obtained; reduce textural degradation caused by thermal expansion of gases during blanching and cooking operations; and prevent can corrosion and off-flavour development caused by residual oxygen. Peeling and slicing operations, the use of additives, process run times, blanching and thermal processes are other key variables in the processing phase. Factors that affect fresh and processed apple slice texture and quality are reviewed in Chapter 2. Other pertinent literature relating to the structural basis of texture, ripening and processing induced textural changes and texture evaluation is also covered in that chapter.

A diverse array of preharvest, postharvest and processing factors have the potential to influence both fresh and processed apple quality. Whilst considerable research effort has been directed at understanding how various postharvest and processing factors affect processed apple quality (particularly applesauce), many questions still remain concerning the effects of the pre- and post- harvest environment on processing quality and the relationship between fresh and processed slice quality. In addition, achieving complete infiltration of slices during the vacuum infiltration process is often still difficult during some years, particularly early in the season (J. Wattie Foods, personal communication, 1993; Rahman and Perera, 1995). Achieving

complete infiltration using a cost effective approach is of key interest to processors. J. Wattie Foods is a food processing company that produces a wide selection of food products including processed apple products. The work described in this thesis was initiated in response to a request from J. Wattie Foods to: 1) enhance infiltration in difficult-to-infiltrate fruit; 2) identify and investigate key pre-processing factors that affect product quality; and 3) improve the consistency of quality of solid-pack apple slices. This request followed reports from customers of J. Wattie Foods that the quality of these apple slices was inconsistent and sometimes unsuitable for the institutional uses of the product (eg. baked pies).

The objectives of the study described in this thesis were:

1) to re-examine methods for assessing the degree of infiltration; evaluate each component of the vacuum infiltration sequence; identify potential techniques for enhancing infiltration in difficult-to-infiltrate fruit by modification of the vacuum infiltration sequence and/or infiltrating solution; to assess the effects of maturity (as determined by harvest date) on infiltration; and to characterise the relationship between vacuum infiltration and slice texture (Chapter 4);
2) to investigate the effects of cultivar, storage temperature, storage duration, and RH on both fresh and processed slice texture and quality (Chapter 5);
3) to evaluate the feasibility and potential physiological benefits and risks of using edible surface coatings on ambient and cool-stored fruit destined for processing (Chapter 6);
4) to investigate the effect of calcium chloride applied during the pre- or post-harvest phases on fresh and processed apple texture and quality (Chapter 6).

The findings from these chapters, together with suggestions for further work, are discussed and evaluated in Chapter 7.

Chapter 2

Literature Review

2.1 What is texture?

Texture is an important quality attribute of raw and processed horticultural products. Bourne (1982a) defined the textural properties of a food as "that group of physical characteristics that arise from the structural elements of the food, are sensed by the feeling of touch, are related to the deformation, disintegration, and flow of food under force, and are measured objectively by functions of mass, time and distance". This definition recognises the multifaceted nature of texture. The texture of a product is generally not adequately defined by a single measurement but is more appropriately represented by a collection of measurements (Szczesniak, 1987). Texture may be characterised instrumentally or by sensory evaluation. Table 2-1 outlines the components of texture.

Table 2-1.a. Textural properties of foods (Szczesniak, 1963; Kays, 1991)

Textural term	Popular term
1. Mechanical characteristics	
a. Hardness: the force necessary to attain a given deformation	soft-firm-hard
b. Cohesiveness: the strength of internal bonds of the product	
c. Viscosity: the rate of flow per unit force	thin-viscous
d. Elasticity: the speed at which the material returns to its original shape after deformation	plastic-elastic
e. Adhesiveness: the work required to overcome the attraction between food and mouth	sticky-tacky-gooey

Table 2-1.b Textural properties of foods (continued)

Textural term	Popular term
1. Mechanical characteristics (cont.)	
f. Brittleness: the force required to fracture a product	crumbly-crunchy-brittle
g. Chewiness: the energy required to masticate a solid food until it can be swallowed	tender-chewy-tough
h. Gumminess: the energy required to masticate a semisolid food	short-mealy-pasty-gummy
2. Geometrical characteristics	
a. Particle size and shape	gritty-grainy-coarse, etc.
b. Particle shape and orientation	fibrous-cellular-crystalline, etc.
3. Other characteristics	
a. Moisture content	dry-moist-wet-watery
b. Lipid content	oily-greasy

For apples destined for fresh consumption and those made into canned slices, texture is a vital component of overall product quality. Hardness (firmness), cohesiveness, particle size, shape and orientation are particularly important components of apple texture. Fresh apples used to make solid-pack slices should be firm and maintain their wholeness characteristics (Luh *et al.*, 1986; Wiley and Binkley, 1989).

2.2 The structural basis of fruit texture

The perceived texture of fresh apples and other horticultural commodities is derived largely from the composition and organisation of plant tissues, and turgor pressure generated within the cells by osmosis (Knee and Bartley, 1981; Tucker, 1993; Jackman and Stanley, 1995). Heat processing has a profound effect on product texture. Canning results in considerable softening brought about by loss of turgor pressure and occluded air, thermal degradation of the middle lamella and starch

gelatization (Aguilera and Stanley, 1990; Stanley *et al.*, 1995). The first part of this section reviews current theories on cell wall structure and composition (as most texture changes are associated with cell wall degradation), while the second part focuses on textural changes brought about by fruit ripening and/or processing.

2.2.1 Apple morphology

Apple morphology is a key contributor to perceived fruit texture. Several studies have investigated the cellular structure of apple fruit (Reeve, 1953; Mohr, 1979; Mohr, 1989; Trakoontivakorn *et al.*, 1988; Khan and Vincent, 1990; Lapsley *et al.*, 1992). The edible portions of apple fruit are composed largely of parenchyma cells. These cells tend to be small (50 μm) and radially flattened near the fruit surface, but towards the core there is a gradual increase in cell size (200-500 μm, at about 5 mm from the surface) and it becomes apparent that the cells are radially elongated and organised into radial columns (Bain and Robertson, 1951; Khan and Vincent, 1990; Khan and Vincent, 1993; Lapsley *et al.*, 1992). Intercellular air spaces and vascular strands also follow this radial pattern. These intercellular spaces may be up to 4000 μm in length and 100-200 μm in diameter (Reeve, 1953). The volume of intercellular spaces may range from 8-36 %, depending on cultivar and maturity (Soudain and Phan Phuc, 1979; Hatfield and Knee, 1988). The arrangement of cells, intercellular air spaces and vascular strands can have a large impact on fruit texture. Vincent (1989) demonstrated that apples behave differently mechanically when tested radially, as opposed to tangentially. These studies clearly show apple tissue to be anisotropic and inhomogeneous. The proportion of intercellular space is also important. During fruit development, ripening, and during storage, the intercellular space volume increases, leading to the development of a more open and porous structure. Associated with this increase in intercellular volume there is a decline in cell-to-cell contact area and fruit firmness (Hatfield and Knee, 1988; Vincent, 1989; Knee, 1993; Harker and Hallett, 1992; 1994).

2.2.2 Cell wall structure

The fundamental unit of structure is the cell. Plant cells consist of cytoplasm and cellular organelles (golgi bodies, chloroplast, ribosomes etc.) surrounded by a plasma membrane and cell wall (Fig. 2-1; Becker and Deamer, 1991). Adjacent cell walls are connected by a pectin rich middle lamella (Darvill *et al.*, 1980; Dey and Brinson, 1984) and plasmodesmata. Plasmodesmata are symplastic connections between neighbouring cells, which traverse localised regions of the cell wall known as pit fields. These plasmodesmata are thought to give ripe fruit a degree of cohesion (John and Dey, 1986). The composition and degree of structural integrity of the cell wall and middle lamella are key determinants of fruit texture.

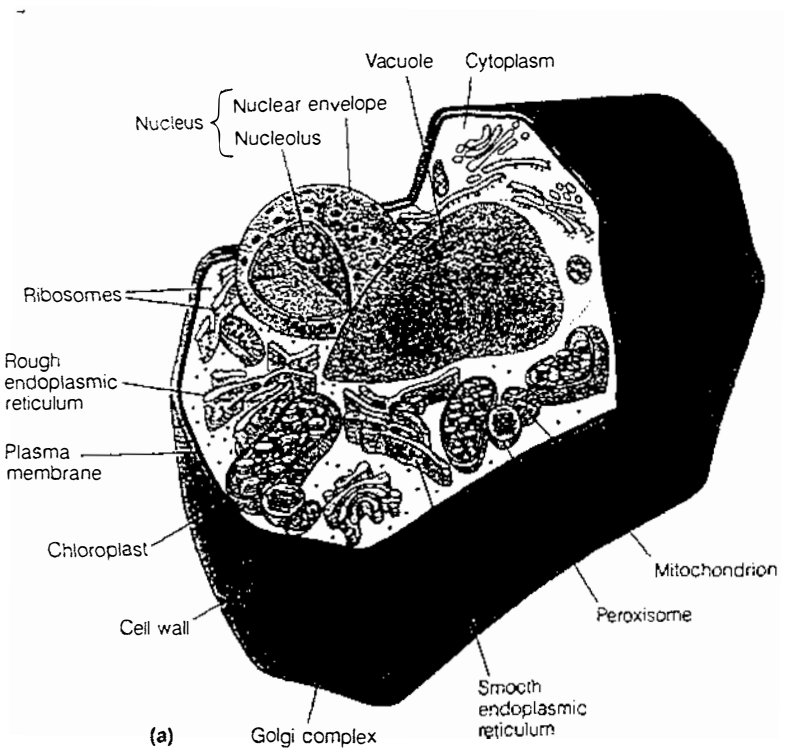


Fig. 2-1. A typical plant cell (Becker and Deamer, 1991).

2.2.2.1 Composition of the cell wall

The cell wall is composed of cellulose fibres embedded in a matrix of polysaccharide and protein. Primary cell walls in dicotyledonous plants consist of approximately 30 % cellulose, 30 % hemicellulose, 35 % pectin and 5 % protein (Fry, 1988; Jackman and Stanley, 1995), although the relative proportions of each of these constituents vary with plant source. For example, apple fruit cell walls consist mainly of cellulose and pectin, with some hemicellulose and a very small amount of hydroxyproline-rich glycoprotein (often referred to as extensin; Knee and Bartley, 1981).

Cellulose microfibrils (5-15 nm wide), comprising several dozen linear chains of β-(1-4)-linked D-glucose provide the framework and mechanical strength of the cell wall (McCann *et al.*, 1990; Fischer and Bennett, 1991; Carpita and Gibeaut, 1993). Xyloglucans, the principal hemicellulose in dicotyledonous plants, consist of a linear backbone chain of β-(1-4)-D-glucan with sidechains containing xylose, galactose and fucose. They are considered to be the main interlocking components of the cell wall linking cellulose, pectin and lignin (if present) by hydrogen bonding (Carpita and Gibeaut, 1993). Pectins are complex polysaccharides made up of 'smooth' zones of partially esterified α-galacturonic acid residues (homogalacturonan) and 'hairy' zones of rhamnogalacturonans which are heteropolymers comprised of 12 different sugars (Fischer and Bennett, 1991). Of the glycoproteins, extensin is probably the most well studied. Extensin is rich in hydroxyproline and contains relatively large amounts of alanine, serine and threonine.

2.2.2.2 Cell wall models

Traditional concepts of cell wall structure tended to view the cell wall as a static, inert, load-bearing structure (Jackman and Stanley, 1995). Recent discoveries have resulted in the cell wall being viewed as a dynamic organelle vital to cell growth, metabolism, shape and resistance to both disease and stress (Carpita and Gibeaut,

1993). Despite general agreement on the polymeric make-up of primary cell walls, there is limited data and considerable debate over specific interactions and cross-linkages between polymers (Harker *et al.*, 1997a). However, a number of three-dimensional models have been proposed (Darvill *et al.*, 1980; Keegstra *et al.*, 1973; Lamport, 1986; Carpita and Gibeaut, 1993). A recent model by Carpita and Gibeaut (1993) proposes that the primary cell wall comprises three structurally independent but interacting domains (Fig. 2-2). In this model, a cellulose-hemicellulose domain (comprising 50-65 % of the cell wall dry weight) is embedded in a second domain of pectic polysaccharides (comprising approximately 30 % of cell wall dry weight). Calcium bridges between de-esterified pectin molecules facilitate crosslinking within the matrix. The third domain consists of covalently crosslinked structural proteins.

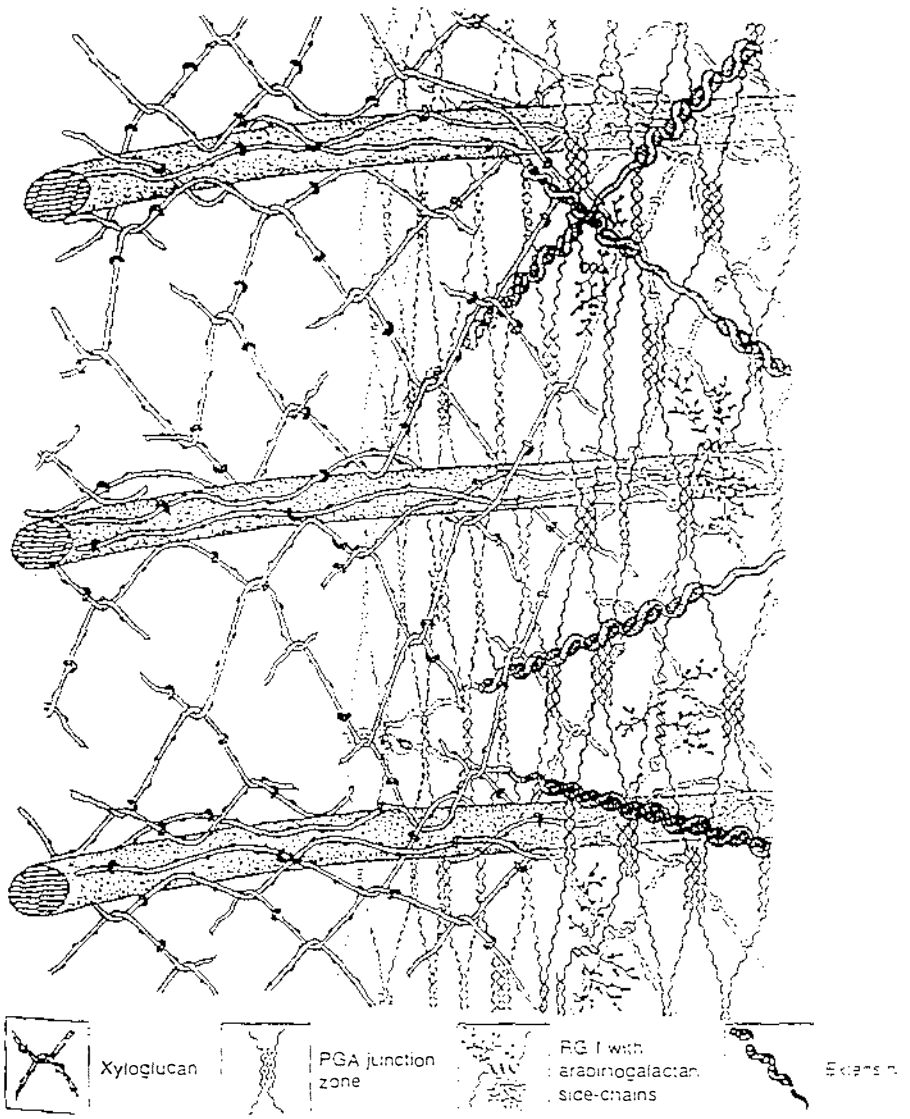


Fig. 2-2. Carpita and Gibeaut's model (1993) of the expanding primary cell wall of flowering plants (excluding grasses). The figure depicts a single layer, several such layers condense to form the wall. Microfibrils are aligned in parallel but in a helical formation around elongating cells. They are crosslinked with hemicellulosic xyloglucan polymers that have been partially cleaved to permit microfibril separation. Embedded in this domain is a second one consisting of a matrix of pectic polygalacturonic acid (PGA), which forms junction zones in the presence of Ca^{2+} and rhamnogalacturonan 1 (RG 1) with arabinogalactan side chains. A third domain of extensin molecules, interlocks the separated microfibrils and limits further stretching once growth has ceased.

2.2.2.3 Role of calcium

Calcium plays an integral part in maintaining cell wall structure and cell-to-cell cohesion (Glenn and Poovaiah, 1990). It is thought that Ca^{2+} ions confer rigidity to cell walls and maintain cell cohesion by forming bridges between pectin molecules (Knee and Bartley, 1981; Poovaiah *et al.*, 1988). Application of pre- or post-harvest calcium treatments are known to retard textural loss in apples (Mason *et al.*, 1974; 1975; Glenn and Poovaiah, 1990; Wang *et al.*, 1993; Siddiqui and Bangerth, 1995a). Stow (1989) demonstrated that textural loss in apples after a prolonged storage period could be partially reversed by vacuum infiltration with calcium chloride. This suggests that loss of calcium from the middle lamella region could potentially be partially responsible for fruit softening and loss of cell-to-cell cohesion. The importance of calcium in retarding textural loss is discussed in more detail in section 2.5.3.4.

2.2.3 Turgor pressure

The perceived crispness and rigidity of fresh fruits and vegetables is to a large extent determined by the turgidity of the tissue (Bourne, 1976; Khan and Vincent, 1993). Plant cells are surrounded by semi-permeable membranes which allow small molecules such as water to pass through, but which restrict the transport of larger molecules such as sugars. The semi-permeable nature of the membrane and the relatively high concentration of solutes within the cell (osmotic potential) results in water being held under pressure within the cell (Aguilera and Stanley, 1990; Jackman *et al.*, 1992). The turgor pressure generated within the cell exerts a stress on the cell wall and imparts rigidity, turgidity and crispness to the plant tissue.

Lin and Pitt (1986) demonstrated the effect of turgor pressure on texture, in an experiment in which they incubated plugs of apple and potato tissue in a range of concentrations of mannitol, before measuring the mechanical properties of the tissue by applying a compressive load. They found that samples incubated in hypotonic

solutions gave a low yield stress, suggesting that the cells had burst before the test. Tissue failure occurred by cell rupture in plugs incubated in isotonic solutions whereas, in those samples incubated in hypertonic solutions, tissue failure occurred by cell-to-cell debonding. Jackman *et al.* (1992) reported similar results for tomato. These results clearly demonstrate the potential for cell turgor pressure to influence texture of plant organs.

2.3 Textural changes

Fruit softening may occur naturally through ripening and senescence or be induced artificially through processing. Apples are climacteric fruit, displaying a characteristic peak of respiratory activity during ripening (Fidler and North, 1967). In apples, softening and other ripening induced changes tend to be closely associated with the climacteric (Knee, 1993). In fresh fruit, softening and texture degradation may be caused by loss of turgor, degradation of starch or breakdown of the structural integrity of the cell wall and middle lamella (Bartley and Knee, 1982; Tucker, 1993). Of these, fruit softening is thought to be primarily induced by the breakdown of cell wall and middle lamella pectic polysaccharides, resulting in the loss of cell wall integrity and hence inducing fruit softening. Postharvest water loss, which occurs at a rate dependent upon storage environment is also important and will be considered in section 2.5.3.3. Turgor pressure is thought to provide the driving force for cell separation following structural changes in middle lamella and cell wall (Hatfield and Knee, 1988). Textural changes brought about by starch degradation may assume some importance in fruit high in starch, such as bananas.

Thermal processing causes considerable tissue softening (Bourne and Comstock, 1986; Mittal, 1994). In processed fruit, softening and texture degradation is brought about by loss of turgor pressure and extensive pectin hydrolysis, leading to degradation of the middle lamella and eventual cell separation (Stanley *et al.*, 1995).

This section examines modifications to fruit cell walls brought about by ripening and thermal processing.

2.3.1 Ripening induced textural changes

Ripening-induced physical changes in cell wall structure can include: dissolution of the pectin rich middle lamella; swelling of cell walls; rounding and separation of cells and an increase in intercellular air space. These changes have been observed under the electron microscope in many fruits including kiwifruit (Hallett *et al.*, 1992), apple (Mohr, 1979; Harker and Hallett, 1992), nectarine (Heyes and Sealey, 1996), avocado (Pesis *et al.*,1978), pear (Martin-Cabrejas *et al.*, 1994) and tomato (Jackman and Stanley, 1995).

At the biochemical level, the ripening process involves major changes in the pectin components of the wall. Changes in the pectic polymers are two-fold. During ripening, there is a loss of neutral sugars, mainly galactose and sometimes arabinose (Tucker and Grierson, 1987). This loss in galactose and/or arabinose has been noted in apples (Knee, 1973; Fischer and Amado, 1994; Fischer *et al.*, 1994), pears (Dick and Labavitch, 1989), nectarines (Lurie *et al.*, 1994) and kiwifruit (Redgwell *et al.*, 1992). The other major change to the pectin components of the wall, is an increase in the solubility of polyuronides associated with the acidic pectin or rhamnogalacturon fraction of the wall (Tucker and Grierson, 1987; Fischer and Bennett, 1991; Tucker, 1993). Increases in water-soluble polyuronides (WSP) have been observed during ripening of apple (Knee 1973; Mahajan, 1994), pear (Ahmed and Labavitch, 1980; Bartley and Knee, 1982; Dick and Labavitch, 1989; Martin-Cabrejas *et al.*, 1994), banana (Wade *et al.*, 1992) and nectarines (Dawson *et al.*, 1992). These two phases of pectin modification appear to be independent (Tucker and Grierson, 1987). Redgwell and Harker (1995) demonstrated that loss of cell wall-associated galactose and pectin solubilisation in ripening kiwifruit are separate processes, since the inhibition of galactose loss did not retard tissue softening or pectin solubilisation. Dawson *et al.* (1992) found that mealiness in nectarines was

associated with impaired solubilisation of pectin, reduced removal of galactan side chains and the accumulation of insoluble high molecular weight pectins in the cell wall. Depolymerisation of pectins also occurs during ripening in some fruit including pears (Yoshioka *et al.*, 1992) and nectarines (Hobbs *et al.*, 1991). Conversely, there is no evidence for depolymerisation of pectins in apples (Yoshioka *et al.*, 1992; Fischer *et al.*, 1994), suggesting that depolymerisation is not a prerequisite for pectin solubilisation in this fruit. The degree of esterification of pectins can also change during ripening (Tucker, 1993). In nectarines, Hobbs *et al.* (1991) found that the degree of methyl esterification decreased during ripening from 80 % in unripe fruit to 69 % in ripe fruit. In contrast, in apples, Knee (1978) and Yoshioka *et al.* (1992) reported an increase in the degree of esterification of water-soluble polyuronide. However Yoshioka *et al.* (1992), also found that there was a decrease in the degree of esterification in the EDTA-soluble fraction.

Compositional changes during ripening in pome fruits, appear to be largely restricted to the pectic polymers (Bartley, 1976; Knee, 1993). It is however likely that changes in non-pectic fractions of the wall do play a part in tissue softening at least in some fruit (Cutillas-Iturralde *et al.*, 1994). Depolymerisation of cell-wall hemicelluloses has been reported in hot pepper (Gross *et al.*, 1986), muskmelon (McCollum *et al.*, 1989, persimmon (Cutillas-Iturralde *et al.*, 1994) and avocado (O'Donoghue and Huber, 1992). There is also some evidence for changes in the cellulose fraction of the cell wall in avocado fruit (O'Donoghue *et al.*, 1994). They proposed that initial softening in avocado may be caused by a change in the organisation of cellulose microfibrils through limited hydrolysis by Cx-cellulase.

2.3.2 Enzymes involved in fruit softening

Much of the work on cell wall changes associated with ripening has concentrated on the identification of enzymes that bring about these changes. Pectinesterase, polygalacturonase, β-(1-4) glucanase or cellulase and β-galactosidase have all been implicated in some way to be involved in the complex process of fruit softening.

2.3.2.1 Pectinesterase (PE)

Pectinesterase (PE) catalyses the demethylation of the C6 carboxyl group of galacturonosyl residues in the pectic polysaccharide backbone (Dey and Brinson, 1984; Fischer and Bennett, 1991). At present the role of PE in fruit softening is unclear, but one possibility is that its action may be needed prior to action of polygalacturonase, which tends to prefer demethylated pectin (Huber, 1983; John and Dey, 1986; Massiot *et al.*, 1994). Wegrzyn and MacRae (1992) found that treating kiwifruit with ethylene led to an initial rise in PE activity followed by a rapid drop as fruit softened. Abu-Sarra and Abu-Goukh (1992) reported similar findings in naturally ripened 'Abu-Samaka' mango fruit. They proposed that in this particular cultivar PE activity may control the rate of softening. Massiot *et al.* (1994) demonstrated in apples that the depolymerisation of the soluble pectins from the parenchyma zone with an endo-polygalacturonase required the action of PE.

2.3.2.2 Polygalacturonase (PG)

Endo-polygalacturonase (endo-PG) acts on demethylated pectin molecules and attacks linkages between galacturonic acid groups in the polyuronide (Rhodes, 1980). PG as either the endo-acting (EC 3.2.1.15) or exo-acting (EC 3.2.1.67) enzyme has been isolated from many fruits including tomato, pear, date, peach, cucumber and avocado (John and Dey, 1986). Endo-PG has only recently been discovered in apples (Wu *et al.*, 1993). Tomato fruit have been used as a model system for investigating the somewhat controversial role of endo-PG in fruit softening (Giovannoni *et al.*, 1992;

Kramer *et al.*, 1992). Until relatively recently, endo-PG was considered to be the primary enzyme responsible for pectin degradation and fruit softening. Evidence supporting this hypothesis was largely correlative in nature and included:

1) the onset of fruit softening coincided with a dramatic increase in endo-PG activity (Huber, 1983; Tucker and Grierson, 1987);
2) in different cultivars and ripening impaired mutants (*rin*, *nor*, *Nr*) there was a rough correlation between endo-PG activity and softening (Tigchelaar *et al.*, 1978; Brady *et al.*, 1983; DellaPenna *et al.*, 1987);
3) application of endo-PG to cell-wall preparations *invitro* resulted in ultrastructural changes resembling those induced by ripening (Crookes and Grierson, 1983).

However, a number of recent studies have brought into question endo-PG's central role in fruit softening. Experiments with transgenic tomato plants, in which endo-PG levels were altered did not correlate endo-PG activity with fruit softening. Giovannoni *et al.* (1989) found that incorporating a modified endo-PG gene into a ripening-inhibited (*rin*) mutant tomato, resulted in the accumulation of active endo-PG, which degraded pectin but did not enhance fruit softening, ethylene evolution or colour development. They concluded that while endo-PG was required for pectin degradation, it was not the primary determinant of softening in tomato. Smith *et al.* (1990) reached a similar conclusion, using antisense mRNA technology to suppress endo-PG gene expression in several tomato lines. However, Kramer *et al.* (1992) found that fresh and processing market genotypes transformed with antisense PG construct, retained their firmness better during storage and produced a more viscous juice and paste product, compared to non-transgenic plants. In addition, several fruit including muskmelon (McCollum *et al.*, 1989), persimmon (Gross *et al.*, 1986) and bananas (Wade *et al.*, 1992) appear to lack this enzyme yet still soften normally. The results from these studies indicate that while endo-PG has a role to play in pectin degradation and fruit softening (especially in the later stages), at least in some fruit it is not primarily responsible for inducing the textural changes associated with fruit ripening (Brady, 1992; Giovannoni *et al.*, 1992).

2.3.2.3 β-(1-4) glucanase or cellulase

Cellulase hydrolyses the β-(1-4) link between adjacent glucose residues. In mango fruit cellulase activity increased progressively during fruit ripening with a high correlation between enzyme activity and loss of firmness (Abu-Sarra and Abu-Goukh, 1992). In apples, unlike other climacteric fruits, ripening does not appear to be associated with an increase in cellulase activity (Abeles and Biles, 1991). Cellulase involvement in fruit softening is at present unclear. The natural substrate for this enzyme is unknown, but is thought to be a hemicellulose polymer (Tucker, 1993). However, O'Donoghue *et al.* (1994) have suggested that in avocado fruit Cx-Cellulase may cause minor changes in the cellulose microfibrils, resulting in an initial weakening and loss of cohesiveness of the cellulose network.

2.3.2.4 Other cell wall hydrolases

β-galactosidase activity increases during the ripening process, but its role in fruit softening remains at present unresolved. It has been proposed that β-galactosidase may be responsible for the solubization of galactose observed during fruit ripening (Fischer and Bennett, 1991). Yoshioka *et al.* (1995), in their recent work on apples, have shown that β-galactosidase and α-arabinofuronosidases may have a key role in the degradation and solubilisation of polyuronide, araban and galactan.

Xyloglucan endotransglycosylase (XET) has also recently been implicated in fruit softening. XET could potentially both cleave xyloglucan chains and then rejoin the cut portion to a nonreducing end of another xyloglucan chain (Redgwell and Fry, 1993; Cutillas-Iturralde *et al.*, 1994). XET may loosen the cell wall in preparation for further modification by other cell wall enzymes.

2.3.3 Cell wall changes that occur during thermal processing

Thermal processing causes major alterations to fruit and vegetable structure, normally resulting in severe texture degradation. Fruit softening through heating is brought about by a loss of turgor pressure and occluded air, degradation of cell wall polysaccharides and starch gelatization (Stanley *et al.*, 1995). Cell separation also generally results, which has a dramatic effect on product texture. Fresh fruit texture can have a large impact on final product texture. For example, apples with a mealy texture tend to sauce on heating (Reeve and Leinbach, 1953). There can also be large differences between cultivars.

Thermally induced texture degradation in fruits and vegetables can be offset to some extent by the incorporation of calcium into the tissue. Calcium is used as a firming agent in a number of processing regimes including beans (Van Buren *et al.*, 1988), carrots (Sterling, 1968), strawberries (Main *et al.*, 1986), peaches (Javeri *et al.*, 1991), pickled pepper (Fleming *et al.*, 1993) and apples (Wiley and Lee, 1970; Wiley and Binkley, 1989). The mechanism behind this firming of the tissue is thought to involve Ca^{2+} ions forming crosslinks between adjacent pectin molecules through reactive carboxyl groups (Van Buren, 1979). Not all heating effects are deleterious as PE, which demethylates pectin and hence increases the number of carboxyl groups available to react with Ca^{2+} ions, has a higher activity at warmer temperatures (50-80 °C; Van Buren, 1979).

2.4 Evaluation of fruit texture

Fresh or processed fruit texture is ultimately assessed sensorily by the consumer. The consumer uses a combination of oral, tactile and auditory organs to evaluate fruit texture. Sensory evaluation of products is an important component of quality assessment and relies on well trained panellists evaluating and describing a range of sensory attributes (Meilgaard *et al.*, 1991). Texture may also be described using instrumental methods. A wide array of tests have been developed for measuring the

textural properties of foods. Instrumental procedures can be broadly classified into four categories: fundamental, empirical, imitative and nonmechanical (Szczesniak, 1963; Aguilera and Stanley, 1990; Apostolopoulos and Brennan, 1994a). Fundamental rheological tests are largely concerned with engineering based measurements, such as Young's Modulus, Poisson's ratio, ultimate strength etc. (Holt and Schoorl, 1984; Fekete, 1994). Unfortunately these tests often correlate poorly with sensory evaluation of the textural properties of foods (Bourne, 1978; Apostolopoulos and Brennan, 1994a). Empirical tests include an array of puncture, compression, shear and extrusion tests. These tests tend to be less well defined when considered from an engineering perspective (often involving a mixture of forces) but often tend to correlate well with sensory evaluation. Some food testing may also be considered to be have fundamental and empirical aspects (Aguilera and Stanley, 1990). Imitative tests attempt to imitate the processes that occur in the mouth. Texture profile analysis (Szczesniak *et al.*, 1963; Abbott *et al.*, 1984) falls into this category. Nonmechanical properties such as electrical (Harker and Maindonald, 1994) and auditory (Vickers, 1988) characteristics can also correlate well with fruit texture. Experiments with apples have shown that resonant or vibration frequencies in apples are influenced significantly by fruit maturity, ripeness, firmness, size, and cuts and bruises (Abbott *et al.*, 1968a; 1968b; 1992). This section examines some of the instrumental tests that are available for assessing horticultural product texture.

2.4.1 Puncture tests

Puncture tests are commonly used by horticulturalists to assess fruit texture in the field, packhouse or research laboratory (Abbott *et al.*, 1992). In New Zealand, texture of fresh fruits is commercially assessed using a penetrometer. Puncture tests measure the force required to push a probe a defined distance into a product. There is a variety of instruments available to carry out puncture tests, and most of these are hand-operated. Hand-held penetrometers were initially developed by Magness and Taylor (1925). Today there are a range of devices developed by different companies available on the market. Hand-operated penetrometers have several advantages

including their low cost, light compact design and ease of use. Disadvantages associated with these instruments are largely due to their tendency to vary considerably between operators (Harker *et al.*, 1996). For this reason it is usually recommended that the same person carry out all the measurements in a particular study (Blanpied *et al.*, 1978; Watkins and Harman, 1981). In recent years, semi-automated penetrometers such as the hand-operated EPT pressure tester (Lake City Technical Products Inc., Kelowna, Canada) have been used in some research laboratories. Automated devices such as the EPT pressure tester have several advantages over their more conventional counterparts including speed of measurement and the facility for automatic collection of digitised data (Harker *et al.*, 1996). The Instron materials testing machine can also be used to accurately measure flesh firmness using puncture tests. The Instron's enhanced accuracy is largely due to the removal of operator error as the speed and distance travelled by the probe can be controlled accurately. A further advantage is that output from the Instron can be plotted automatically as force-distance curves.

Bourne (1980) described three different types of force-distance curves that occur during puncture testing of foods using penetrometer-type probes (Fig 2-3). Initially, force increases rapidly as the fruit deforms under the load. This stage ends abruptly when the probe penetrates the fruit, causing irreversible crushing. This point is referred to as the bio-yield point. At this point the force may a) continue to increase, b) remain constant or c) decline with subsequent increases in distance. Freshly harvested apples tend to produce type A curves, whereas stored apples characteristically trace type B or C curve profiles (Bourne 1980; Yuwana, 1991).

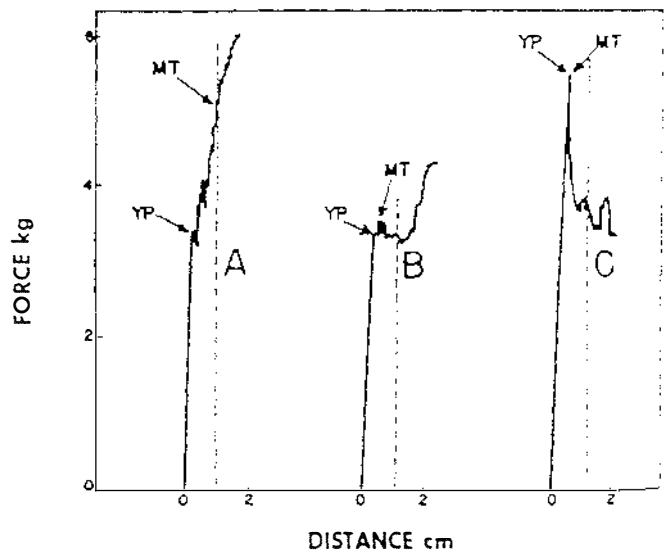


Fig 2-3. Characteristic force-distance curves obtained on apples using a 7.9 mm Magness Taylor Pressure Tester tip mounted in the Instron (Bourne, 1980)

The bioyield point (F) measured by these instruments is described by:

$$F = K_c * A^{punch} + K_s * P^{punch} \quad \textbf{(2-1)}$$

where K_c is the compression coefficient of the commodity, A^{punch} the area of the punch, K_s the shear coefficient of the commodity, and P^{punch} the perimeter of the punch (Bourne, 1980).

2.4.2 Tensile tests

Tensile tests have been used effectively to describe fresh fruit texture (Stow, 1989; Harker and Hallett, 1992; 1994; Harker and Sutherland, 1993; Tu *et al.*, 1996). These workers measured the force required to pull apart plugs of fruit tissue cut in the form of an H-shaped or ring section, using an Instron Universal materials testing machine. The force required for tissue failure using these tensile tests provides an estimate of the strength of cell adhesion (Harker and Hallett, 1992). Viewing the fractured surfaces using low-temperature scanning electron microscopy can provide additional information on the mode of tissue failure. In apples, Harker and Hallett (1992) were able to effectively describe changes in tissue texture with time using tensile tests and electron micrographs of the fractured surface. From these they were able to distinguish between samples in which individual cells had been ruptured at the fracture surface and those in which neighbouring cells had been pulled apart leaving undamaged cells exposed at the fracture surface.

2.4.3 Shear and extrusion tests

Applying a shearing force and/or extruding a product is a popular method of assessing fruit texture. A number of devices are available that estimate fruit texture in this manner. One such popular empirical test is the Kramer shear cell (Kramer *et al.*, 1951; Voisey 1977). The Kramer shear cell has been used extensively for firmness measurements on a large number of food products, including white bread, sponge cake, canned beets, peas, carrots, lima beans, raw snap beans, bananas, apples, peaches and pears (Brennan *et al.*, 1977; Bin and McLellan, 1988; McLellan *et al.*, 1990; Apostolopoulos and Brennan, 1994a). Apostolopoulos and Brennan (1994a) found relatively good agreement between sensory and Kramer shear measurements of canned peach and pear texture.

A Kramer shear cell consists of two parts - a blade section consisting of 10 flexible blades and a rectangular cell which houses the product being tested. The blade

section is mounted on the Instron's crosshead and driven into the cell, compressing, shearing and finally extruding part of the sample through slots in the bottom of the cell (Szczesniak *et al.*, 1970; Apostolopoulos and Brennan, 1994a). The Instron data acquisition system records the force-deformation curve.

Voisey (1977) observed the action of the Kramer shear cell on a selection of foods including fresh and wilted apples, using a modified cell in which the front wall of the cell was replaced with clear plastic. Voisey's results confirm that foods are subject to complex stresses in the Kramer shear cell and that it is incorrect to assume that the peak force always reflects the shear strength of the food. Since foods vary considerably in their response, observing the action of shear-compression cell can assist in obtaining valid interpretations of the force-deformation curve. Voisey (1977) observed that apples undergo considerable compression and compaction, before the blades begin to cut through the product, followed by shear rupture. Voisey (1977) concluded that the peak force was an indication of rupturing, cohesive and adhesive effects, and the shear strength was indicated by a change in the slope of the force-distance curve.

The relationship between maximum force and sample weight was studied by Szczesniak *et al.*, (1970). Of the products they studied only two (white bread and sponge cake) exhibited a linear relationship between sample weight and maximum force. Of the other foods tested the majority showed a non-linear relationship, tending towards a constant force-weight relationship at high fill weights (eg. canned beets, canned and frozen peas, carrots, bananas). However, several products including raw apples exhibited neither a linear nor constant relationship. Bin and McLellan (1988) investigated further the effect of sample weight and orientation on maximum shear force for apple slices. They found that for fresh slices maximum force increased with sample weight, whereas in blanched slices it tended towards a maximum at a 70 g sample weight. Slice orientation was also found to be important with crosswise or random orientations rendering higher forces than lengthwise positioning. These studies show the importance of using a standard sample weight

and orientation.

2.4.4 Compression tests

Compression tests using either small or large deformations are commonly used by researchers to describe food texture (Abbott *et al.*, 1984). During these tests, an Instron (or similar machine) records the force required to compress a uniform specimen to a standard degree of deformation. Compression tests may also be cyclic. Apostolopoulos and Brennan (1994a) described canned peach texture using a two-cycle uniaxial compression test. They found that some of the parameters generated from the force-deformation curve correlated well with firmness as determined by sensory analysis. Lurie and Nussinovitch (1996) found that Instron compression tests of strength and stiffness correlated well with sensorily assessed crispness for 'Golden Delicious' and 'Granny Smith' apples.

2.4.5 Texture profile analysis (TPA)

Proctor et al. (1955) developed the first machine to imitate mastication. The MIT denture tenderometer consisted of a motorised set of dentures that simulated chewing and measured the peak force that occurred during chewing. This machine was one of the first steps in the development of texture profile analysis (TPA). The major breakthrough in texture profile analysis (TPA) came with the development of the General Foods Texturometer (Friedman et al., 1963; Szczesniak et al., 1963). The texturometer compressed a sample to 25% of its original height, twice using an action that simulated the human jaw. Analysis of force-deformation curves (Fig. 2-4) from these tests led to the extraction of seven textural parameters:

a) Fracturability - defined as the force at the first significant break in the curve.

b) Cohesiveness - defined as the ratio of the positive force area during the second compression to that during the first compression.

c) Springiness - defined as the height that the food recovers during the time that elapses between the end of the first bite and the start of the second bite.

d) Gumminess - defined as the product of hardness and cohesiveness.

e) Chewiness - defined as the product of gumminess and springiness.

Szczesniak et al., (1963) reported excellent correlations between each of the textural parameters described above and sensory ratings.

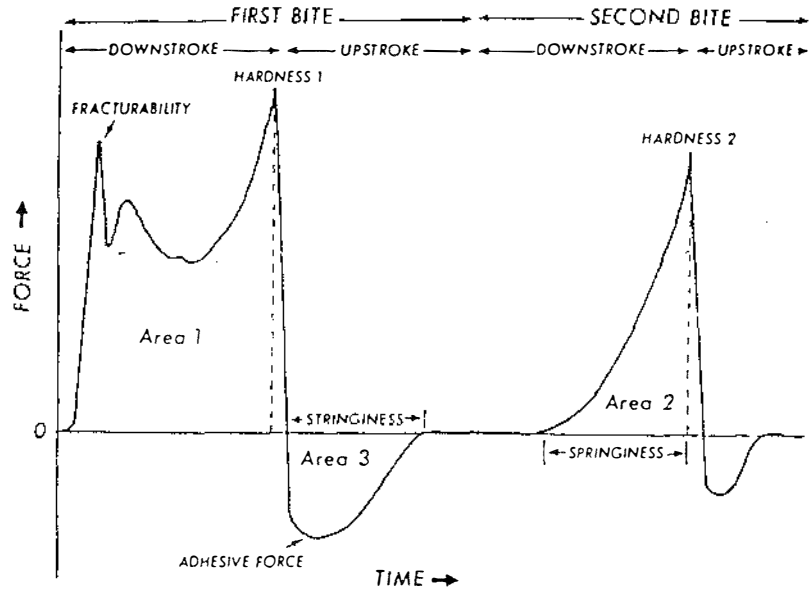


Fig. 2-4 Generalized texture profile curve obtained using the Instron testing machine (Bourne *et al.*, 1978).

Bourne (1968) used TPA to describe pear ripening (Fig. 2-5). One of the most striking features of these data is that all the texture parameters from TPA and the Magness Taylor puncture test changed in the same direction and at the same time. This contrasts with the situation in apples, in which there was no such orderly change (Fig. 2-6), though the absence of statistical measures of variability makes it difficult to assess the reliability of the trends presented. Describing apple texture would appear to be considerably more difficult (Bourne, 1979; 1980)

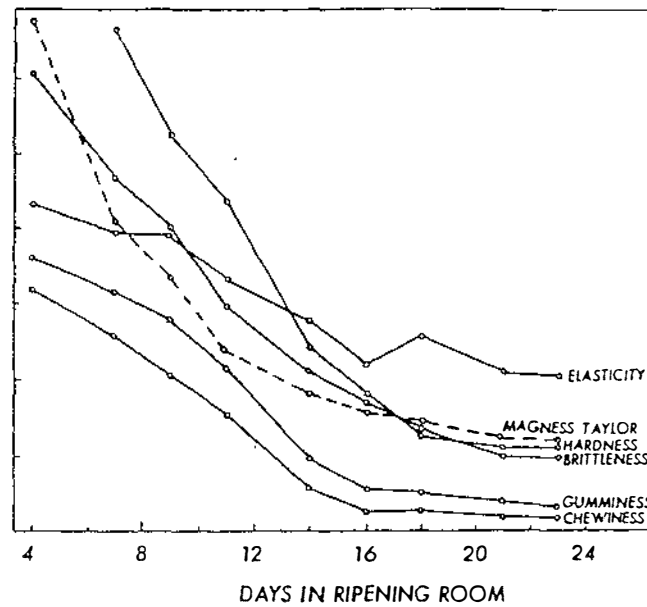


Fig. 2-5 Changes in texture profile of 'Ovid' pears as they ripen. Texture profile performed on 20 mm diameter cylinders 10 mm high, with 75 % compression on an Instron materials testing machine (Bourne, 1980).

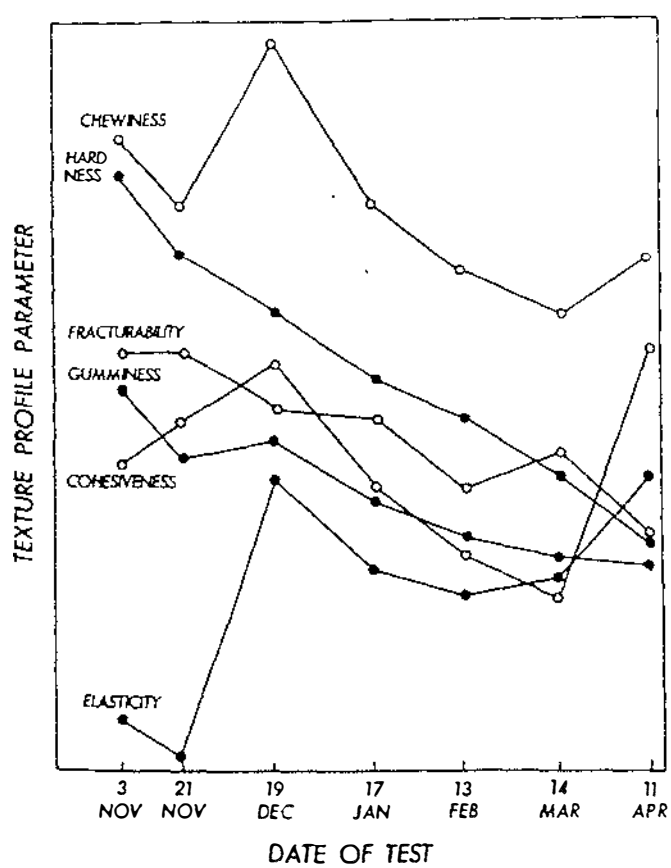


Fig. 2-6 Changes in texture profile of 'Delicious' apples in cold storage (Bourne, 1980).

Abbott *et al.*, (1984) used a modified form of texture profiling to describe apple texture (Fig. 2-7). They found that using a combination of TPA parameters correlated better with sensory evaluation than a single texture test such as Magness Taylor. From these results it would appear that TPA is particularly useful where a more complete picture of product texture is desired.

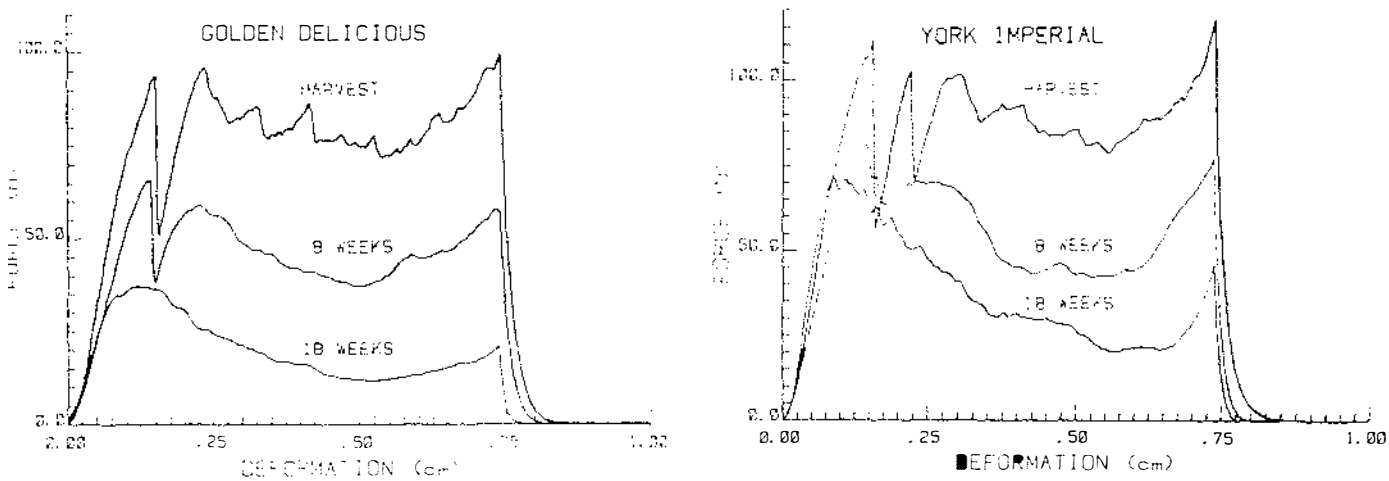


Fig. 2-7 Instron texture profile curves of representative individual 'Golden Delicious' and 'York Imperial' apples after each storage period (no ripening; Abbott *et al.*, 1984).

2.4.6 Nonmechanical tests

There is an array of nonmechanical tests available that correlate well with fruit texture, including electrical impedence and sonic resonance (Aguilera and Stanley, 1990). Sonic resonance is a non-destructive method for measuring the deformability of horticultural produce (Bourne, 1980). Vibrational techniques to measure fruit ripeness were first devised by Clark and Mikelson (1942). Since then vibrational tests have been made on a wide range of horticultural produce (Finney, 1972; Abbott *et al.*, 1992). Abbott *et al.*, (1968b) proposed a stiffness coefficient (f^2M^{fruit}), defined as the square of the second resonance frequency (f) times the mass (M^{fruit}) of the apple. Abbott *et al.*, (1992) and Abbott, (1994) showed that sonic resonance

functions correlated significantly with mean inspectors (USDA licensed apple inspectors) scores and with Magness-Taylor firmness.

2.4.7 Sensory evaluation

Methods used to describe texture using sensory evaluation can be broadly classified into three groups: difference, preference (including relative-to-ideal) and attribute methods (Jack *et al.*, 1995). Attribute or profiling methods are used extensively to provide a full sensory description of product texture. The most popular attribute or profiling methods are: the texture profile method, descriptive analysis and free choice profiling (FCP). FCP is predominantly used in consumer studies and will not be considered further here.

The sensory texture profile method parallels instrumental TPA in that it uses the same textural attributes. The texture profile method was developed by General Foods (Brandt *et al.*, 1963). In this procedure samples are rated on scales for degree of hardness, brittleness, chewiness, gumminess, viscosity and adhesiveness. For each attribute, standard product reference samples are provided to define each point on a nine point equidistant scale. This method tends to involve extensive training and calibrating of panellists (Skinner, 1988). Civille and Szczesniak (1973) established some guidelines for training texture profile panels.

Descriptive analysis (Stone *et al.*, 1974) is more flexible than the texture profile method, in that textural terms can be defined more precisely in terms of the product under study. In this method samples are scored in terms of intensity, using a fixed vocabulary of textural descriptors. Williams and Carter (1977) developed a language and procedure for sensory assessment of 'Cox's Orange Pippin' apples which included developing useful descriptors for the textural attributes under study. It is important when using these methods to have a good range of textural descriptors that are relevant to the product being tested, therefore extensive time and effort is put into developing suitable descriptors. McLellan *et al.* (1984a) used quantitative descriptive

analysis (QDA) and factor analysis to determine sensory components accounting for intervarietal variation in apple sauce and slices. Descriptive analysis also involves considerable panel training and retraining to maintain accuracy and consistency.

Sensory evaluation is an important tool for obtaining a complete picture of product texture. Humans are able to perceive and evaluate an array of sensory attributes in a single test, whereas instrumental tests only quantify certain aspects of product texture. On the other hand, human evaluators of texture can be difficult to calibrate and are prone to fatigue and drift. This tends to make sensory analysis relatively time-consuming and hence expensive.

2.4.8 Relationship between instrumental and sensory tests

A considerable amount of research effort has been directed at investigating the interrelationships between instrumental and sensory tests (McLellan *et al.*, 1984b; Szczesniak, 1987; Van Woensel *et al.*, 1987; Paoletti *et al.*, 1993; Apostolopoulos and Brennan, 1994a). The desire to 1) effectively imitate sensory evaluation instrumentally, 2) develop effective quality control instruments, 3) understand what is being perceived in sensory texture assessment and 4) predict consumer response, are some of the key goals of researchers looking at correlations between sensory and instrumental tests (Szczesniak, 1987). Traditionally, relationships between sensory and instrumental properties were expressed using simple correlation coefficients (McLellan *et al.*, 1984b; Apostolopoulos and Brennan, 1994a). However, in recent times, there has been a move towards describing the interrelationships between the two sets of attributes using multivariate statistical techniques such as principal component analysis (PCA; Resurreccion, 1988; Dijksterhuis, 1995).

A number of studies have been carried out looking at the relationships between the sensory and mechanical properties of fruits and vegetables. Apostolopoulos and Brennan (1994a) used PCA to investigate the intra and inter relationships of the sensory and instrumental characteristics of canned peaches. They found that two

principle components, 'viscoelasity' and 'pleasantness of sensory characteristic' adequately described the data. They also found that most of the mechanical attributes measured were good predictors of the textural characteristics of the fruit. McLellan *et al.* (1984b) used stepwise regression to describe the relationship between six previously defined sensory components for apple slice quality (McLellan *et al.*, 1984a) and instrumental measurements. Harker *et al.* (1997b) investigated the relationship between mechanical properties and sensory quality in a range of fruits and vegetables with different textures. They found that the mechanical tests had some problems discriminating between certain fruit textures. For example, the penetrometer could not discriminate between the texture of muskmelon, watermelon or apple. Other tests (Kramer shear and tensile) performed slightly better. These studies demonstrate that some aspects of fruit texture can be adequately described by instrumental means, but that instruments do not provide a complete picture of fruit texture. However, they can be used with relative confidence, provided a reasonable relationship has been demonstrated between sensory and instrumental measurements of texture. In apple at least, this appears to be plausible, with most studies demonstrating a reasonable relationship between sensory textural evaluation and a number of instrumental tests including puncture (Abbott *et al.*, 1984; 1992), texture profile analysis (Brennan *et al.*, 1970; Abbott *et al.*, 1984) and Kramer shear (Brennan *et al.*, 1970).

2.5 Factors that affect fruit texture

2.5.1 Cultivar

Apple cultivars vary considerably with regard to fresh fruit texture (Abbott *et al.*, 1984; Paoletti *et al.*, 1993) and processing characteristics (Reeve and Leinbach, 1953; McLellan *et al.*, 1984a). Cultivars vary in their storage potential with some maintaining their textural qualities after long term storage while others become mealy or soft after a relatively short storage period (Mohr, 1989). Textural differences between cultivars can be partially attributed to differences in morphology

(Trakoontivakorn *et al.*, 1988; Lapsley *et al.*, 1992). From a processing perspective, some cultivars such as 'Gravenstein', 'McIntosh' and 'Cortland' tend to sauce readily on heating. Mealy apples also readily sauce (Reeve and Leinbach, 1953). The behaviour of fruit on heating is therefore an important consideration when selecting cultivars for various processing applications (eg. sauce, slice, dice manufacture).

2.5.2 Preharvest factors

Postharvest and processed fruit quality is also influenced by a number of preharvest factors including mineral nutrition, soil quality, irrigation, rootstock selection, tree management (pruning, bending and girdling of branches, fruit thinning), environmental conditions during fruit development and maturity at harvest (Watada and Abbott, 1985; Monselise and Goren, 1987). Perhaps one of the most widely studied areas is that of mineral nutrition, and in particular the effect of calcium on fruit quality. As highlighted in other parts of this literature review (sections 2.2.2.3 and 2.5.3.4), calcium has a key part to play in retarding textural loss (Siddiqui and Bangerth, 1995a) and preventing the development of certain physiological disorders. Calcium nutrition is a complex issue, that appears to be more a problem with distribution within the plant than one of soil supply (Monselise and Goren, 1987; Wilton, 1991). Calcium is translocated from the roots to the leaves, fruits, apical meristems mainly through the xylem. Young growing fruits and apical meristems are strong calcium "sinks", needing a constant supply for rapid cell division. However, in apples, calcium accumulation by the fruit generally ends early in fruit development, when fruit growth changes from cell division to cell expansion (Vang-Petersen, 1980). To alleviate these distribution problems, pre-harvest calcium sprays are often applied directly onto fruit to enhance fruit calcium levels (Raese *et al.*, 1990).

A number of factors are known to influence calcium uptake by trees including high cation concentration and/or excessive amounts of NH_4, K, Mg or Na in the soil (Wilcox *et al.*, 1973; Shear, 1975; Wilton, 1991), pollination and seed number

(Bramlage *et al.*, 1990), pruning and girdling (Perring and Preston, 1974; Tomala and Dilley, 1990). The effect of seed number and girdling on fruit calcium levels is thought to be related to auxin levels in the plant. Calcium transport in plants is acropetal and is thought to be linked to basipetal auxin transport (Banuelos *et al.*, 1987). Seeds produce auxins, so fruit with high seed numbers are more likely to attract calcium (Bramlage *et al.*, 1990). Girdling prevents auxin transport in the phloem and is hence likely to have a negative effect on calcium uptake. Summer pruning may enhance fruit calcium status by reducing the tree's leaf:fruit ratio, hence reducing leaf transpiration thereby enabling more calcium to be taken up by the fruit (Tomala and Dilley, 1990).

Nitrogen nutrition can also affect calcium uptake and postharvest fruit quality (Ferguson and Watkins, 1989). Nitrogen stimulates vegetative growth and hence increases the demand for calcium by growing shoots and reducing the availability of calcium to fruits. Excess or late applications of nitrogen have also been shown to be detrimental to fruit quality, with affected fruit exhibiting poor colour, soft texture and a higher level of storage disorders (Monselise and Goren, 1987).

Fruit quality is affected by the time of harvest and corresponding fruit maturity. There are two aspects of fruit maturity: 1) physiological maturity - which is the stage of development when a plant or plant part will continue ontogeny even if detached, and 2) horticultural maturity - the stage of development when a plant or plant part possess the prerequisites for utilisation by consumers for a particular purpose (Watada *et al.*, 1984). Apple fruit maturity may be assessed by a number of methods including titratable acidity, soluble solids, fruit firmness, starch-iodine test, skin and flesh colour etc.(Knee *et al.*, 1989; Kingston, 1992). 'Optimum' harvest maturity is variable since it depends on whether the fruit is to be marketed directly or stored long term. Immature fruit with high starch content, high chlorophyll levels and poor colour tend to produce poor quality solid-pack slices. Over mature fruit generally give poor product yields and may result in the production of soft textureless slices (Fisher and Kitson, 1991).

Climatic conditions have a considerable effect on postharvest fruit quality. Climate represents the integration of a number of factors, such as temperature, humidity, daylength, radiation, cloudiness and wind. Temperature tends to have a large effect on fruit growth, development and ripening. High temperatures and high light levels can cause radiation damage in fruits, due to the fruit's inability to cool adequately (Monselise and Goren, 1987).

Rootstocks can affect apple ripening, textural properties and overall quality. 'Goldspur Golden Delicious' apples harvested from trees with 'M26' rootstocks were firmer, developed more colour and contained more calcium, acids and soluble solids than those from trees with 'MM 111' (Drake *et al.*, 1988). Autio (1991) investigated the effect of rootstock on 'Delicious' apple fruit characteristics and concluded that the effects of rootstock on storability appeared to relate primarily to their effects on fruit maturity and calcium concentration.

Irrigation has been shown to influence fruit composition (Proebsting *et al.*, 1984; Irving and Drost, 1987) and fruit storage life and keeping quality (Irving and Drost, 1987; Failla *et al.*, 1990; Behboudian and Lawes, 1994). Apples produced under deficit irrigation tend to have higher levels of soluble solids than fruit produced under normal irrigation regimes (Proebsting *et al.*, 1984; Irving and Drost, 1987). Fruit titratable acidity, mineral content and colour were found to vary little between irrigation treatments (Proebsting *et al.*, 1984; Irving and Drost, 1987; Behboudian and Lawes, 1994). Guelfat-Reich and Ben-Arie (1980) found 'Caville de San Sanveur' apples grown under low irrigation regime were significantly firmer than those produced under non-deficit irrigation regimes. In contrast, Proebsting *et al.* (1984) and Irving and Drost (1987) found little difference in fruit firmness between deficit and non-deficit treatments. Differences in severity of the irrigation treatment imposed, timing of the treatment and or cultivar differences may help explain the conflicting results obtained by these research groups. Irrigation has also been shown to influence fruit physiological disorders including bitterpit and watercore in apple (Lotter *et al.*, 1985; Irving and Drost, 1987; Failla *et al.*, 1990) and flesh spot decay

in nashi (Marsh *et al.*, 1989; Behboudian and Lawes, 1994).

Crop load also affects apple fruit quality and mineral status. Volz *et al.* (1993) found that fruit from light cropping or thinned trees had lower calcium, magnesium and potassium levels and higher incidences of bitter pit and internal breakdown after storage, than fruit from heavily cropping trees. Their study illustrates the balance that needs to be achieved between enhancing fruit size and maintaining high fruit quality.

Whilst it has not been the purpose of this review to give an in-depth account of the effects of preharvest factors on postharvest fruit quality, it has demonstrated the contribution that preharvest factors play in determining fruit quality.

2.5.3 Postharvest factors

Retaining fruit quality and storage life throughout the postharvest phase is a key issue for the fresh and processing fruit industries. Inappropriate handling or storage conditions can result in excessive waste or sub-standard product reaching markets. This section examines some of the key components of the postharvest phase, and how they affect fresh and processed fruit quality.

2.5.3.1 Storage duration

In general, fresh fruit texture and overall quality decline with time spent in storage. Refrigerated, high RH, controlled or modified atmosphere storage are some of the storage technologies used extensively in the fresh fruit export industry to maintain and extend product storage life (Kader *et al.*, 1989). Achieving an optimal storage life is influenced not only by the storage environment, but also by cultivar, maturity, mineral nutrition and a range of other preharvest factors (Watada and Abbott 1985; Ingle and Morris, 1989).

Information on how texture and other quality attributes change with storage duration is useful for predicting maximum storage life. Tijskens (1979) monitored textural changes in 'Golden Delicious' apples, during long term storage at 3-4 °C. The study found that fruit texture declined exponentially with storage duration, with most of the changes occurring in the first 2 to 4 months. Ingle and Morris (1989) examined prediction of firmness changes of 'Rome' apples in refrigerated storage (0 °C). On average over the 3 years of the study, they found that 'Rome' apples softened at a mean rate of 0.31 N day^{-1}, with an overall firmness loss of 35 N. Using regression analysis, they also developed a model to predict firmness loss during refrigerated storage. However, the model tended to overestimate softening rates and could only be used to provide a rough estimate of maximum storage period.

Fresh fruit storage duration also affects processed slice texture (Wiley and Binkley, 1989). Wiley and Thompson (1960) found that slices made from apples harvested early in the season, tended to be tough and rubbery. They found that a short storage period generally alleviated this problem. Slices made from fruit harvested mid or late season declined in quality with increases in raw apple storage duration. The length of fresh apple storage has also been shown to affect apple sauce texture, generally referred to as 'grain' or 'finish'. Mohr (1989) found that the effect of storage on sauce particle size was cultivar dependent, with some cultivars showing an overall decrease in particle size, while others increased. McLellan and Massey (1984) reported similar results.

2.5.3.2 Temperature

Storage temperature has a direct effect on product storage life and quality. Apples destined for the fresh fruit market are cool-stored to retain fruit quality and extend product storage life. Fruit destined for processing are often cool-stored, but are also commonly stored in ambient conditions for at least a portion of their storage life. Temperature has a direct effect on produce respiration rate, fruit softening and other physiological processes (Fidler and North, 1967; Wills *et al.*, 1981). The relationship

between the rate of respiration and temperature can be described using Q_{10} values (temperature quotient; where the Q_{10} is the relative increase in respiration rate for a 10 °C rise in temperature; Blanke, 1991) or an Arrhenius relationship (Cameron *et al.*, 1995). Over the temperature range 5-25 °C, Q_{10} values vary between 1.5 and 2.5, i.e. a temperature increase of 10 °C results in a 1.5 to 2.5 fold increase in fruit respiration rate (Blanke, 1991). High respiration rates (within a fruit species) are generally indicative of short storage life and rapid quality and nutritive loss (Wills *et al.*, 1981).

D'Souza and Ingle (1989) investigated the effect of cool-storage delays (comprising 1-15 days at 7 °C) on fruit softening for three apple cultivars - 'Jonared', 'Stayman' and 'Rome Beauty'. They found that the effect of cooling delays varied markedly with cultivar. Reducing cooling delays somewhat reduced poststorage firmness losses in 'Stayman' and 'Rome Beauty' cultivars, but had no effect on 'Jonared'.

Product temperature also affects texture evaluation procedures. This is because the temperature of the fruit or vegetable at the time of testing directly affects the recorded firmness value. Bourne (1982b) developed the concept of the firmness-temperature (K_{FT}) coefficient to describe this relationship between product temperature and firmness. The K_{FT} coefficient is defined as the percent change in firmness per degree temperature increase over the temperature range studied. Bourne (1982b) studied the effects of temperature on firmness for a wide range of commodities. He found that for most commodities firmness decreased with increasing temperature. For apples, firmness-temperature coefficients ranged from -0.04 to -0.90 %/°C, depending on cultivar and test used. Bourne and Comstock (1986) carried out a similar study calculating firmness-temperature coefficients for thermally processed fruits and vegetables. Values for apple slices ranged from -0.17 to -1.09 %/°C, depending on the test used. These results clearly demonstrated the importance of measuring product texture within a narrow temperature range.

2.5.3.3 Gas exchange

Gas exchange in apples and other horticultural commodities occurs via the passive process of diffusion. Gases diffuse along partial pressure gradients from regions of high partial pressure to regions of low partial pressure (Kader *et al.*, 1989). In respiring fruits, O_2 diffuses from the ambient air where the partial pressure is relatively high (approx. 21 kPa) into the fruit. Conversely, CO_2 and C_2H_4 move from centres of high partial pressure in the fruit to the ambient air where the partial pressures are very low. Water vapour also tends to diffuse from the fruit to the surrounding environment, since the fruit normally has a higher water vapour pressure (WVP).

In fruits and other horticultural commodities, the rate of diffusion of H_2O, O_2, CO_2 and other physiologically important gases is affected by: skin permeance; product respiration and transpiration rates; mass, volume and maturity of commodity; temperature; external gas concentration; and the extent of the diffusion gradient (ie. the difference between internal and external gas partial pressures) (Banks, 1984; Smith and Stow, 1984; Kader *et al.*, 1989; Banks *et al.*, 1993b).

Diffusion of O_2, CO_2 or water vapour between the internal and external atmospheres of a fruit through the skin can be quantified using Fick's First Law of diffusion (Cameron and Reid, 1982; Hagenmaier and Shaw, 1992; Banks *et al.*, 1997):

$$\Delta p_j = \frac{r_j M^{fruit}}{P_j' A} \qquad \textbf{(2-2)}$$

where:
- A = fruit surface area (m^2)
- Δp_j = difference in partial pressures of gas j between internal and external atmospheres (Pa)
- P_j' = permeance to gas j ($mol.s^{-1}.m^{-2}.Pa^{-1}$)

r_j = specific rate of transfer of gas j between internal and external atmospheres ($mol.kg^{-1}.s^{-1}$)

M^{fruit} = fruit mass (kg)

Rates of transfer

Respiration and transpiration are two processes occurring in the fruit that directly affect the rate of transfer of gases between the fruit and the surrounding atmosphere. Respiration involves the oxidative breakdown of starch, sugars and organic acids, into simpler molecules such as CO_2 and H_2O. Energy in the form of adenosine triphosphate (ATP) is also produced during respiration and used in the maintenance of cellular biochemical activity (Wills *et al.*, 1981, Burton, 1982). The respiration rate of a fruit depends on maturity stage, physical condition, external concentration of O_2, CO_2, C_2H_4 and temperature (Kader *et al.*, 1989; Blanke, 1991). The rate at which a fruit respires affects the concentration of O_2 and CO_2 in the internal atmosphere of the fruit, with respiration tending to reduce the internal oxygen partial pressure ($p^i_{O_2}$, Pa), and increase the internal carbon dioxide partial pressure ($p^i_{CO_2}$; Dadzie, 1992; Banks *et al.*, 1993b). This in turn has a direct effect (in conjunction with other factors such as skin permeance and temperature etc.) on the rate of diffusion of CO_2 out of the fruit and O_2 into the fruit.

Respiration may proceed under aerobic or anaerobic conditions. Under aerobic conditions glucose is converted to CO_2, H_2O and ATP, through a series of biochemical pathways (Fig. 2-8). The first of these, glycolysis, can proceed under aerobic or anaerobic conditions, and produces pyruvate. Under anaerobic conditions pyruvate is metabolised to lactic acid (in the case of animals), or acetaldehyde and ethanol (as is generally the case for plants; Wills *et al.*, 1981).

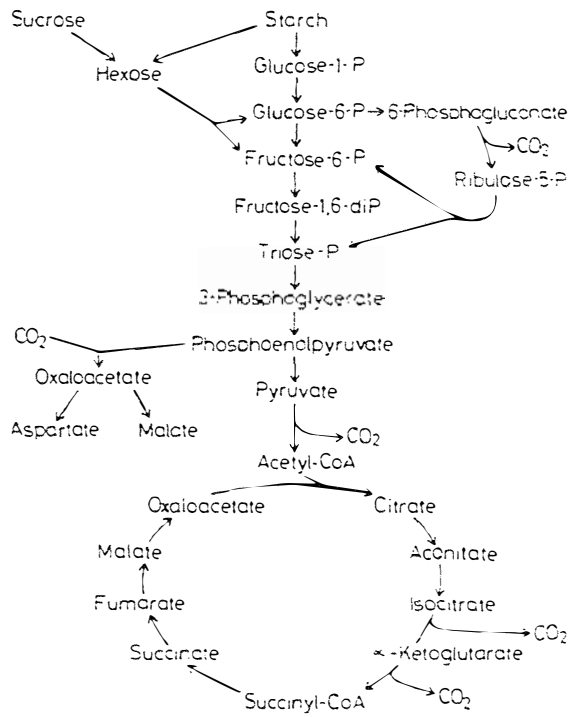


Fig. 2-8 Principal pathways responsible for the respiration of carbohydrate (ap Rees, 1980).

Respiration normally proceeds aerobically, since the atmosphere is rich in oxygen. However, under some storage regimes oxygen may be severely limiting and this may result in anaerobic respiration. The oxygen concentration at which there is a shift from aerobic respiration to anaerobic respiration is referred to as the lower oxygen limit (LOL), which may be expressed in terms of the 'Anaerobic Compensation Point' (ACP) or 'Fermentation Threshold' (FT; Yearsley *et al.*, 1996). The ACP is defined as the O_2 concentration at which CO_2 production is at a minimum (Boersig *et al.*, 1988). The FT may relate to the 'Respiratory Quotient Breakpoint' (RQB;

defined by Beaudry (1993) as the p_{O_2} at which the steady-state respiratory quotient (RQ) begins to increase as O_2 level decreased) or 'Extinction Point' (EP; defined by Blackman (1928) as the threshold O_2 concentration at which all anaerobic respiration was just extinguished). LOL's may be defined in terms of internal or external oxygen partial pressures (Yearsley *et al.*, 1996).

The majority of weight lost by harvested fruits and vegetables is through the process of transpiration, although small losses are attributable to respiration. Apples have been reported as being able to tolerate a weight loss of 5 % (Grierson and Wardowski, 1978) or 7.5 % (Hruschka, 1977), before they become unsaleable due to shrivelling. Transpiration in harvested materials is thought to occur largely through the cuticle, although some water loss may occur through lenticels (Burton, 1982; Ben-Yehoshua, 1987; Banks *et al.*, 1997). The rate of transpiration of a harvested product is affected by a number of factors including surface area to volume ratio; natural skin permeance; temperature; relative humidity and air movement (Wills *et al.*, 1981; Woods, 1990).

Driving force

As is made clear from Eq. 2-2, internal atmosphere composition depends upon external atmosphere composition and Δp_j: $p^i_j = p^e_j - \Delta p_j$. Modifying the gaseous environment around the fruit is therefore a key way of changing the fruit's internal atmosphere composition. Modified atmosphere (MA) or controlled atmosphere (CA) storage regimes are commonly used to maintain freshly harvested product quality. Under MA or CA storage regimes the atmosphere surrounding the fruit normally contains reduced O_2 and/or elevated CO_2 partial pressures. In CA storage, the levels of O_2, CO_2 and other gases are controlled more precisely than in MA storage. Lowering the oxygen levels surrounding the fruit lowers $p^i_{O_2}$ and decreases the respiration rate of the fruit. Internal atmosphere composition is optimised when $p^i_{O_2}$ is reduced to a level that minimises respiration without inducing anaerobiosis (Banks et al., 1993a). The point at which this can be achieved safely lies just above the

LOL^i defined by Yearsley *et al.* (1996). At $p^i_{O_2}$ levels above LOL^i respiration rate increases and hence the physiological benefits associated with a declining respiration rate decrease. At $p^i_{O_2}$ levels below LOL^i anaerobic respiration rapidly increases and fruit quality declines. From a quality perspective, super-optimal $p^i_{O_2}$ provides little benefit over storage in air, whereas sub-optimal $p^i_{O_2}$ conditions can result in rapid loss of quality due to anaerobiosis (Banks *et al.*, 1993a).

In the case of water vapour Δp_{H_2O} is commonly referred to as the water vapour pressure difference (WVPD). WVPD may be defined as the difference between the vapour pressure in the intercellular spaces of the harvested product and that of the surrounding air. The extent of the WVPD is determined by the temperature and relative humidity of the product and that of the surrounding air (Scheer, 1994). If the product is warmer or at a higher WVP than the surrounding air, then the product will lose water. Other factors also contribute, including the extent of the boundary layer around the product (Woods, 1990). If there is considerable air movement within a store, the boundary layer effects may be small. However if the air in the store is relatively still, then boundary layer effects may be considerable and the product may lose less water, although in apple the contribution of boundary layer to total resistance in apples is likely to be small as the resistance of the skin is so high.

There are a number of methods available to reduce the WVPD between the product and the surrounding air and hence decrease water loss from the harvested crop. Increasing the relative humidity in the store, regulating air movement within the store and using effective packaging materials are some of the options available (Kays, 1991).

Permeance

Natural levels of permeance

The skin represents a major barrier to the diffusion of O_2, CO_2 and water vapour between the commodity and external atmosphere (Cameron and Yang, 1982; Knee, 1991). Skin permeance differs for different gases, with the skin being considerably more permeable to water vapour than O_2 (Cameron *et al.*, 1995). Skin permeance in apples has been shown to vary with cultivar, physiological age and relative humidity (Wilkinson, 1965; Banks, 1985; Dadzie, 1992). Fruit or vegetable skin permeance is affected by a number of physical factors including the thickness and composition of the peel, quantity and distribution of open lenticels, surface cracks or other irregularities and wax deposits. There is also considerable fruit-to-fruit variation, which may be at least partially explained by slight differences in the physical makeup of the skin (Banks, 1985; Dadzie, 1992; Dadzie *et al.*, 1993). Dadzie (1992) found the skin resistance of individual fruit within a cultivar varied by a factor of between 2 and 7. Natural variations in skin permeance to O_2, CO_2 and water vapour can result in considerable variation in the internal atmosphere composition of these gases within the fruit. Lower P'_j (other factors remaining unchanged) would be associated with lower $p^i_{O_2}$ (Dadzie, 1992).

Modification of fruit permeance

Applying a surface coating to a fruit decreases skin permeance to gases and, via the processes of diffusion and respiration, modifies the internal atmosphere composition within a fruit. Application of a surface coating to a fruit generally results in reduction in $p^i_{O_2}$ and respiration rate, an increase in $p^i_{CO_2}$, altered ethylene concentrations, and possible changes in other physiologically active compounds, such as α-farnesene and quality-related volatile components such as esters (Smith *et al.*, 1987a).

Lipids, resins, polysaccharides, and proteins are generally the major components of surface coatings (Baldwin *et al.*, 1995). Edible coatings may be made using either a single group of compounds (eg. polysaccharides), or as in case of composite coatings be made from two or more types of compound (Kester and Fennema, 1986; Baldwin *et al.*, 1995). Other substances such as plasticizers, waxes, oils, emulsifiers and surfactants may also be incorporated into the coating mix. The permeability of a particular coating material is affected by a number of factors including: composition and the material's response to temperature and relative humidity (Park and Chinnan, 1995). McHugh and Krochta (1994) and Hagenmaier and Shaw (1991) found that oxygen permeability increased exponentially with increasing RH for whey protein and shellac coatings, respectively. Surface coatings can decrease the permeance of the skin to gas diffusion differentially. Hagenmaier and Shaw (1992) found that common materials used to coat fruits and vegetables had permeabilities to CO_2 which were between 2 and 8 times greater than their respective O_2 permeabilities. Coatings also vary considerably in their permeance to water vapour. Hagenmaier and Shaw (1992) found that for the commercial coatings they measured, there was up to a 17-fold difference in water vapour permeability. Hydrophobic substances such as lipids have been shown to be more effective at reducing water vapour permeance than hydrophillic substances including polysaccharides and proteins (Kester and Fennema, 1986; Martin-Polo *et al.*, 1992; Avena-Bustillos and Krochta, 1993; Gontard *et al.*, 1994).

Temperature effects on internal atmosphere composition of coated fruit

Elevated temperatures stimulate respiration, resulting in a decrease in $p^i_{O_2}$ and an increase in $p^i_{CO_2}$ (Banks, 1985, Banks *et al.*, 1993b). This change may be partially offset by an increase in coating permeability at higher temperatures (Hagenmaier and Shaw, 1991), but the increase in respiration is likely to be considerably larger. It is therefore important that optimisation of a surface coating treatment is at the maximum temperature the commodity is likely to be exposed to.

Effects of surface coatings on fruit quality

Edible coating technology provides an effective means of improving fruit or vegetable quality by enhancing product appearance, reducing water loss and achieving modified atmosphere benefits (Baldwin *et al.*, 1995; Banks *et al.*, 1997). Crop cosmetic features such as gloss, sheen, and perceived depth of colour can be readily enhanced through the use of surface coatings (Hagenmaier and Baker, 1995). However, from a processing perspective, it is the reduction in water loss and MA associated benefits that are of interest and will be reviewed here.

Extensive studies have been carried out to look at the effects of coating-induced modified atmosphere storage on postharvest physiology and quality attributes of apples destined for the fresh fruit market (Smock, 1935; Trout *et al.*, 1952; Smith and Stow, 1984; Chu, 1986; Smith *et al.*, 1987b; Santerre *et al.*, 1989; Drake and Nelson, 1990; Chai *et al.*, 1991; Köksal *et al.*, 1994; Lau and Meheriuk, 1994; Miszczak, 1994). Beneficial effects resulting from a reduction in $p^i_{O_2}$ and/or an increase in $p^i_{CO_2}$ include a reduction in product respiration and ethylene production rates; retention of chlorophyll (green colour), textural quality, nutritional value and sensory quality; and inhibition of some physiological disorders (Kader, 1980; Weichmann, 1986; Kader *et al.*, 1989; Ke *et al.*, 1991). There are also some detrimental effects associated with MA storage including the development of off-flavours, accumulation of ethanol and acetaldehyde, and development of low-O_2 and/or high CO_2 disorders (Kader, 1986; Cohen *et al.*, 1990; Ke *et al.*, 1991). The degree of atmosphere modification affects the level of MA benefits achieved by surface coatings. If the degree of modification is small then the benefits are negligible, whereas if there is excessive modification then physiological disorders and anaerobiosis can occur (Banks *et al.*, 1993a). Application of edible coatings also tends to increase the variability in $p^i_{O_2}$ and $p^i_{CO_2}$ values. Smith *et al.*, (1987a) reported that 'Cox's Orange Pippin' apples treated with a 2 % sucrose ester coating had internal CO_2/O_2-atmospheres of 9.0 ± 1.36 %/5.8 ± 0.76%, compared with 2.3 ± 0.17 %/16.6 ± 0.4 % in untreated fruit. This enhanced level of variation may be due

to unevenness in coating application or exaggeration of the natural variation in skin permeance values.

Meheriuk and Lau (1988) reported that 'Bartlett' and 'd'Anjou' pears coated with Pro-long or Nutri-Save were firmer, higher in titratable acidity, and greener in skin colour than non-coated fruit stored in air at 0 °C. Chai *et al.* (1991) reported that Semperfresh retarded ripening in 'Golden Delicious', 'Ida Red' and 'McIntosh' apples stored at 5 °C, although they found that cultivars responded differently to the coating treatments with 'Ida Red' coated fruit showing no textural advantage. Other workers have had limited success using surface coatings at refrigerated storage temperatures. Smith and Stow (1984) found that in 'Cox's Orange Pippin' apples treated with a 1% sucrose polyester (SPE) formulation and stored at 3.5 °C for up to 5 months, SPE did not affect texture, colour or weight loss. Differences among cultivars or species may be due to anatomical differences influencing their gas-diffusion characteristics. Differences in skin or flesh permeance would affect the degree of modification of the internal environment. If the levels of O_2 remain substantially above a super-optimal level the advantages over air storage would be minimal. Differences among coating products may also account for some of these quality differences as coating materials vary in their permeance characteristics to O_2 and CO_2 (Kester and Fennema, 1986).

Surface coatings have also been used successfully during the marketing phase (Chu, 1986; Drake et al., 1987; Santerre et al., 1989). Smith and Stow (1984) applied a sucrose polyester coating to 'Cox's Orange Pippin' apples prior to a 21 day simulated marketing period. This resulted in apple tissues with increased CO_2 concentrations, decreased yellow colour development and increased firmness. The benefits of surface coatings on delaying ripening and senescence are potentially greater at higher temperatures, though the risks of anaerobiosis, fermentation and the development of off-flavours are also increased (Kester and Fennema, 1986; Cohen *et al.*, 1990; Hagenmaier and Shaw, 1992).

Surface coatings do not appear to have been used on apples destined for processing. However, CA storage has been used to store fruit prior to processing with beneficial effects. McLellan *et al.* (1990) found that delays in placing fruit in CA store after harvest adversely affected the firmness of processed apple slices. Blanched 'Golden Delicious' slices from a late harvest with a four week delay into CA storage were 40% softer than those immediately CA stored. Textural loss was greater in partially processed fruit compared with fresh fruit. This emphasises the likely importance of imposing MA treatments, for fruit to be processed, as soon as possible after harvest.

Low O_2 and/or high CO_2 conditions can reduce the incidence and severity of physiological disorders, such as scald. Meheriuk and Lau (1988) found that the incidence of scald in 'Bartlett' pears and superficial scald in 'd'Anjou' pears were lower in coated fruit than in noncoated fruit kept in air storage. However, O_2 or CO_2 levels beyond those tolerated by the crop can induce physiological disorders such as internal browning and pitting in apples or abnormal ripening (Smith et al., 1987a; Meheriuk and Lau, 1988).

Surface coatings have also been used successfully to reduce transpiration rates in produce (Ben-Yehoshua, 1969; Ben-Yehoshua, 1985; Erbil and Muftugil, 1986). Coating materials vary in their water barrier properties (Kester and Fennema, 1986). Banks et al., (1997) found that while shellac and polyethylene coatings considerably reduced fruit water permeance in apples, carboxymethylcellulose (CMC) had no effect. Composite or layered coatings may be used to achieve both a reduction in product water loss and MA associated benefits. However, the risk for overmodification of the internal atmosphere may be enhanced (Hagenmaier and Baker, 1993; Hagenmaier and Baker, 1995).

2.5.3.4 Calcium

Calcium's role in maintaining fruit firmness and reducing the incidence of bitter pit, scald, internal breakdown and other calcium related disorders has been well documented (Mason and Drought, 1975; Mason *et al.*, 1974; Mason, 1976; Scott and Wills, 1977; Abbott *et al.*, 1989; Ferguson and Watkins, 1989; Glenn and Poovaiah, 1990; Sams *et al.*, 1993; Wang *et al.*, 1993). Two general mechanisms have been proposed to explain the role of calcium in delaying textural loss in apples and other fruits (Glenn and Poovaiah, 1990). The first of these pertains to the subtle effects calcium has on cell membranes and cell wall proteins (Brady, 1987; Glenn *et al.*, 1988). The second relates solely to Ca-cell wall interaction (Grant *et al.*, 1973; Brady, 1987). It is thought that calcium enhances cell wall strength and maintains cell-to-cell cohesion by crosslinking pectin molecules in the middle lamella (Knee and Bartley, 1981; Stow, 1989). Glenn and Poovaiah (1990) using tensile tests on cylinders from stored 'Golden Delicious' apples found that tissue from Ca-treated and control fruit fractured differently. Ca-treated fruit generally sheared through cells, whereas control tissue tended to separate between cells. Tensile strength was also low in the untreated samples. Roy *et al.* (1994) used a cationic colloidal probe in conjunction with light and electron microscopy to analyse differences in the distribution of anionic binding sites (ie. pectic sites available for calcium binding), in water and calcium infiltrated apples. They observed that two areas of the cell wall were transformed by calcium treatment: (1) the primary cell wall on either side of the middle lamella and (2) the middle lamella intersects that delineate the intercellular spaces. They proposed that calcium's role in reducing fruit softening centred on its ability to strengthen cell walls, hence preventing cell separation that leads to the formation of intercellular spaces. Stow (1993) concluded that loss of calcium from the middle lamella was partially responsible for fruit softening but other factors (such as turgor effects, changes in membrane permeability, change in the three dimensional structure of apple tissue) were also likely to be involved.

Postharvest applications of calcium generally involve vacuum or pressure infiltration, or dipping apples in calcium chloride. Abbott *et al.* (1989) found that pressure infiltrating 'Golden Delicious' apples with $CaCl_2$ increased up to 5-fold the amount of cell wall-bound calcium in the flesh. They also reported considerable textural benefits in calcium treated fruit. Drake and Spayd (1983) also reported that prestorage infiltration of 'Golden Delicious' apples with 3 % $CaCl_2$ improved the keeping quality of fresh apples and enhanced the quality of processed products (apple sauce and apple slices) made from these apples. Pressure or vacuum infiltrating tends to be a more effective means than dipping for raising calcium levels and maintaining fruit quality (Drake and Fridlund, 1986; Abbott *et al.*, 1989; El-Ansary *et al.*, 1994). Adding food thickeners into calcium dips can enhance calcium uptake further (Mason *et al.*, 1974). The incorporation of food thickeners into dip solutions probably increased fruit calcium levels by increasing the length of time the fruit is in contact with the moist calcium film and also the thickness of the film, hence allowing more calcium to be taken up by the fruit (Mason *et al.*, 1974; Glenn *et al.*, 1985). Mason (1976) also demonstrated that there was a small additional textural advantage to be gained by incorporating a thickener into the dip, with 'McIntosh' apples coated in dip with thickener being slightly firmer than those dipped in a calcium solution without thickener.

Considerable research effort has been directed at looking at the transport of calcium through the cuticle and within the fruit. The cuticle is a major barrier to spray and dip penetration. Using isolated cuticles, Glenn *et al.* (1985) investigated the relative importance of various pathways of calcium penetration into apple fruit including, diffusion through the cuticle, mass flow through stomata, lenticels and other surface breaks. They concluded that although lenticels were a major pathway for calcium penetration under saturated conditions (such as postharvest dips), they may assume less importance under unsaturated conditions (eg. pre-harvest orchard sprays). Under these conditions they propose that cracks and other surface irregularities may assume a greater role. Compound formulation, concentration, pH, and rate of drying were identified as important factors in determining the level of calcium uptake. Glenn and

Poovaiah (1985) demonstrated using isolated cuticles that $CaCl_2$ permeated the cuticle faster that other forms of calcium (calcium acetate, calcium nitrate and two commercial formulations of calcium). $CaCl_2$ also took longer to dry than the other compounds tested, enabling calcium to be taken up by the fruit over a longer period. Solution pH was also an important factor, with $CaCl_2$ penetrating the cuticle faster under acidic conditions. Temperature also affected calcium penetration, with higher diffusion rates being observed at warmer temperatures. Changes in solution viscosity with temperature are thought to be largely responsible for these observed changes in diffusion rates (Glenn and Poovaiah, 1985).

Transport of calcium in apple cortical flesh is by diffusion through the apoplast, facilitated by exchange with binding sites on the cell walls (Harker *et al.*, 1989). Harker and Ferguson (1988) showed using *in vitro* studies that calcium transport through discs was influenced by the exchange properties of the cell wall, amount and nature of air space and calcium concentration in the extracellular solution.

2.5.4 Processing factors

Apples have traditionally been processed into an array of different products including apple sauce, solid-pack pie slices, pie filling, spiced apple rings, canned baked apples, and canned apple pieces in syrup (Fisher and Kitson, 1991). In more recent times there has been a move towards minimally processed products (Dennis, 1993).

The processing phase comprises a number of individual operations, each of which can have a direct effect on final product quality. This section concentrates particularly on those operations used in the production of solid-pack canned apple slices, and examines their potential effect on final product texture and overall quality.

2.5.4.1 Vacuum infiltration

Vacuum infiltration to remove occluded gases from apple tissue is part of the pre-processing phase in the commercial production of solid-pack apple slices. Apples contain a network of intercellular air spaces that transport O_2, CO_2, C_2H_4 and other physiologically important gases. The amount of air space within a fruit is generally expressed in terms of porosity (where porosity is defined as the proportion of the volume of the intercellular air spaces to the total volume of the organ). Porosity values for apples may range from 8-36% (Soudain and Phan Phuc, 1979). Vacuum infiltration is the preferred method for removing gases from the fruit. This procedure provides several benefits to the processor. It: 1) reduces texture degradation caused by thermal expansion of gases in the intercellular spaces, during blanching and cooking; 2) enables product texture and quality to be enhanced through the addition of calcium and other additives; 3) prevents can corrosion and off-flavour development caused by residual oxygen; 4) enables the prescribed can fill weight to be more readily achieved by increasing the density of the tissue (MacGregor and Kitson, 1981). Adequate removal of these gases and replacement with solution is essential to ensure that product quality remains high.

The vacuum infiltration process

Fito (1994) developed a model to describe vacuum infiltration in 'Granny Smith' apples. Fig. 2-9 (redrawn from Fito, 1994) shows schematically the processes thought to occur in intercellular spaces (pores) during vacuum infiltration. Fito described the uptake of liquid by a pore in relation to the following four operational stages:

Step 1 Fruit tissue was immersed in the infiltrating liquid at atmospheric pressure.

Step 2 Working pressure was developed in the system ($p_{vac} < p_{atm}$; where p_{vac} was the pressure during vacuum treatment, and p_{atm} was atmospheric pressure.

Step 3 p_{vac} was maintained for a time

Step 4 The system was returned to atmospheric pressure and the slice became infiltrated. The apple slice was removed from the liquid.

Liquid uptake during Step 1 would be due primarily to capillarity (Figs. 2-9 A & B). During the second stage (Fig. 2-9 C) gases within the occluded pores would expand out of the pores. Returning the working pressure to atmospheric would result in a large influx of solution. This mass transfer of liquid to the pore was referred to by Fito (1994) as the hydrodynamic mechanism (HDM).

Fito and Pastor (1994) developed a series of equations that permitted the calculation of the volume of liquid transferred by HDM (Eq. 2-3), taking into account the influence of pressure and the microstructural characteristics of the apple. They suggested that the volumetric fraction of liquid (x) transferred by HDM was:

$$x = \epsilon_e x_v \qquad \textbf{(2-3)}$$

where ε_e = the effective porosity and x_v = volume fraction of the pore occupied by the liquid.

The volume fraction of the pore occupied by liquid (x_v) could be estimated from:

$$x_v = 1 - \frac{1}{r_a} \qquad \textbf{(2-4)}$$

where r_a = the actual compression ratio:

$$r_a = \frac{(p_{atm} + p_c)}{p_{vac}} = \left(\frac{p_{atm}}{p_{vac}}\right) + \left(\frac{p_c}{p_{vac}}\right) \qquad \textbf{(2-5)}$$

where p_{atm} = atmospheric pressure; p_c = capillary pressure and p_{vac} = working pressure.

The apparent compression ratio (R) was defined as: $R = p_{atm} / p_{vac}$ and reduced capillary pressure (p_r) as: $p_r = p_c / p_{vac}$ hence:

$$r_a = R + p_r \qquad \textbf{(2-6)}$$

At low working pressures $R >> p_r$ and hence it can be assumed that $r_a = R$.

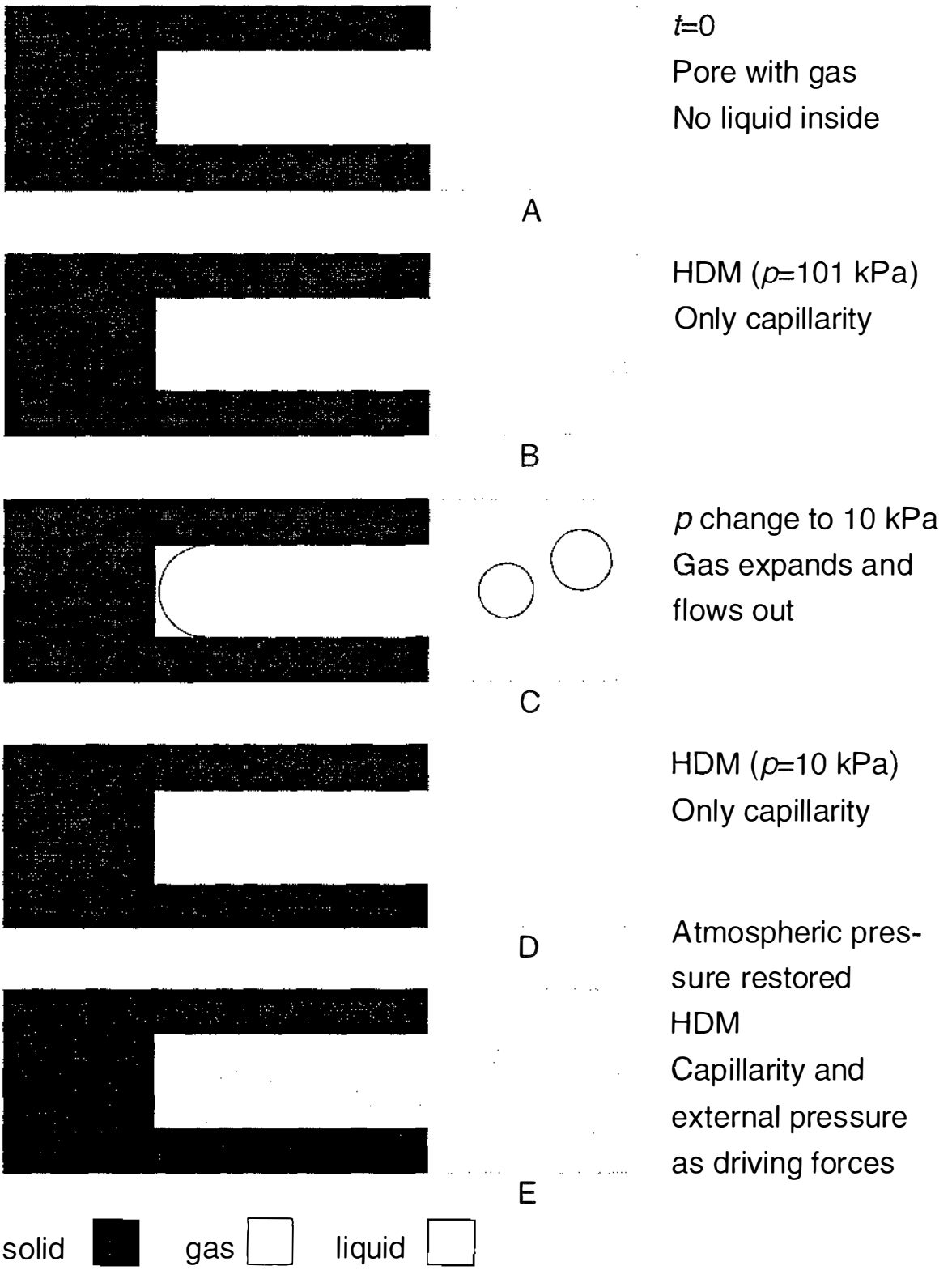


Fig. 2-9. Typical steps in a mass transfer operation between a porous food and a liquid in which it is immersed during a vacuum infiltration sequence (Modified from Fito (1994)).

Fito and Pastor's (1994) experimental verification of the model showed that ignoring the p_r component at working pressures below 60 kPa (absolute pressure) resulted in an error in calculating x_v of less than 2.5 %.

Degree of infiltration

To determine the success of modifications to a vacuum infiltration sequence it is necessary to quantify the degree of tissue infiltration. This section examines methods traditionally used to assess degree of infiltration and methods used to measure tissue porosity that are potentially suitable for quantifying the degree of infiltration of plant tissue achieved by vacuum infiltration.

Several workers (Gallander and Kretchman, 1976; Hoover and Miller, 1975; Banaszczyk and Plocharski, 1993) have used the weight gained by the apple slices as an index for the degree of infiltration obtained. This water infiltration method has been used by numerous workers to estimate tissue porosity (Byott, 1976; Smith and Heuer, 1981). One potential problem with this method is that the increase in tissue mass does not necessarily represent infiltration of the intercellular spaces but may in part be due to the cells absorbing water. To improve the water infiltration method some workers (Smith and Heuer, 1981; Fito and Pastor, 1994) have looked at using a solution with a chemical potential similar to cellular water potential, aiming to avoid water absorption by cells by removing the chemical potential gradient. However, as discussed by Calbo and Nery (1995), the chemical potential of the infiltrating solution may be equal to the apoplast osmotic potential at the surface of an organ, but is likely to differ from the apoplast osmotic potential at the centre of the organ, and hence cells are still likely to take up or lose some water.

Plant organ porosity has also been successfully estimated using techniques based on Archimedes principle in which porosity is obtained as the difference between the impelling force acting on an organ before and after vacuum infiltration. Some straightforward techniques are described by Kushman and Pope (1968), Raskin

(1983) and Reeve (1953). Techniques based on Archimedes principle are less subject to errors due to cellular water absorption.

Hamblin *et al.* (1987) and Heil *et al.* (1988) used residual headspace oxygen and vacuum levels in cooled samples taken directly after processing to assess the adequacy of air removal. However they did not specify an 'ideal' level of residual oxygen which makes it difficult to assess when satisfactory oxygen removal has occurred.

Factors affecting vacuum infiltration

Several factors are known to influence the degree of infiltration including cultivar, maturity, temperature, storage duration and the soluble solids content of the fruit (Hoover and Miller, 1975; Gallander and Kretchman, 1976; Wiley and Binkley, 1989).

Hoover and Miller (1975) investigated some of the factors that influence vacuum infiltration. Slice weight gain was used to quantify liquid uptake. Hoover and Miller (1975) found that increasing the vacuum time from 1 second to 4 minutes resulted in a small increase (7%) in slice weight. It should be noted that this study did not distinguish between two important components of the vacuum infiltration sequence, namely vacuum time (i.e. the time spent at a particular level of vacuum) and absorption time (i.e. time allowed for solution uptake after the vacuum was released). It is therefore difficult to draw any outright conclusions about the importance of vacuum time and absorption time from this portion of the work. Hoover and Miller (1975) also found that sub-optimal vacuum levels (< 91 kPa) were detrimental to liquid uptake. Increasing the vacuum from 47 kPa to 71 kPa resulted in a 40% increase in slice weight, a further increase in vacuum from 71 kPa to 91 kPa resulted in a further 20% increase in weight. Infiltrating solution temperature had a marked effect on degree of infiltration. This study found that slice weight increased from 22% at 23°C to 28.5% at 49°C. Hoover and Miller (1975) also found sucrose content

of the infiltrating solution affected solution uptake. Water infiltrated slices gained 33% more weight than slices infiltrated with a 36% sucrose solution.

Other workers (MacGregor and Kitson, 1981; Dougherty et al., 1966; Wiley and Lee, 1970) have evaluated the effect of vacuum infiltration on texture. The inclusion of the vacuum infiltration step in the pre-processing phase of apple slice production enhanced slice texture.

These studies indicate that vacuum infiltration is an important component of the pre-processing phase of solid-pack apple production. Optimisation of the vacuum infiltration is important if final product quality is to remain high.

2.5.4.2 Blanching and thermal process

The thermal processes of blanching and sterilization significantly alter the nutritional value, texture, colour and flavour of fruits and vegetables (Anantheswaran *et al.*, 1985; Mittal, 1994; Apostolopoulos and Brennan, 1994b). While blanching can result in considerable softening, this can be limited through the use of low temperature long time (LTLT) blanch procedures, altering tissue pH and/or incorporating calcium into the tissue (Beveridge and Weintraub, 1995; Usiak *et al.*, 1995; Stanley *et al.*, 1995). Low temperature blanching enhances PE activity, thereby increasing the demethylation of pectin and increasing Ca^{2+} cross-linking (Van Buren, 1979; Usiak *et al.*, 1995). Enhanced firmness in canned green beans and carrots, blanched at 65 °C for an extended time, was attributed to greater PE activity (Stanley *et al.*, 1995). Apple sauce thickness was also improved by a low temperature long time blanch (59-71 °C for 20 min) (Usiak *et al.*, 1995). Texture degradation may be retarded further by vacuum infiltrating fruits or vegetables with PE and/or calcium prior to blanching. Peaches infused for 2 h with a PE extract containing $CaCl_2$ before thermal processing, registered firmness values of 13.9 $J.kg^{-1}$ compared to 3.2 $J.kg^{-1}$ for noninfused, processed controls. The specific activity of PE showed more than a 20 fold increase in infused fruit, with calcium levels raised

from 278 to 432 mg.kg^{-1} (Javeri *et al.*, 1991). Altering the pH of the tissue, in combination with the addition of calcium and/or exogenous PE, and LTLT blanch practices, can further reduce texture degradation. This is particularly effective in vegetable processing as the natural pH of the product is relatively high. In canned green beans and carrots, firmness was improved by lowering the pH (down to about pH 4.5) and adding calcium (Stanley *et al.*, 1995). Wiley and Lee (1970) found that firmness and PE activity of calcium treated apple slices, increased as the pH was raised from 3 to 6.5. The extent of fruit softening during blanching, depends on blanch temperature and duration, the pH of the system, activity of PE, and the potential for incorporating calcium into the tissue.

Huang and Bourne (1983) developed a model, using two simultaneous first order kinetic mechanisms to describe thermal softening in vegetables. The softening curve (comprising a plot of log extrusion force versus process time), was characterised by an initial steep negative slope that was almost linear, but which curved off into a second straight line with a shallow negative slope at longer process times. They extracted two rate constants from this curve, one describing the high initial rate of softening (mechanism I), and the second explaining the softening at prolonged heating times (mechanism II). Arrhenius activation energy values were also evaluated for these rate constants. They ranged from 15-35 kcal.mol^{-1} for mechanism I and between 0.5-24 kcal.mol^{-1} for mechanism II. Huang and Bourne (1983) attributed mechanism I to pectic changes in the interlamellar layer. Anantheswaran *et al.* (1985) developed a similar model to describe thermal degradation in apple slices. They found that mechanism I, through which there was a rapid drop off in firmness with process time, was considerably shorter in apples, only lasting up to 5 min. After this initial period of rapid textural loss, the rate of softening was much slower. Since most thermal processes need to be longer than 5 min to ensure commercial sterility, mechanism II is probably more important for apples. Anantheswaran *et al.* (1985) found that softening rates varied considerably with cultivar. Calculated activation energies for 'Cortland' and 'Spigold' varieties were 26.5 kcal.mol^{-1} and 15.6 kcal.mol^{-1}, respectively. Changes in product quality with

respect to temperature are often described using Z values (defined as a temperature interval to make a 10-fold change in product quality; Mittal, 1994). Anantheswaran *et al.* (1985) reported Z values for loss of hardness of 24.8 °C and 42.2 °C for 'Cortland' and 'Spigold' respectively. Processing temperature also affected cohesiveness and chewiness (as determined by TPA) in both cultivars. The cultivars responded differently in terms of processing time, with 'Spigold' changing significantly in terms of cohesiveness and gumminess, while 'Cortland' changed with regard to springiness and chewiness. These results demonstrate the dominance of the varietal effect in determining the effect of thermal processing.

2.5.5 Relationship between fresh and processed apple quality

Quantifying the relationship between raw product quality and processed slice quality remains one of the key objectives for researchers and processors alike. Wiley and Thompson (1960) investigated the relationships between various physical and chemical raw product tests and the sensory quality of canned apple slices. They found that for 'Golden Delicious', 'Rome Beauty' and 'Stayman' 59-66 % of the variation in processed slice quality could be accounted for by raw product firmness, titratable acidity and soluble solids levels. In contrast, 'York Imperial' and 'Jonathan' final product quality could not be adequately predicted from these or other test combinations. McLellan *et al.* (1984a) developed a set of orthogonal sensory components to account for the intervarietal variation of applesauce and apple slices. For apple slices they found that 72 % of the intervarietal variation among the six cultivars could be accounted for by six sensory components (colour; sourness and astringency; sweetness and fruit oral aroma; grain type and particle breakdown size; cooked nasal aroma; firmness and cooked oral aroma). McLellan *et al.* (1984b) investigated the relationship between these sensory attributes and various objective measurements of raw product quality. Using a regression approach they developed a series of models quantifying each of the previously defined sensory components in terms of one or more objective tests. However, they did not evaluate the proportion of variation explained by each of the models, hence the models were only used to

describe general relationships and trends between appropriate objective measurements and sensory descriptors. Establishing and quantifying the relationships between key objective raw fruit measurements and processed slice quality should assist processors in producing a consistent, high quality product throughout the season.

Chapter 3

General materials and methods

3.1 Fresh fruit measurements

3.1.1 Determining internal O_2 and CO_2 partial pressures

Internal atmospheres were sampled destructively by direct removal (Banks, 1983; Dadzie, 1992) from the core cavity. A 1 ml disposable syringe was fitted with a stainless steel cannula containing a pin. Dead space in the syringe was flushed with water to remove any trapped air. The cannula was inserted into the core via the calyx end of the apple, whilst the whole system was immersed in water. Internal atmosphere was drawn into the syringe by gently pulling the cannula and syringe away from the pin head and easing back the plunger. The sample was then capped and stored temporarily under water. For analysis of internal O_2 and CO_2 concentrations a 90 mm^3 sub-sample was transferred into a Hamilton 100 mm^3 syringe.

Sample O_2 and CO_2 contents were determined using an O_2 electrode (Citicell C/S type, City Technology Ltd., London, UK) in series with a miniature infra-red CO_2 transducer (Analytical Development Company, Hoddesdon, UK) with O_2-free N_2 as carrier gas (flow rate 580 $mm^3.s^{-1}$). Data were converted from mole fractions to partial pressures by adjusting for atmospheric pressure (Banks *et al.*, 1995).

3.1.2 Background colour

Background colour was measured using a Minolta CR-200 portable chromameter (Minolta Camera Co., Ltd). The meter was calibrated using a green standard

calibrating square. A chromameter characterises the composition of colour from an object by recording light reflected back from the object when illuminated by a pulse of light from a Xenon lamp through an 8 mm diameter measuring area. The results were expressed in terms of lightness (L), chroma (C) and hue angle (°; McGuire, 1992). Two readings were taken per fruit.

3.1.3 Texture measurements

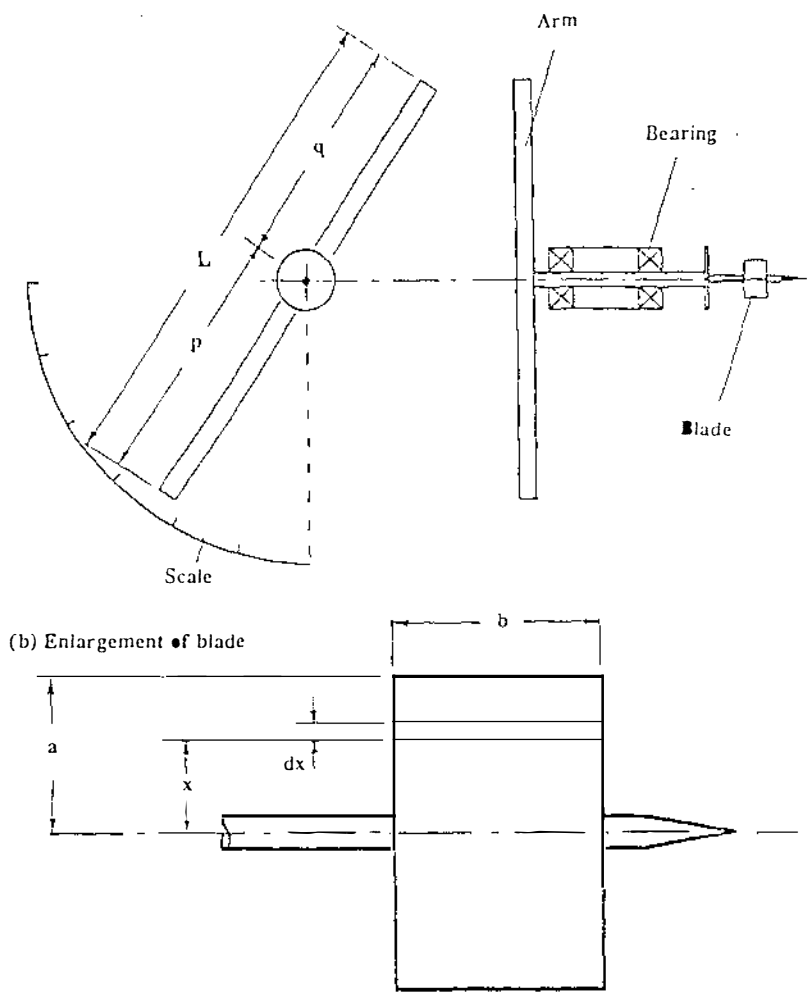
3.1.3.1 Twist tester

The motor-driven twist tester used in this study is shown schematically in Fig. 3-1 (Yuwana, 1991; Studman and Yuwana, 1992; Studman, 1993). A prototype of the twist tester, comprising a blade fixed at 90 ° to a horizontal spindle, was described by Studman and Yuwana (1992). Removal of operator error, through mechanically twisting the fruit was the major advancement of the motor-driven model (Fig. 3-2). The motorised model had a second blade (of the same dimensions as the first) attached to the output shaft of a low speed gearbox driven at 2 rpm by a small motor, aligned on the same axis as the first. The fruit was pushed onto the motor-driven blade, before being pushed onto the spindle and rotated around the spindle until the blade (1st) crushed the flesh and the fruit turned freely. The resisting moment (m_T) was generated by a counterweight attached to the offset arm. Rotation was recorded with a precision potentiometer mounted on the shaft of the driven blade, connected to a data acquisition system. Maximum value and bioyield angles (θ) were converted to crush strengths (σ) using formulae described by Studman and Yuwana (1992; Eq. 3-1). The maximum value (TMax) was the crush strength calculated from the greatest recorded angle, while the apparent "Bioyield" (TBio) was calculated from the value where the first failure occurred.

$$m_T = 2 \int_{a_0}^{a} \sigma \; x \; b \; dx = \sigma \; b \; (a^2 - a_0^2) = M \; g \; Z \sin \theta \qquad \textbf{(3-1)}$$

where m_T was the moment required to crush the fruit tissue, where m_T can be estimated by integrating each radial element dx (width b) over the blade; σ was the crush strength of the fruit (Pa); a was the radius of the blade (m); a_0 was the radius of the spindle, M was the mass of the arm (kg); Z was the distance of the centre of mass of the rod from the axis of rotation; θ was the angle of rotation (degrees); and g was the gravity constant (9.80 $m.s^{-2}$). A rectangular blade (9.6 x 3.8 mm) was used throughout this work.

Fig. 3-1 Schematic diagram of the twist tester



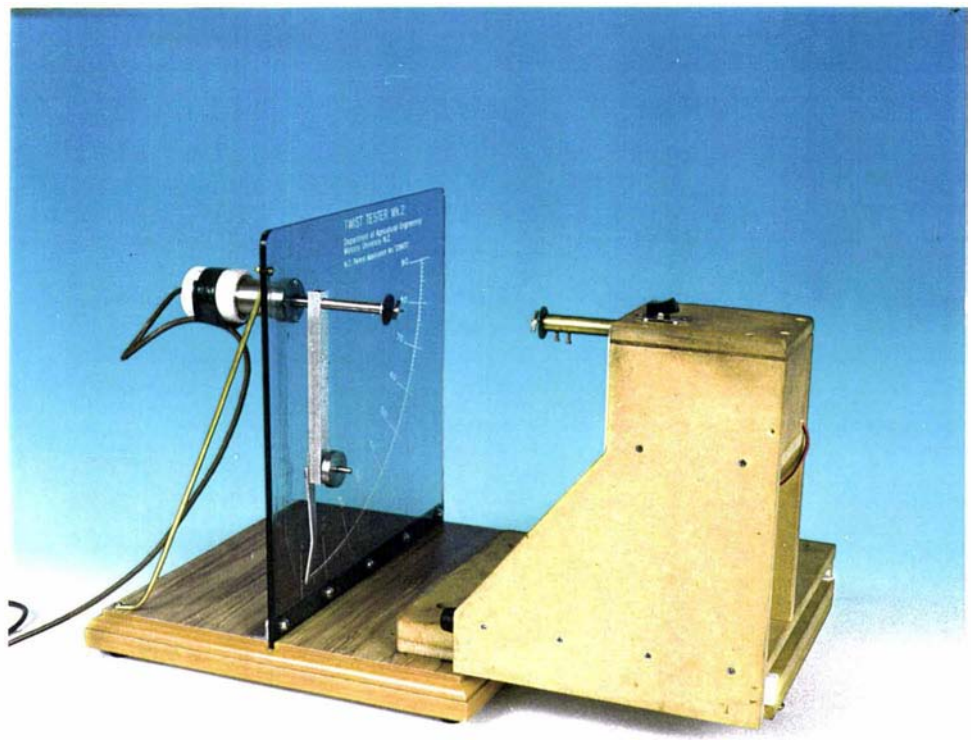


Fig. 3-2. The motor-driven twist tester

3.1.3.2 Penetrometer

Flesh firmness was measured using an Effegi penetrometer (Blanpied *et al.*, 1978; Facchini, Alfonsine, Italy) fitted with an 11.1 mm head, mounted in a drill press (Black and Decker). Skin from the test area was removed before the test. This measure of fruit firmness is a standard test used by the New Zealand apple industry.

3.1.3.3 Instron textural tests

An Instron 4052 universal materials testing machine (Instron, Canton, Mass.) was used to carry out the following textural tests:

Penetrometer

The peak force required to drive an Effegi penetrometer probe with a crosshead speed of 100 mm/min into the fruit to a depth of 9.4 mm was recorded. Skin was removed from the test area before the test.

Kramer Shear

A Kramer shear compression cell with 10 flexible blades each 3 mm thick, was also used. The blades were mounted on the Instron's crosshead and driven into the cell, compressing, shearing and finally extruding part of the sample through 10 slots in the bottom of the cell. Apple slices were placed in the cell perpendicular to the blades. The peak force required to shear 50 g (2-3 slices) of freshly peeled apple slices, at a crosshead speed of 400 mm/minute was recorded. Considerable care was taken with blade alignment before testing to ensure that friction forces were minimal. A typical force-deformation curve is shown in Fig. 3-3.

3.1.4 Soluble solids

An estimate of soluble solids was obtained using a hand-held temperature compensating Atago refractometer (range 0 to 20 °Brix; Atago Co. Ltd., Tokyo, Japan). Juice expressed during the penetrometer test was used to measure soluble solids.

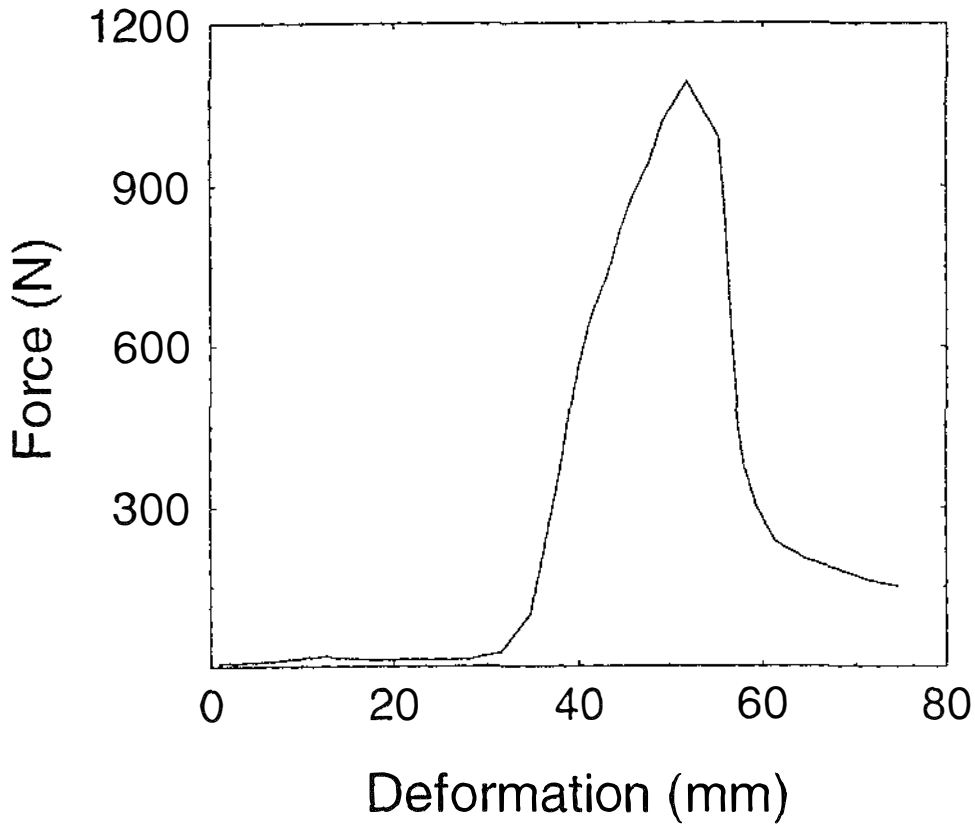


Fig. 3-3 Typical force-deformation curve of a Kramer shear test on fresh apple slices.

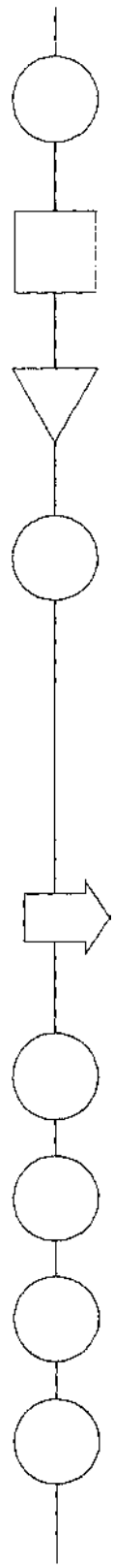
3.1.5 Calcium analyses

For analysis of fruit calcium content, 1 ml samples were taken from the cortical tissue using a corer. Samples were oven dried at 80 °C and ground using a coffee grinder. Samples of dried, ground tissue (0.1 g) were refluxed with concentrated nitric acid (4 ml) in digestion tubes occluded with small funnels at 150 °C overnight or until the solution cleared; they were then boiled to dryness at 250°C. The warm residue was re-dissolved in 50 ml of strontium and caesium (2.4% w/w for each element) in 0.2 M HCl and stored at 4 °C in a dark refrigerator until analysis of Ca by atomic absorption spectrophotometry.

3.2 Processing procedure for the production of solid-pack apple slices

The generalised flow process diagram (Fig. 3-4) describes the procedure for producing solid-pack apple. Variations are described in the appropriate chapters. Fruit were manually peeled, cored and sliced into eight equal segments. Slices were temporarily stored in a 0.1 M (3.5 %) sucrose solution until a complete batch of fruit was ready to be processed. A 0.1 M sucrose solution was used as this is approximately equivalent to the water potential of the apple pip, which may be used to roughly approximate the water potential of the whole fruit (Samim and Banks, 1993). Using a weak sucrose solution instead of water should have minimised any water uptake by the cells. Before entering the de-aeration sequence, slices were rinsed with cold water to remove any residual sugar. Vacuum infiltration was carried out in a small 0.02 m^3 stainless steel vessel. Slices were loaded into the chamber and a vacuum of 95 kPa drawn using a Javac double stage high vacuum pump (Model JDX 220, Javac Pty. Ltd., Australia). The vacuum was broken with a 0.2 % calcium chloride and 0.05 % ascorbic acid solution (w/v). Calcium was added to improve product texture and ascorbic acid to reduce product browning, during the pre-processing phase. The product was then held in the solution for a designated time (refer to individual chapters for details). Slices were then blanched in steam for 4.5 min. Cans were filled and closed using a can seamer (John Hein, Model 710, Series 2, Sydney). Cans were thermally processed in 99 °C water and cooled for 40 min. in 15 °C water.

Fig. 3-4 Production of solid-pack apple (generalised form)



Peeling and coring

Inspection - pips/core, disease, skin, stalk removal

Store temporarily in sugar solution

De-aeration sequence
(1) Load vessel
(2) Pull vacuum to > 95 kPa
(3) Hold for predetermined time
(4) Break vacuum with $CaCl_2$ & ascorbic acid solution
(5) Hold to allow absorption

Transfer to blancher

Steam blanching; target 85°C exit temperature

Can filling and closing

Thermal process - water bath 99°C

Cooling - water bath 15°C

3.3 Processed product assessment

Processed product texture and juice volume are the two quality attributes of most concern in this study as these are of primary interest to J. Wattie Foods.

3.3.1 Preliminary measurements

The following final measurements were made to assess the consistency of the production process: 1) gross weight, 2) vacuum pressure (using a Teltherm vacuum gauge) and 3) headspace.

3.3.2 Juice measurements

3.3.2.1 Juice volume

Juice volume was measured after draining the can contents on a 20 cm diameter sieve with 2.8 x 2.8 mm openings for 2 minutes. The product drained weight was also recorded.

3.3.2.2 Juice quality

The pH and soluble solids of the drained juice were measured using an Orion pH meter and a refractometer (section 3.1.4), respectively.

3.3.3 Relative density of the tissue

Tissue relative density (ρ_{rel}^{slice}) was estimated on slices of tissue using:

$$\rho_{rel}^{slice} = \frac{M^{app}}{(M^{app} - M_w^{app})} \quad \text{(3-2)}$$

where: M^{app} = apparent mass of slice in air (kg); M_w^{app} = apparent mass of slice submerged in water (kg). Slices were weighed using a hook suspended from a Mettler AE200 balance (Mettler Instrumente, AG Greifensee - Zürich, Switzerland).

3.3.4 Dry matter content

Percentage dry matter was determined after oven drying 2-3 slices for several days. Samples were weighed before and after drying on a Mettler AE200 balance (Mettler Instrumente, AG Greifensee - Zürich, Switzerland).

3.3.5 Textural measurements

The product was visually assessed for slice integrity and appearance using a five point scale (1 = excellent, 5 = very poor). The following instrumental tests were carried out on an Instron Model 4502 universal materials testing machine:

3.3.5.1 Compression

A two-cycle uniaxial compression was applied on wedges (12 mm high) cut from individual slices with a double blade cutter. Slices were compressed to 80 % of their original height. Crosshead speed was 25 mm/min. A typical force-deformation curve obtained by this two cycle compression test is shown in Fig. 3-5. The curve can be divided into three stages: the non-linear viscoelastic stage (A - B), the linear

viscoelastic stage (B - C), and the recovery stage (C - D; where the sample partially recovers from its previous deformed state; Apostolopoulos and Brennan, 1994a). The second curve is a repetition of the first, except that deformation is smaller due to the permanent deformation incurred during the first compression. Three parameters were selected from the two-cycle compression test: 1) slope of linear portion of curve; 2) curve 1 peak force and 3) permanent deformation (distance AD).

3.3.5.2 Shear

Measurements were carried out in an identical manner to those outlined for fresh fruit in section 3.1.3.3, except that the size of the sample was increased from 50 g to 70 g.

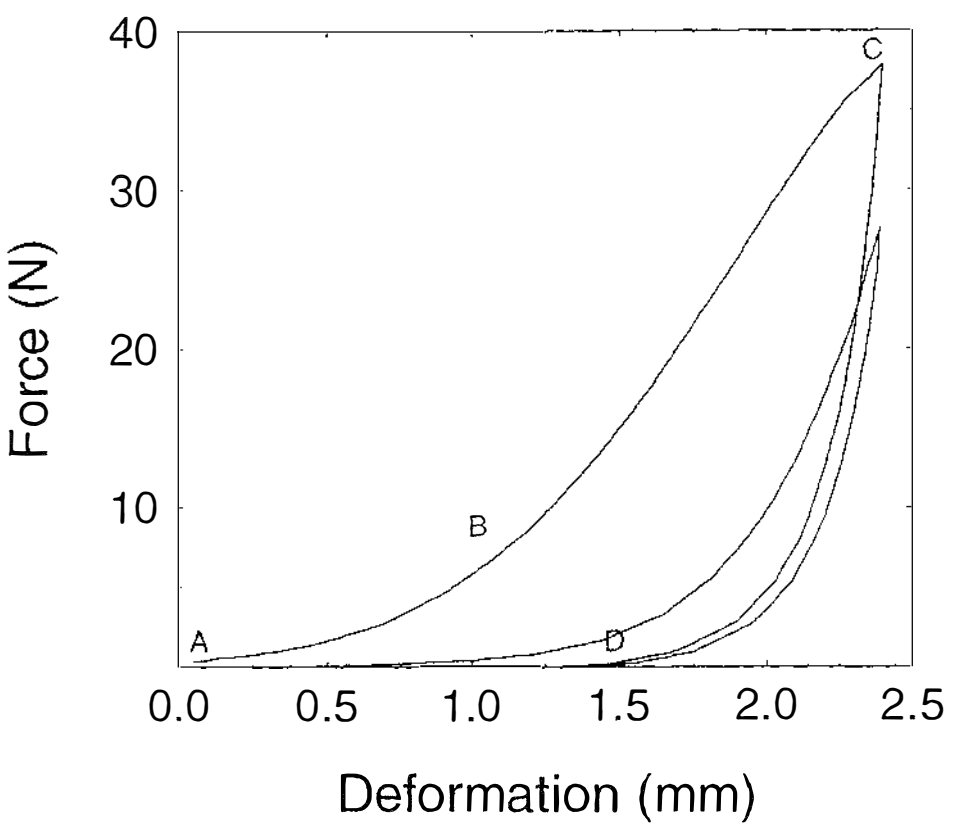


Fig. 3-5. Typical force-deformation curve of a two-cycle uniaxial compression test on processed apple slices.

Chapter 4

Factors affecting vacuum infiltration in 'Braeburn' apples

4.1 Introduction

4.1.1 Background justification

Vacuum infiltration to remove occluded gases from apple tissue is part of the pre-processing phase in the commercial production of solid-pack apple slices. This procedure: 1) increases the relative density of the tissue enabling the prescribed can fill weight to be achieved; 2) reduces texture degradation caused by thermal expansion of occluded gases during blanching and cooking; 3) facilitates the addition of calcium and other additives; 4) prevents can corrosion and off-flavour development (MacGregor and Kitson, 1981). Vacuum infiltration, performed as a batch process is considered to be a 'bottle-neck' in solid-pack apple slice production. Failure to achieve complete infiltration is a potential problem following cold growing seasons and also with immature fruit (J.Wattie Foods, personal communication, 1993). Any reductions in time required to complete this phase of the operation could substantially lower production costs. Several factors are thought to influence the degree of infiltration including cultivar, maturity, temperature, storage duration and the soluble solids content of the fruit (Wiley and Binkley, 1989).

During the 1993 production season, J. Wattie Foods experienced difficulty achieving complete infiltration in its apple slice product. To overcome this problem the company increased the duration of the vacuum infiltration sequence, increasing both process times and production costs (J. Wattie Foods, personal communication, 1993). It is thought that the cold summer during the 1992/93 growing season may have led

to apples being produced with a tightly knit cellular structure and with small intercellular spaces that were difficult to infiltrate.

The overall objective of this part of the programme was to identify potential techniques for enhancing infiltration in difficult-to-infiltrate fruit. This study sought to:

1) quantify relationships between the key variables under study, namely: the relative density of whole fruit or individual segments, and the porosity of the fruit.
2) identify ways to enhance infiltration through modification of:
   a) the vacuum infiltration sequence, which included level of vacuum, vacuum time, vacuum release speed and soaking time in the solution following release of vacuum (absorption time).
   b) composition and temperature of the infiltration solution.
3) determine the relative importance of fruit maturity and storage conditions on slice infiltration.

4.1.2 Theoretical development

Apple tissue is anisotropic and heterogenous (Vincent, 1989; Khan and Vincent, 1990), with porosity (ε) values ranging from 8-36 % (Soudain and Phan Phuc, 1979). The vacuum infiltration procedure removes occluded gases from the intercellular air spaces (IAS) and replaces them with the infiltrating solution. Optimum infiltration is achieved when all the IAS are filled with solution. Development of a quantitative means of assessing degree of infiltration is not only necessary for measuring absolute infiltration but also for comparing treatments designed to enhance infiltration. In this study, change in relative density ($\Delta\rho_{rel}^{slice}$; i.e. ratio of the density of apple tissue to that of water at the same temperature) was the method used to assess infiltration. The change in relative density of the tissue provides an estimate of the volume of filled intercellular air space. It does not take into account the total porosity of the sample and therefore does not distinguish between wholly infiltrated samples with a

low air space volume and partially infiltrated samples with a large air space volume. A more accurate estimate of degree of infiltration would include an estimate of total porosity. Two approaches can be used to estimate porosity from the relative density of the slice before infiltration ($\rho_{rel,\,init}^{slice}$). The first approach involved characterising the relationship between $\rho_{rel,\,init}^{slice}$ and ε (where $\Delta\rho_{rel}^{slice}$ of fully infiltrated tissue is equivalent to ε), to establish whether or not ε could be effectively predicted from $\rho_{rel,\,init}^{slice}$. A second estimate of ε can be obtained from $\rho_{rel,\,init}^{slice}$ and $\rho_{rel,}^{juice}$, using:

$$\epsilon = 1 - \frac{\rho_{rel,init}^{slice}}{\rho_{rel}^{juice}} \qquad \textbf{(4-1)}$$

(Hatfield and Knee, 1988; Knee, 1991). Estimates of ρ_{rel}^{juice} in New Zealand 'Braeburn' apples range from 1.040 to 1.055 (Harker, unpublished data).

Using calculated values of $\Delta\rho_{rel}^{slice}$ and estimated values of slice porosity it is possible to estimate the proportion of intercellular air space that was fully infiltrated or degree of infiltration (DOI; %):

$$DOI = \frac{\Delta\rho_{rel}^{slice}}{\epsilon} \times 100\,\% \qquad \textbf{(4-2)}$$

Comparing DOI with $\Delta\rho_{rel}^{slice}$ would enable assessment of whether or not $\Delta\rho_{rel}^{slice}$ could be used as a reliable means of estimating level of infiltration.

4.2 Materials and methods

4.2.1 Fruit source

Early season 'Braeburn' apples (*Malus domestica* Borkh.) were used throughout this study. Fruit were obtained from Massey University Fruit Crops Unit, Palmerston North. Fruit were stored at 0 °C (unless otherwise stated) until required.

4.2.2 Fruit relative density

All materials were equilibrated to 20 °C before measurements were made. A beaker partially filled with water was placed on a Mettler PE3600 balance, and the balance tared to zero. An apple was placed on the surface of the water and the apparent mass recorded (M^{app}). A second apparent mass (M_n^{app}) was recorded with the apple held below the water surface by three fine needles that did not influence the balance reading. The relative density of whole fruit (ρ_{rel}^{fruit}) was estimated using:

$$\rho_{rel}^{fruit} = \frac{M^{app}}{M_n^{app}} \qquad \textbf{(4-3)}$$

4.2.3 Slice relative density

Tissue relative density ($\rho_{rel,\,init}^{slice}$) was estimated on wedges of tissue (comprising 1/8 th sections of apple), from which the skin and core tissue had been removed. A slice was suspended from a hook beneath an analytical balance (Mettler AE200) and the volume of the tissue determined:

$$V_s = \frac{(M^{app} - M_n^{app})}{\rho_{H_2O}} - V_h \qquad \textbf{(4-4)}$$

where: M^{app} = mass of non-infiltrated slice in air (kg); M_n^{app} = apparent mass of non-infiltrated slice submerged in water (kg); ρ_{H_2O} = density of water (kg m^{-3}); V_h = volume of submerged portion of hook (m^3); and V_s = volume of slice (m^3).

$\rho_{rel,\,init}^{slice}$ was calculated as:

$$\rho_{rel,\,init}^{slice} = \frac{M^{app} / V_s}{\rho_{H_2O}} \qquad \textbf{(4-5)}$$

4.2.4 Change in slice relative density

Change in relative density of apple slices ($\Delta\rho_{rel}^{slice}$) was used to determine the degree of infiltration during vacuum infiltration as outlined below. Change in relative density is equivalent to tissue porosity (ε) provided the apple slice is fully infiltrated. M_n^{app} and V_s were determined as described in section 4.2.3. Slices of tissue were then vacuum infiltrated with water. Final pressure, time spent under vacuum and absorption period were varied, as detailed under individual experiments. The apparent mass of infiltrated slices submerged in water was determined and $\Delta\rho_{rel}^{slice}$ calculated:

$$\Delta\rho_{rel}^{slice} = \frac{(M_i^{app} - M_n^{app})/V_s}{\rho_{H_2O}} \qquad \textbf{(4-6)}$$

where: M_i^{app} = apparent mass of infiltrated slice submerged in water (kg).

This method for determining $\Delta\rho_{rel}^{slice}$ is similar to those outlined by Kushman and Pope (1968), Raskin (1983) and Calbo and Nery (1995) for measuring volume of internal air space. Following infiltration, each slice was visually assessed to determine if it was fully or partially infiltrated. Based on this examination, the percentage of fully infiltrated slices was calculated.

4.2.5 Tissue porosity

4.2.5.1 Method a: $\Delta\rho_{rel}^{slice}$ of fully infiltrated tissue

Tissue porosity was estimated on sections of tissue taken from different parts of the apple (Fig. 4-1). Apple tissue porosity is not homogenous (Soudain and Phan Phuc, 1979; Reeve, 1953; Vincent, 1989). Taking samples from different portions of the fruit provided a larger range of tissue porosities. Samples were vacuum infiltrated at 6 kPa absolute pressure (i.e. 95 kPa vacuum) for 5 min followed by a 5 min

absorption period. Porosity was estimated using Eq. 4-6 (since for fully infiltrated tissue $\Delta\rho_{rel}^{slice}$ is equivalent to ε). Samples that were not fully infiltrated were removed from the analysis. Estimation of tissue porosity in this manner enabled investigation of the relationship between ε^a (porosity estimates using method a) and $\rho_{rel,\,init}^{slice}$.

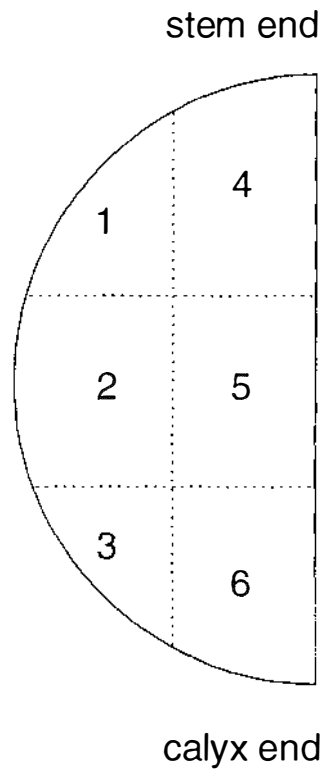


Fig. 4-1. Diagram showing how the apple slices were sectioned for the experimental work outlined in section 4.2.5.1

4.2.5.2 Method b: ε estimated from $\rho_{rel,\,init}^{slice}$ and $\Delta\rho_{rel}^{juice}$

Estimates of tissue porosity obtained by Method b (ε^b) were obtained using Eq. 4-1, assuming ρ_{rel}^{juice} was 1.040.

4.2.6 Harvest date

'Braeburn' trees growing on a Tatura trellis training system, at Massey University's Fruit Crops Unit were used for this experiment. Three hundred fruit were labelled on these trees and harvest dates randomly allocated to fruit. Fruit were harvested on seven occasions between the 15 March and the 29 May 1995 (Table 4-1). Fruit maturity was assessed using a starch pattern index. Apples were cut in half through the equator and one half dipped in iodine solution. The pattern of staining was then assessed using an Enza starch index ('Braeburn') where 0 = stain fully stained and 5 = no staining. Background colour, fruit firmness and soluble solids were assessed as described in sections 3.1.2, 3.1.3.2 and 3.1.4. $\Delta\rho_{rel}^{slice}$ and whole fruit relative density measurements were estimated as described in sections 4.2.4 and 4.2.2, respectively. A standard vacuum infiltration sequence with 8 min vacuum and 12 min absorption was used at each assessment.

Table 4-1. List of harvest dates for experiment outlined in section 4.2.6.

Harvest number	Harvest date	Days before or after commercial opening date[z]
1	15 March	-13
2	29 March	1
3	7 April	10
4	12 April	15
5	19 April	22
6	5 May	38
7	29 May	62

[z] where the opening date for commercial harvest in 1995 was 28 March

Data obtained from the harvest date experiment were also used to investigate the relationship between whole fruit relative density and $\Delta\rho_{rel}^{slice}$.

4.2.7 Storage conditions

Sixty 'Braeburn' apples were randomly allocated to each of the following storage regimes:

1) 20 °C, high RH (90 - 95 %)

2) 20 °C low RH (46 - 63 %, average 56 %)

3) standard storage, 0 °C high RH (94 %)

Relative humidity was estimated using Hy-cal 1H-3602 Monolithic 1C humidity probes connected to a Grant 1200 Series Squirrel data logger (Grant instruments Ltd. Cambridge, England). Fruit weight and $\Delta\rho_{rel}^{slice}$ were assessed at the start of the treatments and after 3, 7 and 14 days storage.

4.2.8 Modification of the vacuum infiltration sequence

4.2.8.1 1994 season

Phase one involved optimising vacuum infiltration time. For the purposes of this work, vacuum time included pull down time (approx. 3.5 min) and the period spent at maximum vacuum. Vacuum times from 0.5 min (i.e. only partial pull down completed) to 30 min were assessed. Two sub-optimal vacuum levels 54 and 30 kPa final pressure were also compared with a standard vacuum (6 kPa absolute pressure). Absorption time and vacuum release speed were held constant during these tests at 5 min and 19 s, respectively.

Phase two involved optimising the final two components of the vacuum infiltration sequence: absorption time and release speed. Preliminary work indicated an interaction between these two factors. Absorption times ranging from 0 to 32 min were tested at each of two release speeds. Different release speeds were achieved by varying the size of the aperture on the inlet pipe. An Actronic Systems Limited AS 4-75 (1.5-A) pressure transducer used in conjunction with a Grant 1200 series

Squirrel data logger recorded absolute pressure in the chamber at 1 s intervals. Vacuum time was maintained at 6 min throughout these tests.

4.2.8.2 1995 Season

Vacuum time

A smaller chamber (approx. 0.02 m^3) was used in 1995, to enable work to be carried out in a controlled temperature environment. A series of vacuum times ranging from 1 to 32 min was investigated using both water and a weak sucrose solution (0.1 mol l^{-1}; 3.4 % (w/v)) as the infiltrating solution. The absorption time was held constant at 5 min for these tests.

Absorption time and release speed

Absorption times from 0 to 32 min were tested at each of three release speeds (2, 25 and 60 s). A constant vacuum time of 10 min was employed throughout these tests.

4.2.9 Modification of temperature and composition of the infiltrating solution

4.2.9.1 1994 Season

Influence of pH, osmotic potential and temperature of the infiltrating solution on the degree of infiltration were investigated using a sub-optimal vacuum infiltration sequence (involving a vacuum time of 6 min, a release speed of 19 s and an absorption time of 2 min). The experiment was a complete factorial with two levels of pH (7 and 3), two osmotic concentrations (0 and -.25 MPa (equivalent to a 3.5% sucrose solution)) and two solution temperatures (15 and 50 °C).

4.2.9.2 1995 Season

The influence of solution temperature on degree of infiltration was investigated further during the 1995 season. Fruit were equilibrated to 5 °C prior to vacuum infiltration. A series of solution temperatures from 5 - 50 °C were assessed using a sub-optimal vacuum infiltration sequence involving vacuum and absorption times each lasting 5 min. Solution temperature was maintained throughout the test by placing the chamber in a controlled temperature room set to the appropriate solution temperature.

4.2.10 Relationship between level of infiltration and product texture

A series of slices with different levels of infiltration ranging from nil to fully infiltrated were generated by varying the absorption time from 0 to 32 min during the vacuum infiltration sequence. The vacuum time was maintained at 10 min throughout these tests. Fruit were processed as described in section 3.2. Processed slice texture was then assessed as described in section 3.3.5.

4.2.11 Statistical analysis

Where appropriate, curves were fitted using the non-linear or linear regression modules in the SAS system (SAS, 1990). Data from 4.2.9.1 were subjected to analysis of variance using the general linear models procedure of SAS.

4.3 Results

4.3.1 Relationship between porosity and $\rho_{rel,\,init}^{slice}$

Porosity varied greatly between sections of apple tissue taken from different regions of the fruit, with values ranging from 0.08 - 0.178 (Fig. 4-2). Porosity of fruit sections was linearly, negatively related to $\rho_{rel,\,init}^{slice}$ ($P < 0.0001$):

$$\epsilon = 0.8793 - 0.835 \times \rho_{rel,init}^{slice} \qquad r^2 = 0.91 \qquad \textbf{(4-7)}$$

where the standard errors for the intercept and slope were 0.00809 and 0.0331, respectively.

4.3.2 Comparison of methods for measuring porosity

Both methods reached similar estimates of tissue porosity (Fig. 4-3), with 91 % of the variation in ε^b (porosity estimated by method b) being accounted for by ε^a.

4.3.3 Harvest date

Fruit maturation advanced with progressive harvest dates as indicated by increasing starch pattern index, soluble solids and background colour (Figs. 4-4a, b and d). Firmness declined with harvest date, with fruit harvested at the final harvest being 19 % softer than those at the first (Fig. 4-4c). Average whole fruit relative density decreased from 0.909 at harvest 1 to 0.894 at harvest 7 (Fig. 4-4e). Fig. 4-5 shows more clearly the distribution of whole fruit relative density values with harvest date. Early in the harvest season a large proportion of the apples had a $\rho_{rel}^{fruit} \geq 0.91$ with very few fruit having values ≤ 0.89. As the season progressed the proportion of apples with $\rho_{rel}^{fruit} \geq 0.91$ decreased progressively to less than 5 % at harvest 7, with substantial numbers of fruit then having values ≤ 0.89. Changes in ρ_{rel}^{fruit} were

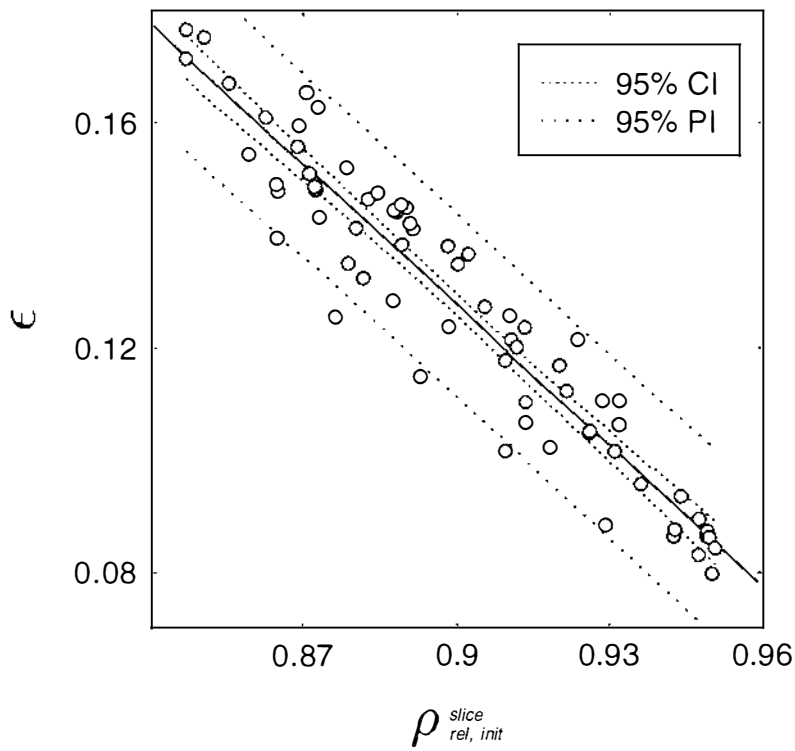


Fig 4-2. The relationship between porosity (ϵ) and $\rho^{slice}_{rel,\ init}$, in 'Braeburn' apples using sections of tissue taken from different parts of the apple, as illustrated in Fig.4-1. CI and PI are the 95 % confidence and prediction intervals, respectively.

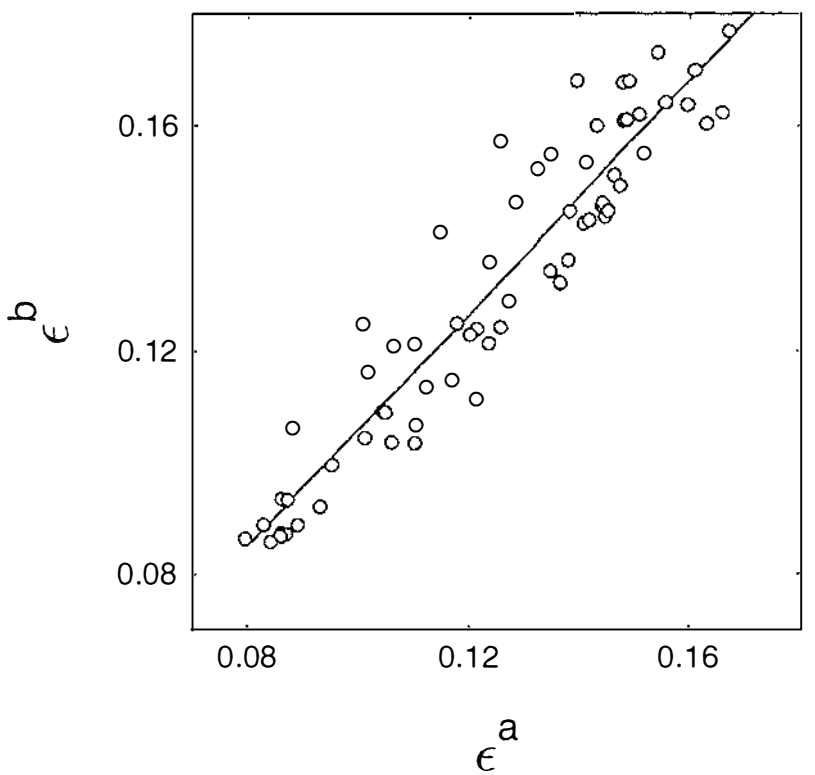


Fig 4-3. The relationship between porosity estimated by method b (ϵ^b) and porosity estimated by method a (ϵ^a) for sections of 'Braeburn' apple slices cut as shown in Fig. 4-1 (ϵ^b=0.0012+1.044 $\times\epsilon^a$, r^2= 0.91; where the standard errors for the intercept and the slope were 0.00535 and 0.0413, respectively).

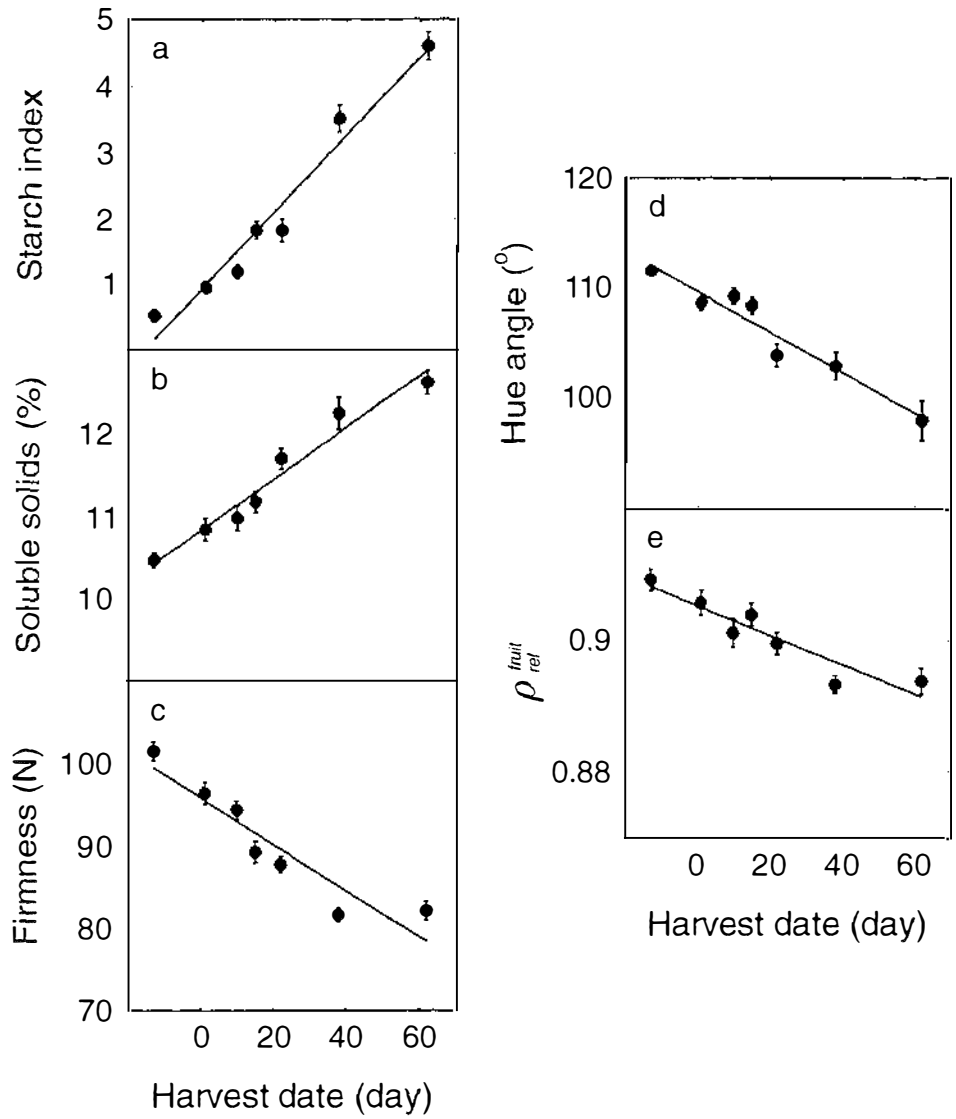


Fig. 4-4 Changes in a) starch index (SI=0.936+0.058×HD, r^2= 0.96); b) soluble solids (SS=10.84+0.031×HD, r^2= 0.96); c) firmness (*f* =95.83-0.281×HD, r^2= 0.88); d) background colour (BC=109.59-0.184 ×HD, r^2= 0.94); and e) whole fruit relative density (ρ_{rel}^{fruit}=0.905- 0.0002×HD,r^2= 0.87) with time of harvest (HD) relative to the commercial opening date (where harvest date is the number of days before or after the commercial opening date (March 28)). Vertical bars indicate standard errors of means.

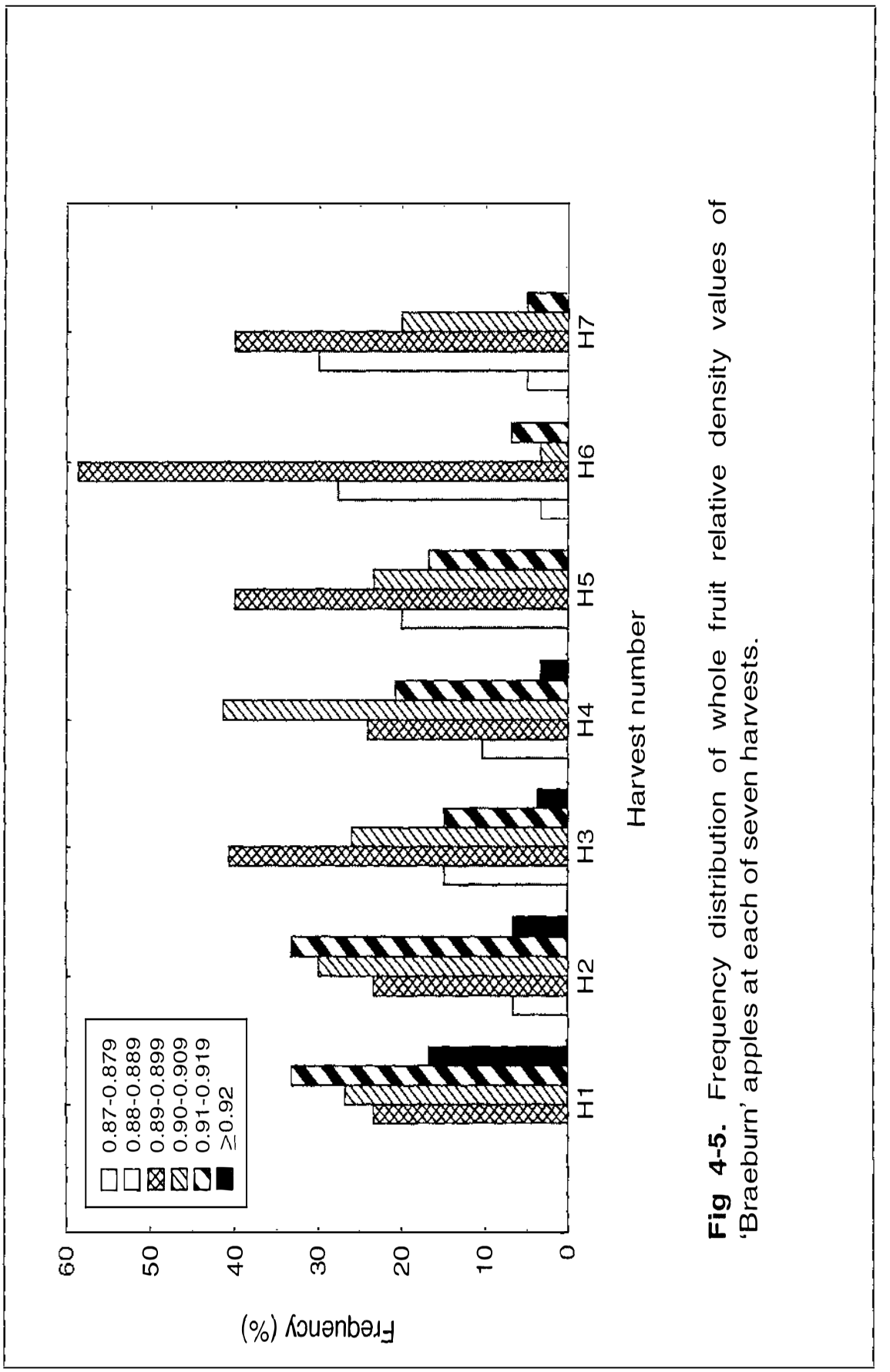


Fig 4-5. Frequency distribution of whole fruit relative density values of 'Braeburn' apples at each of seven harvests.

matched by $\Delta\rho_{rel}^{slice}$ increasing linearly with harvest date (Fig. 4-6a; $P < 0.01$).

4.3.4 Relationship between whole fruit relative density and degree of infiltration

Whole fruit density was related to degree of infiltration as measured by $\Delta\rho_{rel}^{slice}$ in a linear manner (Fig. 4-6b; $P < 0.001$). Fruit with a ρ_{rel}^{fruit} of 0.9091 had a $\Delta\rho_{rel}^{slice}$ of 0.0616, whereas fruit with a ρ_{rel}^{fruit} of 0.8938 had a $\Delta\rho_{rel}^{slice}$ of 0.1022. These data illustrate that slices from fruit with high relative density were more difficult to infiltrate.

4.3.5 Storage conditions

Storage temperature had a large effect on the subsequent level of infiltration achieved in fruit (Fig. 4-7). In fruit stored at 20 °C there was a strong linear relationship between storage time and $\Delta\rho_{rel}^{slice}$ ($P < 0.0001$). Degree of infiltration in fruit stored at 20 °C increased by 94 % of the initial value over the storage period (14 days), whereas fruit stored at 0 °C showed only a slight increase.

Fruit stored at 20 °C under low RH conditions lost 80 % more weight than those stored under high RH conditions (Table 4-2). Despite the relative differences in weight loss between the two RH regimes the effect on $\Delta\rho_{rel}^{slice}$ was negligible (Fig. 4-7). Regression analysis of the 20 °C data showed that a common line would fit the data almost as well as two separate lines.

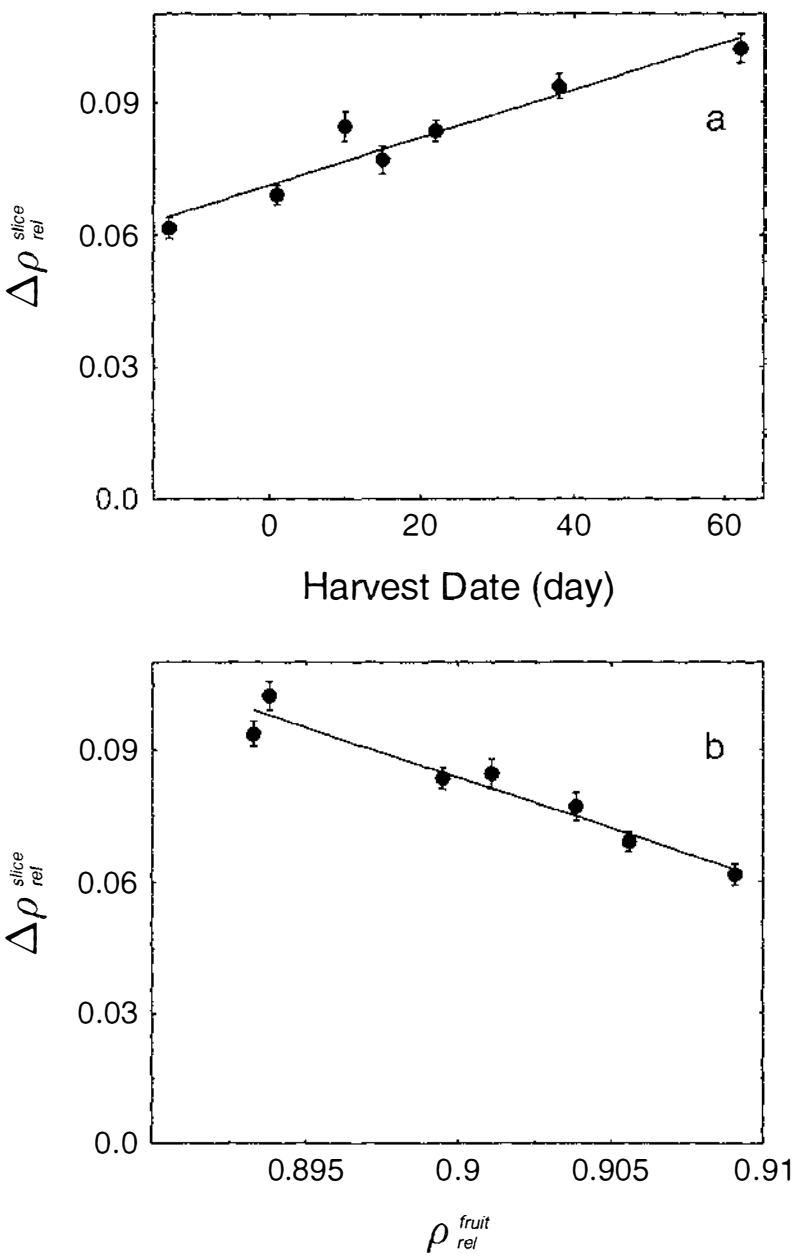


Fig 4-6. a) Changes in $\Delta\rho_{rel}^{slice}$ of slices of 'Braeburn' apples with time of harvest (HD) relative to opening date of the commercial harvest in 1995 (March 28; $\Delta\rho_{rel}^{slice}$ = 0.071 +0.00054×HD, r^2= 0.92; where the standard errors for the intercept and slope are 0.0021 and 0.000071, respectively); b) The relationship between $\Delta\rho_{rel}^{slice}$ and whole fruit relative density (ρ_{rel}^{fruit} ; $\Delta\rho_{rel}^{slice}$ = 2.14 - 2.28× ρ_{rel}^{fruit} , r^2= 0.94; where the standard errors for the intercept and slope are 0.004 and 0.261, respectively). Vertical bars indicate standard errors of means.

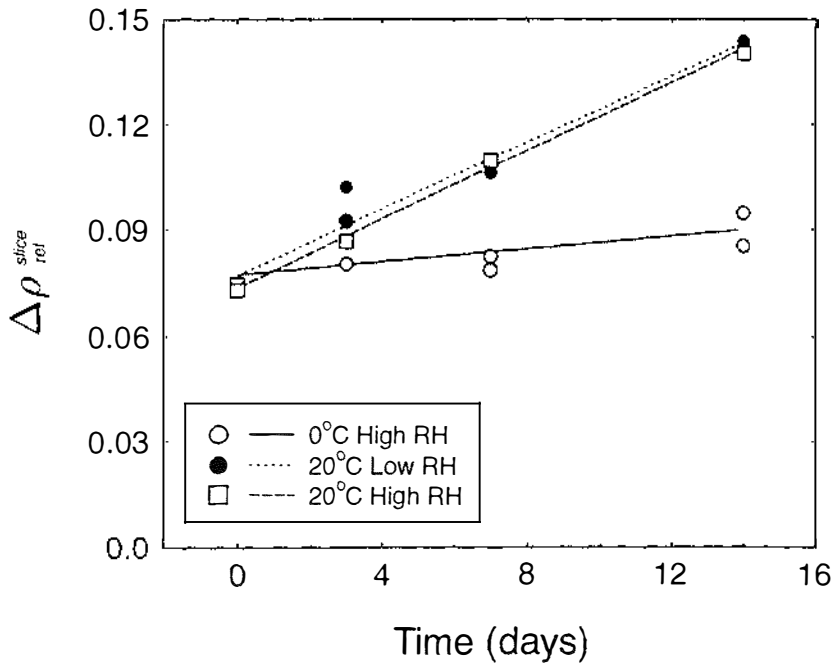


Fig 4-7 Changes in $\Delta\rho_{rel}^{slice}$ of 'Braeburn' apples associated with storage temperature and relative humidity during a 14 day storage period, which began after 2 months storage at 0°C. Evaluation at time 0 is shown as an open square.

Table 4-2. Effect of storage temperature and RH on water loss in 'Braeburn ' apples.

Treatment	Time (days)	Weight loss (g/100g)	SE
0 °C High RH	3	0.28	0.018
	7	0.34	0.024
	14	0.48	0.030
20 °C Low RH	3	0.68	0.046
	7	1.60	0.107
	14	2.92	0.163
20 °C High RH	3	0.56	0.037
	7	0.86	0.055
	14	1.62	0.074

4.3.6 Modification of the vacuum infiltration sequence

4.3.6.1 Vacuum level and time

Sub-optimal vacuum levels were detrimental to liquid impregnation. Lowering the vacuum level from 6 to 54 kPa (absolute pressure) resulted in an 84 % decrease in liquid uptake. The relationship between $\Delta\rho_{rel}^{slice}$ and vacuum time was well described using the following asymptotic function (Fig. 4-8):

$$\Delta p_{rel}^{slice} = c \times (1 - e^{(d \times t)}) \qquad \textbf{(4-8)}$$

The fitted values for the parameters c and d, and their standard errors are shown in Fig. 4-8. During the initial phase of the curve $\Delta\rho_{rel}^{slice}$ increased steeply with vacuum time. An estimate of optimum vacuum time was obtained by calculating the time required to reach 90 % of maximum infiltration using Eq. 4-8. The optimum vacuum time for the 1994 data set was 5 min 43 s. In 1995, the optimum vacuum time was 1 min 56 s and 1 min 59 s for the water and weak sucrose solutions,

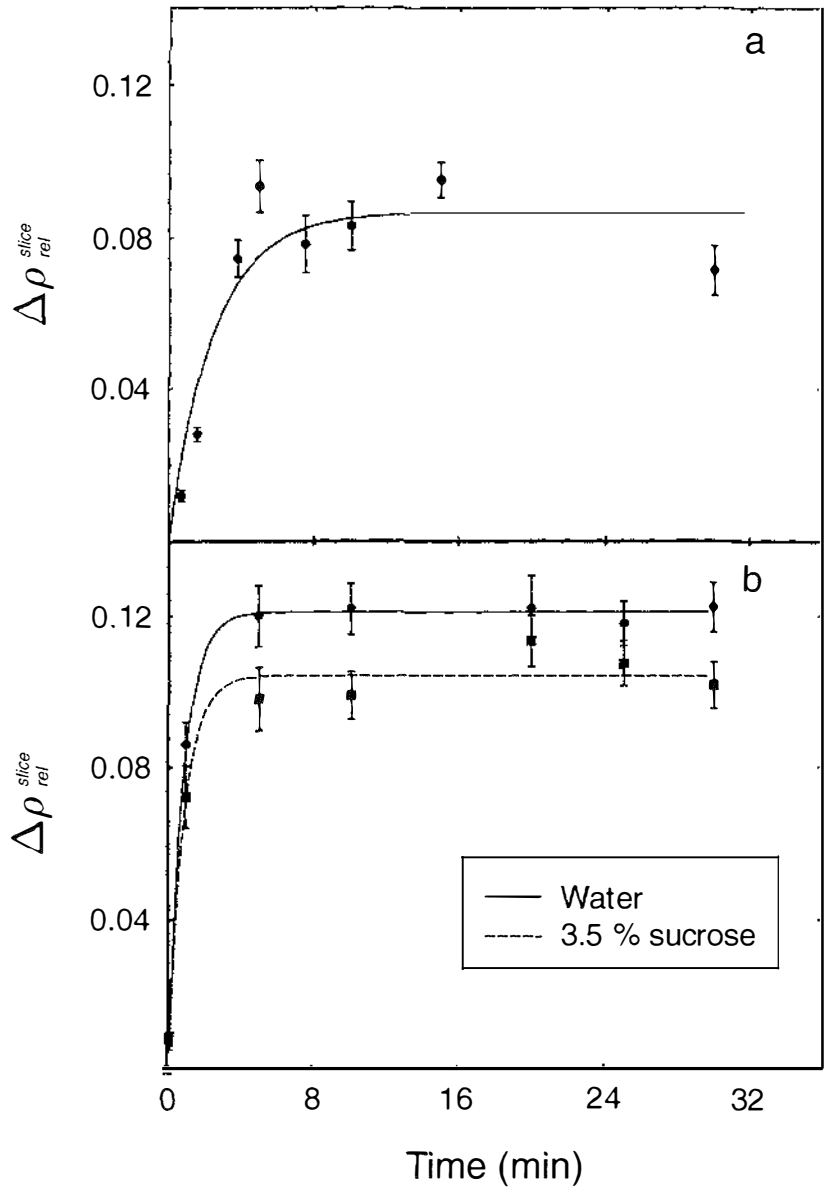


Fig 4-8. Effect of vacuum time on $\Delta\rho_{rel}^{slice}$ of a) 1994 and b) 1995 'Braeburn' apple slices. The fitted curves show the lines of best fit obtained by non-linear regression. $\Delta\rho_{rel}^{slice}$ was calculated using Eq. 4-6. Fitted values for the parameters were: Fig 4-8a: c=0.0868±0.0072; d =-0.4023±0.1297; Fig 4-8b c=0.1210±0.0014; d =-1.1881±0.860 (water); c=0.1039±0.0024; d= -1.1547±0.1671(3.5% sucrose solution). Vertical bars indicate standard errors of means.

respectively.

4.3.6.2 Absorption time and release speed

Degree of infiltration was enhanced at longer absorption times (Fig. 4-9). The relationship between absorption time and $\Delta\rho_{rel}^{slice}$ was well described using the Michaelis Menten function (Fig. 4-9; Table 4-3):

$$\Delta\rho_{rel}^{slice} = g + \frac{(h \times t)}{(i + t)} \qquad \textbf{(4-9)}$$

Infiltration initially increased steeply with absorption time but, as absorption time was increased further, the gains in infiltration were less substantial. Adding in the time taken to release the vacuum to estimates of absorption time evened out differences between release speed treatments (Fig. 4-10; Table 4-3). Fig. 4-11 illustrates the effects of different apertures on the speed of release of vacuum in the chamber.

Table 4-3. Parameters and their standard errors for the curves fitted in Fig. 4-9 and 4-10 using Eq. 4-9.

Year	Release time (s)	$g \pm$ SE	$h \pm$ SE	$i \pm$ SE
1994	19	0.0451 ± 0.0031	0.1137 ± 0.0062	5.95 ± 1.20
1995	2	0.0367 ± 0.0044	0.1073 ± 0.0059	2.95 ± 0.64
	25	0.0557 ± 0.0064	0.0849 ± 0.0076	1.71 ± 0.58
	60	0.0479 ± 0.0044	0.1016 ± 0.0057	2.59 ± 0.57
	Combined fit[x]	0.0342 ± 0.0070	0.1129 ± 0.0070	2.56 ± 0.62

[x] non-linear regression taking into account vacuum release speed

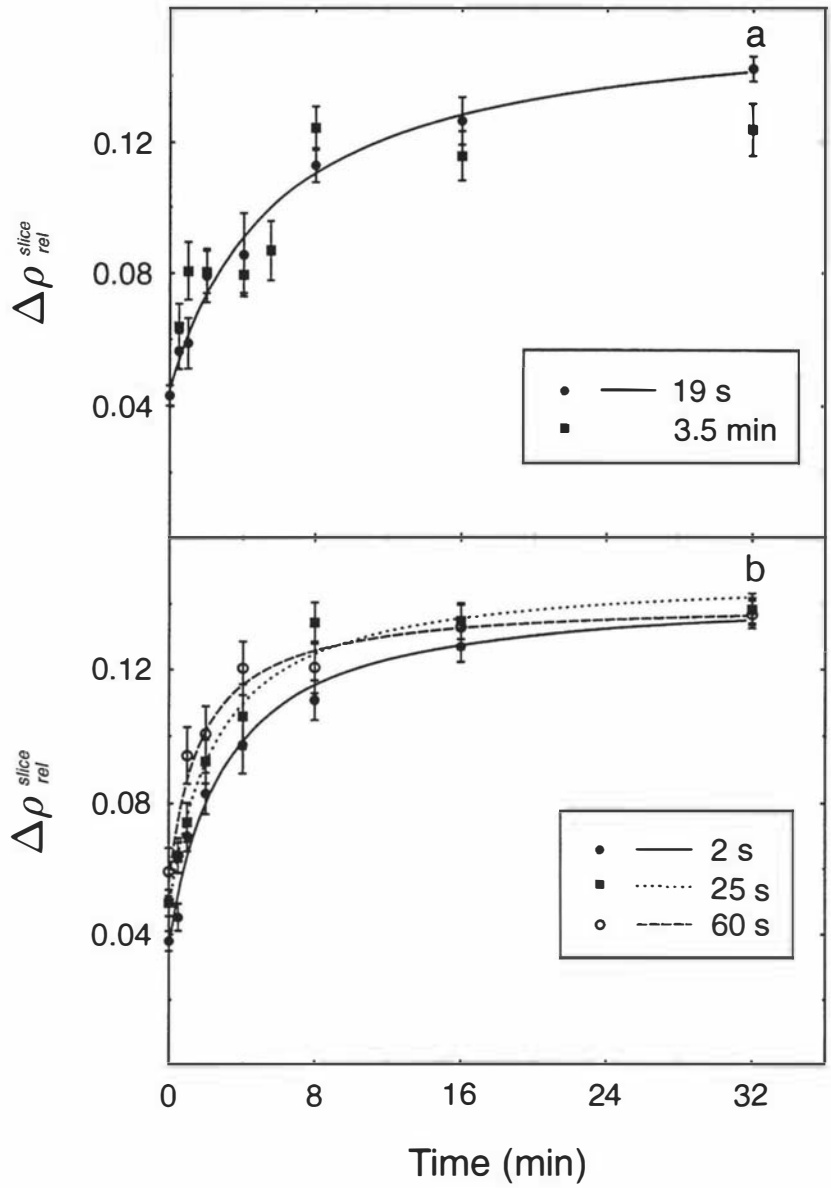


Fig 4-9. Effect of absorption time, excluding release time, on $\Delta\rho_{rel}^{slice}$ of a) 1994 and b) 1995 'Braeburn' apple slices at a series of different vacuum release speeds. The fitted curves show the lines of best fit obtained by non-linear regression using the equation: $\Delta\rho_{rel}^{slice} = g + (h \times t)/(i + t)$. Fitted values for the parameters are shown in Table 4-3. Vertical bars indicate standard errors of means.

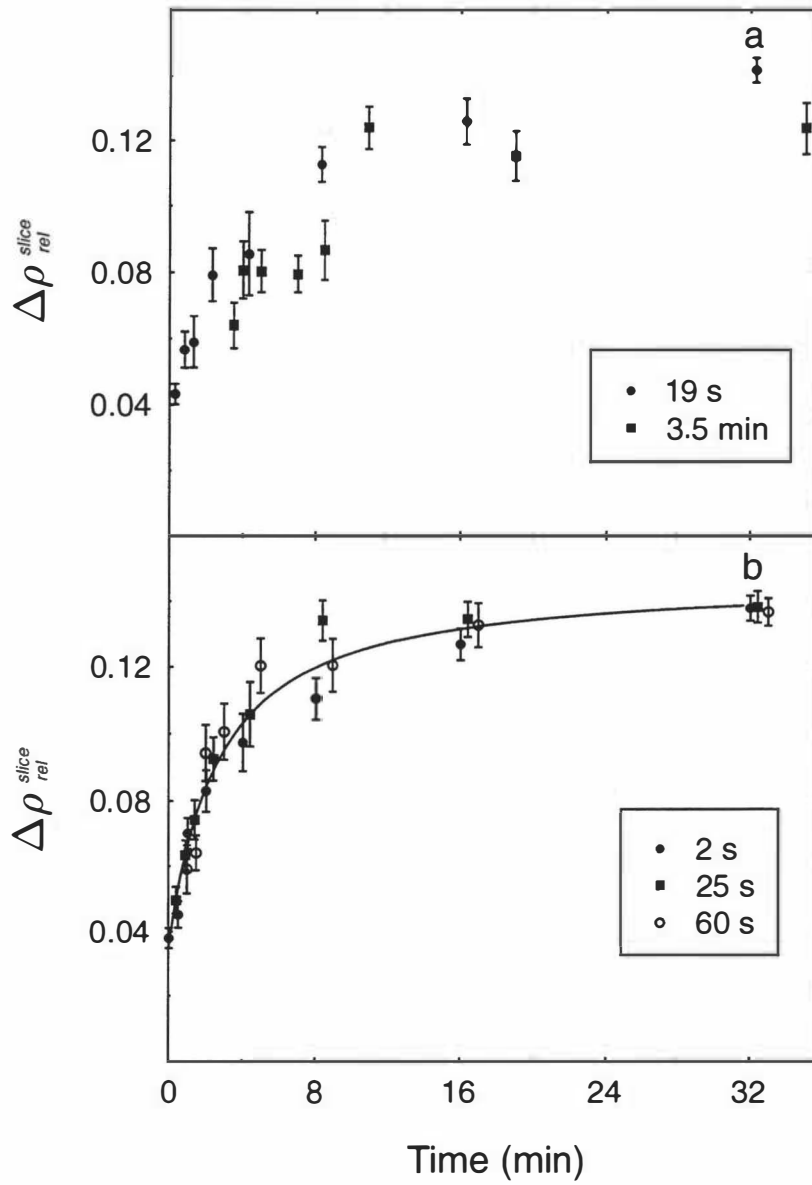
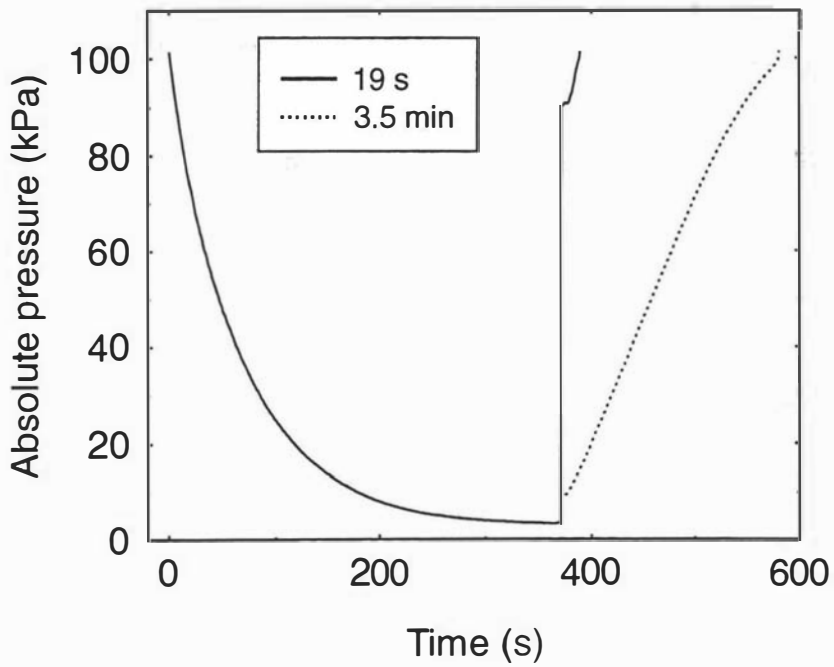


Fig 4-10. Effect of absorption time, including release time, on $\Delta\rho_{rel}^{slice}$ of a) 1994 and b) 1995 on solution uptake by 'Braeburn' apple slices. The fitted curve is the line of best fit obtained by non-linear regression using the equation: $\Delta\rho_{rel}^{slice} = g+(h\times t)/(i+t)$. Fitted values for the parameters are shown in Table 4-3. Vertical bars indicate standard errors of means.



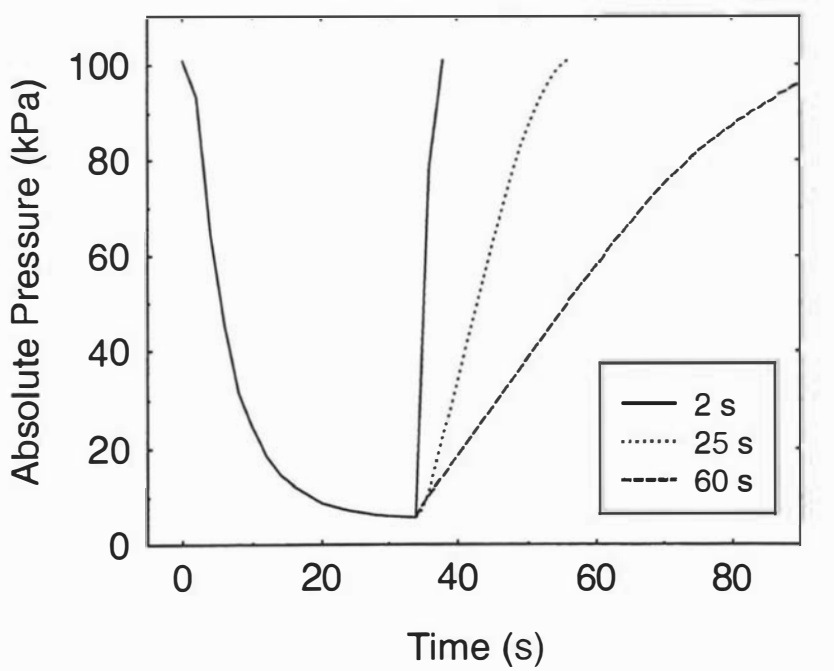


Fig 4-11 Effects of vacuum release speed on changes in pressure within the vaccum infiltration chamber

4.3.7 Modification of the infiltration solution

4.3.7.1 1994 Season

Increasing the temperature of the infiltrating solution from 15 to 50 °C resulted in a 52 % increase in the degree of infiltration (Table 4-4; $P < 0.0001$). At 50 °C, 70 % of the slices were fully infiltrated compared with 6.2 % at 15 °C. Lowering pH of the infiltrating solution from 7 to 3 enhanced solution uptake ($P < 0.01$). Using water in preference to a weak sucrose solution also resulted in a higher degree of infiltration ($P < 0.002$). Infiltrating with a weak sucrose solution with an osmotic potential of -.25 MPa resulted in 28.8 % of the slices being fully infiltrated compared with 47.5 % for those infiltrated with water. The effects of pH and osmotic potential however were less substantial than temperature. There were no significant interactions between temperature, pH and/or osmotic potential.

Table 4-4. Effect of the composition and temperature of the infiltrating solution on $\Delta\rho_{rel}^{slice}$ and the percentage of fully infiltrated slices in 'Braeburn' apples.

Treatment		$\Delta\rho_{rel}^{slice}$	SED	% Fully infiltrated
A	15 °C	0.0810	0.00355	6.3
B	50 °C	0.1233		70
C	Water (Osm 0)	0.1110	0.00355	47.5
D	Sucrose (Osm -0.25)	0.0932		28.8
E	pH 3	0.1089	0.00355	45
F	pH 7	0.0954		31.3

4.3.7.2 1995 Season

Solution temperature enhanced liquid uptake with slices infiltrated with a 50 °C solution taking up 49 % more than those infiltrated with a 5 °C solution. The relationship between $\Delta\rho_{rel}^{slice}$ and solution temperature (T) was well described using the quadratic function (Fig. 4-12):

$$\Delta\rho_{rel}^{slice} = j + k \times T + l \times T^2 \qquad \textbf{(4-10)}$$

with the exception of the data obtained at 20 °C.

4.3.8 Relationship between degree of infiltration and product texture

Varying absorption time was an effective way of obtaining slices with different levels of infiltration (Fig. 4-13). Slice texture also varied with degree of infiltration. Initially slicefirmnessincreased dramatically as absorption time was increased. Slices with an absorption time of 1 min were 68 % firmer than those that did not receive such a soak treatment. Absorption treatments longer than 8 min did not enhance slice texture, and there was some evidence to suggest that longer absorption times were detrimental to slice texture (Fig. 4-13). Longer absorption times also increased the amount of free juice in the can (Table 4-5).

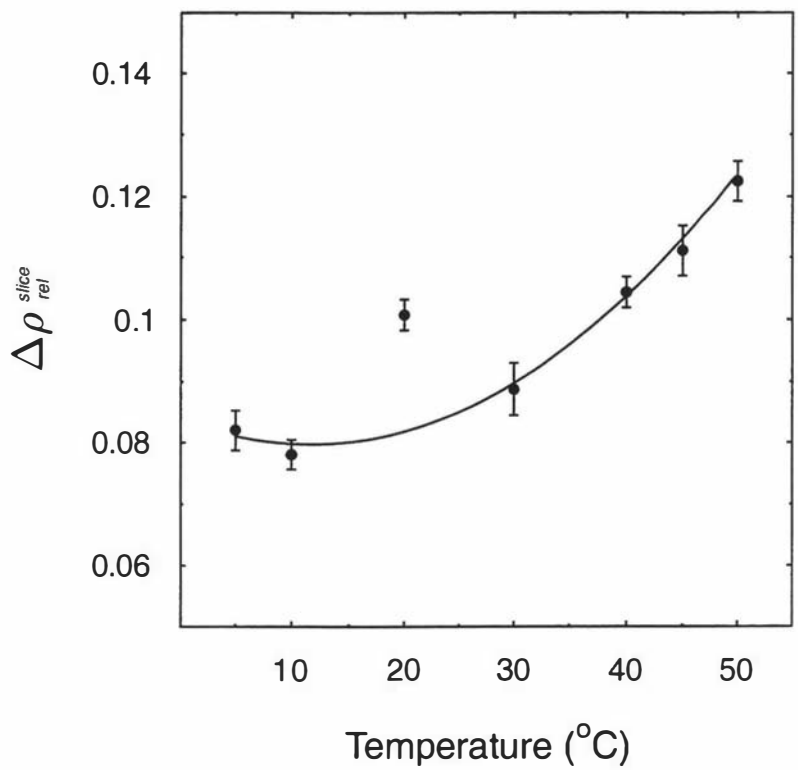


Fig 4-12. Effect of solution temperature on $\Delta\rho_{rel}^{slice}$ The fitted curve shows the line of best fit obtained by non-linear regression using the equation: $\Delta\rho_{rel}^{slice}=j+k\times T+ l\times T^2$. Fitted values for the parameters were: j=0.0836±0.0018; k=0.0007±0.0002; l=0.00003±0.000003. Vertical bars indicate standard errors of means.

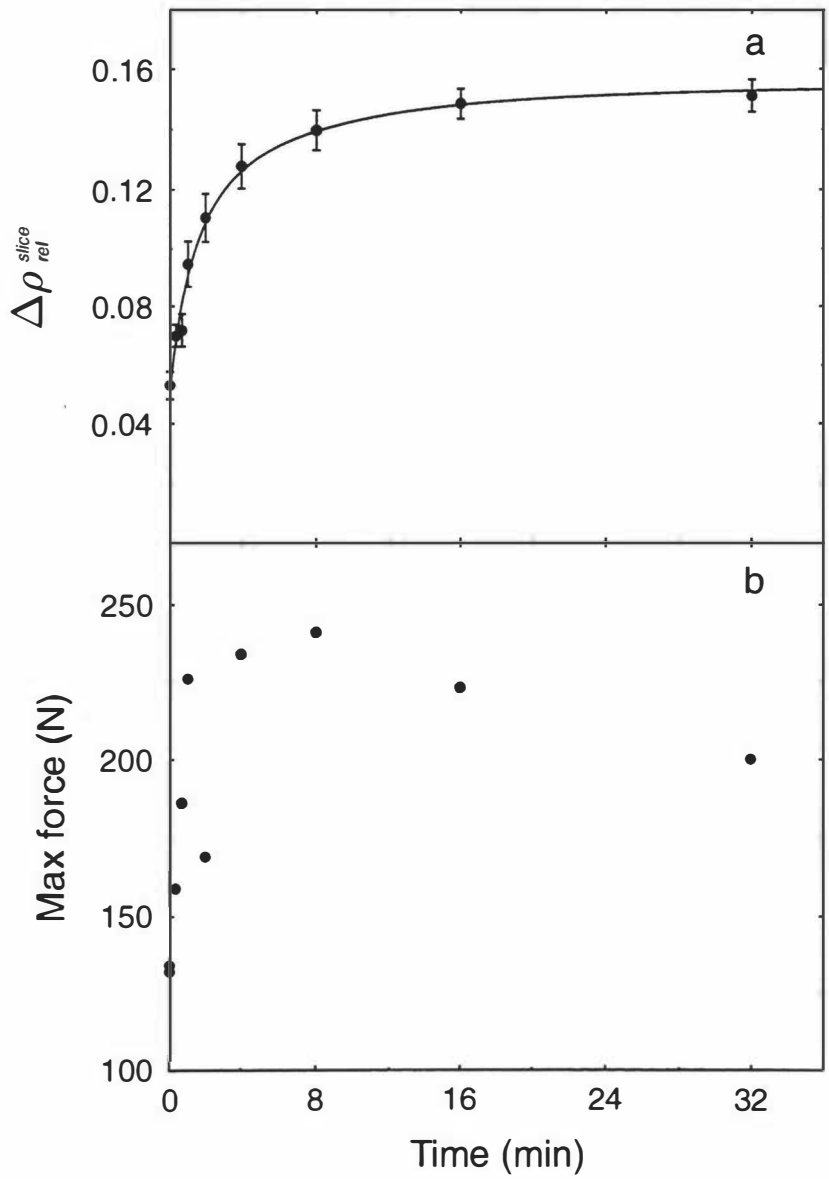


Fig 4-13. Effect of absorption time on a) $\Delta\rho_{rel}^{slice}$ and b) slice texture of 'Braeburn' apple slices as measured by Kramer shear. The fitted curve shows the line of best fit obtained by non-linear regression using Eq. 4-9. Fitted values for the parameters were: g=0.0514±0.0038; h =0.1067±0.0045; i=1.7183±0.287. Vertical bars indicate standard errors of means.

Table 4-5. The effect of absorption time on canned slice drained weight, juice volume and soluble solids.

Absorption time (min)	Drained weight (g)	Juice volume (ml)	Soluble solids (%)
no vacuum treatment	622	0.3	-
0	685	3.6	8.8
0.33	705	-	-
0.66	710	3	9.6
1	680	16	11.7
2	684	19	9.6
4	677	31	9.1
8	704	11	9.4
16	670	34	9.6
32	676	24	8.3

4.3.9 Comparing DOI with $\Delta\rho_{rel}^{slice}$

ε calculated using the two methods outlined in 4.2.5 produced similar results, hence only method b was used to calculate DOI. To ascertain whether or not DOI provided a better measure of ease of infiltration, the 1995 vacuum time data (Fig. 4-8) were reanalysed using DOI (Fig. 4-14). Comparing Figs. 4-8 and 4-14 reveals that DOI followed a similar pattern to $\Delta\rho_{rel}^{slice}$. Fig. 4-14b shows that DOI and $\Delta\rho_{rel}^{slice}$ were linearly related with 99.9 % of the variation in DOI being accounted for by $\Delta\rho_{rel}^{slice}$.

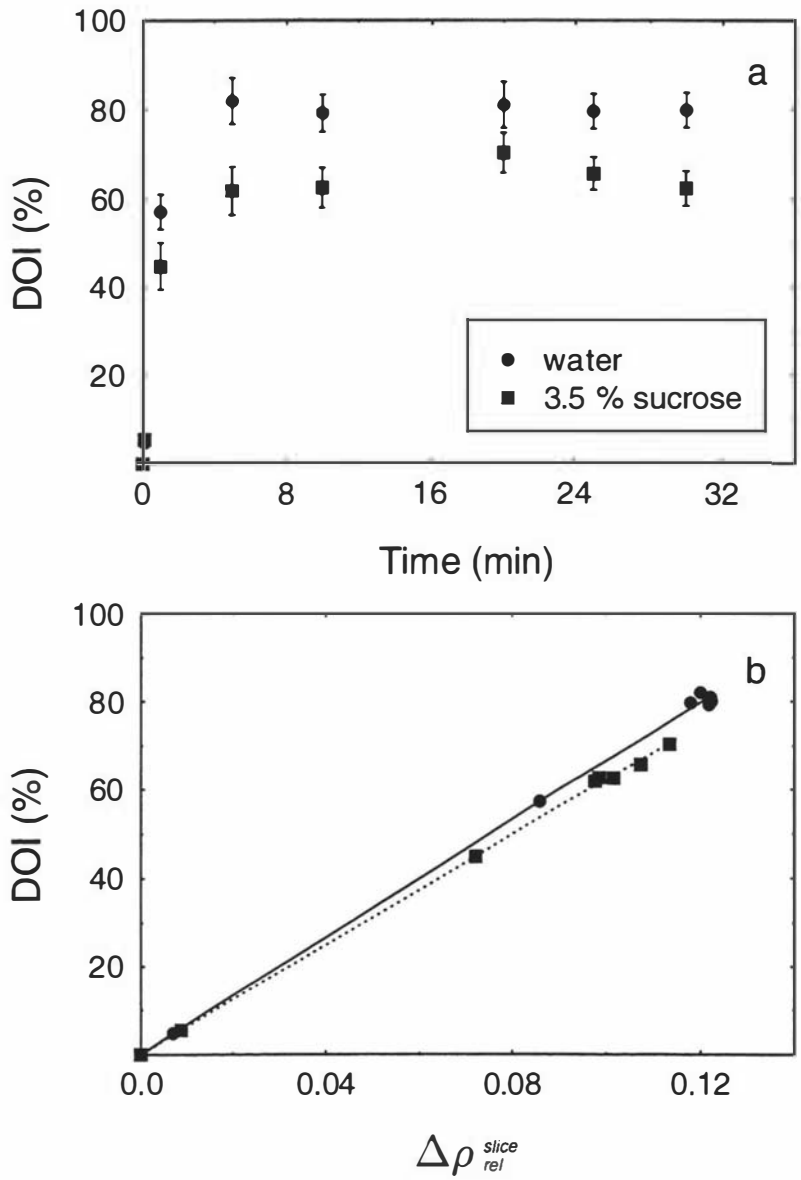


Fig 4-14. a) Effect of vacuum time on DOI of 'Braeburn' apple slices. b) Relationship between DOI and $\Delta\rho_{rel}^{slice}$ for 'Braeburn' apple slices infiltrated with water (DOI = 0.05 + 664× $\Delta\rho_{rel}^{slice}$, r^2= 0.999; where the standard errors for the intercept and slope are 0.981 and 9.8, respectively) or a weak sucrose solution (3.5 %) (DOI = 0.04 + 622× $\Delta\rho_{rel}^{slice}$, r^2= 0.999; where the standard errors for the intercept and slope are 0.63 and 7.3, respectively). Vertical bars indicate standard errors of means.

4.4 Discussion

4.4.1 Developing a method for estimating degree of infiltration

4.4.1.1 Estimating tissue porosity from $\rho_{rel,\,init}^{slice}$

In this study, there was good agreement between the two estimates of tissue porosity, when a ρ_{rel}^{juice} of 1.040 was used to calculate ε^b (Fig. 4-3). Each of these methods for estimating ε from $\rho_{rel,\,init}^{slice}$ can incur several errors. Estimating ε using the regression approach (Method a) can result in significant errors due to the spread in data about the fitted line (wide prediction interval). In this work there were also concerns relating to fitted intercept value. From a theoretical perspective, a value of 1 would be expected, as porosity should be 1 when $\rho_{rel,\,init}^{slice}$ is 0. This disagreement between actual and predicted intercepts may be due to: a) the limited range of x values, resulting in the need to extrapolate back a long way to obtain the intercept and/or b) the inclusion of some samples that were not quite fully infiltrated. Potential errors associated with Method b relate mainly to the assumed value used for the relative density of the juice. Hatfield and Knee (1988) reported that a change of 10 $mg.g^{-1}$ in apple juice sugar content would cause a change of 0.004 in ρ_{rel}^{juice}. In a fruit with a ε of 0.2 this would translate into a 1.5 % error in the estimate of ε.

4.4.1.2 DOI vs $\Delta\rho_{rel}^{slice}$

DOI and $\Delta\rho_{rel}^{slice}$ were closely correlated, and produced very similar results when used to assess level of infiltration (Fig. 4-14). The major advantage of DOI over $\Delta\rho_{rel}^{slice}$ is that it would distinguish between wholly infiltrated samples with a low air space volume and partially infiltrated samples with a large air space volume. However with the close correlation between these two variables (and the results from the harvest date experiment; Figs. 4-3; 4-6b), it would appear that less dense tissue

infiltrates more readily, and hence this is unlikely to be a problem.

4.4.2 ρ_{rel}^{fruit} as a predictor for ease of infiltration

$\Delta\rho_{rel}^{slice}$ was linearly related to ρ_{rel}^{fruit}, with 94 % of the variation in $\Delta\rho_{rel}^{slice}$ being accounted for by ρ_{rel}^{fruit} (Fig. 4-6b). This suggests that ρ_{rel}^{fruit} may be a useful measure for predicting ease of infiltration. More dense fruit were clearly more difficult to infiltrate. The concept of using ρ_{rel}^{fruit} for grading fruit destined for processing is not new. Shaw (1974) looked at whether or not segregating apples according to ρ_{rel}^{fruit} would result in enhanced apple sauce quality. The study found that some improvements in sauce quality could be obtained by using the least dense fruit from the earlier harvests and the more dense fruit from the later harvests.

If ρ_{rel}^{fruit} could accurately predict the ease of infiltration for a batch of fruit, this would create the possibility for processors to grade fruit according to ρ_{rel}^{fruit} and develop a series of vacuum infiltration sequences based on the level of ρ_{rel}^{fruit}. This would presumably rely on segregation of the fruit population on the basis of their ability to float on solutions of different relative densities. The operational complexity of such an approach would be likely to limit application of this possibility, although Cavalieri *et al.* (1996) utilised this principle successfully to separate fruit with watercore from fruit without.

4.4.3 Harvest date

Harvest date had a large effect on ease of infiltration, with fruit from later harvests infiltrating more readily than those from earlier harvests. Fruit harvested later in the season are less dense and have correspondingly larger intercellular air space volumes (Figs. 4-4 and 4-6; Shaw, 1974; Blanpied, 1965; Westwood, 1962; Westwood *et al.*, 1967). Cell separation during growth and development leads to an increase in air space volume in apples (Knee, 1993; Khan and Vincent, 1990). In apple, air spaces

tend to form radial 'canals' through the cortex (Khan and Vincent, 1990). As the fruit matures these 'canals' increase in volume, resulting in a more open, porous structure. The observed increase in $\Delta\rho_{rel}^{slice}$ during the harvest period in the current study was most likely due to: 1) an increase in total intercellular air space volume and 2) enhanced infiltration due to a more porous open structure.

4.4.4 Storage temperature

Higher storage temperatures (20 °C) also enhanced infiltration (Fig. 4-7). $\Delta\rho_{rel}^{slice}$ increased linearly with storage duration for fruit stored at 20 °C. This increase in $\Delta\rho_{rel}^{slice}$ would have been largely due to changes associated with ripening, which would lead to an increase in the total volume of intercellular air space and also enhance communication between intercellular air spaces (Knee,1993). This more open porous structure would result in slices infiltrating more readily. Conversely, storage RH had a minimal effect on ease of infiltration. This contrasts with Hatfield and Knee's (1988) work in which they found that fruit stored under high RH developed a larger internal air space volume compared to fruit which had been subjected to an initial weight loss regime. The lack of differentiation between the RH treatments used in this study may have been due to:

1) the length of storage period - Hatfield and Knee's work was carried out over a longer storage period (6 months) at 0 °C, whereas this study was carried out over a 2 week period at 20 °C;

2) the level of weight loss achieved - Hatfield and Knee induced a greater weight loss (5-6 %) than was achieved in low RH treatment in this work (2.9%);

3) the changes associated with ripening brought about by storage at 20 °C may have overshadowed any differences due to RH;

4) the difference in cultivars - 'Cox's Orange Pippin' is an early season apple that softens substantially (large loss in terms of absolute firmness) and rapidly (high softening rate) compared to 'Braeburn', a late season variety that (under standard cool-storage conditions) would be considered moderate in terms of absolute firmness loss and softening rate (Harker, personal communication, 1997).

Thus, the most practical measure to improve levels of infiltration would be to allow a period at 20 °C to allow ripening to occur before processing was started. This effect would be expected to be enhanced by increased RH and possibly also by ethylene treatment to stimulate the onset of ripening. In addition, the processing sequence itself could be modified to improve level of infiltration.

4.4.5 Enhancing infiltration in difficult-to-infiltrate fruit

4.4.5.1 Modification of the vacuum infiltration sequence

Infiltration initially increased steeply with vacuum time (Fig. 4-8). The slopes of the fitted curves for the 1995 data were greater due to the faster pull down time achieved in the smaller chamber (30 s compared with 3.5 min). Sub-optimal levels of vacuum were particularly detrimental to liquid uptake. Other workers (Heil *et al.*, 1988; Hoover and Miller, 1975; Fito, 1994; Fito and Pastor, 1994) have also found that operating the system under maximum vacuum is important to achieve efficient infiltration. Fito and Pastor (1994) modelled vacuum infiltration in 'Granny Smith' apples (refer 2.5.4.1). They found that as the apparent compression ratio (R; Eq. 4-11) decreased, liquid uptake also decreased. In other words, the volume of liquid taken up by the tissue decreases as the driving force is reduced.

$$R = \frac{p_{atm}}{p_{vac}} \qquad \textbf{(4-11)}$$

where p_{vac} is pressure during vacuum treatment and p_{atm} is atmospheric pressure.

An exponential function (Eq. 4-8) fitted the data well and enabled vacuum times required for 90 % of maximum infiltration ($t_{0.9}$) to be estimated. Selection of a 90 % level of infiltration was arbitrary, but due to the shape of the function is likely to represent an economically feasible time, since increases in vacuum time beyond this point resulted in relatively small changes in $\Delta\rho_{rel}^{slice}$. $t_{0.9}$ was substantially lower in 1995 due to the faster pull down time of the smaller chamber (Fig. 4-8). Optimum

vacuum times were an order of magnitude lower than optimum absorption times. This was presumably a reflection of the differing viscosities of the fluids (internal atmosphere and infiltration solution) involved in the two phases. The small increase in uptake upon reaching maximum vacuum was probably due to enhanced capillarity at lower pressures (Fig. 2-9). Diffusion (which has a larger interphase surface due to enhanced capillarity under vacuum) may also partially account for a small increase in liquid uptake during this period.

The duration of the hold time after release of the vacuum appeared to be the most critical phase of the vacuum infiltration sequence. Longer absorption times enhanced liquid uptake (Fig. 4-9), suggesting that the re-establishment of pressure equilibrium within the tissue took some time. Diffusion of the infiltration solution into the intercellular spaces would have been the main process occurring during this phase. Longer absorption times may have resulted in cells taking up water, providing an alternative mechanism for achieving equilibration of pressure in inaccessible intercellular spaces. Diffusion would continue until the system reached a new equilibrium. Gradual resolubilisation of gases over time may also create a vacuum, drawing more solution into the tissue. Exceedingly long absorption times would be unlikely to provide benefit from an economic perspective. This is due to the shape of the Michaelis Menten function fitted to this data (Fig. 4-9), whereby initially $\Delta\rho_{rel}^{slice}$ increased steeply with absorption time, before starting to flatten off, resulting in less substantial gains in $\Delta\rho_{rel}^{slice}$.

It would appear that increasing the time over which the vacuum was released could be explained by the resulting increase in absorption time. In other words, the effect of speed of vacuum release could be explained in terms of the corresponding lengthening or shortening of the absorption time.

4.4.5.2 Modification of the infiltrating solution

Solution temperature had a dramatic effect on liquid uptake. The results from this study agree with those of Hoover and Miller (1975) who also found that solution uptake was enhanced when the temperature of the infiltrating solution was raised. In this study a wider range of solution temperatures (5-50 °C) was used to characterise the relationship between solution temperature and uptake. This relationship was found to be curvilinear (Fig. 4-12). This temperature effect may be due to a number of factors including:

1) differences in kinetic energy of the two solutions;

2) differences in viscosity of the two solutions. The viscosity of water varies considerably with temperature with the viscosity at 5 °C being 1.8 times that at 50 °C (Weast, 1977). Viscosity would appear to be a contributing factor to solution uptake, but, although the relative differences between the solutions were great, the absolute differences between the solutions were small, and so it is difficult to determine the relative importance of solution viscosity;

3) changes in permeability of the cell membranes caused by temperature;

4) possible loosening of cell wall - cell wall bonding, resulting in enhanced gas expulsion and solution uptake;

5) possible increases in pore wettability leading to enhanced diffusion of liquid into the intercellular spaces.

The boiling point or "flash point" of the liquid at a given vacuum is the major limiting factor in the utilization of a hot solution for increasing the penetration of the liquid into the slices (Hoover and Miller, 1975; Heil *et al.*, 1988). Texture degradation would also be an important point to consider.

Lowering the pH of the infiltrating solution also had a significant effect on liquid uptake. Embolisms would be less likely to form in acidic solutions (Durkin *et al.*, 1991), and this would lead to more efficient infiltration of the apple slice.

Slices infiltrated more readily with water compared to a weak sucrose solution. This osmotic effect may be due to:

1) cells taking up water during the absorption phase, rounding off and partially pulling apart, resulting in a larger estimate of $\Delta\rho_{rel}^{slice}$;

2) the higher viscosity of the sucrose solution impeding uptake by the tissue. Other workers (Hoover and Miller, 1975; Gallander and Kretchman, 1976) also found that solutions with sucrose or fruit juice resulted in lower levels of solution uptake. Hoover and Miller (1975) attributed this to differences in solution viscosity. Although Hoover and Miller were dealing with solutions with considerably greater viscosities, this may still have been a contributing factor in the current work;

3) cells rupturing in water (Simon, 1977) which would have made all tissue volume accessible, whereas in a weak sucrose solution a proportion of cells would have remained undamaged and thus not all tissue volume would have been directly accessible.

4.4.6 Quantifying the influence of degree of infiltration on product texture

In this experiment, the overall firmness of the slices was somewhat softer than those produced in other experiments described in this thesis, probably because of the exclusion of calcium from the infiltrating solution. Wiley and Lee (1970) demonstrated the importance of calcium in enhancing processed slice firmness. In this experiment it was necessary to exclude calcium due to the manner in which absorption time was used to obtain slices with different levels of infiltration. If calcium had been included in the solution the effects of absorption time and slice calcium concentration on slice texture could not have been differentiated .

Slice texture was affected by the level of infiltration achieved (Fig. 4-13). Slices not given a vacuum treatment produced soft, soggy slices as did those receiving either none or a minimal absorption period. $\Delta\rho_{rel}^{slice}$ values in these slices were also low suggesting that they still contained substantial quantities of gas. Air remaining in

slices after evacuation may cause considerable texture degradation due to thermal expansion occurring during the blanching and cooking phases of the operation (MacGregor and Kitson, 1981). In addition to this, slices in which the occluded gases were not completely removed could also take up liquid during storage, resulting in soggy and waterlogged slices. Data presented here are similar to those of Dougherty *et al.* (1966) who found that non-vacuum treated 'Golden Delicious' slices were 28 % softer than those experiencing a 1.5 min evacuation period. They also observed large amounts of sloughing in slices which had no vacuum treatment.

Slices subjected to an absorption time longer than eight minutes showed no improvement in firmness, and there was some suggestion of a negative trend, perhaps due to excessive tissue swelling and associated disruption of intercellular bonding. If calcium had been included in the infiltrating solution slice texture may well have improved with length of absorption time due to increased uptake of calcium.

4.4.7 Commercial implications

Effective and efficient removal of occluded gases from apple tissue and subsequent replacement with solution is necessary if high quality, consistent apple slices are to be produced. Failure to achieve complete or sufficient infiltration is a potential problem (Rahman and Perera, 1996), especially following cold growing seasons and with immature fruit (J. Wattie Foods, personal communication, 1993). Since the problem is largely experienced in immature or underdeveloped fruit, the problem may lie in the poor interconnectiveness of intercellular spaces in these fruit. Trakoontivakorn *et al.* (1988) found clear structural differences in terms of size and shape of intercellular spaces in mature and immature 'Granny Smith' and 'Red Delicious' apples. Soudain and Phan Phuc (1979) also reported considerable differences in intercellular air space volume (or porosity) for mature and immature apples. This study has optimised key components of the vacuum infiltration sequence and identified several potential techniques for enhancing infiltration in difficult-to-infiltrate fruit.

Much of this work has focused on the vacuum infiltration sequence, with the objective of optimising the various components (level of vacuum, vacuum time, vacuum release speed and absorption time). Vacuum level was an important consideration, with this and other studies (Fito, 1994; and Fito and Pastor, 1994) showing that as pressure was reduced, liquid uptake was increased. Sub-optimal vacuum levels were highly detrimental to liquid uptake. $t_{0.9}$ vacuum times were calculated using Eq. 4-8; with a rapid pull-down and an absorption time of 5 min, 90 % of maximum infiltration was achieved with a vacuum time of just under 2 min. In an analogous manner, $t_{0.75}$ absorption times were calculated using Eq. 4-9, which indicated that 75 % of maximal absorption was achieved in 6 min (calculated using 2 s release speed data). Application of these equations tailored to the specific conditions in the processing environment (ie. chamber specifications) would enable prediction of optimal vacuum and/or absorption times.

This work has clearly shown the potential for processors to use heated solutions to enhance infiltration in difficult-to-infiltrate slices (Table 4-4; Fig. 4-12). To ensure the process is industrially viable, processors would need to re-evaluate their solution management system in terms of microbial safety, and solution composition and recycling. An economic analysis of the system would also need to be carried out to determine whether or not further benefits could be gained in the vacuum infiltration of standard fruit by using a heated solution and shorter absorption time.

The results of this study have also demonstrated the potential to enhance infiltration by storing fruit for short periods of time at high temperatures (20 °C; Fig. 4-7). Enhancing ripening in this manner had a positive effect on slice infiltration, but this benefit would have to be offset by the potential risks associated with texture degradation at these temperatures.

Pre-grading fruit by ρ_{rel}^{fruit}, may prove to be an effective means of grouping fruit according to ease of infiltration. This would enable an appropriate vacuum infiltration sequence to be selected, and ensure greater consistency in product

infiltration. This could be achieved by separating fruit based on their ability to float on solutions of different relative densities, although as mentioned earlier this is likely to be difficult from an operations perspective.

In conclusion, to consistently achieve high levels of infiltration in apple slices requires: 1) an assessment of the pre-condition of the tissue; and 2) the implementation of an appropriately tailored vacuum infiltration sequence. Results from this study suggest that a vacuum sequence comprising a vacuum level of > 95 kPa (< 6 kPa absolute pressure), a vacuum time of 2 min and an absorption time of 6 min, would adequately infiltrate most fruit (using a chamber with a rapid pull-down time and release speed). However, to achieve complete infiltration in difficult-to-infiltrate fruit may require: 1) a pre-treatment such as a short period of storage at 20 °C and/or 2) some modification to the infiltration process such as use of a warm infiltrating solution or a longer absorption time.

Chapter 5

Variation in raw and processed apple texture associated with differences in cultivar and storage conditions

5.1 Introduction

Temperature management is an important factor in maintaining fruit quality of harvested fruits (refer 2.5.3.1 & 2.5.3.2). Exposure of fruits to undesirable temperatures can result in product deterioration due primarily to enhanced transpiration, respiration and other associated metabolic processes such as softening and yellowing, and increased pathogen activity. Coolstorage of fruits is therefore desirable for extending product life and maintaining fruit quality. However, coolstorage of fruits destined for processing is not always feasible due to the high cost and seasonal demand for coolstorage facilities.

Cultivars vary in their tolerance of ambient temperatures (refer 2.5.1). D'Souza and Ingle (1989) investigated the effects of delays into coolstorage on the poststorage flesh firmness of apples. They found that certain cultivars were more susceptible than others to softening if cooling was delayed. Information on cultivar tolerance to ambient storage temperatures would enable processors to more effectively utilise coolstorage facilities (i.e. giving priority for coolstorage to the most sensitive cultivars) and to schedule processing runs to ensure that fruit were not stored too long. Because of the wide diversity in cultivar performance it is important for there to be a good understanding of how the various cultivars withstand storage and processing. In New Zealand, apples are not grown specifically for processing, so the range of cultivars available to processors is largely determined by the fresh fruit export industry. 'Braeburn' and 'Fuji' are popular export cultivars and, as such,

supply of these cultivars to processors is on the increase. By contrast, 'Granny Smith' is in decline as an export cultivar, resulting in less apples of this cultivar being available for processing into apple slices. This reliance of the processing industry on 'reject' fruit from the export industry, necessitates the continued gathering of information on how cultivars respond to storage and processing. This study has concentrated on two 'up-and-coming' processing cultivars 'Braeburn' and 'Fuji', and assessed their processing potential. 'Granny Smith' was included in the 1993 experiment as it is still a major New Zealand processing apple, and is considered a 'benchmark' against which other apples are compared.

Apple textural quality may be described using an array of terms including firmness/softness, crispness, coarseness/fineness, juiciness/mealiness (Brennan *et al.*, 1977). Of these, firmness has perhaps received the most attention and is today the key textural attribute focused on by both the fresh fruit export industry and apple processors. Firmness may be viewed in terms of absolute flesh firmness, rate of softening, or variability in firmness. Each of these aspects of firmness is critical if a canned product of high and consistent quality is to be produced. Absolute firmness values are required to establish quality guidelines and standards for both raw apples going into the process and canned apple coming out of the plant. Knowledge of a cultivar's softening rate under a particular set of conditions is necessary for effective scheduling of processing and maintaining a consistent product line. Reducing apple-to-apple variability is important for reducing within-product variability.

This chapter describes two experiments designed to examine primarily the effects of storage temperature and storage duration on subsequent quality of raw and processed slices. In the first of these experiments, fruit from two cultivars were stored at 0, 10, or 20 °C and assessed at regular intervals throughout the storage period. Results from this study enabled comparison of suitability of these cultivars for processing and a determination of their potential storage life. The second study was designed to focus more on differences in rates of softening between cultivars, look at variability in softening rates and determine whether or not some treatments that extend

postharvest storage life may increase variability in processed product. These treatments included CMC (an edible surface coating) that may have some potential to reduce softening (see 2.5.3.3) as a result of its depressive effects on $p^i_{O_2}$, respiration and associated metabolic processes. CMC effects on $p^i_{O_2}$ can be variable and this in turn may enhance fruit-to-fruit variability in fresh and processed apple texture.

5.2 Materials and methods

5.2.1 1993 storage temperature experiment

5.2.1.1 Fruit supply

Commercially mature apples (*Malus domestica* Borkh.) of two cultivars, 'Granny Smith' and 'Braeburn' (100 count; approx. 0.185 kg average weight), were obtained during the mid-season harvest from 4 Hawkes Bay growers. 'Granny Smith' and 'Braeburn' fruit were held in air at 0 °C for approx. 2 days and 2 weeks, respectively, before application of treatments.

5.2.1.2 Experimental design

Cartons of fruit were randomly allocated to one of three storage regimes: 0, 10, or 20 °C. Perforated plastic bags were placed around trays of fruit. The relative humidity of the air surrounding the fruit was between 90 and 100 %. Samples of fruit from each storage temperature were assessed regularly for up to 20, 12 or 4 weeks for fruit stored at 0, 10 and 20 °C respectively. An entire tray of fruit was randomly sampled from each grower line at each assessment date, for each temperature, with up to 13 fruit being used in fresh fruit assessments and 7 for processing.

5.2.1.3 Assessment procedure

At each sampling period, raw fruit texture was assessed using the twist test (TMax, TBio), a drill-mounted penetrometer (DPen), the Instron operated penetrometer (IPen) and Kramer shear cell (FKra), as detailed in section 3.1.3. Fruit were equilibrated at 20 °C before assessment. Juice extracted from the drill-mounted penetrometer test was used to determine percentage soluble solids as described in section 3.1.4. Fruit were processed (refer 3.2), with the thermal process time being 22 min. Processed product assessments were carried out as detailed in section 3.3.

5.2.1.4 Data analysis

Separate analyses were carried out for each cultivar. Initially, a series of ANOVAs was performed (SAS, 1990), to examine differences between storage times, growers and, where appropriate (i.e. common storage time), temperature. Linear regression analysis was then performed using overall means to describe the relationship between firmness and storage duration, for each storage temperature. To investigate the relationship between the instrumental texture tests, a principal component analysis (PCA) was performed on the data (where the data set included results from both cultivars, across all storage assessments).

5.2.2 1994 Fruit softening behaviour experiment

5.2.2.1 Fruit supply

Commercially mature 'Fuji' and 'Braeburn' apples of count size 100 (approx. 0.185 kg average weight) were obtained from the mid-season harvest from a single Hawkes Bay grower. 'Braeburn' and 'Fuji' fruit were stored in air at 0 °C for approx. 1 and 2 weeks respectively, before the start of experiments.

5.2.2.2 Experimental design

The following treatments were applied:

1) Standard coolstorage: (0 °C, 90 % RH approx.)
2) Warm, low RH storage: (20 °C, 50 % RH approx.)
3) Warm, high RH storage: (20 °C, 100% RH approx.)
4) Surface coating and coolstorage: (2% CMC, 0 °C, 90% RH approx.)
5) Surface coating and warm, low RH storage: (2% CMC, 20 °C, 50 % RH approx.)

Cartons of fruit were randomly allocated to each storage regime, with trays and part trays being allocated to different storage periods. Each sample comprised 30 fruit. Samples of fruit were assessed regularly (every 1, 2, or 3 weeks) throughout storage for up to 21 weeks in the case of fruit stored at 0 °C (treatments 1 and 4).

5.2.2.3 Assessment procedure

An initial sample was assessed before the application of storage treatments. Fruit were removed from storage and allowed to equilibrate overnight at 20 °C, before textural measurements and processing. At each sampling time, raw fruit texture was measured using the twist tester (TMax, TBio) and drill-mounted penetrometer (DPen) as outlined in sections 3.1.3.1 and 3.1.3.2. Fruit soluble solids were also measured as detailed in section 3.1.4. Each fruit was then peeled and sliced into 8 wedges. Slices damaged by the twist test or penetrometer were discarded. The remaining slices from each apple were vacuum infiltrated with water (vacuum time: 10 min; absorption time: 5 min) in individual pottles. This was followed by water blanching at 99 °C, in a steam jacketed pan, for 5 minutes. On removal from the water, slices were cooled and left to equilibrate to room temperature. Blanched slice texture was then determined using the Kramer shear cell (BKra), as described in section 3.3.5.2.

5.2.2.4 Data analysis

To describe fruit softening behaviour, linear and non-linear regression analyses were performed (SAS, 1990). Where appropriate, linear regression lines were compared to establish whether either parallel lines or a common line, could be used to fit the data. A PCA was performed to investigate the relationships between the instrumental tests, and to determine whether or not the dimensionality of the data could be reduced. A stepwise multiple regression analysis was also performed to describe the relationship between blanched slice texture (BKra) and one or more fresh fruit measurements (TMax, TBio, DPen and SS). Standardised data (mean=0, std. dev.=1) were used to enable comparison of the magnitude of the effects of the variables. A minimum significance level of 0.05 was used for purposes of accepting or rejecting predictor variables.

5.3 Results

5.3.1 1993 storage temperature experiment

5.3.1.1 Fresh Fruit

Firmness of 'Granny Smith' apples decreased linearly with storage time, across all storage temperatures (Figs. 5-1, 5-2 and Table 5-1.). At 0 °C, the maximum crush strength (TMax) declined from 936 kPa to 599 kPa over the 20 week storage period. Fruit stored at 10 or 20 °C deteriorated at a faster rate, taking approximately 12 and 6 weeks, respectively, to reach the same level of firmness as those stored at 0 °C for 20 weeks.

As measured by the penetrometer (IPen), fruit softened approximately 2 and 3 times as fast at 10 and 20 °C, respectively, as at 0 °C. Similar results were produced by each of the instrumental tests used, although the Kramer Shear cell failed to distinguish between fruit stored at 10 or 20 °C (see section 5.3.3 for a comparison of

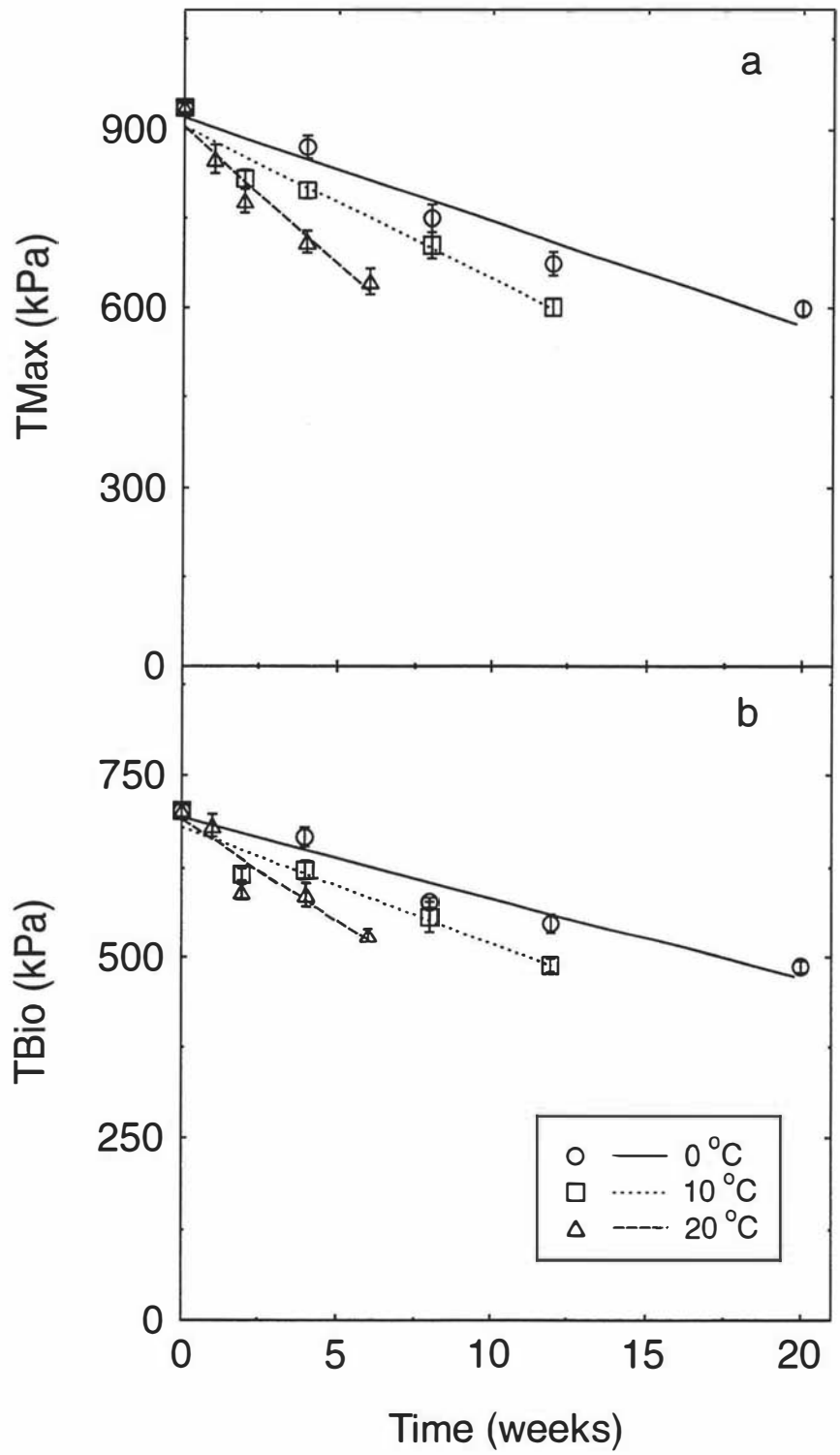


Fig. 5-1 Effect of storage temperature on fresh fruit texture of 'Granny Smith' apples as determined by the twist test a) TMax and b) TBio. Bars represent standard error of means (SEM). Regression equations are tabulated in Table 5-1.

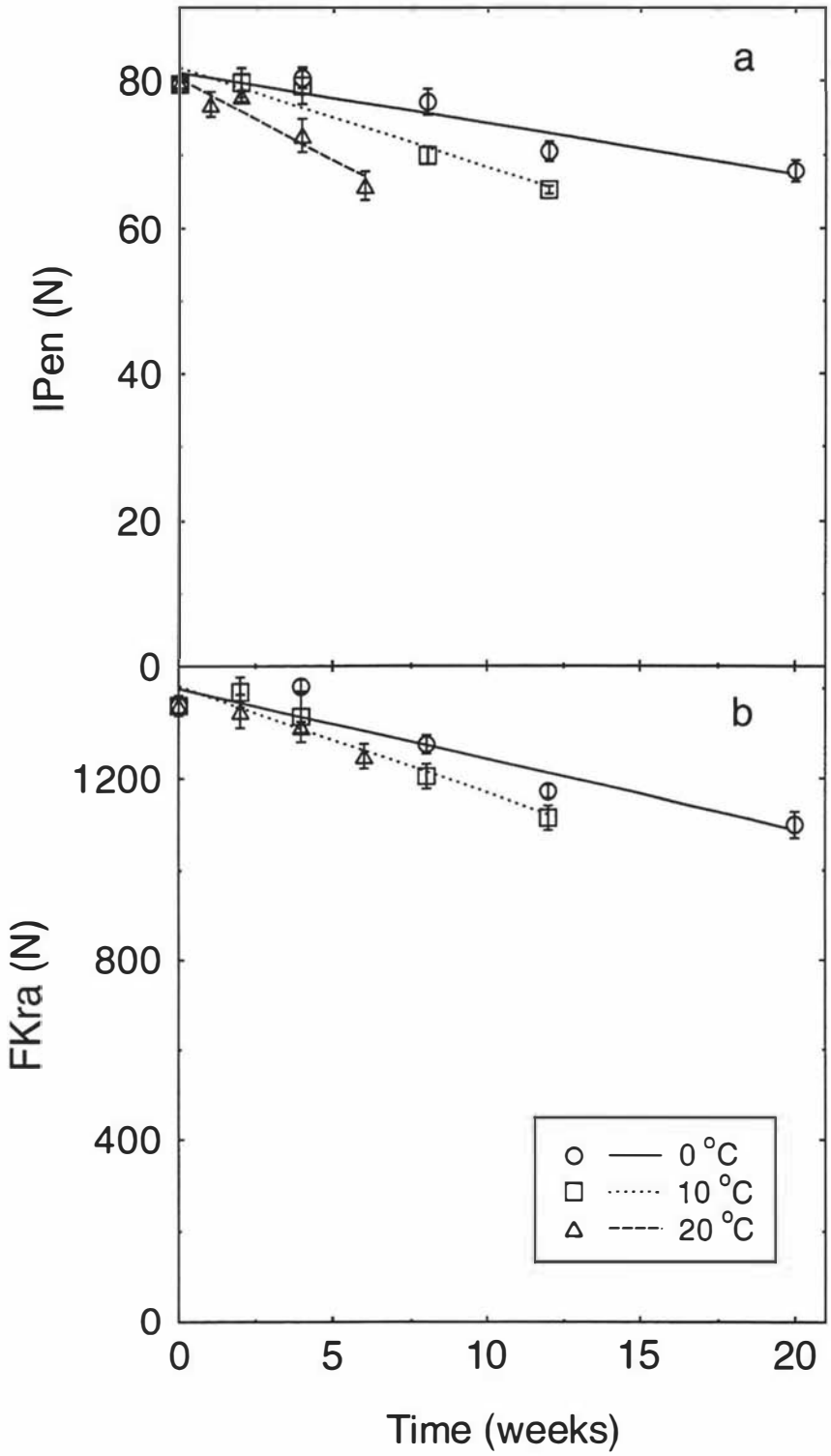


Fig. 5-2 Effect of storage temperature on fresh fruit texture of 'Granny Smith' apples as determined by a) penetrometer (IPen) and b) Kramer shear cell (FKra). Bars represent SEM. Regression equations are tabulated in Table 5-1.

the instrumental tests).

Table 5-1. Parameters and their standard errors, r^2 and CV values for the linear regressions (y=*m-nt*) fitted to the 'Granny Smith' fresh fruit firmness data, illustrated in Figs. 5-1 and 5-2.

Measurement[x]	*T* (°C)	*m* ± SE	*n* ± SE	r^2	CV
TMax					
	0	920 ± 26	17.5 ± 2.29	0.95	4.61
	10	905 ± 19	25.7 ± 2.87	0.96	3.59
	20	905 ± 20	46.5 ± 5.91	0.95	3.63
TBio					
	0	695 ± 17	11.2 ± 1.49	0.95	3.83
	10	681 ± 16	16.2 ± 2.40	0.94	3.87
	20	692 ± 20	28.1 ± 6.00	0.88	4.67
IPen					
	0	81.0 ± 1.61	0.68 ± 0.144	0.88	2.96
	10	81.7 ± 1.59	1.34 ± 0.235	0.92	3.03
	20	80.2 ± 1.23	2.20 ± 0.364	0.92	2.35
FKra					
	0	1400 ± 37	15.7 ± 3.29	0.88	4.02
	10	1406 ± 25	23.8 ± 3.75	0.93	2.81

[x]TMax = Twist test - maximum crush strength; TBio = Twist test - bioyield; IPen = Instron operated penetrometer and FKra = Kramer shear test (fresh fruit).

'Braeburn' fruit texture deteriorated more rapidly than 'Granny Smith' fruit when stored at 10 or 20 °C (Figs. 5-3 and 5-4). 'Braeburn' fruit stored at 10 °C or 20 °C for 3 weeks were on average 27% and 39% softer (as determined by the twist test; TMax) respectively than fruit stored at 0 °C for 4 weeks. 'Braeburn' fruit stored at 10 °C and 20 °C became mealy after 3 weeks storage and disintegrated on processing, hence no further assessments were made on 'Braeburn' fruit stored at these two

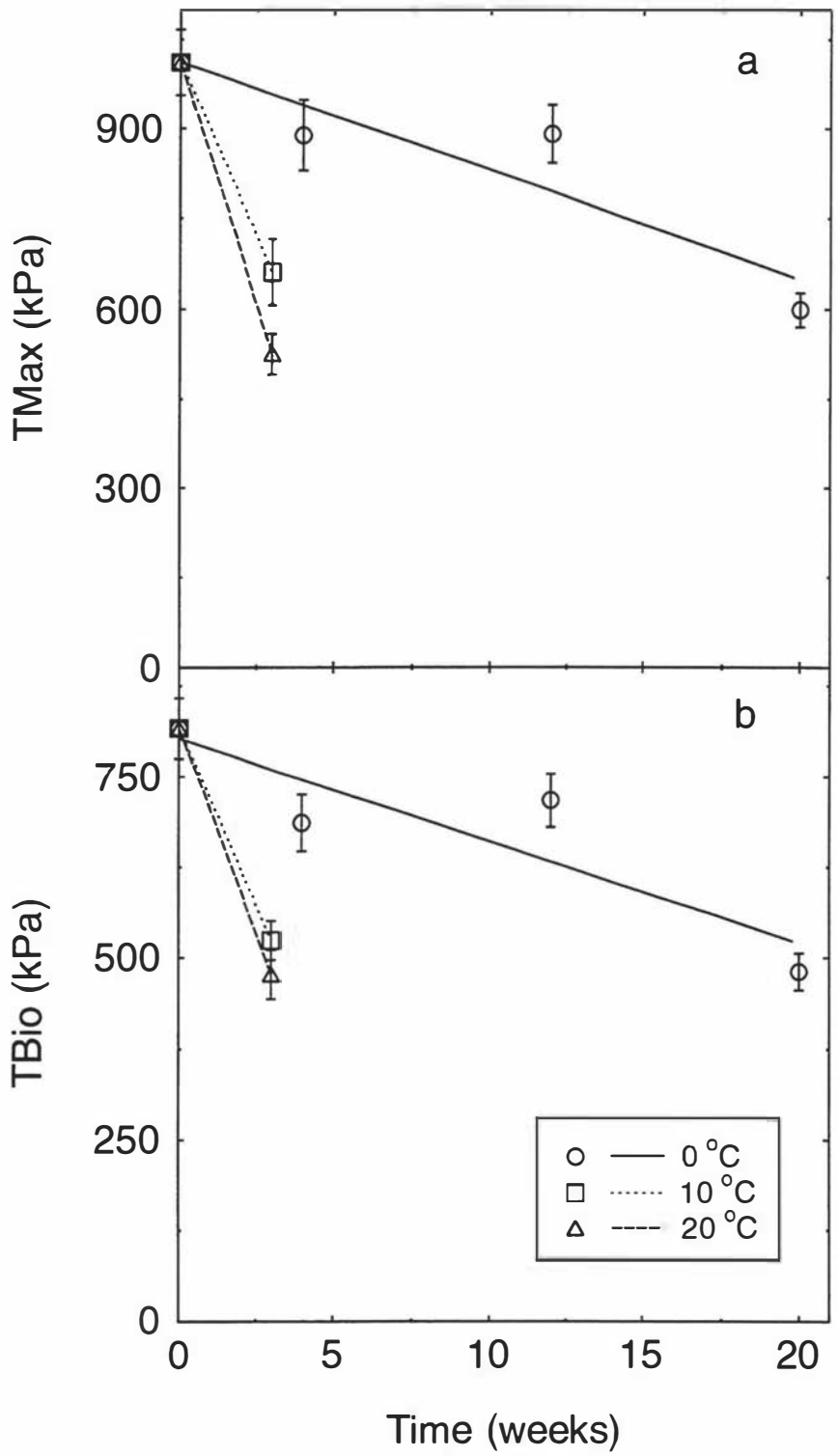


Fig. 5-3 Effect of storage temperature on fresh fruit texture of 'Braeburn' apples as determined by the twist test a) TMax and b) TBio. Bars represent SEM. Regression equations are tabulated in Table 5-2.

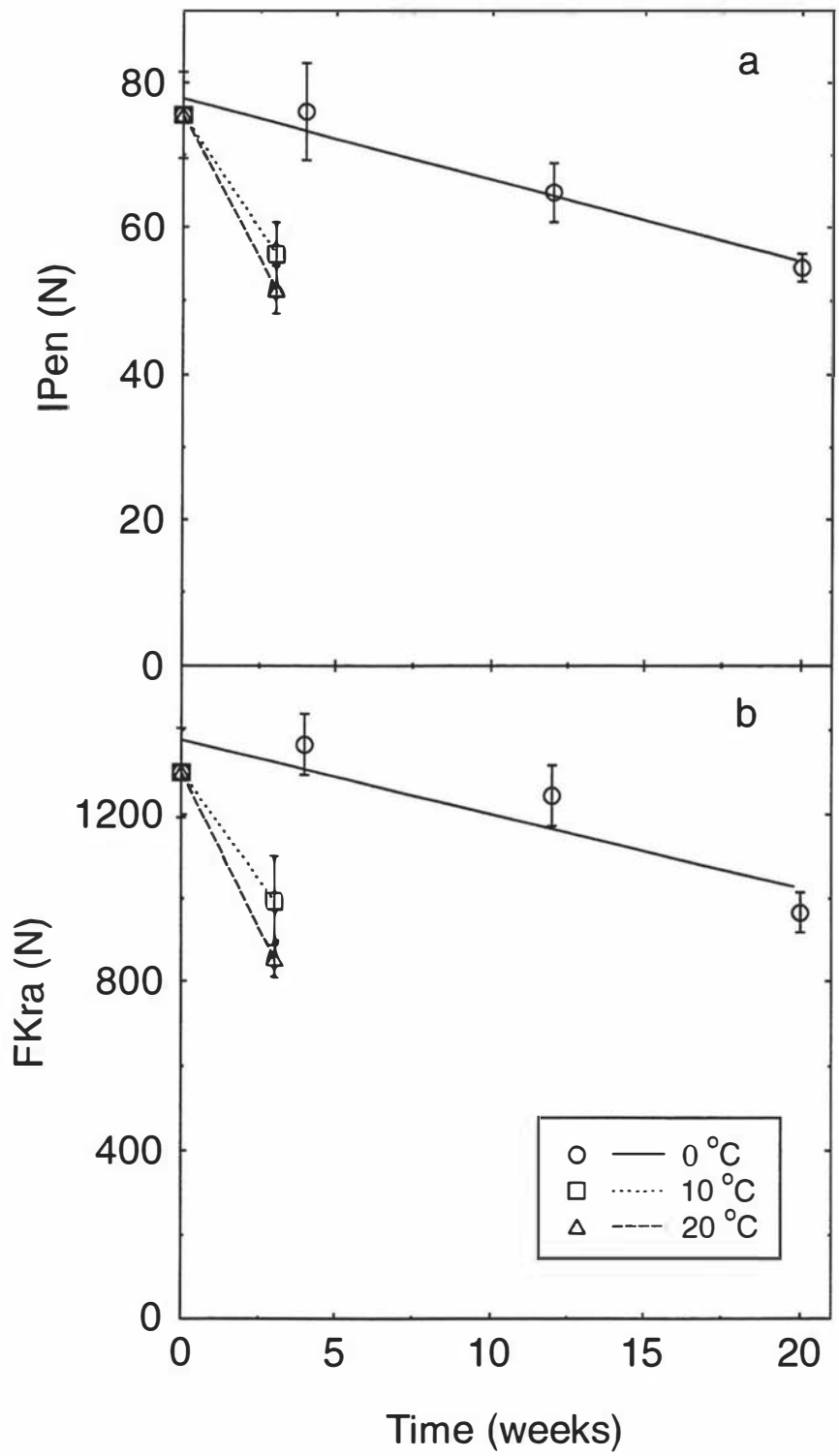


Fig. 5-4 Effect of storage temperature on fresh fruit texture of 'Braeburn' apples as determined by a) penetrometer (IPen) and b) Kramer shear cell (FKra). Bars represent SEM. Regression equations are tabulated in Table 5-2.

temperatures. For fruit stored at 0 °C there was a linear relationship between loss of firmness and storage duration, with fruit softening at a rate 1.7 times as fast as 'Granny Smith' fruit (IPen; Table 5-2).

Table 5-2. Parameters and their standard errors, r^2 and CV values for the linear regressions ($y=m-nt$) fitted to the 'Braeburn' fresh fruit firmness data for fruit stored at 0 °C, illustrated in Figs. 5-3 and 5-4.

Measurement[x]	$m \pm$ SE	$n \pm$ SE	r^2	CV
TMax	1010 ± 65	18.1 ± 5.50	0.84	9.99
TBio	802 ± 61	14.1 ± 5.12	0.79	11.65
IPen	77.8 ± 2.00	1.13 ± 0.169	0.96	3.83
FKra	1378 ± 75	17.6 ± 6.38	0.79	8.04

[x]TMax = Twist test - maximum crush strength; TBio = Twist test - bioyield; IPen = Instron operated penetrometer and FKra = Kramer shear test (fresh fruit).

The two cultivars also differed in terms of the spread of firmness values. Variation in cultivar firmness can be compared using the coefficient of variation (CV; Tables 5-1 and 5-2). For the firmness tests carried out on 'Braeburn' fruit stored at 0 °C, the CV ranged from about 4-12. This compared with CV values for 'Granny Smith' of between about 3 and 5. Throughout the assessment period, and across treatments, 'Braeburn' fruit consistently showed more variability in firmness values.

5.3.1.2 Processed fruit

The textural quality of solid-pack slices made from 'Granny Smith' apples showed little response to storage temperature or duration (Fig. 5-5a). This contrasted with 'Braeburn' in which storage temperature had a large effect on processed slice quality - both in terms of textural quality and free-juice volume (Fig. 5-5b and Table 5-4). Slices made from 'Braeburn' apples stored for 3 weeks at 10 or 20 °C were largely of an unacceptable quality. This is reflected by the objective texture tests, slice integrity scores and juice content (Table 5-4).

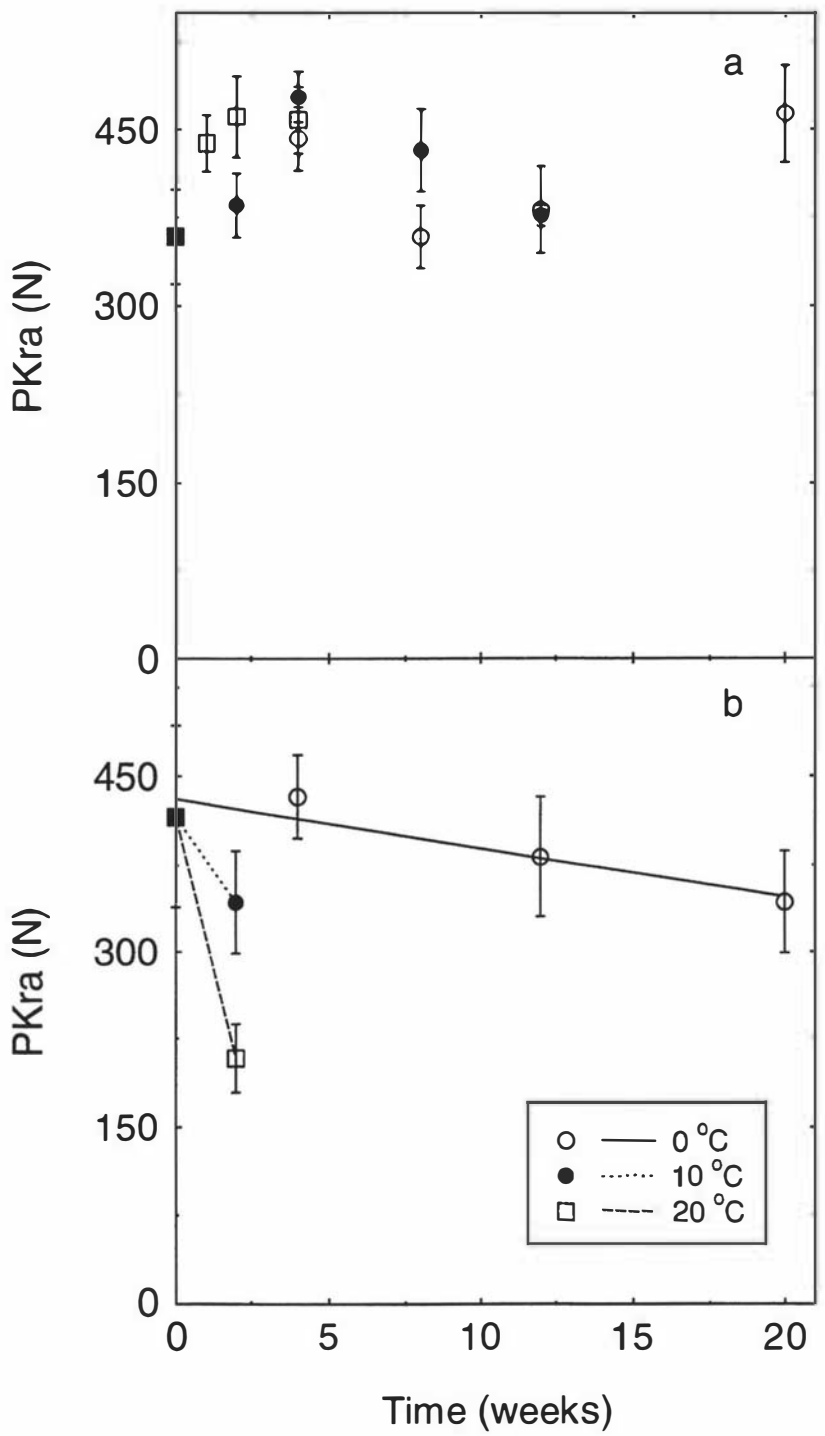


Fig. 5-5 Effect of fresh fruit storage temperature and duration on process slice firmness for a) 'Granny Smith' and b) 'Braeburn' as determined by the Kramer shear cell (PKra). Bars represent SEM. Regression equations are tabulated in Table 5-2.

Table 5-3 Effect of storage temperature and duration on the quality attributes (juice volume, pH, SS, slice integrity and overall appearance) of processed 'Granny Smith' apple slices.

Temp (°C)	Assess (wks)	Juice vol (ml)	pH	SS (%)	Slice integrity[x]	Overall appearance[y]
	0	13.3	3.10	8.3	1	1.3
0	4	18.3	3.21	8.6	1	1
	8	28.0	3.16	8.7	1	2
	12	34.0	3.25	8.3	1	1
	20	36.0	3.39	7.9	1	1.5
SED		5.08	0.034	0.22		
10	2	20.1	3.20	9.0	1	1
	4	26.3	3.22	8.1	1	1
	8	33.0	3.28	7.6	1	1
	12	38.5	3.39	7.5	1	1.7
SED		6.41	0.022	0.33		
20	1	32.9	3.23	8.3	1	1
	2	39	3.28	8.3	1	1
	4	23.8	3.26	7.9	1	1
SED		4.53	0.026	0.24		

[x] represents slice integrity scale where 1 was whole, firm slices and 5 was soft, textureless slices.
[y] scale ranking overall appearance where 1 was excellent and 5 was very poor.

'Braeburn' fruit stored at 0 °C produced high quality slices, although variability tended to increase with storage duration. In general, for both cultivars, juice volume and pH values increased with both storage temperature and duration (Tables 5-3 and 5-4), while soluble solids levels increased slightly before declining.

Table 5-4 Effect of storage temperature and duration on 'Braeburn' processed slice quality attributes (juice volume, pH, SS, slice integrity and overall appearance).

Temp (°C)	Assess (wks)	Juice Vol (ml)	pH	SS (%)	Slice integrity[x]	Overall appearance[y]
	0	24.4	3.19	8.4	1	1
0	4	20.8	3.26	10.1	1	1
	12	39.0	3.33	9.2	2	2
	20	36.6	3.38	8.9	2.3	2
SED		6.23	0.030	0.75		
10	3	31	3.3	8.7	3.3	2.7
20	3	37	3.4	8.4	4.7	3.3

[x] represents slice integrity scale where 1 was whole, firm slices and 5 was soft, textureless slices.
[y] scale ranking overall appearance where 1 was excellent and 5 was very poor

5.3.2 1994 softening behaviour experiment

5.3.2.1 'Braeburn'

The twist test and drill-mounted penetrometer were used to follow changes in fresh fruit firmness throughout this study. At 0 °C, 'Braeburn' fruit softened in a linear fashion, at a rate of 21.3 and 18.9 kPa.week^{-1} for TMax and TBio, respectively (Figs. 5-6a and b). Over the 20 week storage period TMax and TBio values decreased from 1079 to 582 kPa and 929 to 496 kPa, respectively. The regression analysis performed on these data showed that there were no significant differences between the two coating treatments, and hence a common regression line was fitted to the data. In the case of fruit stored at 20 °C either a declining exponential function (Eq. 5-1) or an inverse Michaelis Menten function (Eq. 5-2) fitted the data well.

$$f = o \times e^{(-q*t)} + s \qquad \textbf{(5-1)}$$

where: f was fruit firmness as described by the twist test or penetrometer; o was the

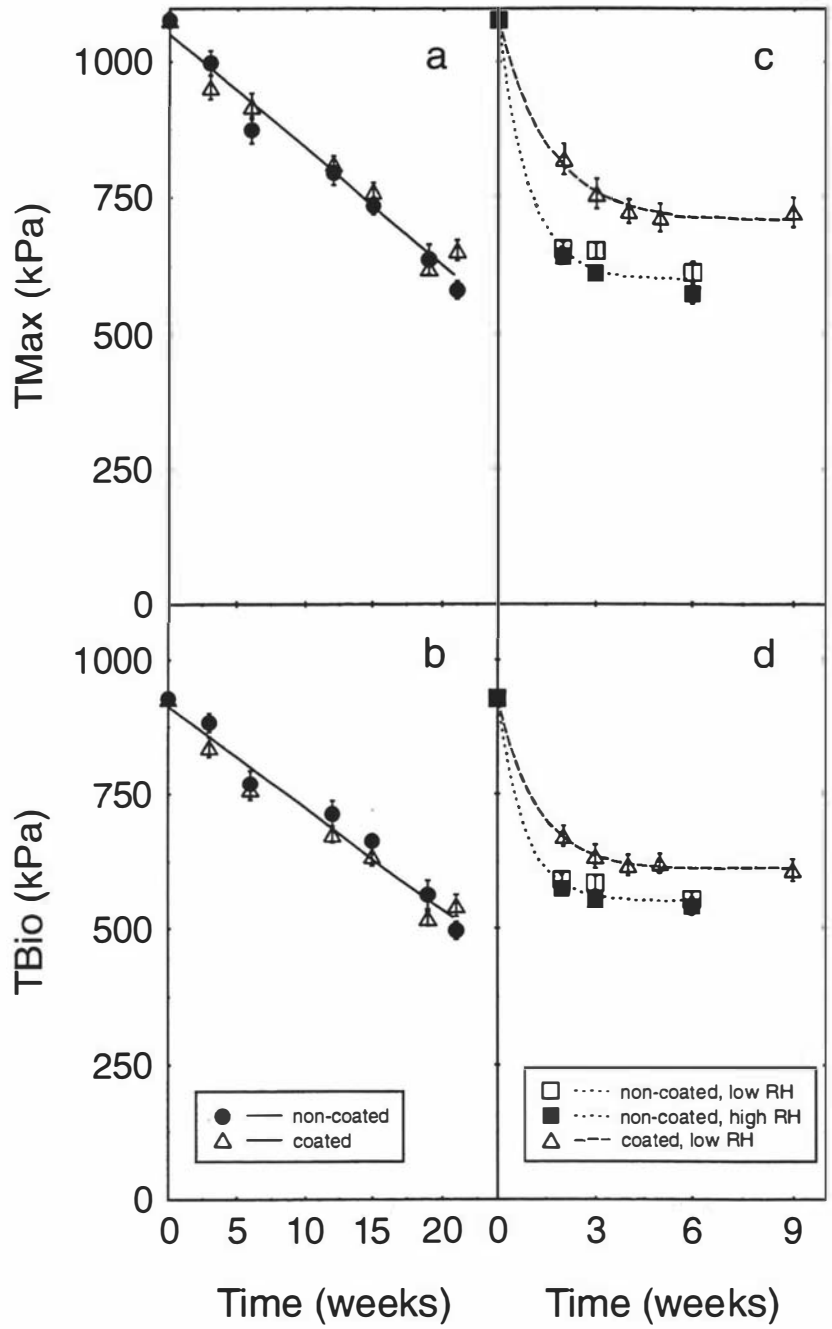


Fig. 5-6 Effect of storage treatment on 'Braeburn' fresh fruit texture as determined by the Twist test (TMax and TBio), for fruit stored at 0 °C (a and b) or 20 °C (c and d). Bars represent SEM. Regression equations are tabulated in Table 5-5.

difference between initial and final asymptotic firmness; q was the exponent describing the rate of decline in firmness; and s was the final asymptotic value for fitted firmness.

$$f = u \times \left(1 - \left(\frac{t}{(t+v)}\right)\right) \qquad \textbf{(5-2)}$$

where: u was the initial fruit firmness; and v described the rate of decline in fruit firmness and was the time required for f to drop from u to $u/2$.

For both TMax and TBio, there was little difference between the two non-coated treatments, enabling the data sets to be combined (Figs. 5-6 c and d). At 20 °C, coated and non-coated fruit differed in their softening rates, with proportional rates of softening in non-coated fruit being 1.7 and 1.4 times as fast as coated fruit, as determined by TMax and TBio, respectively.

General trends were similar for changes in fruit firmness measured by the penetrometer (Fig. 5-7) although, for fruit stored at 0 °C, rates of change slowed somewhat after an initial drop in fruit firmness.

Table 5-5. Parameters and their standard errors, r^2 values for the linear regression lines (y=*m-nt*) fitted to data for firmness of fresh and blanched 'Braeburn' apples previously stored at 0 °C and illustrated in Figs. 5-6 - 5-8.

Measurement[x]	*m* ± SE	*n* ± SE	r^2
TMax			
0 °C (coated & non-coated)	1052 ± 14	21.3 ± 1.04	0.97
TBio			
0 °C (coated and non-coated)	914 ± 13	18.93 ± 0.954	0.97
BKra			
0 °C (coated and non-coated)	794 ± 44	16.3 ± 3.08	0.74

[x]Tmax = Twist test - maximum crush strength; TBio = Twist test - bioyield; and BKra = Kramer Shear test performed on blanched slices.

Table 5-6. Parameters and their standard errors for curves fitted in Figs. 5-5-5-8.

Measurement[x]	*o* ± SE	*q* ± SE	*s* ± SE
TMax			
20 °C LRH & HRH[y]	479 ± 28	1.09 ± 0.214	600 ± 16
20 °C CMC[y]	374 ± 16	0.66 ± 0.08	707 ± 11
TBio			
20 °C LRH & HRH[y]	379 ± 18	1.18 ± 0.210	550 ± 9.9
20 °C CMC[y]	318 ± 6	0.83 ± 0.046	610.9 ± 3.38
DPen			
0 °C HRH & CMC[y]	22.2 ± 1.92	0.19 ± 0.04	58.2 ± 1.11
20 °C LRH & HRH[y]	40.9 ± 3.63	0.68 ± 0.142	39.7 ± 2.42
20 °C CMC[z]	*u* = 75.3 ± 4.70	*v* = 17.6 ± 5.97	

[x] Tmax = Twist test - maximum crush strength; TBio = Twist test - bioyield; and DPen = Drill-mounted penetrometer.
[y] Generalised form of fitted function given by Eq. 5-1.
[z] Generalised form of fitted function given by Eq. 5-2.

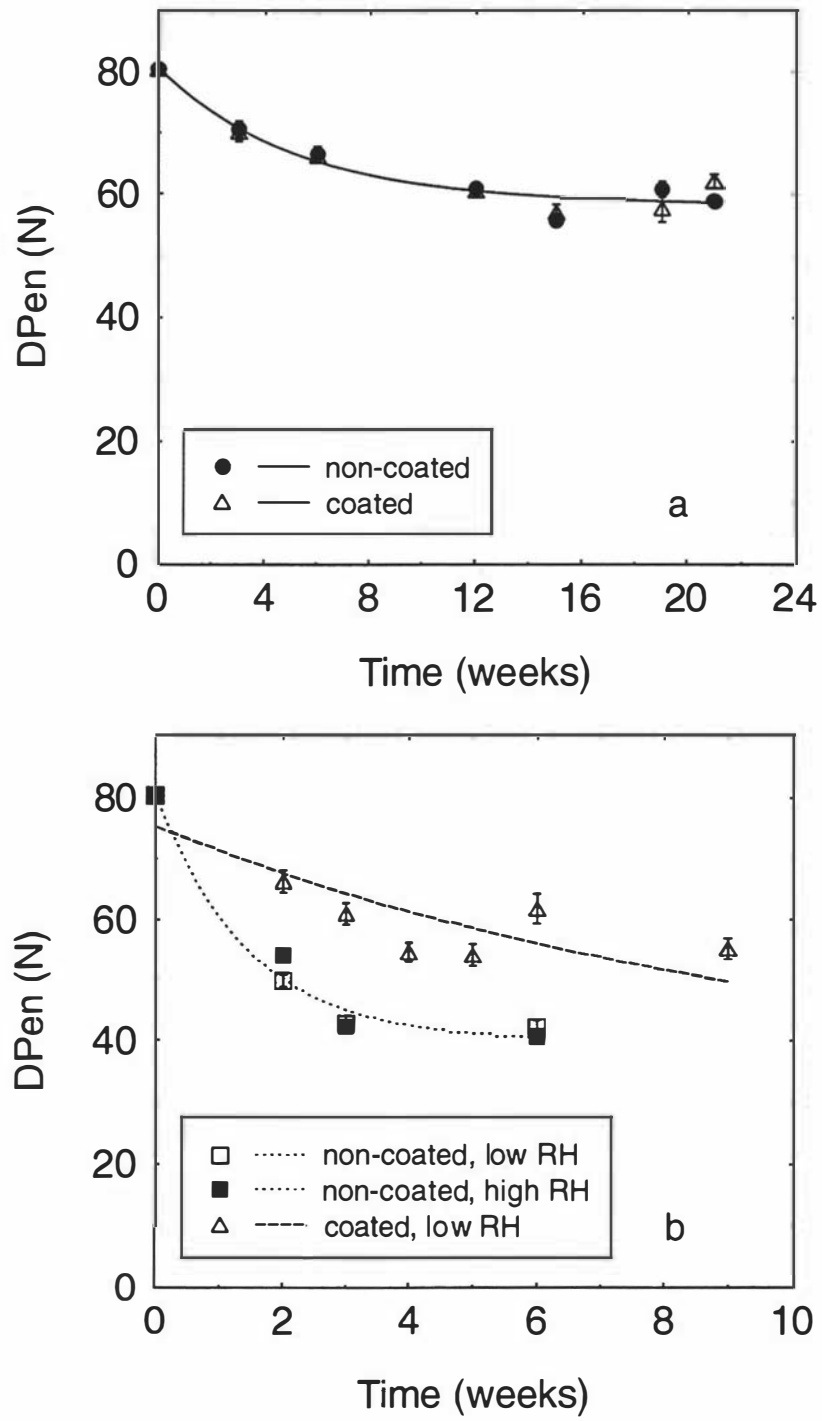


Fig. 5-7 Effect of storage treatment on 'Braeburn' fresh fruit texture as determined by the penetrometer for fruit stored at a) 0°C and b) 20°C. Bars represent SEM. Regression equations are tabulated in Table 5-6.

The texture of blanched slices produced from these apples tended to be more variable (Fig. 5-8). Slices produced from fruit stored at 0 °C gradually declined in firmness as duration of storage before blanching increased. There did not appear to be any significant differences in terms of texture between coated and control fruit. A regression analysis showed that a common line could be used to describe this textural loss, with 74 % of the variation in slice texture being accounted for by the fit.

Slices made from non-coated fruit stored at 20 °C were considered to be too soft after just two weeks storage (Fig 5-8 b). Unfortunately, some unforeseen technical difficulties prevented earlier data on blanched fruit being obtained. Coated fruit produced slices of a superior texture, although there was considerable variation at each sampling time. None of the non-linear regression models used in this study adequately fitted the data.

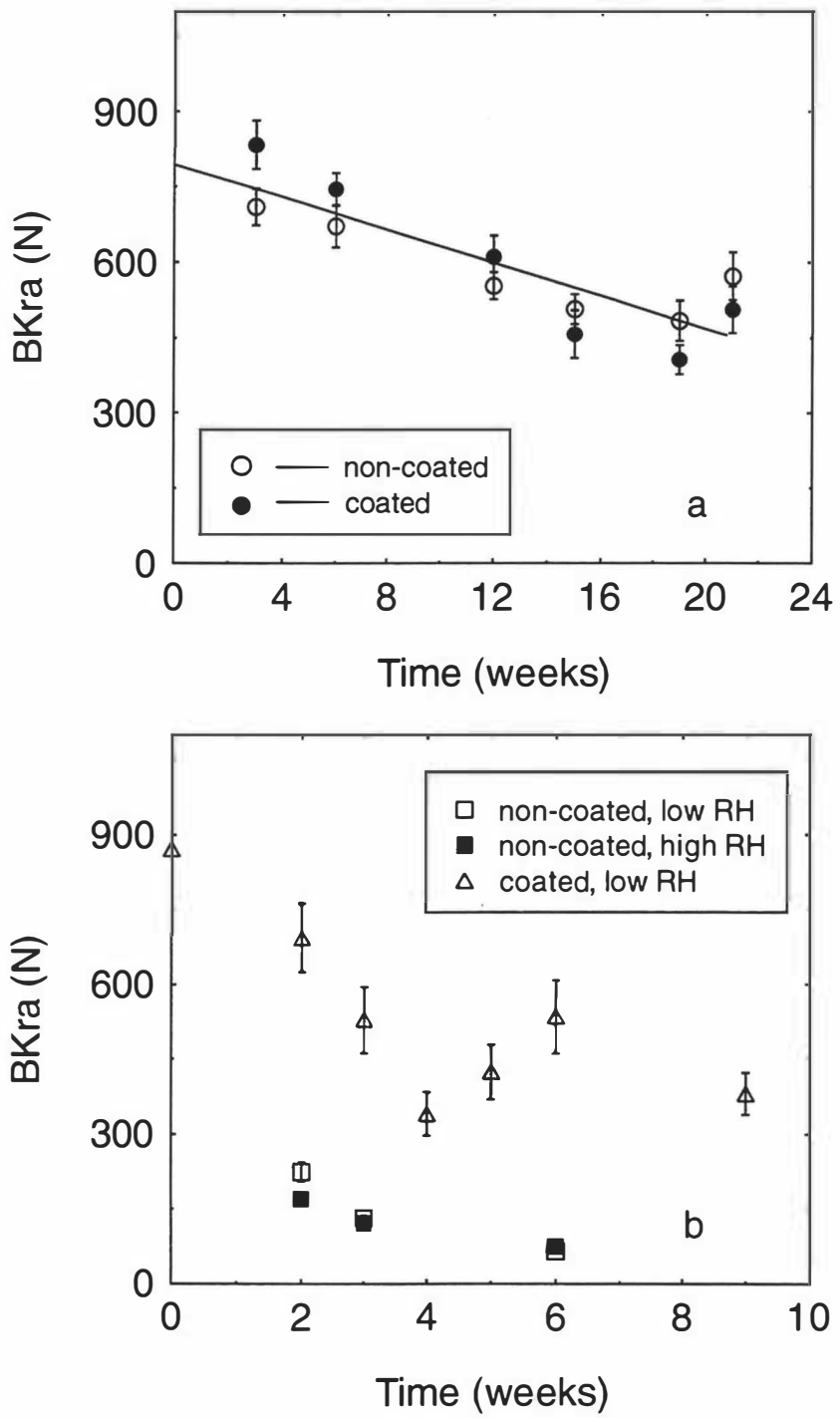


Fig. 5-8 Effect of storage treatment on blanched 'Braeburn' slice texture as determined by the Kramer shear cell for fruit stored at a) 0°C and b) 20°C. Bars represent SEM. Regression equations are tabulated in Table 5-5.

5.3.2.2 'Fuji'

'Fuji' fruit retained their texture considerably better than their 'Braeburn' counterparts. For fruit stored at 0 °C, TMax and TBio decreased linearly with storage time (Fig. 5-9a and b). At 0 °C, textural loss was similar for coated and non-coated fruit, enabling a common regression line to be fitted to the data. Fruit stored at 0 °C were 26 % and 29% softer as determined by TMax and TBio respectively after 21 weeks storage. For fruit stored at 20 °C, the twist test did not appear to effectively characterise the softening behaviour, with the curve plateauing soon after an initial drop in firmness. Fruit firmness as determined by the penetrometer decreased linearly with storage time at 20 °C. Fig. 5-10a illustrates the relationship between fruit firmness as determined by the penetrometer, and storage duration at 0 °C. There was an initial drop in fruit firmness, followed by a flattening of the curve after 6 weeks storage.

Table 5-7. Parameters and their standard errors and r^2 values for the linear regressions ($y=m-nt$) fitted to 'Fuji' fresh and blanched fruit firmness data illustrated in Figs. 5-9 - 5-11.

Measurement[x]	$m \pm$ SE	$n \pm$ SE	r^2
TMax			
0 °C (common line)	932 ± 18	9.8 ± 1.44	0.77
TBio			
0 °C (common line)	800 ± 18	8.6 ± 1.47	0.71
DPen			
20 °C	71.5 ± 1.52	2.88 ± 0.327	0.85
BKra			
0 °C (common line)	900 ± 28	11.1 ± 2.05	0.73
20 °C LRH	905 ± 38	18.9 ± 6.9	0.54
20 °C HRH	825 ± 38	18.9 ± 6.9	

[x]Tmax = Twist test - maximum crush strength; TBio = Twist test - bioyield; DPen = Drill-mounted penetrometer and BKra = Kramer Shear, blanched slices.

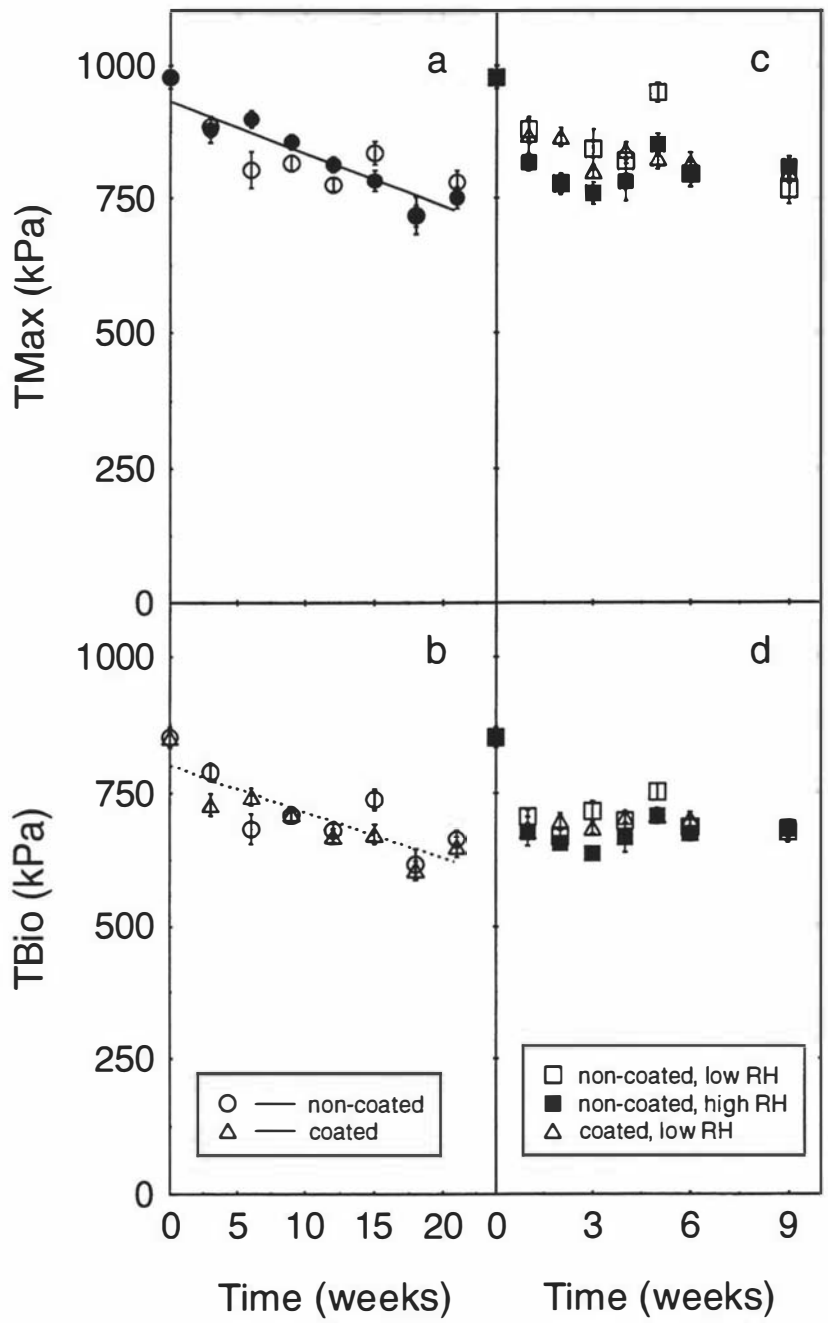


Fig. 5-9 Effect of storage treatment on 'Fuji' fresh fruit texture as determined by the Twist test (TMax and TBio), for fruit stored at 0 °C (a and b) or 20 °C (c and d). Bars represent SEM. Regression equations are tabulated in Table 5-7.

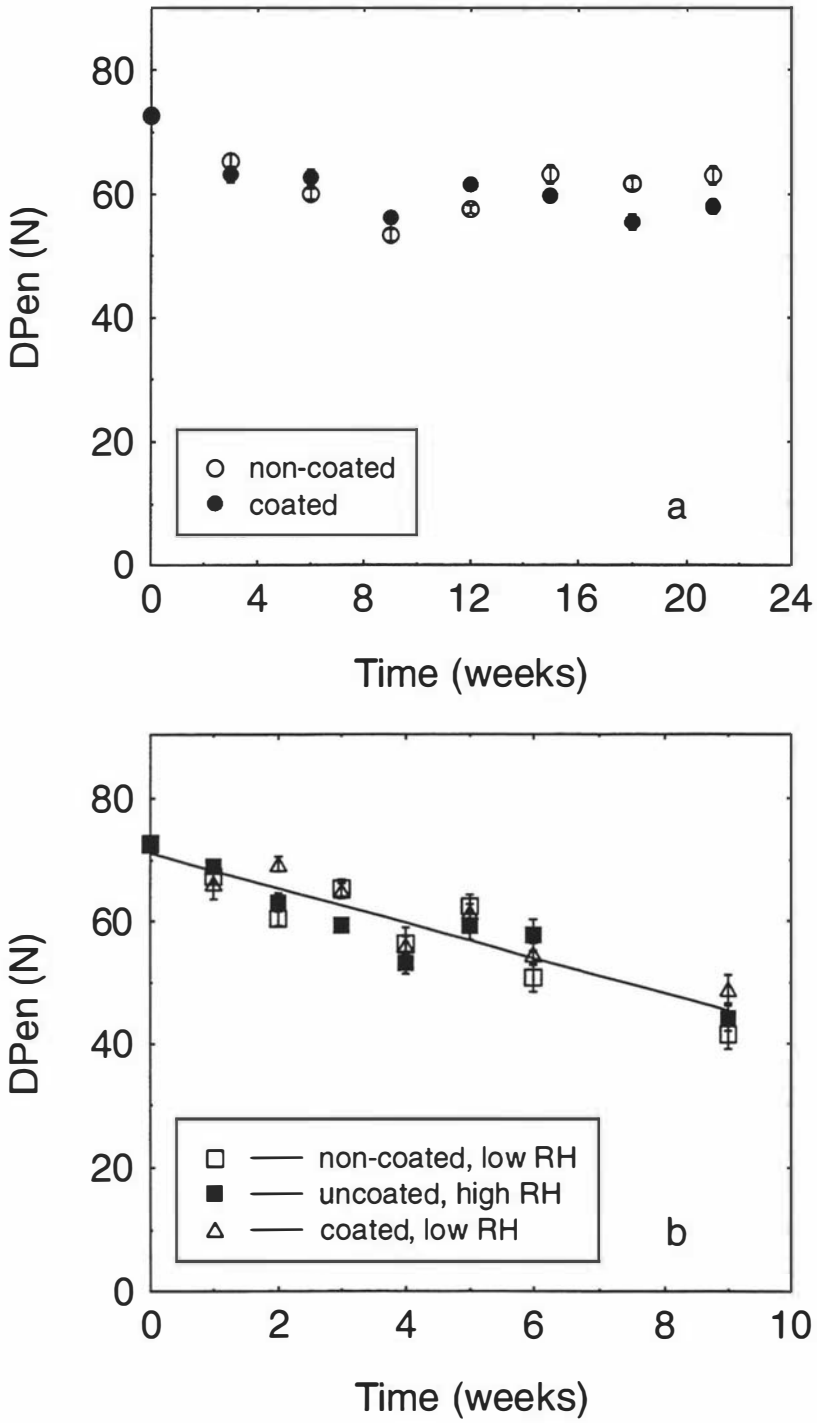


Fig. 5-10 Effect of storage treatment on 'Fuji' fresh fruit texture as determined by the penetrometer for fruit stored at a) 0°C and b) 20°C. Bars represent SEM. Regression equations are tabulated in Table 5-7.

Blanched fruit firmness decreased in a linear manner with storage time, for fruit stored at both temperatures (Fig. 5-11). Following 21 weeks storage at 0 °C, blanched slices had lost 36 % of their initial firmness as determined by the Kramer shear cell, irrespective of coating treatment. For fruit stored at 20 °C there was a difference between the coating treatments with the rate of textural loss being 11.9 $N.week^{-1}$, compared to 18.9 $N.week^{-1}$ in the case of non-coated fruit. After 9 weeks storage at 20 ° C, 'Fuji' apples still produced slices of an acceptable texture.

5.3.3 Comparison of instrumental tests

Figs. 5-12 - 5-14 illustrate the relationships between the various instrumental tests used in this study. The key on the figures differentiates between cultivars and, in the case of the 1994 data, treatments. Tables 5-8 and 5-9 show the correlation coefficients for the 1993 and 1994 data sets, respectively. These are overall correlation coefficients and include data taken from both cultivars and treatments.

In 1993, the highest correlation of 0.98 was between TMax and TBio. Correlations between the penetrometer and either twist test measure were only moderate at 0.73 (TMax) and 0.63 (TBio). FKra correlated highly with IPen, but only moderately with either twist test. Analysing the data by cultivar resulted in significantly higher correlation coefficients. In the case of 'Braeburn', the correlation coefficients ranged from 0.91 to 0.99, while for 'Granny Smith' they ranged from 0.86 to 0.98.

Table 5-8. Relationship among selected instrumental tests for 1993 'Granny Smith' and 'Braeburn' apples (correlation coefficients, r)

Measurement[z]	TBio	IPen	Kramer
TMax	0.98^{***}	0.73^{**}	0.78^{***}
TBio		0.63^{*}	0.70^{**}
IPen			0.94^{***}

[z]TMax = Twist test - maximum force; TBio = Twist test - bioyield; IPen = Instron penetrometer; FKra = Fresh fruit - Kramer shear cell - maximum force.
*, **, *** represent $P < 0.01$, 0.001 and 0.0001 respectively

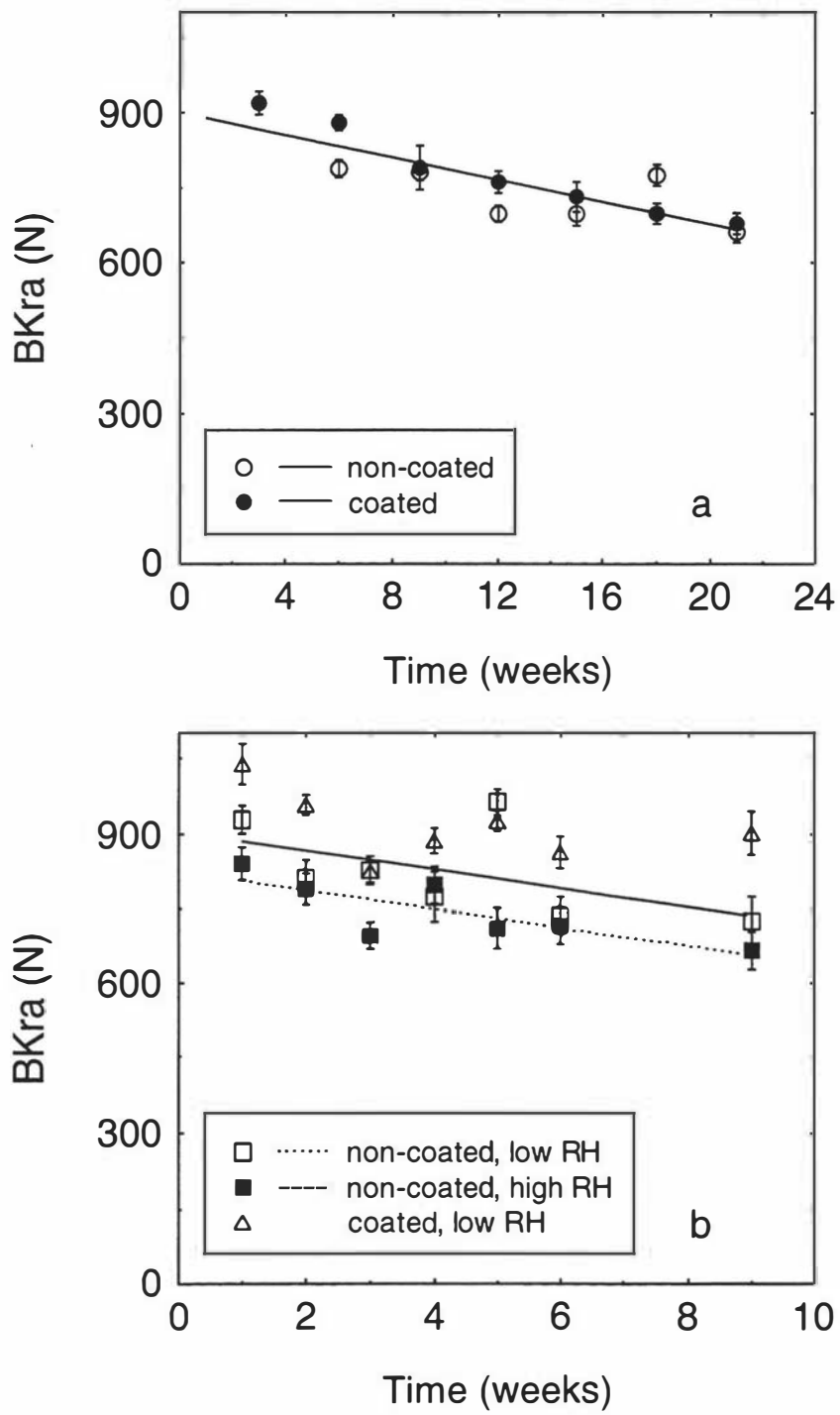


Fig. 5-11 Effect of storage treatment on blanched 'Fuji' slice texture as determined by the Kramer shear cell for fruit stored at a) 0°C and b) 20°C. Bars represent SEM. Regression equations are tabulated in Table 5-7.

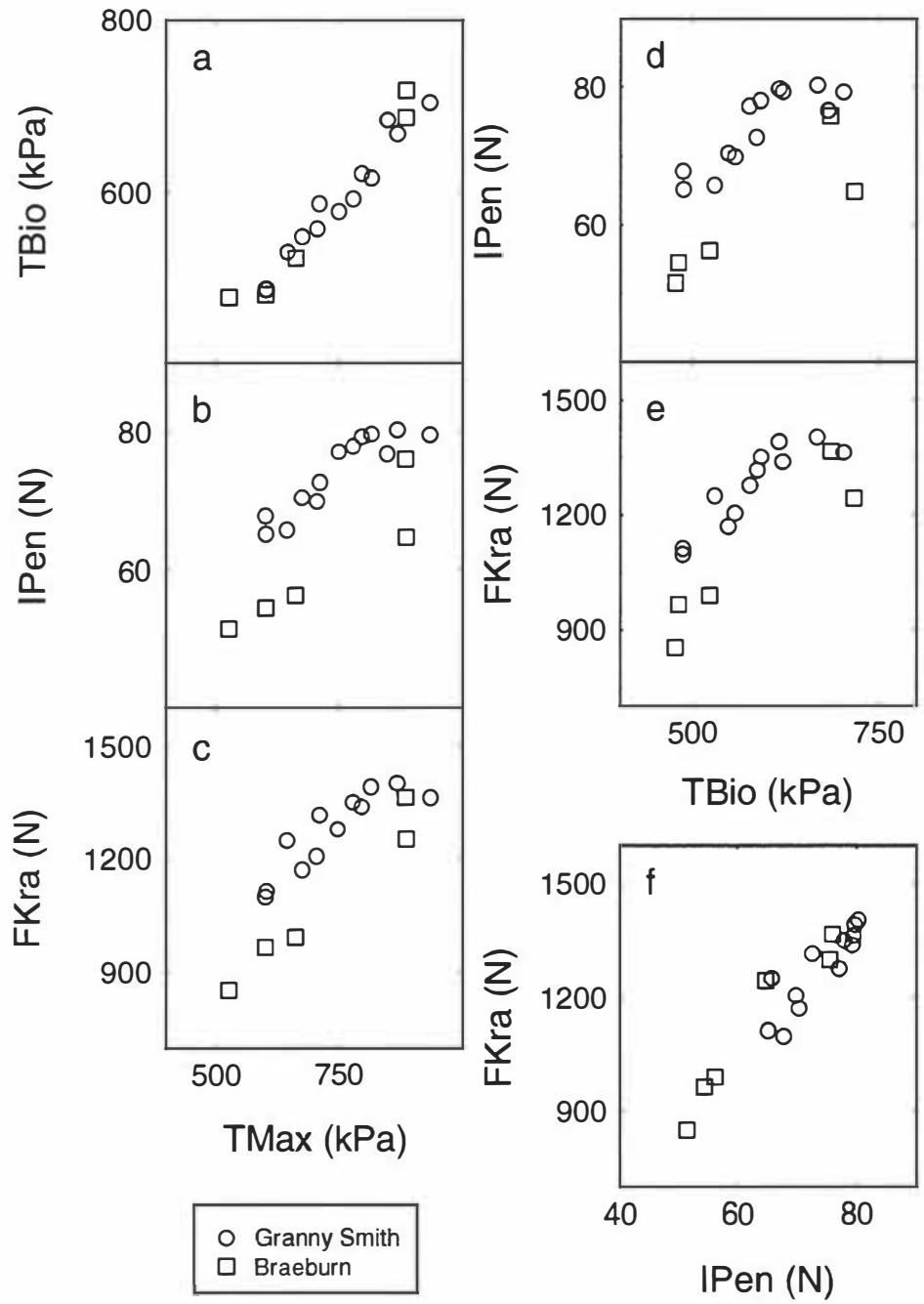


Fig. 5-12 Interrelationships between the instrumental tests carried out on fresh 'Granny Smith' and 'Braeburn' apples stored for different periods in 1993. a) TBio vs TMax; b) IPen vs TMax; c) FKra vs TMax; d) IPen vs TBio; e) FKra vs TBio; and f) FKra vs IPen.

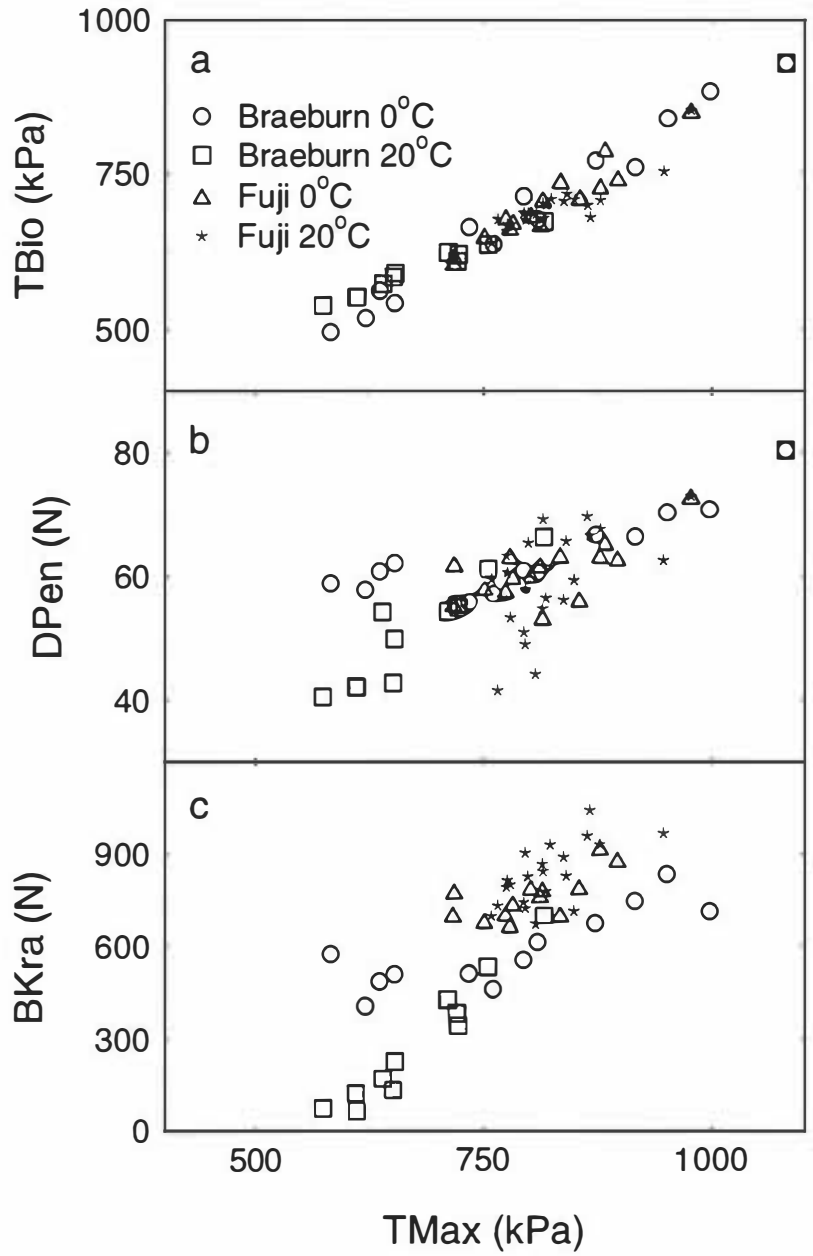


Fig. 5-13 Interrelationships between the instrumental tests carried out on fresh (TMax, TBio, DPen) and blanched (BKra) 'Braeburn' and 'Fuji' apples stored for different periods in 1994. a) TBio vs TMax; b) DPen vs TMax; and c) BKra vs TMax.

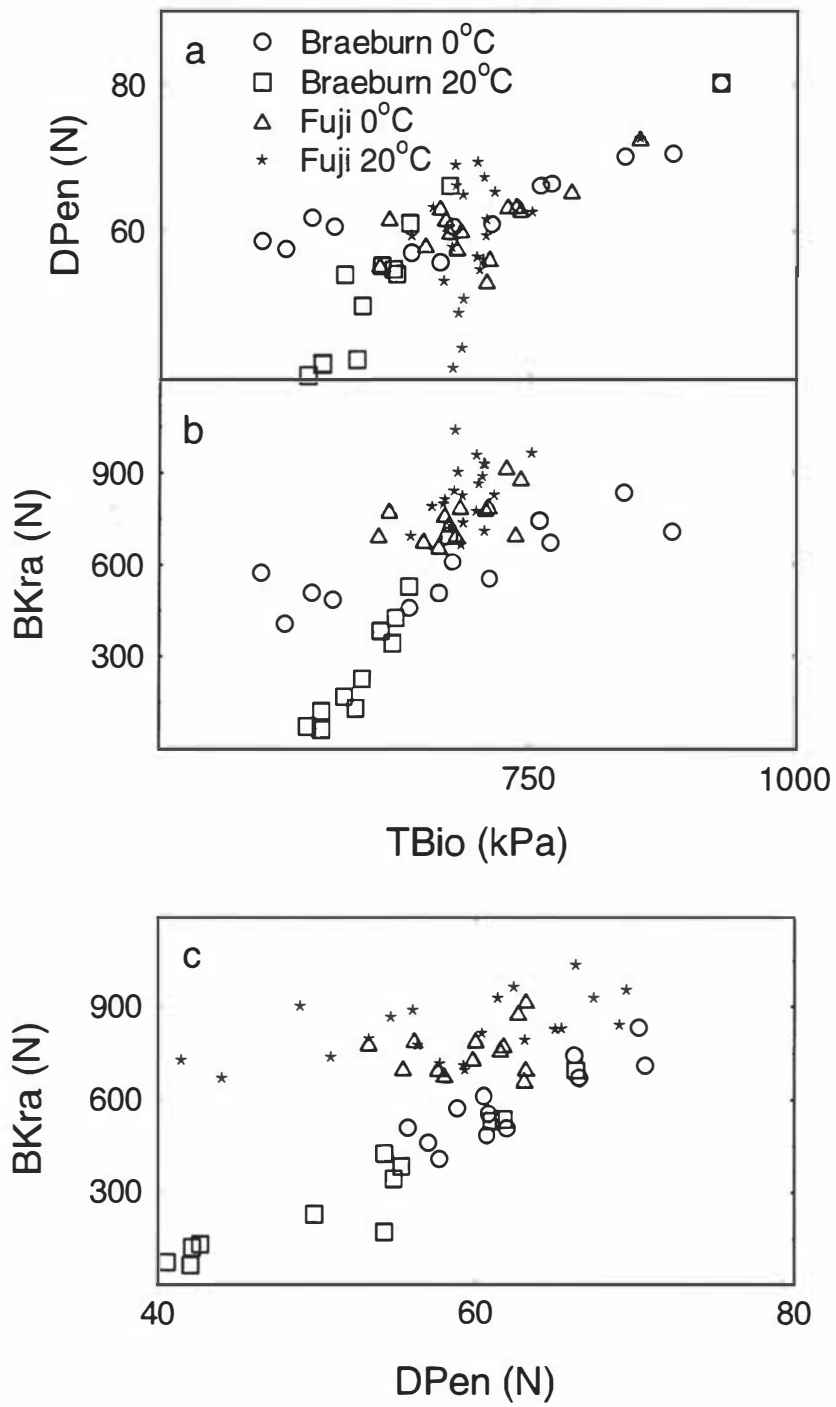


Fig. 5-14 Interrelationships between the instrumental tests carried out on fresh (TMax, TBio, DPen) and blanched (BKra) 'Braeburn' and 'Fuji' apples stored for different periods in 1994(cont.). a) DPen vs TBio; b) BKra vs TBio; and c) BKra vs DPen.

In 1994, TMax and TBio were again highly correlated (0.97). Correlations between the penetrometer and either twist test measure were only moderate at 0.66 (TMax) and 0.59 (TBio). The correlation coefficients between fresh fruit and blanched slice firmness ranged from 0.65 (TBio) to 0.76 (TMax). In some cases, segregating the data into cultivar and temperature classes resulted in considerably higher correlation coefficients. This was especially evident in the case of 'Braeburn' fruit stored at 20 °C where correlations between the instrumental tests ranged from 0.89-0.98. By contrast, segregating the 'Fuji' data often resulted in lower correlation coefficients. In the case of 'Fuji' 20 °C data, correlation coefficients ranged from 0.37-0.88.

Figs. 5-12 - 5-14 provide considerably more information on how cultivar and storage temperature affect the interrelationships between the various instrumental tests. In Figs. 5-13b,c and 5-14a,b, the 'Fuji' twist test data fell within a narrow range, suggesting a lack of characterisation of softening behaviour by the twist test.

Table 5-9. Relationships among selected instrumental tests for 1994 'Braeburn' and 'Fuji' apples (correlation coefficients, r)

Measurement[z]	TBio	Pen	Bl
TMax	0.97	0.66	0.76
TBio		0.59	0.65
Pen			0.67

[z]TMax= Twist test - maximum force; TBio= Twist test - bioyield; Pen= drill-mounted penetrometer; Bl= Blanched slices - Kramer Shear cell -maximum force.

In Fig. 5.14c, the 'Fuji' data were relatively flat indicating that although there were differences in fresh fruit texture (as determined by the penetrometer) blanched slice texture remained relatively unchanged. This effect was also evident to a lesser degree in Figs. 5-13c and 5-14b: although there were considerable differences in fresh fruit texture in 'Braeburn' apples stored at 0 °C, the corresponding change in blanched texture was less than that observed in 'Braeburn' fruit stored at 20 °C.

Principal component analysis (PCA)

The first two components from the PCA accounted for approx. 98 % of the variation among the different instrumental tests used to estimate raw fruit texture in 1993. This would suggest that the dimensionality of the data may be reduced from 4-dimensions to 2. The first PC explained approx. 84 % of the variation in the (standardized) data, hence is overwhelmingly the main source of variation among the instrumental tests. The coefficients of each instrumental test for the first PC are all approximately equal (about 0.5; Table 5-10). Hence, PC1 would appear to be a weighted average of all the texture measurements, and may give an indication of the overall strength of the tissue. The coefficients for the second PC reveal that it is a contrast between the twist test measurements and the other instrumental tests (IPen and FKra). It is presumably a contrast between different force components of the respective tests eg. compression vs shear or extrusion.

Table 5-10. Eigenvectors generated from the PCA analysis of the 1993 instrumental data

	Eigenvectors			
Variable	PC 1	PC 2	PC 3	PC 4
TMax	0.516	-0.409	0.106	-0.745
TBio	0.490	-0.574	0.015	0.656
IPen	0.486	0.567	0.654	0.118
FKra	0.508	0.426	-0.749	0.011

The first PC accounted for approx. 78 % of the variation among the instrumental tests used in the 1994 season. The coefficients of each instrumental test for the first PC were very similar (Table 5-11). PC 1 would therefore appear to represent a weighted average of all the texture measurements, and may provide a measure of overall tissue strength. The second PC accounted for approx. 14 % of the variation in the data. PC2 was largely restricted to tests carried out on raw fruit. It consisted of two negative coefficients for TMax and TBio and a large positive coefficient for DPen, and hence would appear to be a contrast between the twist test and penetrometer instrumental measures of texture. As for the 1993 data, PC 2 appears

to reflect the different forces occurring during the twist and penetrometer tests. PC 3 explained a further 8 % of the variation in the data. It would appear to be a contrast between blanched fruit texture and raw fruit texture, since it has a large negative coefficient for BKra and three smaller but positive coefficients for the remaining variables.

Table 5-11. Eigenvectors generated from the PCA analysis of the 1994 instrumental data

	Eigenvectors			
Variable	PC 1	PC 2	PC 3	PC 4
TMax	0.547	-0.294	0.148	-0.770
TBio	0.517	-0.459	0.378	0.616
DPen	0.434	0.835	0.333	0.054
BKra	0.495	0.072	-0.850	0.161

5.3.4 Relationship between raw fruit texture and blanched slice firmness

A stepwise multiple regression analysis revealed that blanched slice firmness in 'Braeburn' apple slices (as determined by the Kramer shear cell) could be adequately predicted using the penetrometer (Eq. 5-3), with 91 % of the variation in BKra being accounted for by DPen. In the case of 'Fuji', BKra was best described using TMax, TBio and SS, with 62 % of the variation in BKra being accounted for by these three attributes (Eq. 5-4).

$$BKra = 0 + 0.95DPen \quad (5\text{-}3)$$

$$BKra = 0 + 1.15TMax - 0.57TBio + 0.33SS \quad (5\text{-}4)$$

5.4 Discussion

Cultivar differences featured strongly in this study, with the cultivars used varying quite markedly in terms of textural quality, storage potential, tolerance of ambient temperatures and ultimately in their response to processing. These intrinsic differences between apple cultivars have long been recognised, as evidenced by the large number of studies using microscopical, instrumental or sensory techniques to identify and describe key varietal differences (Reeve, 1953; Holt and Schoorl, 1984; Rebouillat and Peleg, 1989; Trakoontivakorn *et al.*, 1988; Lapsley *et al.*, 1992; Gussman *et al.*, 1993; Paoletti *et al.*, 1993). Several studies have also focused on how various cultivars respond to processing (Reeve and Leinbach, 1953; Wiley and Thompson, 1960; Williams *et al.*, 1983; McLellan *et al.*, 1984a, 1984b; Kim *et al.*, 1993a, 1993b) and in particular how varietal effects affect apple sauce grain and consistency (Mohr, 1979; Rao *et al.*, 1986; Mohr, 1989). These differences to a large extent dictate the use (i.e. canned slices, sauce, juice etc.) of each cultivar by the processing industry. Work described in this chapter has provided information on the storage and processing response of 'Braeburn' and 'Fuji', two relatively new cultivars to the processing industry. In addition, storage temperature, RH, and coating effects; fresh fruit texture assessment and the relationship between fresh and processed slice quality are other key aspects of the work outlined in this chapter.

Fruit firmness values expressed in terms of absolute firmness, softening rate or variability in firmness varied considerably amongst the cultivars studied. 'Granny Smith' is renowned as a firm apple with good storage potential (Bradley and Brown, 1969; Tu *et al.*, 1996). In this study, textural degradation in 'Granny Smith' fruit was modest, as evidenced by a small overall loss of firmness (12 N after 20 weeks storage at 0 °C), gradual softening rate (0.68 $N.week^{-1}$ at 0 °C) and a narrow spread of firmness values. By contrast 'Braeburn' fruit softened substantially (21 N after 4 1/2 months storage at 0 °C), softened more quickly (1.13 $N.week^{-1}$ at 0 °C) and had a greater spread in firmness values. 'Fuji' was intermediate both in terms of absolute firmness and softening rate.

Differences between cultivars in terms of absolute firmness, softening rates and variability are partially due to inherent differences in their physical cellular makeup, as well as differences in ripening and respiratory patterns (Reeve, 1953; Wills *et al.*, 1981; Burton, 1982; Rebouillat and Peleg, 1989; Khan and Vincent, 1990; Dadzie, 1992; Lapsley *et al.*, 1992; Paoletti *et al.*, 1993). In terms of physical makeup, cultivars may vary in terms of cell structure, size of cells, intercellular spaces and composition, all of which can have a direct impact on perceived fruit texture (Reeve, 1970). Despite 'Braeburn' fruit starting with a higher density and lower intercellular space than 'Granny Smith', they softened more and had a shorter storage life than 'Granny Smith' when stored at warm temperatures. This result probably reflects 'Braeburns' greater tendency towards mealiness than 'Granny Smith'. Trakoontivakorn *et al.* (1988) reported differences between 'Granny Smith' and 'Red Delicious' apples both in terms of the pattern of intercellular air space and cell length and cell areas. Physical differences in terms of skin permeance to water, either existing natural differences or changes brought about by differences in wax development during storage, may result in cultivars losing water at different rates, which in turn influences fruit texture (Lin and Pitt, 1986). 'Braeburn' permeance to water is considerably greater than that of 'Granny Smith' (Maguire, unpublished). However, in this experiment, fruit kept at 0 °C were stored under high RH conditions, so that any differences between cultivars in terms of weight loss were likely to have been minimised.

In contrast to the fresh fruit industry, fruit destined for processing are often stored under ambient conditions, necessitating information on how cultivars respond to ambient temperature. The softening rate of 'Granny Smith' apples approximately tripled when the storage temperature was raised from 0 to 20 °C (IPen). Despite these significant differences in softening rate, the overall difference in firmness loss between 'Granny Smith' fruit stored at 0 and 20 °C was only 7.7 N after 4 weeks storage. These results are in general agreement with those of Bradley and Brown (1969) who also found only modest textural changes in ambient-stored 'Granny Smith' apples. 'Braeburn' fruit responded quite differently to ambient temperatures,

exhibiting a rapid loss in firmness (Figs. 5-3; 5-4 and 5-6 - 5-8) and a tendency to go mealy at 20 °C. 'Braeburn' apples lost on average 19 and 24 N after 3 weeks storage at 10 and 20 °C respectively. The response of 'Fuji' apples to ambient temperatures was once again intermediate between that of 'Granny Smith' and 'Braeburn'. Comparing 'Braeburn' with 'Fuji' penetrometer results for the 1994 season, the decline in firmness for 'Braeburn' and 'Fuji' stored for 6 weeks at 20 °C was 38 and 22 N respectively. The results from this study are in agreement with those of D'Souza and Ingle (1989), Ingle and Morris (1989), and King and Henderson (1988) who found that the effect of delays into coolstorage or controlled atmosphere on softening behaviour varied with cultivar. The postharvest phase for fruit destined for processing often requires a period at ambient storage temperatures. Information on how cultivars respond to ambient temperatures is therefore important to: 1) ensure that the most vulnerable cultivars are coolstored; 2) enable maximum storage life at a series of temperatures to be predicted and 3) schedule processing so that maximum quality is obtained in all cultivars. In the case of the cultivars used in this study, 'Braeburn' fruit should be given priority with regard to coolstorage and scheduling, as 'Fuji' and 'Granny Smith' are considerably more tolerant to ambient conditions and possible delays in processing or coolstorage.

In these experiments, storage RH appeared to have little effect on fruit texture. This contrasts with the work of Hatfield and Knee (1988) who found that fruit subjected to an initial weight loss (5 %) were firmer, tougher and less mealy than control fruit after 4-5 months in cool storage. They attributed the loss of firmness in control fruit to an increase in the intercellular air space of the fruit, with a corresponding decrease in contact area between cells. In this work, the only suggestion of this effect was found in the 'Fuji' twist test data where, for a couple of assessments, fruit from the low RH storage regime were slightly firmer (Fig. 5-9). It is perhaps not surprising that the penetrometer measurements carried out on the same fruit, did not register a difference between the two RH treatments, since the penetrometer is more likely to be influenced by the compressibility of cells, with cells at lower turgor being more compressible, and hence registering a lower firmness value. In the work described in

this chapter, temperature would appear to be the dominant environmental factor affecting fruit texture, with any RH effects being secondary.

Cultivars need to be evaluated using a series of storage regimes in order to obtain sufficient information to tentatively predict storage life and corresponding quality. Linear and non-linear regression techniques can be utilised effectively to describe the relationship between firmness or any other textural attribute and storage duration. In 1993 most of the relationships between fruit texture and storage duration were effectively described using a linear function (Figs. 5-1 - 5-4). In 1994, data was collected more frequently, enabling closer definition of the relationship between fruit texture and storage duration. This was particularly evident in the 20 °C data where, in general, a declining exponential function (Eq. 5-1) effectively characterised fruit softening behaviour. Modelling fruit softening behaviour can provide rough estimates of storage potential for both fresh and processed products. Ingle and Morris (1989) modelled the softening behaviour of 'Rome' apples and used the model to try and predict softening rate at 0 °C from firmness data at harvest. Although the linear models used did not fit the data very well, they still enabled the rough prediction of maximum storage times. In the current study, 'Braeburn' acceptability thresholds were set at 650 kPa, 575 kPa, 59 N, 450 N for TMax, TBio, DPen and BKra, respectively. Non-coated fruit stored at 20 °C took between 1.1 and 2.3 weeks to reach these threshold values. This compared with 18 to 21 weeks for fruit stored at 0 °C.

Apple processors would like to be able to predict apple slice quality from raw product tests. This would enable them to produce a more consistent product line. Unfortunately, tests carried out on raw product quality do not always correlate highly with final product quality. Predicting blanched slice quality from raw fruit textural tests was also a component of this work. The relationship between raw fruit texture and blanched slice texture is illustrated in Figs. 5-13 and 5-14. Stepwise multiple regression revealed that 'Braeburn' blanched slice quality (BKra) could be adequately predicted using DPen (Eq. 5-3; $r^2 = 0.92$). In contrast, three variables (TMax, TBio

and SS) were utilised in the 'Fuji' model and the percentage of variance explained by the model was substantially less (Eq. 5-4; $r^2 = 0.62$). As discussed earlier, 'Braeburn' fresh fruit texture measurements tended to have higher correlation coefficients than 'Fuji': hence this higher level of intercorrelation may explain the reduced number of variables included in the model. The greater spread in 'Braeburn' firmness values generated by the various storage treatments, may also have enhanced the predictability of blanched slice texture in this cultivar. Other workers have also reported considerable differences between cultivars in terms of the mix of variables used in models and the level of success in predicting processed fruit quality. Wiley and Thompson (1960) found that no single raw product quality test correlated highly with overall final product quality. Combining several raw product tests using multiple regression techniques raised the correlation coefficients in some cultivars. Combining titratable acidity, shear-press and soluble solids for cultivars 'Stayman', 'Golden Delcious' and 'Rome Beauty' produced r^2 values between 0.59 and 0.66 in their study. McLellan *et al.* (1984a) developed a series of sensory components to account for intervarietal variation. In a further study (McLellan *et al.* (1984b), they characterised the relationship between these sensory components and objective tests carried out on both fresh and processed product. Perhaps surprisingly, in light of the textural differences found between the cultivars used in this study, they found that sensorily assessed firmness accounted for only 14 % of the variation between the apple slice cultivars used (McLellan *et al.*, 1984a). This may be due to: 1) a smaller spread in firmness values between and within cultivars due to fruit being coolstored throughout the study and/or 2) visual and taste differences between cultivars may be easier to characterise than textural differences.

One of the major objectives of this work was to determine the influence of cultivar and postharvest storage conditions on processing quality (either in terms of fully processed, canned apple or water-blanched apple slices). Once again, there were clear cultivar differences. 'Granny Smith' fruit produced a consistent, high quality product apparently irrespective of storage duration or temperature (Fig. 5-5a). This lack of textural decline in the processed product was probably due to the relatively

small changes in flesh firmness occurring in the raw product. However, free-juice volume did increase with high storage temperature and long duration. This effect may be due to cell fragility increasing, resulting in more cells rupturing and releasing their contents. In general, processors desire to minimise the amount of free-juice in the can, since it is largely considered to be a waste product by end-users such as pie and strudel manufacturers.

The textural quality of blanched slices produced from 'Fuji' fruit decreased linearly with increasing duration at both temperatures (Fig. 5-11). Quality of 'Braeburn' slices produced from fruit stored at 0 °C also declined with storage duration (Figs. 5.5 and 5.8). Wiley and Thompson (1960) also found that slice quality declined with increased storage duration and temperature, although early-harvested fruit required a short period of storage before making slices of highest quality. They compared cold and ambient storage regimes and found that ambient storage approximately halved fruit storage life.

Perhaps the most dramatic results were produced by slices made from 'Braeburn' fruit, in which quality dropped to an unacceptable level after just three weeks storage at 20 °C. This was probably due to the fruit becoming mealy during ambient storage, resulting in cell separation during the blanching phase of processing. Reeve and Leinbach (1953) also found that some apple cultivars had a greater tendency to sauce and that mealy apples were more predisposed towards tissue sloughing. Detecting mealiness in 'Braeburn' apples may therefore be more important than apple firmness, although in this case mealy fruit also tended to be soft. Several studies have recently focused on the development and detection of mealiness in apples (Harker and Hallett, 1992; Khan and Vincent, 1993; Tu *et al.*, 1996). Mealiness in apple fruit has been associated with increases in internal air space, low adhesion between neighbouring cells and a relatively high resistance to cell rupture. Despite the recent attention given to the development of mealiness in apples, the difficulty remains in differentiating between mealy and non-mealy apples by instrumental means (Tu *et al.*, 1996). This contrasts with a recent study on nectarines, in which the presence or

absence of juice on the fracture surface after a tensile test clearly differentiated between mealy and non-mealy fruit (Harker and Sutherland, 1993). However, the destructive and complex nature of such assessment would preclude its use in commercial operations.

Acidity tended to decrease with increasing storage duration and temperature (Tables 5-3 and 5-4). These results agree with those of Wiley and Thompson (1960), Lee *et al.* (1965) and McLellan and Massey (1984). Malic acid, the primary organic acid in apple, is a major respiratory substrate, with levels falling up to 50 % during a fruit's storage life (Fidler and North, 1967; Knee, 1993). This decline may account for the corresponding increase in fruit pH levels.

One of the objectives of the 1994 experiment was to determine whether or not treatments which delay loss of average firmness result in an increased variability in firmness levels. In order to evaluate this hypothesis, one of the treatments in this experiment involved coating the fruit with CMC. Surface coatings such as CMC can result in variable $p^{i}_{O_2}$ values which may lead to an increase in fruit-to-fruit variability in terms of fruit respiration and other associated metabolic processes including fruit softening. Textural degradation in coated fruit tended to be more gradual (Figs. 5-6c & d; 5-7b; 5-8b; 5-11b). Saltveit (1978) found that apple-to-apple variability tended to decrease with storage. In the case of 'Fuji', the coating treatment did not enhance fruit-to-fruit variability. In contrast, coated 'Braeburn' apples produced considerably more variable apple slices (Fig. 5-8). This effect may be due to coated fruit taking longer to get through the intermediate stages of ripening, where there is a greater spread in fruit texture, compared to the initial and final stages of ripening. This increased variability during the intermediate stages may be caused by fruit within a sample entering the rapid softening phases at different times, hence increasing variability. However, this does not appear to have been the case in this study, as coated fruit variance for both the fresh and blanched product did not change appreciably with storage time. For slices made from fruit previously stored at 20 °C, variability was lower for samples made from non-coated fruit (Fig. 5-8b). This

difference in treatment variability was presumably due to the low variation resulting from of excessively soft slices that was found in slices made from non-coated fruit.

The data generated from this work enabled some comparisons to be made of the instrumental tests used in this work. As would be expected, TMax and TBio were highly correlated (r=0.97), arising from different values from the same test. However the penetrometer and twist test were not highly correlated, suggesting they may respond to different properties that affect fruit texture. For example, the penetrometer test may be more influenced by cell turgor and compressibility than the twist test, whereas the twist test may relate more strongly to variation in shear strength.

Principal component analysis showed that in both years the dimensionality of the data could be reduced from 4 to 2. PC1, an apparent measure of overall tissue strength comprised equal contributions from each of the texture measurements. PC2, contrasted the twist test measurements with the other measurements of texture and, as discussed above, would suggest that the two sets of tests are measuring different aspects of texture. Development of models that describe textural degradation in fresh and processed apples is an important tool to being able to predict storage life and quality. In this study, linear and non-linear functions (declining exponential and Michaelis-Menten) were used to describe the relationship between storage duration and fresh or processed slice quality. Fruit softening rates increased with storage temperature for each of the cultivars studied.

Optimising the postharvest environment plays a key role in maintaining fruit texture and quality, and producing apple slices of a high and consistent standard. This study has clearly shown the importance of the pre-processing environment (temperature, storage duration and RH) on product textural quality, and has highlighted the particular importance of cultivar attributes. Of the cultivars used in this study, 'Granny Smith' was the best performer, producing high quality, consistent slices throughout the course of these experiments. 'Fuji' apples also processed well,

retaining their texture well throughout storage and being relatively tolerant of ambient temperatures. 'Braeburn' fruit produced good consistent slices provided the fruit remained in coolstorage throughout the postharvest period. 'Braeburn' fruit quality rapidly deteriorated on exposure to ambient temperatures.

Chapter 6

Influence of surface coatings and calcium dips on raw and processed apple texture

6.1 Introduction

Retarding texture degradation during the postharvest phase is crucial if processed product quality is to be of a high and consistent standard. Unlike some other quality attributes, such as sweetness (Wiley and Binkley, 1989), texture can not be easily rectified during the processing phase. Ensuring that textural quality remains high is therefore vital if a high quality solid-pack product is to be produced. Apples entering the process should be firm and crisp (but not immature) to ensure that these characteristics are carried through into the processed product (Wiley and Binkley, 1989). Providing a suitable storage environment is therefore crucial if product quality is to be maintained. The fresh fruit export industry in NZ has used refrigerated storage, high RH storage, CA, and MA using polyliners to maintain product quality. Fruit destined for processing tend to be cool or ambient stored (J. Wattie Foods, personal communication, 1992). Retaining raw product quality throughout the postharvest phase by cost effective means is one of the key objectives of processors. The broad objective of the study described in this chapter was to investigate the potential for supplementing or supplanting refrigeration for enriching processed slice quality with the use of edible surface coatings and/or pre- or post-harvest application of calcium.

Edible surface coatings can enhance perceived fruit quality by improving product appearance and diminishing deterioration by reducing water loss and achieving modified atmosphere benefits (Banks *et al.*, 1997). The effects of coatings on fresh fruit quality have been well documented (Smock, 1935; Trout *et al.*, 1952; Smith and

Stow, 1984; Chu, 1986; Santerre *et al.*, 1989; Drake and Nelson, 1990; Lau and Meheriuk, 1994). Recent studies have also investigated the application of edible coatings to minimally processed fruits and vegetables (Baldwin *et al.*, 1995). There is, however, a dearth of information concerning the effects of coatings, or indeed other forms of modified atmosphere (MA) or controlled atmosphere storage (MA storage in which O_2, CO_2 and C_2H_4 levels are precisely controlled), on processed fruit quality. A study on 'pineapple oranges', by Nisperos-Carriedo *et al.* (1990), found that juice made from coated fruit contained higher levels of certain key volatile components responsible for producing a distinctive orange flavour. McLellan *et al.* (1990) carried out a study to determine the effects of CA storage management on blanched apple slice quality. They found that blanched slices made from 'Golden Delicious' apples that were put into CA storage at harvest produced texturally superior slices, compared to those that experienced a delay of up to 4 weeks before entering CA storage.

Benefits associated with MA storage include a reduction in product respiration and ethylene production rates; retention of firmness, skin ground colour, titratable acidity, nutritional value and sensory quality; and inhibition of some physiological disorders (Kader *et al.*, 1989; Ke *et al.*, 1991). A number of risks are also associated with MA storage including the development of off-flavours, accumulation of ethanol and acetaldehyde, and development of low-O_2 and/or high CO_2 disorders (Kader, 1986; Cohen *et al.*, 1990). Potential benefits and risks of MA storage are determined by the level of atmospheric modification achieved in the fruit (Banks *et al.*, 1993a, 1993b; refer 2.5.3.3).

The first part of this chapter describes a series of experiments designed to ascertain the feasibility, and potential benefits and risks, of using edible surface coatings for ambient or cool stored fruit destined for processing (6.2.1 & 6.2.2). One of the objectives of this work was to optimise CMC coating concentration (6.2.2). Unfortunately fruit used in the 1994 experiments were of a lower quality than those from other seasons, due to a supply problem brought about by the devastating effects

of a hail storm in the Hawkes Bay region (one of New Zealand's principal apple producing areas). Hence part of the experiment was repeated in 1995 to confirm trends identified during the 1994 experiments.

The second part of this chapter is concerned with the effects of calcium applied during the pre- or post- harvest phases on processed slice quality. Calcium's role in maintaining fruit firmness and reducing the incidence of physiological disorders is well documented (Poovaiah *et al.*, 1988; Glenn and Poovaiah, 1990; Sams *et al.*, 1993; refer 2.5.3.4). Its role as a firming agent has also long been recognised by the processing industry (van Buren, 1979; Drake and Spayd, 1983; Blackler, 1992; Stanley *et al.*, 1995; Usiak *et al.*, 1995; refer 2.3.3). The experiments described here were designed to determine whether or not additional benefits in the processed product could be gained by enhancing fruit calcium levels during the pre- or post-harvest phase. Several approaches were used to try and increase fruit calcium content, including dips with or without food thickeners. One of the other approaches involved applying a preharvest dip in an attempt to stimulate fruit transpiration and hence boost the amount of calcium taken up in the xylem stream during fruit development. Transpiration accelerants have been successfully used to enhance the calcium status of grapes (During and Oggionni, 1986) and kiwifruit (Davie, 1997).

6.2 Materials and methods

6.2.1 Surface coatings

6.2.1.1 Experimental design

Commercially mature apples (*Malus domestica* Borkh.) of two cultivars, 'Braeburn' and 'Granny Smith' of count size 100 (average weight 0.185 kg) from each of four Hawkes Bay growers were obtained through J. Wattie Foods. 'Braeburn' and 'Granny Smith' fruit were initially stored in air at 0 °C for approx. 3 and 1 week(s) respectively before the application of treatments.

Cartons of fruit were randomly allocated to storage at either 0 or 20 °C. The following treatments were randomly applied to trays of fruit:

1) Control: non-coated
2) Surface coating: 2 % (w/v) low viscosity carboxymethylcellulose sodium salt (CMC; BDH Chemicals, UK)
3) Calcium dip: 0.4 M $CaCl_2$
4) Surface coating incorporating calcium: 2 % CMC (w/v) + 0.4 M $CaCl_2$ (BDH Chemicals, UK)

Treatments 2, 3 and 4 also included the wetting agent 'Pulse' (0.1 % w/v; Monsanto, New Zealand) to facilitate even wetting of the fruit surface. CMC solutions were applied to the fruit surface manually using a soft bristled brush. Fruit receiving the calcium dip were held in the solution for 2 min. Following treatment, fruit were allowed to dry before repacking and transfer to storage environment.

'Granny Smith' fruit stored at 20 °C were assessed after six weeks, while those stored at 0 °C were assessed after 6 and 20 weeks. The initial assessment for 'Braeburn' fruit stored at both temperatures was carried out after 4 weeks. After 20 weeks storage, there was a second assessment for those fruit stored at 0 °C. The experimental design was a randomised block factorial.

6.2.1.2 Fresh and processed product assessment

The internal atmosphere of 4 fruit per treatment per grower was sampled for O_2 and CO_2 as described in section 3.1.1. Raw product texture was assessed using the twist test (TMax, TBio), drill mounted penetrometer (DPen), Instron mounted penetrometer (IPen) and Kramer shear cell (FKra), as described in sections 3.1.3.1-3.1.3.3. Soluble solids were estimated from juice expressed during the penetrometer test, as described in 3.1.4, and plugs of tissue taken for calcium analysis. The method used for calcium analysis is described in section 3.1.5. Slices were processed as described in section 3.2, with a thermal process time of 22 minutes. Processed slice quality was assessed using the procedure outlined in section 3.3, although the compression test

was not carried out.

6.2.2 Optimisation of surface coating

6.2.2.1 1994 Season

Commercially mature 100 count 'Braeburn' and 'Fuji' apples (*Malus domestica* Borkh.) were obtained from 4 Hawkes Bay growers. 'Braeburn' and 'Fuji' fruit were initially stored in air at 0 °C for approx. 5 and 2 weeks respectively, before the application of treatments. The experiment was a randomised block factorial design with growers as blocks. Cartons of fruit were randomly allocated for storage at either 0 or 20 °C. Fruit stored at 20 °C were coated with either 0, 1, 2, 3, or 4 % (w/v) carboxymethylcellulose sodium salt (CMC). Fruit stored at 0 °C were coated with either 0, 2, 4, 6, or 8 % (w/v) CMC. Each CMC solution also contained 0.1 % (w/v) 'Pulse'. Trays within cartons were randomly allocated to coating treatment. Fruit at 20 °C were assessed after 5 weeks, while those stored at 0 °C were assessed after 6 and 16 weeks storage.

6.2.2.2 1995 season

Commercially mature 100 count 'Braeburn' apples were obtained from five Hawkes Bay growers. Fruit were initially stored at 0 °C in air for approx. 1 week before the application of treatments. The experiment was a randomised block factorial design with growers as blocks. Trays within cartons were randomly allocated to coating treatments. Fruit were coated with either 0, 1, 2, 3, or 4% (w/v) CMC. Each CMC solution also contained 0.1 % (w/v) 'Pulse'. Fruit were stored at 20 °C and assessed after 3 weeks.

6.2.2.3 1994 and 1995 assessment procedures

The internal atmospheres of 3 (1994) or 5 (1995) fruit per grower per treatment were

sampled as described in section 3.1.1. Fresh fruit textural quality was assessed using the twist test and drill mounted penetrometer as described in sections 3.1.3.1 and 3.1.3.2, respectively. Fruit background colour and soluble solids contents were also measured as detailed in sections 3.1.2 and 3.1.4, respectively. Fruit were processed using the procedure described in section 3.2, with a thermal process time of 28 min. Processed product was assessed as specified in section 3.3, though juice pH, tissue relative density and slice dry matter content were not determined.

6.2.3 Preharvest experiment

Davie (1992, personal communication) screened a number of potential transpiration accelerants (including oleic acid, calcium chloride, butyric acid, potassium hydroxide, calcium hydroxide). He screened a number of fruit and found oleic acid and calcium chloride the most suitable for enhancing water loss in apples. As part of this study, a preliminary experiment was then carried out using a range of concentrations of oleic acid and $CaCl_2$ to ascertain the most suitable material and concentration (data not presented). Calcium chloride was found to be the most suitable transpiration accelerant of the materials tested. The main experiment was carried out at Massey University's Fruit Crops Unit Orchard, on sixteen mature 'Braeburn' apple trees. The experiment was a split-plot design with pairs of trees as blocks, whole trees as main plots (main plot factor = storage period) and treatments within trees as sub-plots. Each treatment was applied to 30 fruit in each subplot. The following treatments were applied to individual fruit on six dipping dates throughout the growing season:

1) Dry control
2) Wet control - 0.1 % (w/v) Triton X-100 (wetting agent)
3) Transpiration accelerant - 0.09 M $CaCl_2$ & 0.1 % (w/v) Triton X-100

Rate of water loss was estimated on five fruit from each tree 2 days after the first application of $CaCl_2$ and at harvest. Change in fruit or fruitlet weight was measured in an airstream with a water vapour pressure difference between fruit and airstream

(Δp_{H2O}) of approx. 2.1 and 1 kPa for the first and second assessments, respectively. Fans were used to remove any air boundary layer effects. Fruit skin permeance to water vapour (P'_{H2O}) was estimated using a re-arrangement of Eq. 2-2, with surface area being estimated from weight using regression equations developed by Clayton *et al.* (1995).

Fruit were picked during the commercial harvest period and cool stored at 0-1 °C prior to processing. Fruit were assessed at harvest and after 20 weeks cool storage. Fruit were processed and assessed as outlined in section 6.2.1.2.

6.2.4 Calcium dips

The experiment was carried out on 'Braeburn' fruit from four Hawkes Bay growers. Fruit were initially stored in air at 0 °C for approx. 2 weeks before the application of treatments. Fruit were dipped for two minutes in either 0, 0.2, 0.6, 0.8 or 1.0 M solutions of $CaCl_2$. Fruit were cool stored at 0-1 °C for 20 weeks prior to assessment and processing. Fruit were processed and assessed as outlined in section 6.2.1.2.

6.3 Results

6.3.1 Surface coatings

6.3.1.1 1993 experiment

Internal atmosphere composition of the fruit

Application of a surface coating significantly altered the internal atmosphere composition of 'Granny Smith' and 'Braeburn' apples stored at 0 or 20 °C ($P < 0.0001$; Figs. 6-1 and 6-2; Tables 6-1 and 6-2). Atmosphere modification was more pronounced at 20 °C ($P < 0.0001$). 'Granny Smith' CMC-coated fruit stored at 20 °C, contained less than a fifth as much O_2 and almost twice as much CO_2 as

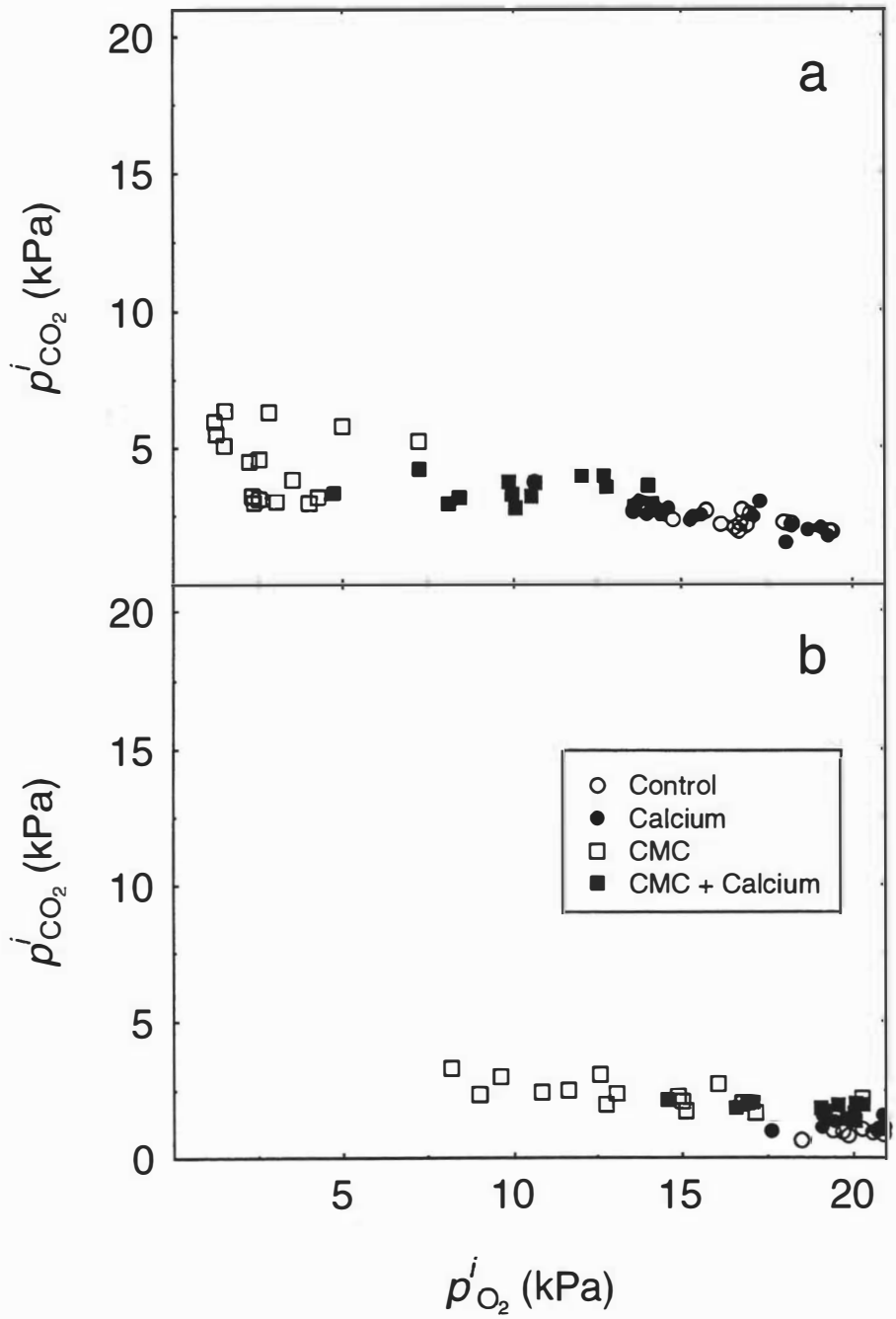


Fig. 6-1 The effect of surface coatings on internal partial pressure of oxygen (p^i_{O2}) and internal carbon dioxide partial pressure (p^i_{CO2}) of 'Granny Smith' apples stored at a) 20°C or b) 0°C in 1993.

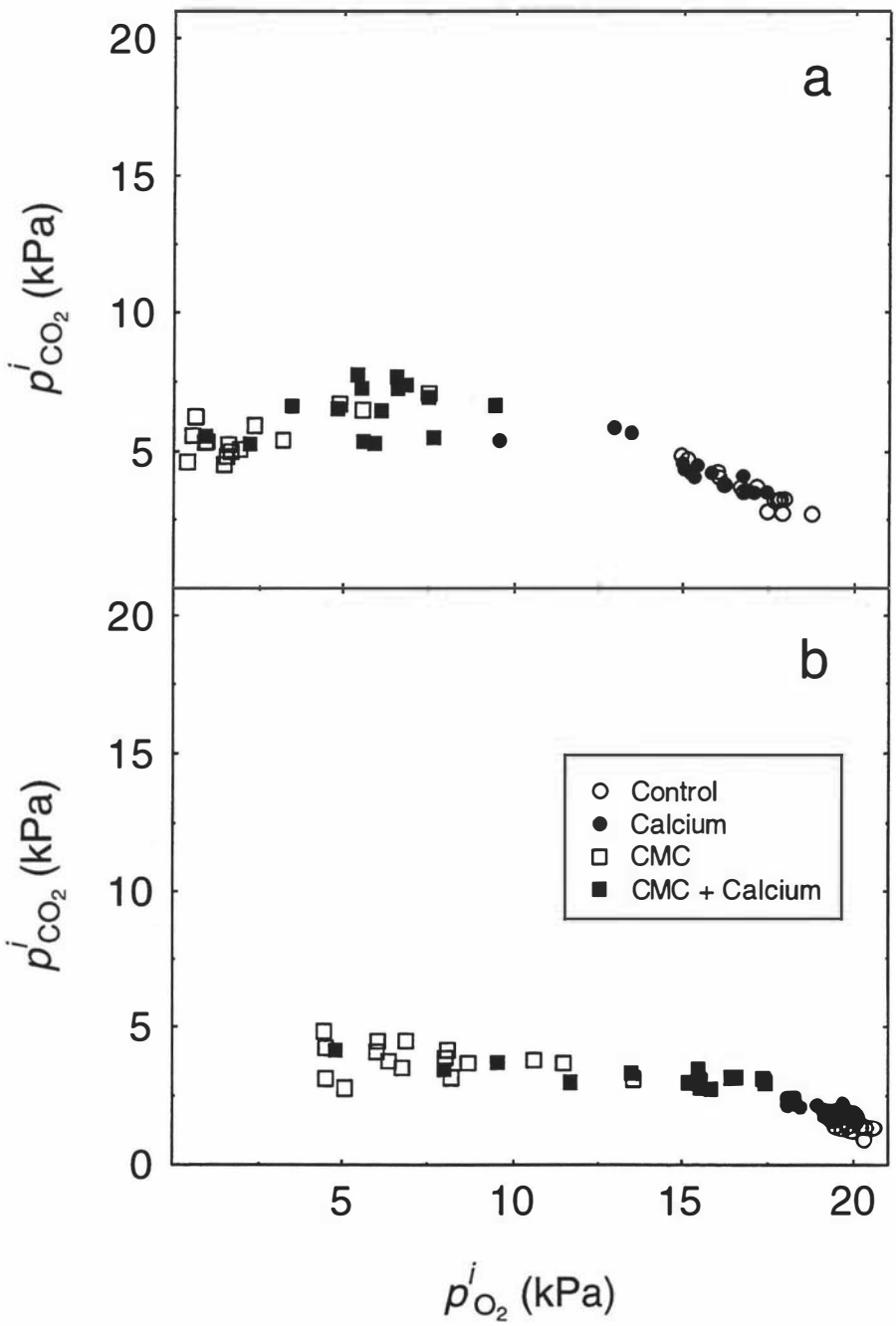


Fig. 6-2 The effect of surface coatings on internal partial pressure of oxygen (p^i_{O2}) and internal carbon dioxide partial pressure (p^i_{CO2}) of 'Braeburn' apples stored at a) 20°C or b) 0°C in 1993.

control fruit. At 0 °C CMC-coated fruit contained two thirds as much O_2 and almost twice as much CO_2 as control fruit. The combined dip containing CMC and calcium was less effective in terms of atmosphere modification, than CMC alone ($p^i_{O_2}$ $P < 0.0001$; $p^i_{CO_2}$ $P < 0.005$).

'Braeburn' fruit behaved in a similar way to 'Granny Smith' fruit, but the degree of internal atmosphere modification was somewhat greater in 'Braeburn' fruit. 'Braeburn' fruit coated with CMC and stored at 20 °C contained less than a fifth as much oxygen and about half as much again carbon dioxide as control fruit. At 0 °C, coated fruit contained only about a third as much oxygen and more than twice as much carbon dioxide than control fruit. Fruit coated with the combined dip containing CMC and calcium contained significantly more O_2 than those coated with just CMC ($P < 0.0001$).

Table 6-1. Internal oxygen ($p^i_{O_2}$) and carbon dioxide ($p^i_{CO_2}$) partial pressures in 'Granny Smith' apples with different coating treatments (means ± SD).

Treat		0 °C	20 °C
Cont	$p^i_{O_2}$	20.9 ± 1.04	16.3 ± 2.18
	$p^i_{CO_2}$	0.9 ± 0.11	2.4 ± 0.37
Ca	$p^i_{O_2}$	20.6 ± 1.23	16.2 ± 1.56
	$p^i_{CO_2}$	1.2 ± 0.17	2.4 ± 0.20
CMC	$p^i_{O_2}$	13.8 ± 2.04	3.0 ± 0.97
	$p^i_{CO_2}$	2.4 ± 0.19	4.5 ± 1.34
CMC&Ca	$p^i_{O_2}$	19.2 ± 1.96	10.8 ± 2.53
	$p^i_{CO_2}$	1.8 ± 0.19	3.4 ± 0.35

Table 6-2. Internal oxygen ($p^i_{O_2}$) and carbon dioxide ($p^i_{CO_2}$) partial pressures in 'Braeburn' apples with different coating treatments (means ± SD).

Treat		0 °C	20 °C
Cont	$p^i_{O_2}$	19.9 ± 0.23	17.0 ± 0.71
	$p^i_{CO_2}$	1.5 ± 0.19	3.5 ± 0.42
Ca	$p^i_{O_2}$	19.2 ± 0.60	15.3 ± 0.31
	$p^i_{CO_2}$	2.0 ± 0.25	4.3 ± 0.23
CMC	$p^i_{O_2}$	7.5 ± 1.69	2.3 ± 0.74
	$p^i_{CO_2}$	3.8 ± 0.25	5.6 ± 0.31
CMC&Ca	$p^i_{O_2}$	14.2 ± 2.60	5.7 ± 1.72
	$p^i_{CO_2}$	3.1 ± 0.14	6.5 ± 0.84

Textural and other quality characteristics of the fruit

Applying CMC as a surface coating to 'Granny Smith' or 'Braeburn' fruit was an effective means of delaying textural loss (Figs. 6-3 - 6-6). Each of the tests used to evaluate fruit firmness showed similar treatment trends but the magnitude of difference between treatments varied with test. Storage temperature ($P < 0.04$-0.0001) and coating treatment ($P < 0.0005$-0.0001) significantly affected texture degradation in short term stored (6 week) 'Granny Smith' fruit (Fig. 6-3). CMC-coated 'Granny Smith' fruit stored at 20 °C were on average 23 % firmer (averaged across all tests) than control fruit after 6 weeks storage. Coated fruit stored at 0 °C for the same period were on average 7 % firmer than non-coated fruit. There was also a significant interaction ($P < 0.01$-0.005) between calcium and coating treatment. CMC combined with calcium was less effective than CMC alone with regard to texture retention ($P < 0.003$). There was no significant difference between control and calcium dipped fruit.

Fruit coated with the combined dip containing calcium and CMC, contained significantly more calcium than either the untreated fruit ($P < 0.0001$) or the fruit

that received a standard calcium dip ($P < 0.0001$; Table 6-3). Storage temperature did not significantly affect fruit calcium status.

Table 6-3. Effect of surface coatings on the calcium content (mg/g dw) of 'Granny Smith' and 'Braeburn' apples.

Cultivar	Cont	Ca	CMC	CMC&Ca	SED
'Granny Smith'	0.328	0.308	0.298	0.489	0.0377
'Braeburn'	0.278	0.348	0.257	0.388	0.0206

For fruit stored at 0 °C and assessed after 6 and 20 weeks, grower line ($P < 0.0001$), assessment date ($P < 0.0001$) and coating treatment ($P < 0.001$-0.0001) significantly affected fruit texture (Fig. 6-4). There was also a significant interaction between calcium and coating treatment ($P < 0.004$-0.001). CMC ($P < 0.01$ -0.0001) and calcium ($P < 0.02$-0.001) treated fruit were significantly firmer than control fruit at 20 weeks.

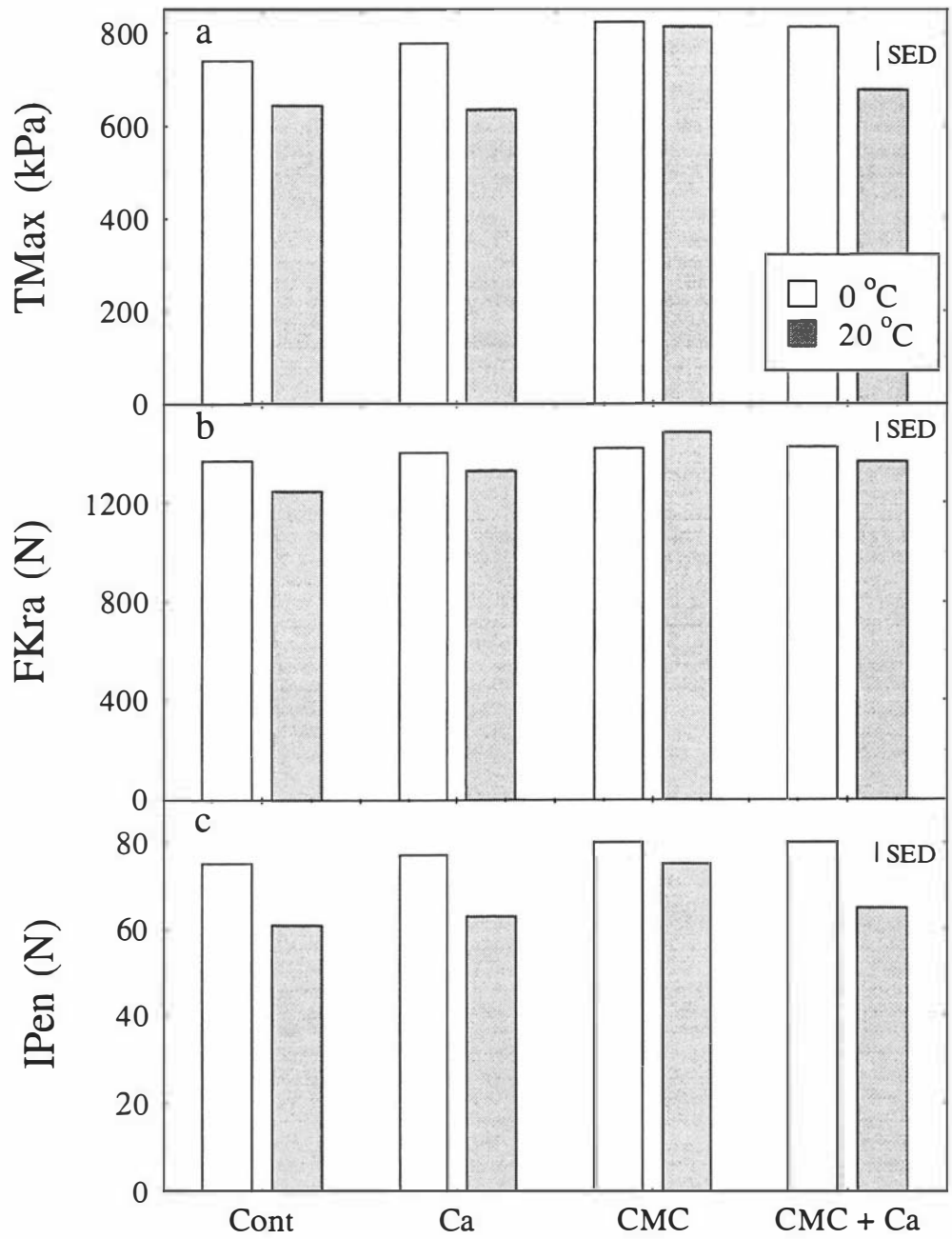


Fig. 6-3 Influence of surface coatings, calcium dips and storage temperature on fruit firmness of 'Granny Smith' apples as determined by a) twist test (TMax); b) Kramer shear cell (FKra) and c) penetrometer (IPen), after 6 weeks.

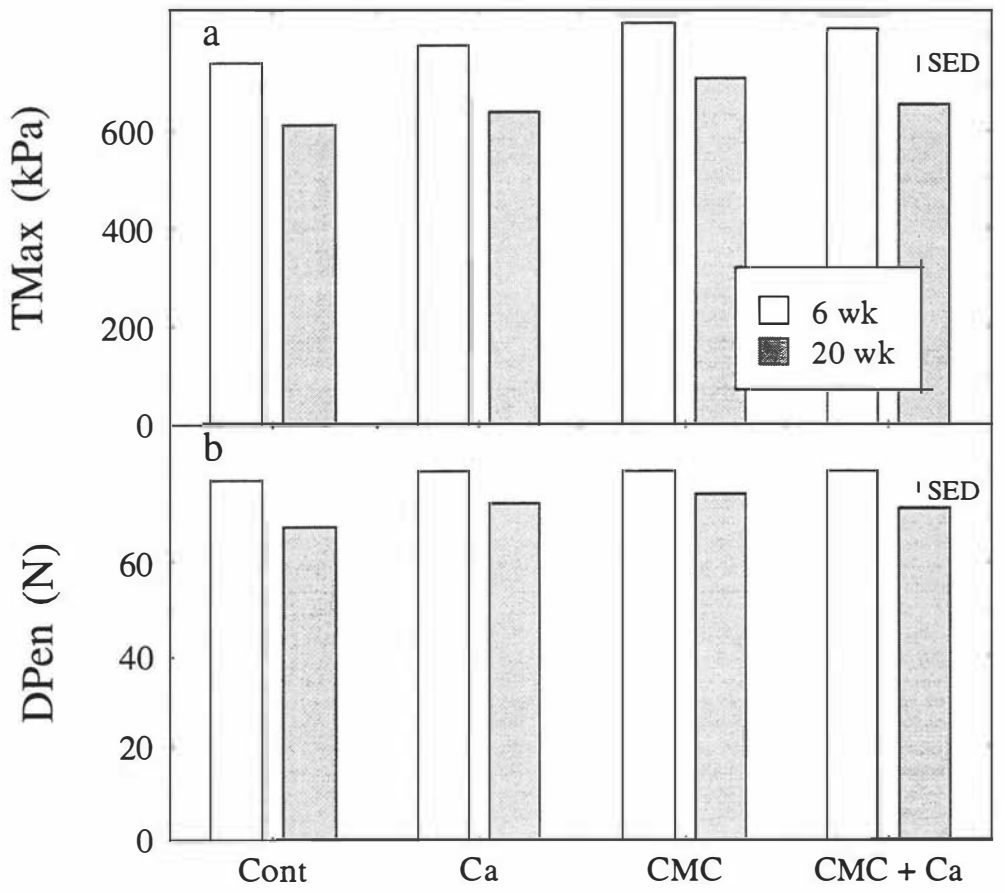


Fig. 6-4 Influence of surface coatings, calcium dips and storage duration at 0 °C on fruit firmness of 'Granny Smith' apples as determined by a) twist test (TMax) and b) penetrometer (DPen).

Similar results were achieved with 'Braeburn' fruit. Storage temperature ($P < 0.01$-0.0001) and coating treatment ($P < 0.09$-0.004) significantly affected fruit texture of 'Braeburn' apples stored for 4 weeks at either 0 or 20 °C (Fig. 6-5). CMC-coated fruit stored for 4 weeks at 20 °C were on average 27 % firmer than non-coated fruit. At 0 °C, only the twist test detected a difference in firmness after 4 weeks between coated and non-coated fruit, with coated fruit being 10 % firmer than non-coated fruit. There was no significant difference between control and calcium dipped fruit or between CMC-coated and CMC & calcium-coated fruit. There were no significant interactions between temperature and coating treatments. Fruit treated with calcium (Ca and CMC&Ca) contained 38 % more calcium than untreated fruit ($P < 0.0002$; Table 6-3). Coating treatments were also effective at delaying textural loss in fruit stored at 0 °C for 20 weeks ($P < 0.07$-0.005; Fig. 6-6). CMC-coated fruit were on average 19 % firmer than non-coated fruit.

Processed product quality

Surface coatings enhanced the quality of slices produced for both 'Granny Smith' and 'Braeburn' cultivars (Tables 6-4 - 6-7). 'Granny Smith' apples produced a good consistent solid-pack product. Textural changes associated with storage duration (6 vs 20 wks) were modest. However, under both storage regimes, CMC-coated fruit produced slices of a better textural quality than non-coated fruit ($P < 0.001$). Slice integrity was maintained well throughout storage at 0 °C, but decreased slightly in slices produced from fruit stored at 20 °C.

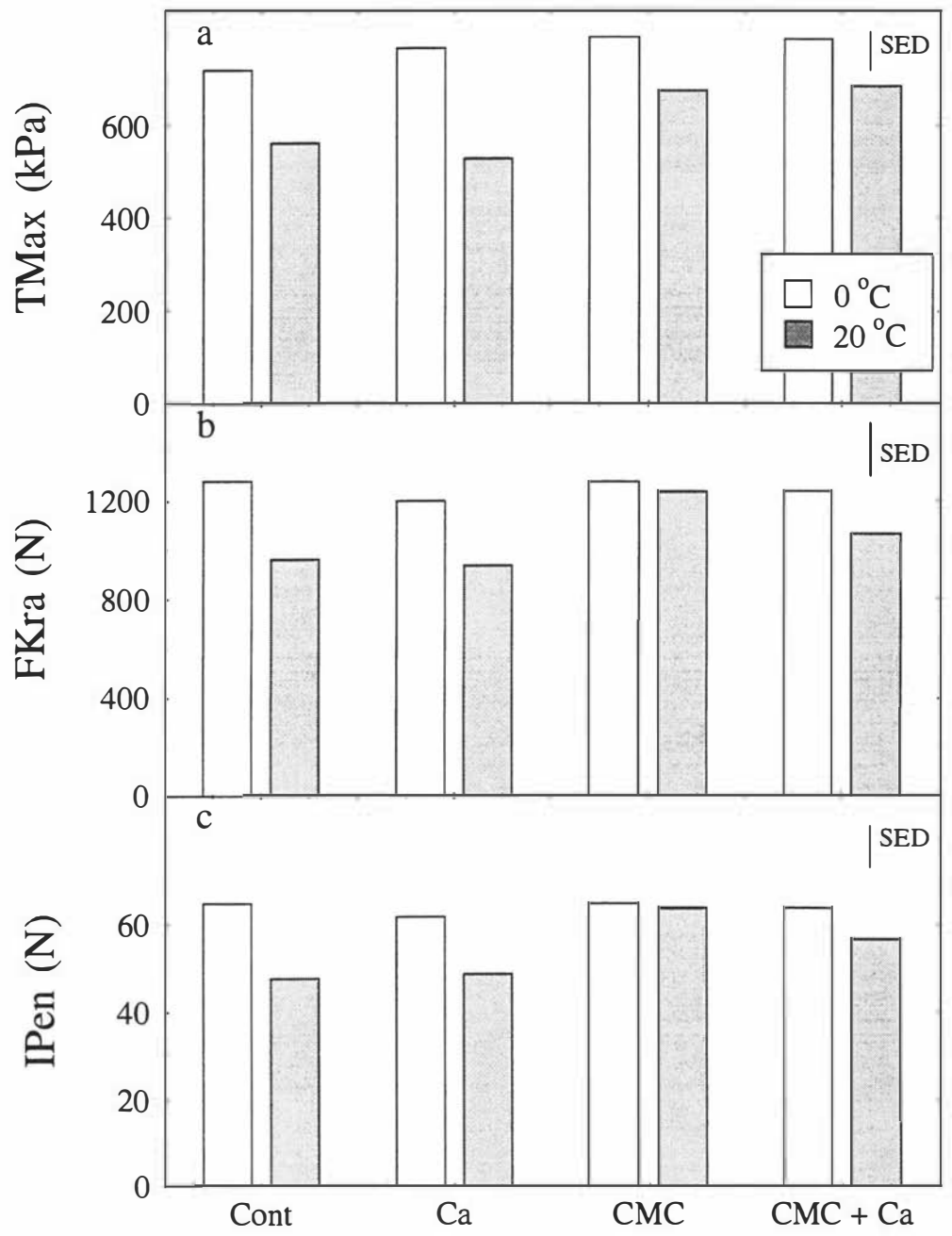


Fig. 6-5 Influence of surface coatings, calcium dips and storage temperature on fruit firmness of 'Braeburn' apples as determined by a) twist test (TMax); b) Kramer shear cell (FKra) and c) penetrometer (IPen), after 4 weeks.

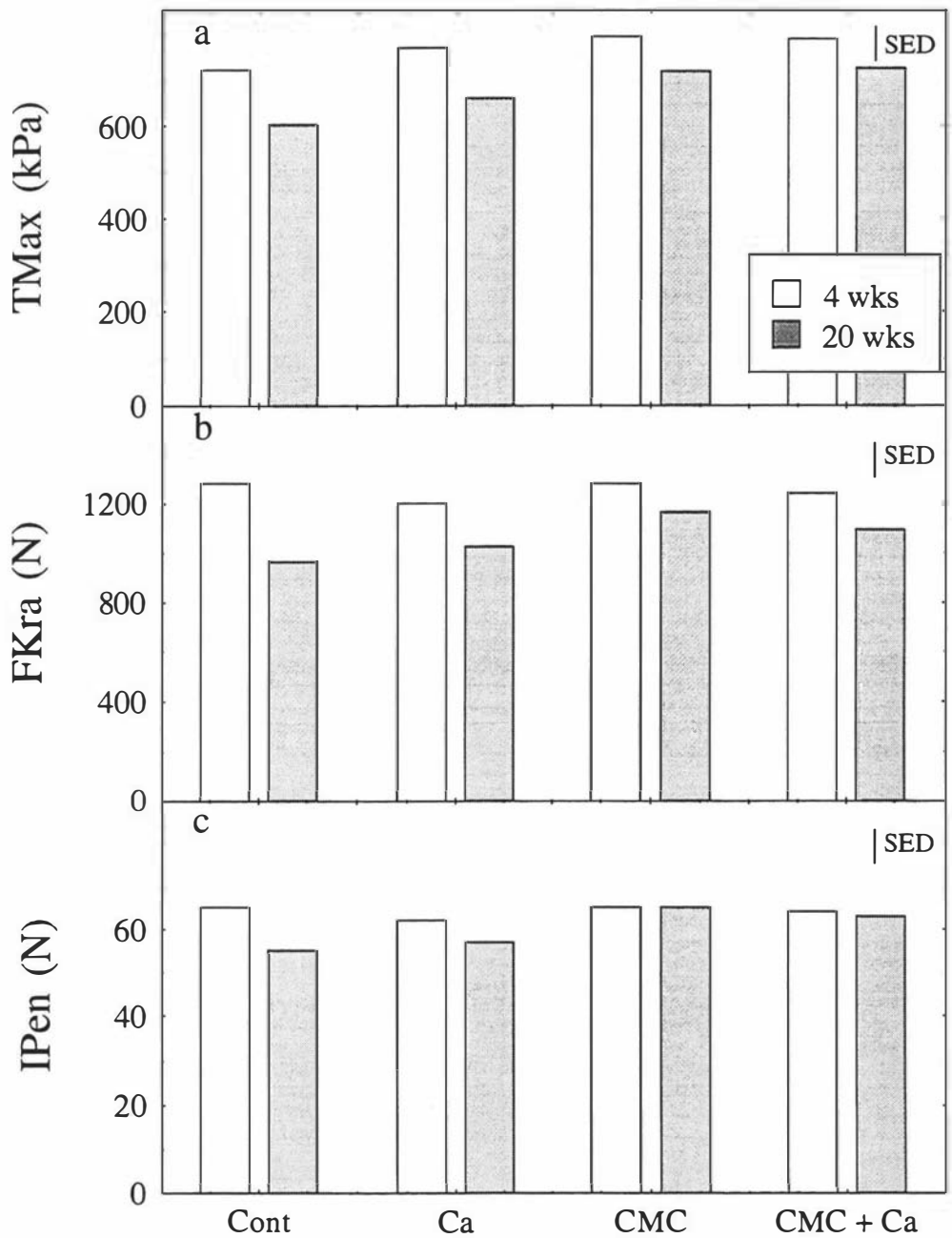


Fig. 6-6 Influence of surface coatings, calcium dips and storage duration at 0 °C on fruit firmness of 'Braeburn' apples as determined by a)twist test (TMax); b) Kramer shear cell (FKra) and c) penetrometer (IPen).

Table 6-4. Effect of surface coatings and temperature on the quality of 'Granny Smith' solid-pack slices, made from fruit stored for 6 weeks before processing.

Variable	Temp	Cont	Ca	CMC	CMC&Ca	SED
Kramer shear	0	362	332	419	434	31
(N)	20	329	356	467	371	
Juice vol.	0	31.8	22.9	15.4	23.4	5.17
(ml)	20	41.3	33.8	29.3	30.8	
pH	0	3.17	3.17	3.15	3.16	0.018
	20	3.28	3.27	3.29	3.28	
SS	0	8.6	8.6	8.6	8.6	0.18
(%)	20	7.9	8	8.3	8.2	
ρ_{rel}^{slice}	0	1.040	1.030	1.028	1.028	0.0052
	20	1.035	1.035	1.038	1.035	
integ.[x]	0	1	1	1	1	
	20	1.25	1.25	1	1.25	

[x] Slice integrity scale ranging from 1 (excellent) to 5 (poor).

The free-juice volume was significantly higher in solid-pack slices produced from 'Granny Smith' apples stored either under high temperatures (20 °C; $P < 0.001$) or for a long period (20 wks; $P < 0.02$) at 0 °C. However, surface coatings significantly reduced the amount of free-juice in the can, under both storage regimes ($P < 0.01$). The pH of the free juice in the can was higher in both the product made from fruit stored at 20 °C ($P < 0.0001$) and the fruit stored at 0 °C for 20 weeks ($P < 0.0001$) than fruit stored at 0 °C for 6 weeks. Soluble solids were also lower in product made from apples stored under these conditions ($P < 0.0001$). The relative density of slices (ρ_{rel}^{slice}) did not change appreciably with storage temperature, but increased slightly with storage duration ($P < 0.01$).

Table 6-5. Effect of surface coatings and storage duration at 0 °C, on the quality of 'Granny Smith' solid-pack slices.

Variable	Storage	Cont	Ca	CMC	CMC&Ca	SED
Kramer shear	6	362	332	419	434	34
(N)	20	399	395	471	433	
Juice vol.	6	31.8	22.9	15.4	23.4	4.41
(ml)	20	39.6	28.7	21.2	26.7	
pH	6	3.17	3.17	3.15	3.16	0.025
	20	3.38	3.38	3.33	3.34	
SS	6	8.6	8.6	8.6	8.6	0.15
(%)	20	7.7	7.8	7.9	7.9	
ρ_{rel}^{slice}	6	1.040	1.030	1.028	1.028	0.0052
	20	1.038	1.038	1.040	1.038	
integ.[x]	6	1	1	1	1	
	20	1	1	1	1	

[x] Slice integrity scale ranging from 1 (excellent) to 5 (poor).

'Braeburn' fruit produced a less consistent product. Non-coated, control 'Braeburn' fruit stored at 20 °C under high RH conditions tended to produce soft processed slices that rapidly disintegrated on handling (Table 6-6). The application of surface coatings to fruit stored under high temperature conditions significantly enhanced the texture of slices produced from these fruit ($P < 0.0001$). CMC was more effective that the combined coating containing CMC and calcium at reducing texture degradation in slices made from fruit stored at 20 °C.

The results suggest that surface coating had no effect on the free-juice content. However, observations made at the time of assessment indicate that the small juice volume obtained in product made from control and calcium dipped fruit stored at 20 °C was due to some of the product being rather saucy. Storage temperature significantly affected the pH and soluble solids content of the juice ($P < 0.0001$), but had no effect on the relative density of the slices.

Table 6-6. Effect of surface coatings and temperature on the quality of 'Braeburn' solid-pack slices, made from fruit stored for 4 weeks before processing.

Variable	Temp	Cont	Ca	CMC	CMC&Ca	SED
Kramer shear	0	417	377	393	435	49
(N)	20	116	133	451	330	
Juice vol.	0	39.3	31.8	32.5	23.5	5.55
(ml)	20	20.3	18.8	32.5	37.0	
pH	0	3.29	3.29	3.33	3.26	0.027
	20	3.4	3.41	3.45	3.41	
SS	0	9.5	9.4	9.6	9.5	0.40
(%)	20	8.6	7.6	8.4	8.8	
ρ_{rel}^{slice}	0	1.035	1.042	1.042	1.043	0.0047
	20	1.044	1.041	1.039	1.042	
integ.[x]	0	1.5	1	1.25	1	
	20	5	4.75	1.25	2.5	

[x] Slice integrity scale ranging from 1 (excellent) to 5 (poor).

Coated 'Braeburn' fruit stored at 0 °C produced slices that were somewhat firmer than the control and calcium dipped fruit (Table 6-7; $P < 0.02$), although texture differences only became evident after long term storage. Storage duration did not affect free-juice volume, but did affect the pH ($P < 0.0001$) and soluble solids content ($P < 0.0001$) of the juice.

Table 6-7. Effect of surface coatings and storage duration at 0 °C, on the quality of 'Braeburn' solid-pack slices.

Variable	Storage	Cont	Ca	CMC	CMC&Ca	SED
Kramer shear	4	417	377	393	435	29
(N)	20	343	279	386	367	
Juice vol.	4	39.3	29.7	32.5	23.5	6.81
(ml)	20	36.6	31.6	32.3	34.3	
pH	4	3.29	3.30	3.33	3.26	0.023
	20	3.37	3.37	3.35	3.33	
SS	4	9.5	9.4	9.6	9.5	0.16
(%)	20	8.9	8.7	9	9.2	
ρ_{rel}^{slice}	4	1.034	1.041	1.042	1.041	0.0044
	20	1.040	1.040	1.040	1.043	
integ.[x]	4	1.5	1	1.3	1	
	20	2.3	2.7	1.5	1.8	

[x] Slice integrity scale ranging from 1 (excellent) to 5 (poor).

6.3.1.2 1994 and 1995 'Braeburn' experiments

Internal atmosphere composition of the fruit

'Braeburn' fruit stored at 20 °C

Applying CMC as a surface coating substantially depressed $p^i_{O_2}$ ($P < 0.0001$), while $p^i_{CO_2}$ was somewhat elevated ($P < 0.0002$; Fig. 6-7). Results varied considerably with year. In 1995 $p^i_{O_2}$ and $p^i_{CO_2}$ values for coated fruit were tightly compressed. This contrasted with the 1994 data where there was a larger spread of values within individual coating treatments. In both years below about 2 kPa $p^i_{O_2}$ there was an upswing in values for $p^i_{CO_2}$. This was more pronounced in 1994, with several fruit from the 4 % coating treatment showing high $p^i_{CO_2}$ values (Fig. 6-7).

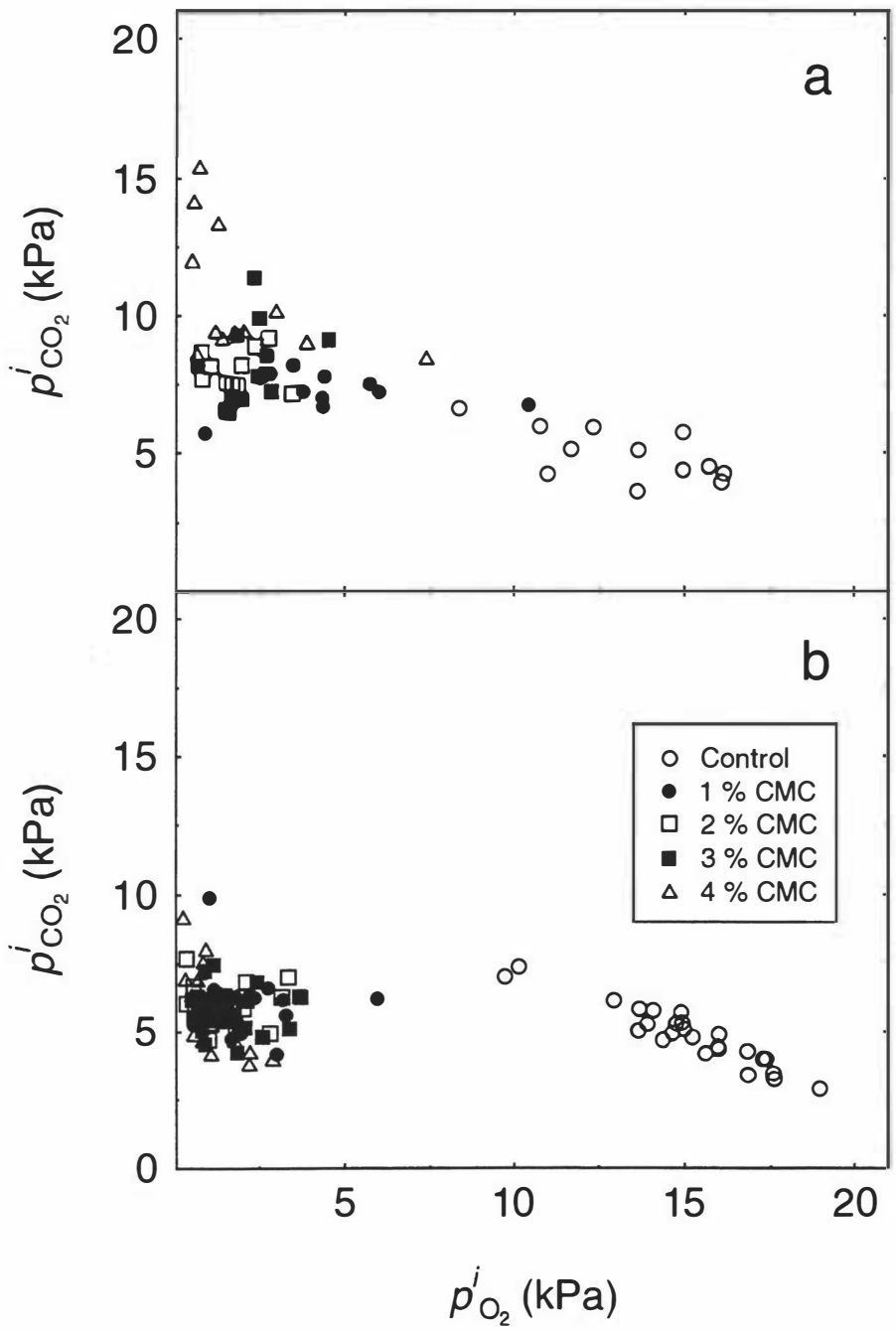


Fig. 6-7 The effect of surface coatings (CMC 0-4 %) on internal partial pressure of oxygen (p^i_{O2}) and internal carbon dioxide partial pressure (p^i_{CO2}) of 'Braeburn' apples stored at 20°C in a)1994 and b)1995.

When $p^i_{CO_2}$ was plotted against CMC concentration, the differences between years became more apparent (Fig. 6-8). In 1995, there was little difference in the degree of modification achieved by different concentrations of CMC; this was not the case in 1994. The 1994 data suggest that increasing CMC concentration from 1 to 4 % would reduce $p^i_{O_2}$, on average, from 4 to 2 kPa with $p^i_{CO_2}$ increasing from 7 to 11 kPa. Orthogonal contrasts revealed that the $p^i_{O_2}$ values for the 1 and 2 % coatings were significantly different ($P < 0.01$), and the $p^i_{CO_2}$ values for the 4 % coating were significantly different from the 2 % coating ($P < 0.01$).

'Braeburn' fruit stored at 0 °C

Internal atmosphere modification was less severe at 0 °C. Plots of $p^i_{O_2}$ and $p^i_{CO_2}$ against CMC concentration confirmed that $p^i_{O_2}$ was depressed in coated fruit while $p^i_{CO_2}$ was slightly enhanced. As $p^i_{O_2}$ was depressed by coating, $p^i_{CO_2}$ increased slightly, reaching a maximum at about 5-7 kPa at very low levels of $p^i_{O_2}$ (Fig. 6-9). Although $p^i_{O_2}$ tended to decrease with increasing CMC concentration, this effect was not statistically significant. Internal atmosphere composition for individual fruit was highly variable within a particular coating treatment. For example, fruit coated with 6 % CMC had $p^i_{O_2}$ values ranging from 1 - 18 kPa with corresponding $p^i_{CO_2}$ values of 2 - 6 kPa.

Textural and other quality characteristics of the fruit

1995 'Braeburn' fruit stored at 20 °C

Fruit texture was enhanced in fruit that were surface coated with CMC (Figs. 6-10 a and b). After 3 weeks storage at 20 °C, CMC coated fruit were on average 31 % firmer (as determined by the twist tester (TMax); $P < 0.0001$) than control fruit. There was some suggestion that fruit that received a coating of 4 % CMC were somewhat firmer than those receiving a 1, 2, or 3 % coating (TMax, DPen $P < 0.01$; TBio <0.05). Fruit that were coated had a considerably greener background

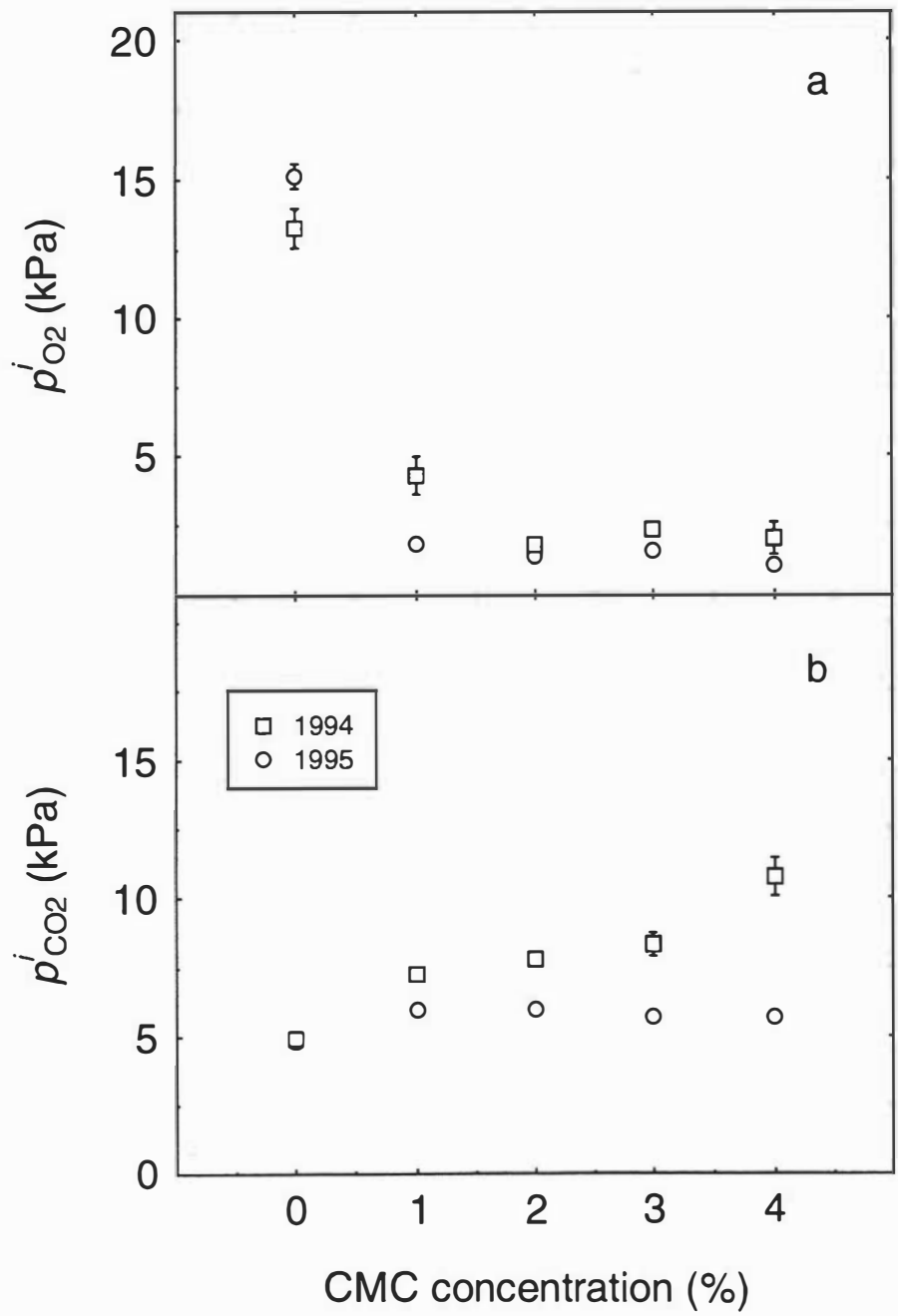


Fig. 6-8 The relationship between CMC concentration and a) internal partial pressure of oxygen (p^i_{O2}) and b) internal carbon dioxide partial pressure (p^i_{CO2}) of 'Braeburn' apples at 20°C.

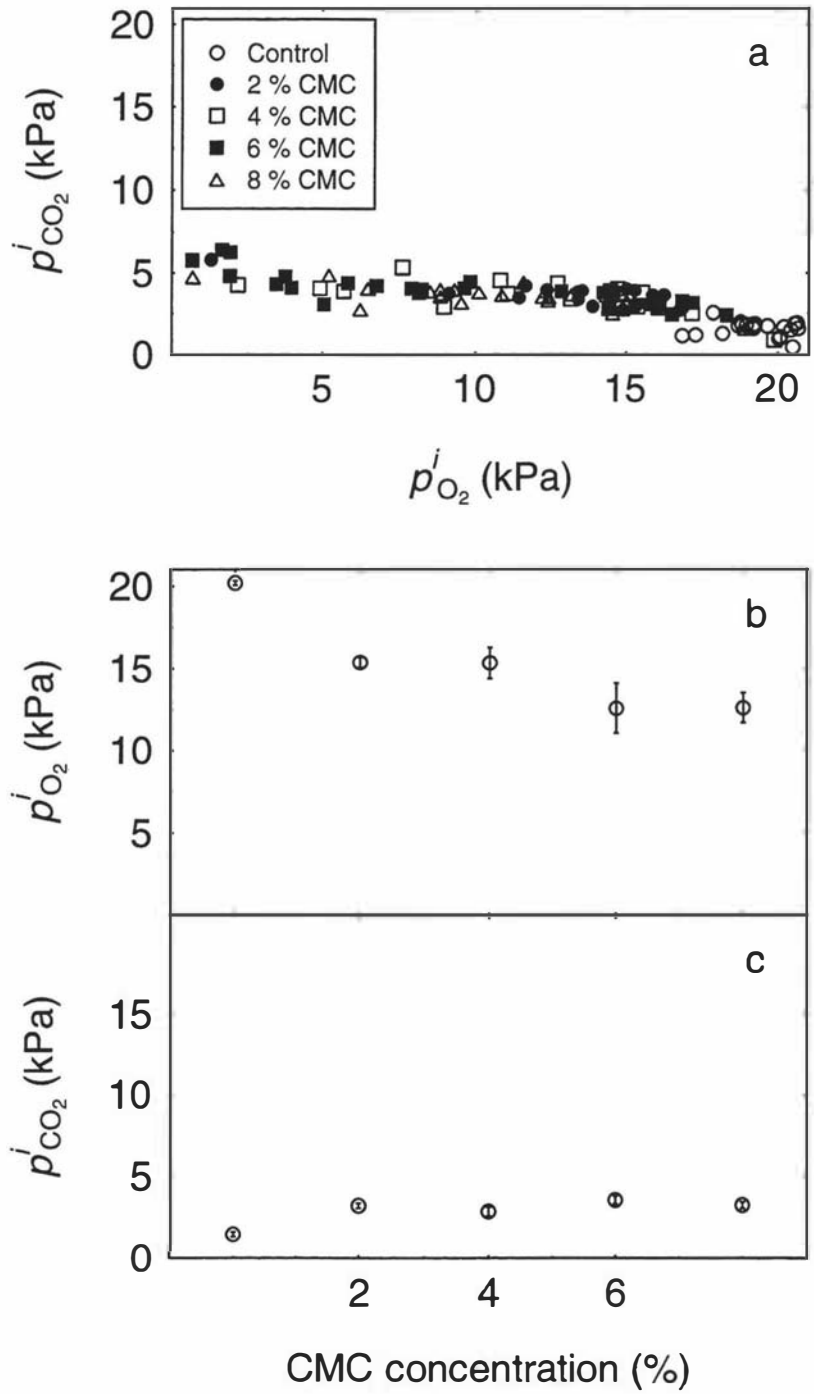


Fig. 6-9 The effect of surface coatings (CMC 0-8 %) on: a) internal partial pressure of oxygen (p^i_{O2}) and internal carbon dioxide partial pressure (p^i_{CO2}); the relationship between CMC concentration and b) internal partial pressure of oxygen (p^i_{O2}) and c) internal carbon dioxide partial pressure (p^i_{CO2}) of 'Braeburn' apples stored at 0°C in 1994.

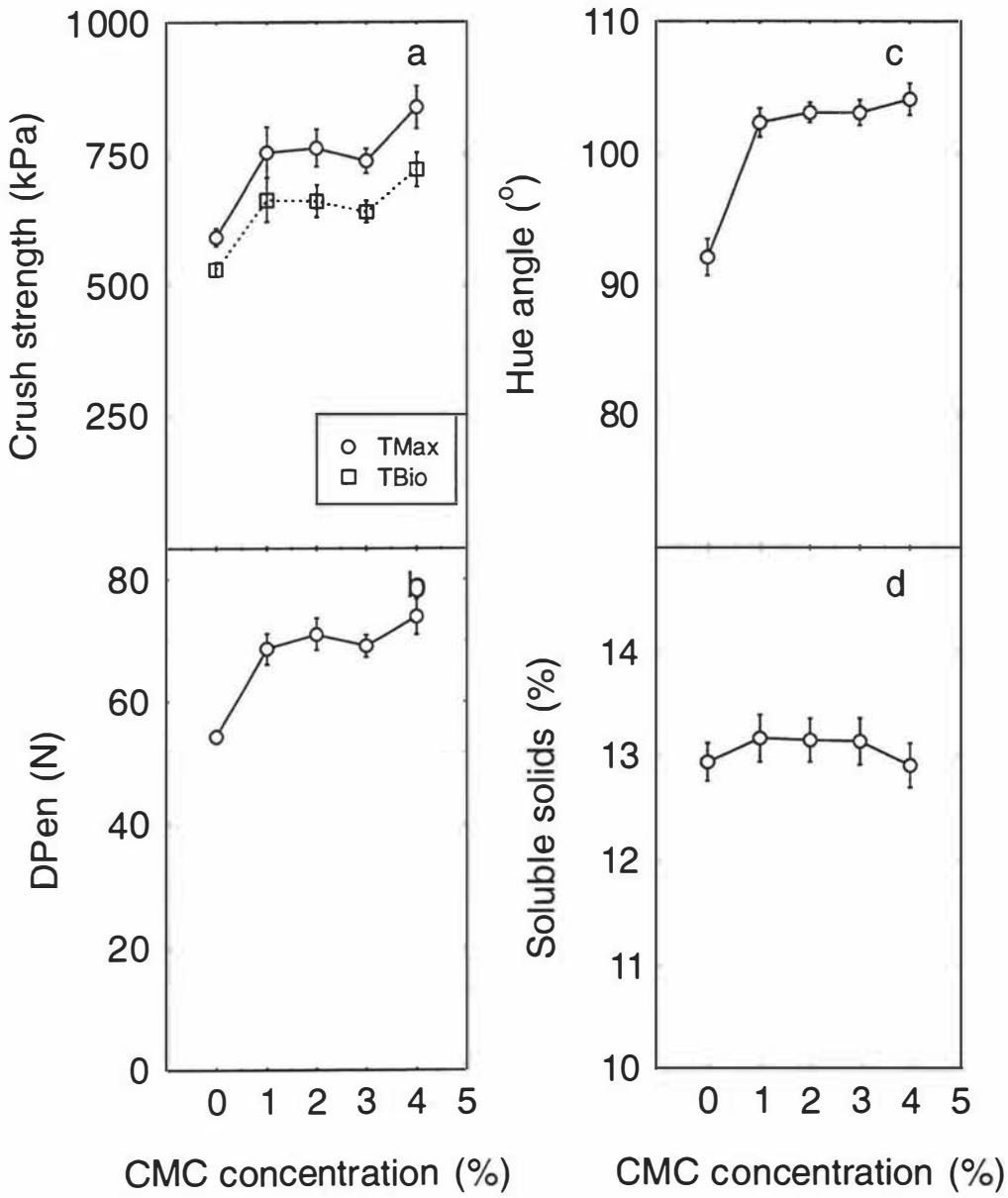


Fig. 6-10 The effect of CMC concentration on fruit firmness (a=TMax and b=DPen), background colour (c) and soluble solids (d) of 1995 'Braeburn' apples stored at 20°C.

colour than those that were not ($P < 0.0001$; Fig. 6-10 c). Most of the benefits for these two variables (i.e. texture and colour) were achieved with a 1 % coating. Coating treatment had no significant effect on fruit soluble solids concentration (Fig. 6-10 d). Grower lines varied significantly with regard to TMax ($P < 0.05$), TBio ($P < 0.05$), DPen ($P < 0.0001$), hue angle ($P < 0.0001$) and soluble solids ($P < 0.0001$).

1994 'Braeburn' fruit stored at 20 °C

Fruit were considerably softer at the start of the 1994 experiments. After 5 weeks storage at 20 °C there was little difference between treatments with regard to firmness as determined by the twist tester (Fig. 6-11 a). The penetrometer results indicated that fruit coated with 2 - 4 % CMC were significantly firmer than control fruit ($P < 0.05$) but the variation within treatments was considerably greater than in 1995. Green background colour loss was successfully retarded in coated fruit ($P < 0.0001$; Fig 6-11 c). As with 1995 season fruit, there were no significant difference between treatments with regard to fruit soluble solids content, but there were significant differences between grower lines for each of the variables measured.

1994 'Braeburn' fruit stored at 0 °C

Coated fruit did not show any improvement in texture, background colour or soluble solids content relative to controls after 6 or 16 weeks storage at 0 °C (Fig. 6-12). Fruit firmness, as determined by the twist tester, declined with time in storage ($P < 0.0001$).

Processed product quality

In general, surface coatings enhanced processed product quality. In 1995, 'Braeburn' fruit to which a 2 % CMC coating had been applied, produced a processed product that was almost four times firmer (as determined by the Kramer shear cell) than non-coated fruit (Table 6-8). Slope and maximum force values taken from the

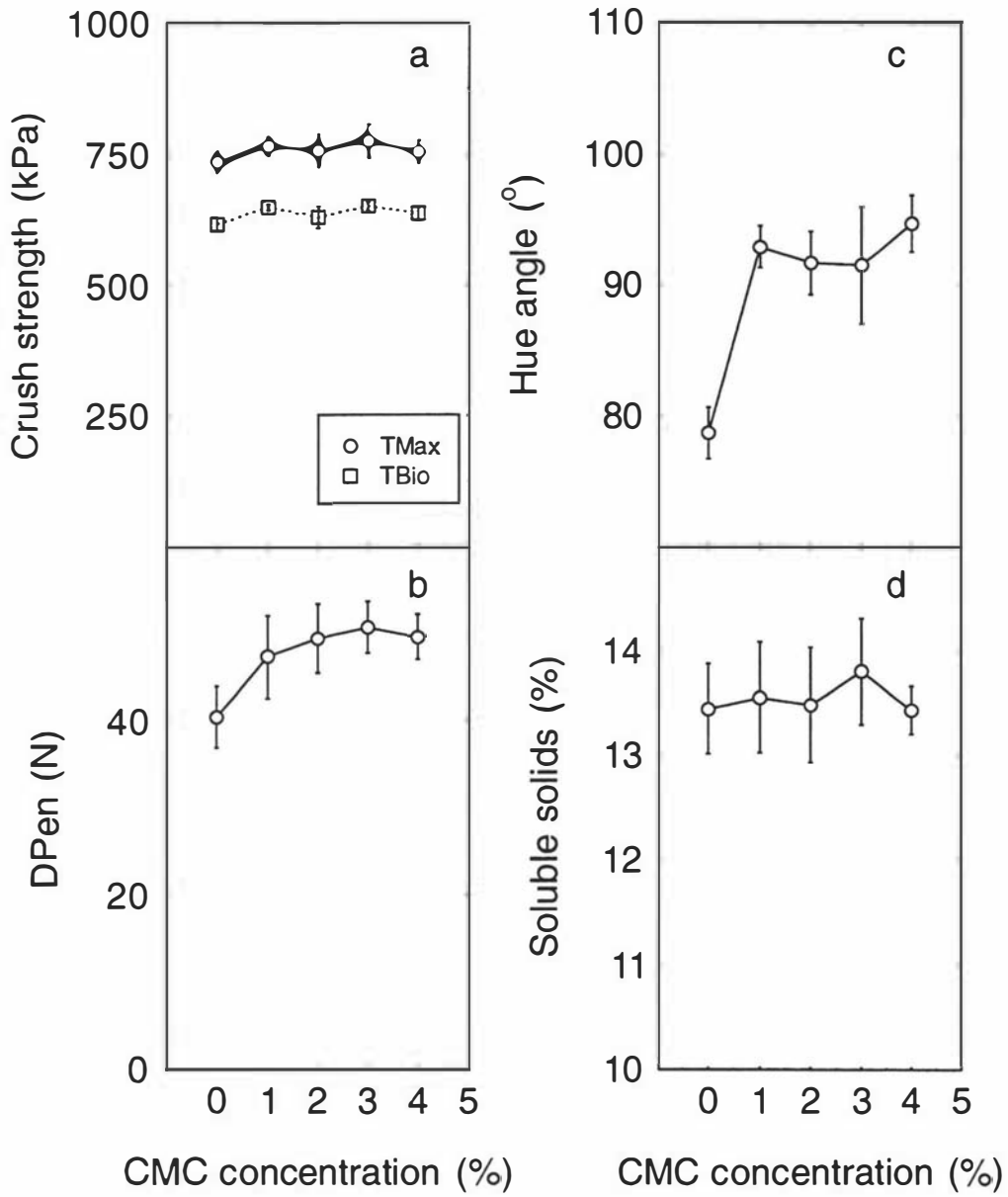


Fig. 6-11 The effect of CMC concentration on fruit firmness (a=TMax and b=DPen), background colour (c) and soluble solids (d) of 1994 'Braeburn' apples stored at 20°C.

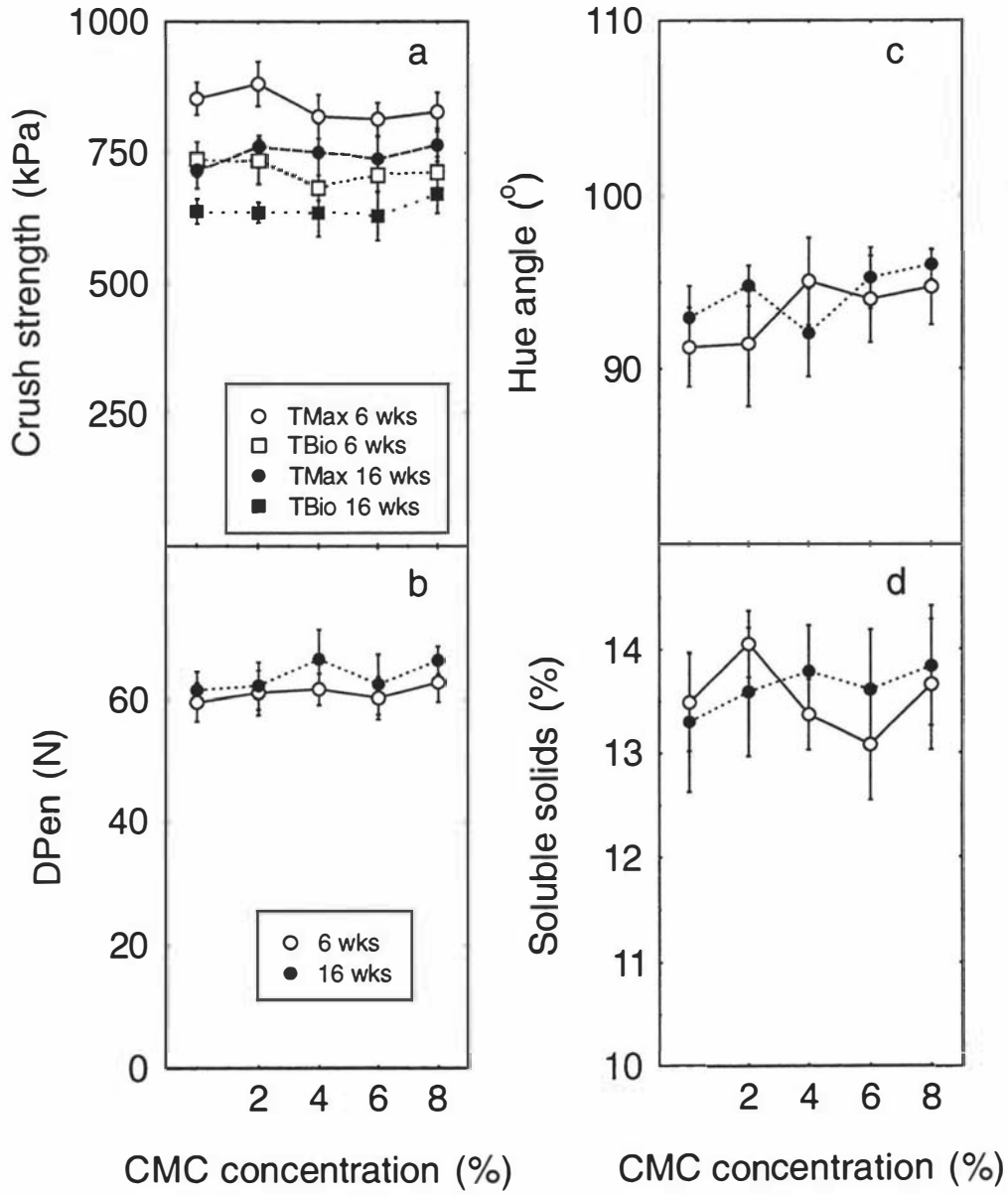


Fig. 6-12 The effect of CMC concentration on fruit firmness (a=TMax & TBio and b=DPen), background colour (c) and soluble solids (d) of 1994 'Braeburn' apples stored at 0°C.

compression test also indicated that there were significant textural differences between coated and non-coated fruit. However, the textural quality of the product did not appear to affected by the concentration of coating applied. The amount of free juice in the can did not appear to vary with coating treatment. However, the soluble solids content of this juice varied significantly both between coating treatments ($P < 0.0001$) and grower lines ($P < 0.0001$). Juice taken from canned slices made from 4 % CMC coated fruit had almost one sixth more soluble solids than those made from non-coated fruit.

Table 6-8. The effect of surface coatings on processed fruit quality of 'Braeburn' apples made from fruit stored at 20 °C for 3 weeks in 1995 before processing.

	CMC concentration (%)					
	0	1	2	3	4	SED
Kramer shear	124	396	465	386	475	41
Compression test						
Slope (N/mm)	5.5	20.6	26.7	22	25.6	4.76
Max F (N)	8.5	29.3	36.9	30.9	30.3	8.36
PD (mm)	1.38	1.35	1.31	1.35	1.32	0.030
Juice vol (ml)	36.4	31.6	40.4	39.9	37.6	4.33
SS (%)	8.1	8.8	8.9	9.2	9.2	0.19

Fruit stored under the same regimes in 1994 produced similar results (Table 6-9), although overall slice firmness values appeared to be slightly lower. This was particularly true for the compression test results, where slices produced from the control fruit were too soft for the test to be carried out. There was also some indication of a concentration effect with fruit coated with 4 % CMC producing slices 86 % firmer than those produced from fruit coated with 1 % CMC. Juice soluble solids level varied significantly between grower lines ($P < 0.0001$) and coating treatment ($P < 0.005$).

Table 6-9. The effect of surface coatings on processed fruit quality of 'Braeburn' apples made from fruit stored at 20 °C for 5 weeks in 1994 before processing.

	CMC concentration (%)					
	0	1	2	3	4	SED
Kramer shear	157	225	312	321	418	55
Compression test						
Slope (N/mm)	-	6.6	10.5	21.1	16.6	3.81
Max F (N)	-	13.0	15.6	29.0	22.8	4.71
PD (mm)	-	1.42	1.41	1.37	1.39	0.031
Juice vol (ml)	28.5	35.6	34.5	42.1	36.4	6.26
SS (%)	8.0	8.6	8.4	8.9	8.8	0.20

The texture of slices stored at 0 °C varied considerably between grower lines ($P < 0.0001$). Kramer shear cell results showed that there were significant differences between coated and non-coated fruit (Table 6-10; $P < 0.01$), although there were no significant differences between the coating concentrations or the storage periods. The compression test data showed significant interactions between length of storage and treatment for both the slope and maximum force estimates ($P < 0.03$). This would appear to be largely related to the high values registered for the control fruit after the first storage period (Table 6-10), whereas in the case of the second storage period the coated fruit were considerably firmer than non-coated fruit. The soluble solids content of the juice varied significantly with grower ($P < 0.0001$) and length of storage ($P < 0.03$). There were no significant treatment differences for the amount of free juice in the can.

Table 6-10. The effect of surface coatings on processed fruit quality of 'Braeburn' apples made from fruit stored at 0 °C for 6 or 16 weeks in 1994 before processing.

Measurement	Storage	CMC concentration (%)					SED
	(wks)	0	2	4	6	8	
Kramer shear (N)	6	339	390	368	410	384	33
	16	348	392	392	400	428	
Compression test							
Slope (N/mm)	6	26.8	23.4	15.8	26.1	22.2	3.36
	16	8.9	15.0	14.8	20.3	17.4	
Max F (N)	6	35.9	30.1	21.8	34.1	29.4	4.29
	16	12.8	20.7	20.6	28.1	23.5	
PD (mm)	6	1.28	1.31	1.34	1.33	1.34	0.093
	16	1.20	1.29	1.36	1.31	1.32	
Juice vol. (ml)	6	36.1	35.6	36.0	35.4	32.1	6.56
	16	43.3	35.0	37.7	32.9	38.4	
SS (%)	6	9.3	9.0	9.4	9.1	9.4	0.25
	16	8.6	8.9	9.0	9.2	9.2	

6.3.1.3 1994 'Fuji' experiment

Internal atmosphere composition of the fruit

Surface coatings significantly altered the internal atmosphere of 'Fuji' apples stored at 0 °C ($p^i_{O_2}$ $P < 0.01$; $p^i_{CO_2}$ NS) or 20 °C ($p^i_{O_2}$ $P < 0.01$; $p^i_{CO_2}$ $P < 0.003$; Figs. 6.13 - 6.15). At 20 °C, there was considerable fruit-to-fruit variation within a particular coating treatment. For example, fruit coated with 4 % CMC had internal $p^i_{O_2}$ values between 0.7 and 15.4 kPa, while $p^i_{CO_2}$ values ranged from 4.6 - 9.8 kPa. In general, though, average $p^i_{O_2}$ values decreased and average $p^i_{CO_2}$ values increased with increasing coating concentration (Fig. 6-14). Not all of the coating treatments were significantly different from one another. At 0°C, fruit-to-fruit variation within a coating treatment was less, but was still considerable. For example, applying an 8 %

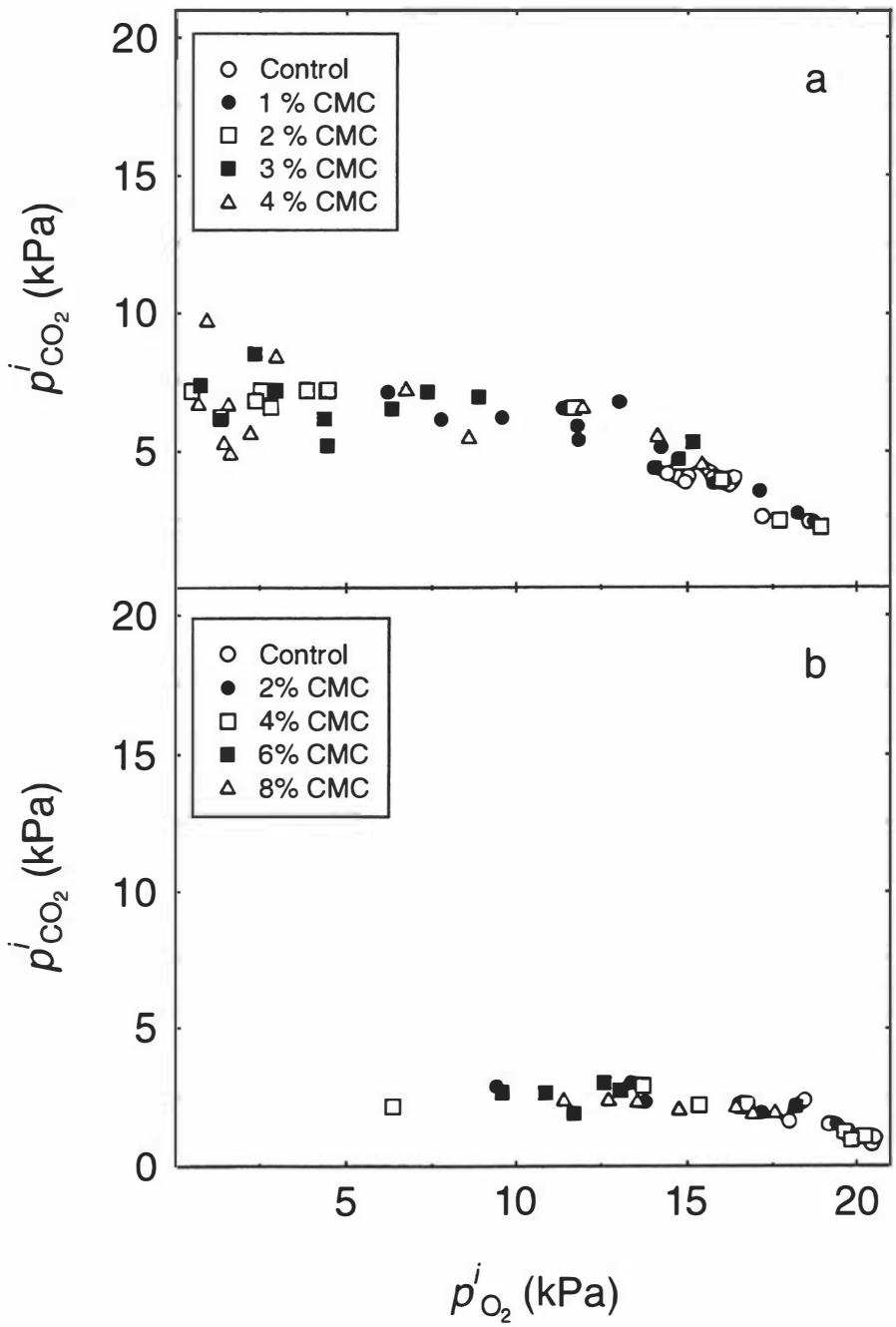


Fig. 6-13 The effect of surface coatings (CMC 0-4 %) on internal partial pressure of oxygen (p^i_{O2}) and internal carbon dioxide partial pressure (p^i_{CO2}) of 1994 'Fuji' apples stored at a) 20°C and b) 0°C.

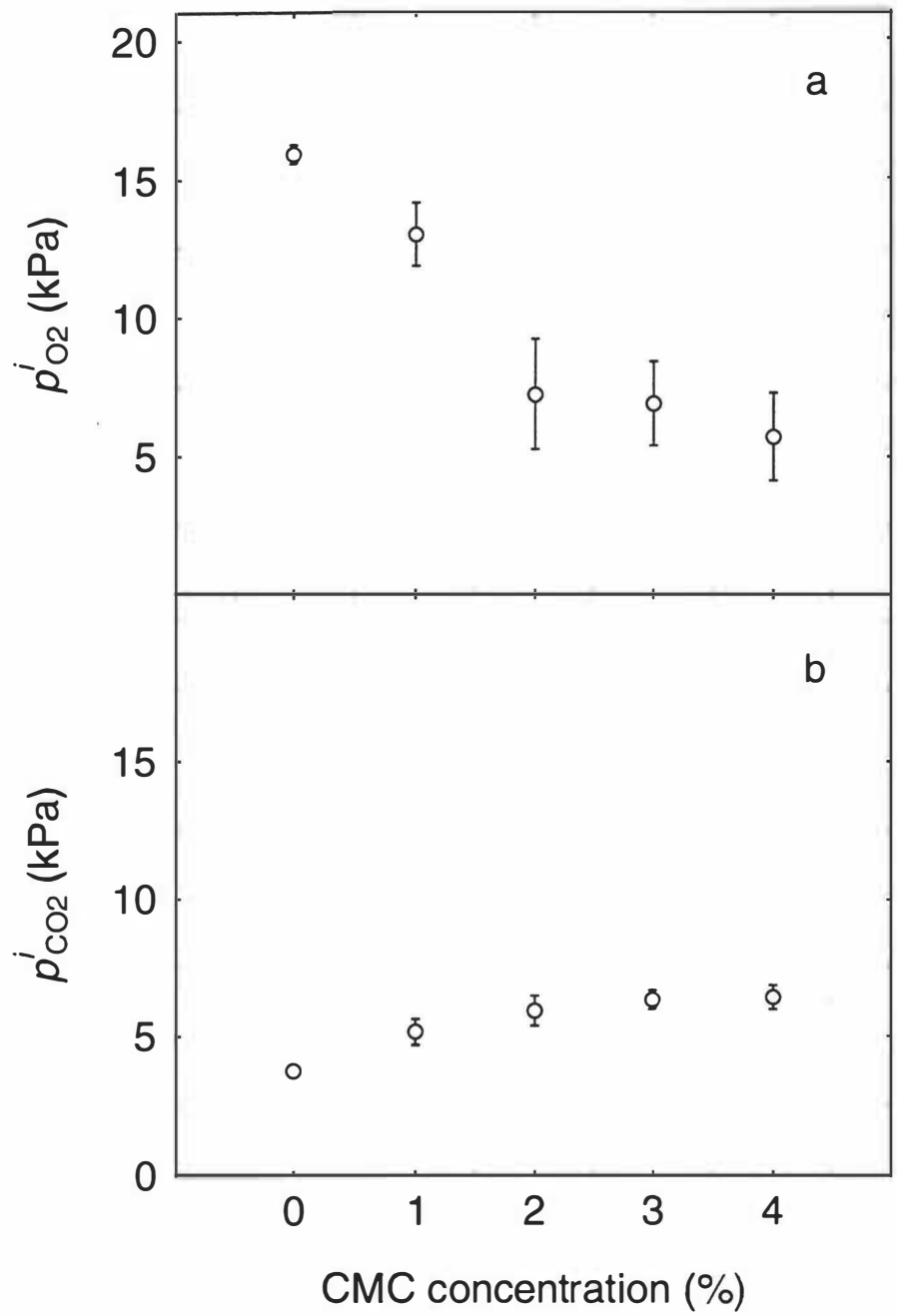


Fig. 6-14 The relationship between CMC concentration and a) internal partial pressure of oxygen (p^i_{O2}) and b) internal carbon dioxide partial pressure (p^i_{CO2}) of 1994 'Fuji' apples stored at 20°C.

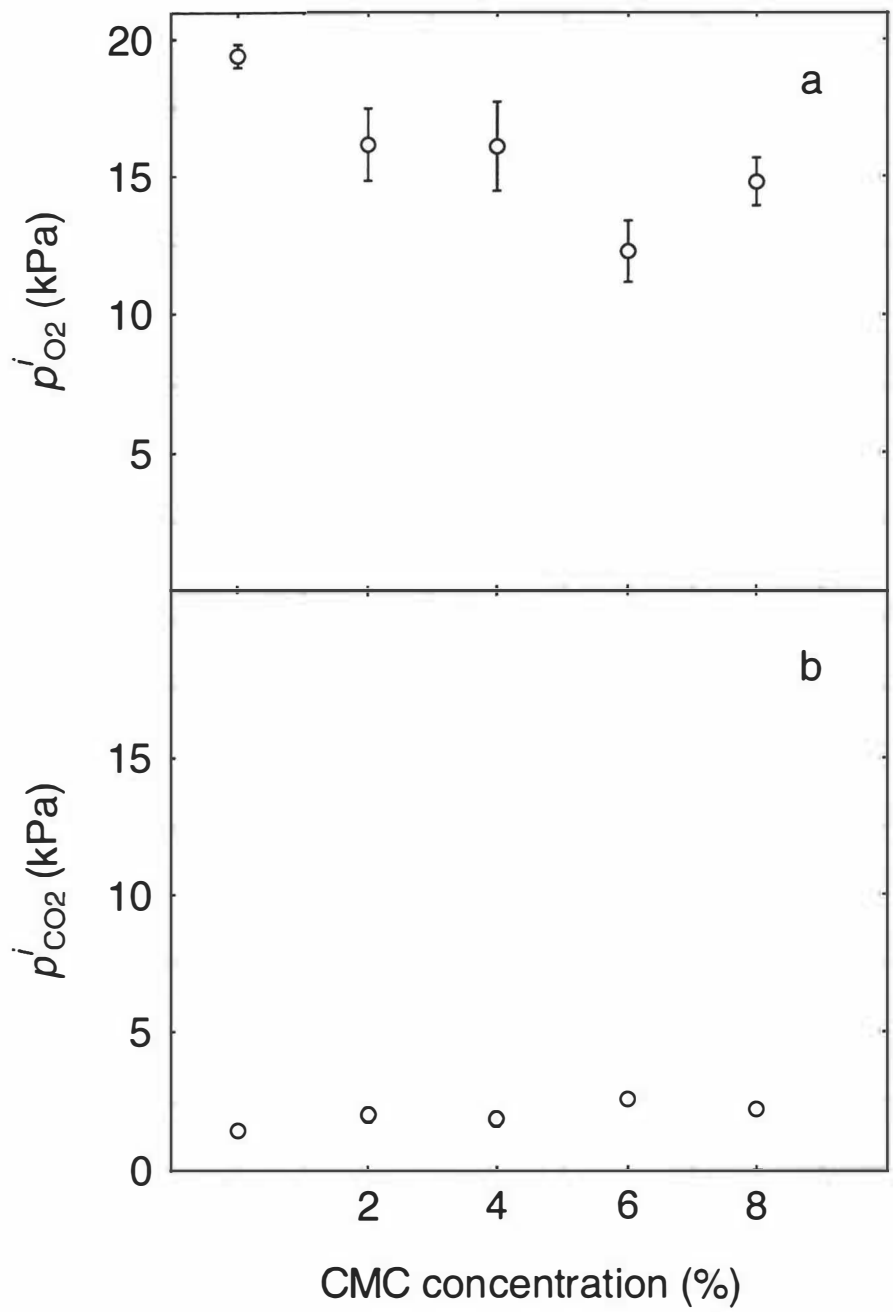


Fig. 6-15 The relationship between CMC concentration and a) internal partial pressure of oxygen (p^i_{O2}) and b) internal carbon dioxide partial pressure (p^i_{CO2}) of 1994 'Fuji' apples stored at 0°C.

coating resulted in fruit having $p^i_{O_2}$ and $p^i_{CO_2}$ values ranging from 11.4 - 16.9 and 2 - 2.45 kPa, respectively (Fig. 6.13). Increasing coating concentration from 0 to 6 % resulted in average $p^i_{O_2}$ values decreasing from 19.4 to 12.2 kPa, with average $p^i_{CO_2}$ increasing from 1.4 to 2.6 kPa (Fig. 6.15).

Textural and other quality characteristics of the fruit

For fruit stored at 20 °C, surface coatings appeared to have little effect on fresh fruit firmness (Figs. 6.16a and b). However, fruit treated with coatings and stored at 20 °C were considerably greener than non-coated fruit ($P < 0.0004$); Fig. 6.16c).

After 16 weeks storage at 0 °C, fruit coated with 8 % CMC retained their texture somewhat better than the other treatments (Figs. 6.17a and b). Chlorophyll retention and soluble solids content were also somewhat higher in these fruit (Figs. 6.17c and d). However after 6 weeks storage at 0 °C there was little difference between treatments.

Processed product quality

The Kramer shear results showed that coated and non-coated fruit values varied significantly ($P < 0.007$; Table 6-11). This contrasted with the uniaxial compression test which revealed no significant differences between the coating treatments, for slices produced from fruit stored at 20 °C.

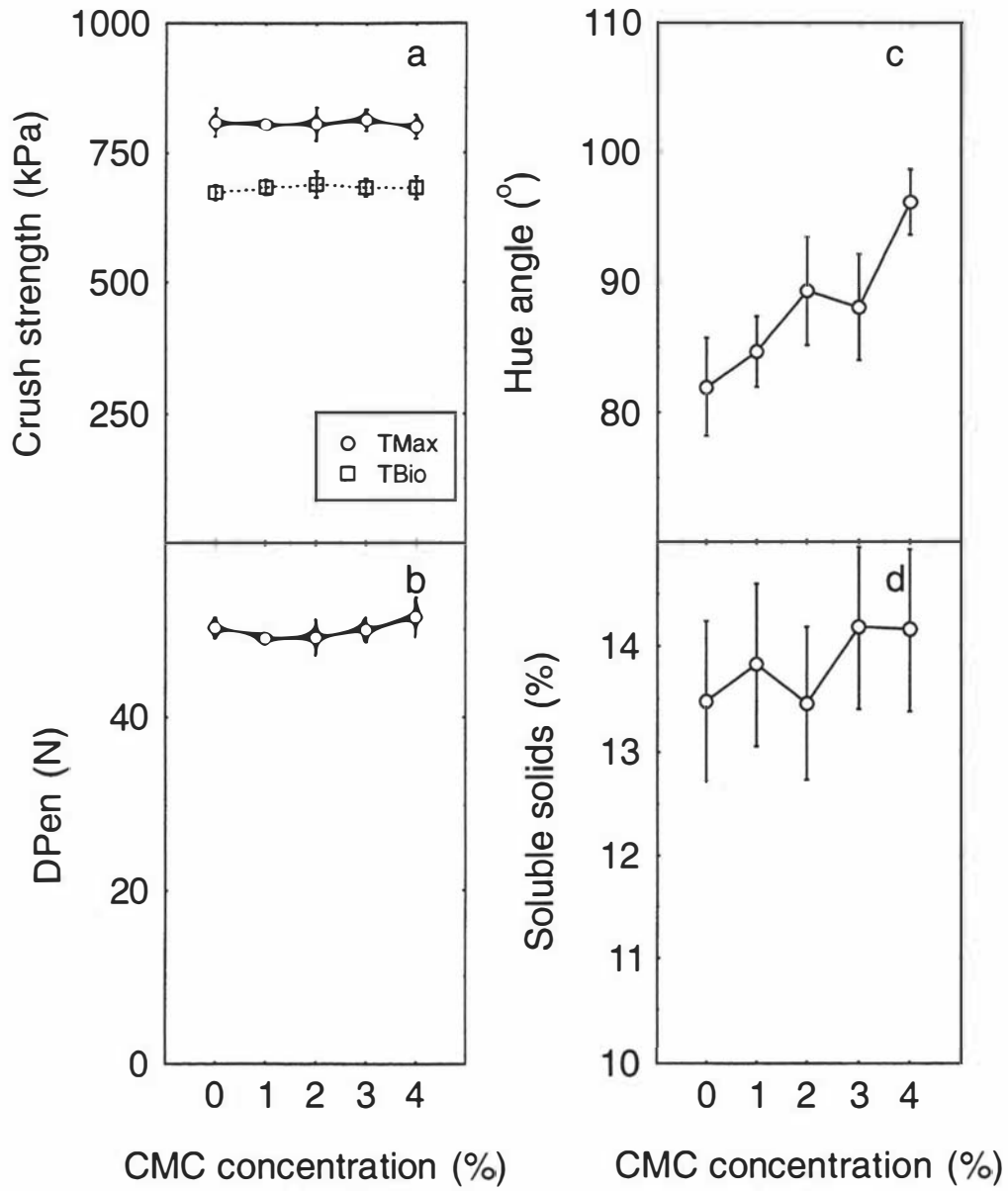


Fig. 6-16 The effect of CMC concentration on fruit firmness (a=TMax and b=DPen), background colour (c) and soluble solids (d) of 1994 'Fuji' apples stored at 20°C.

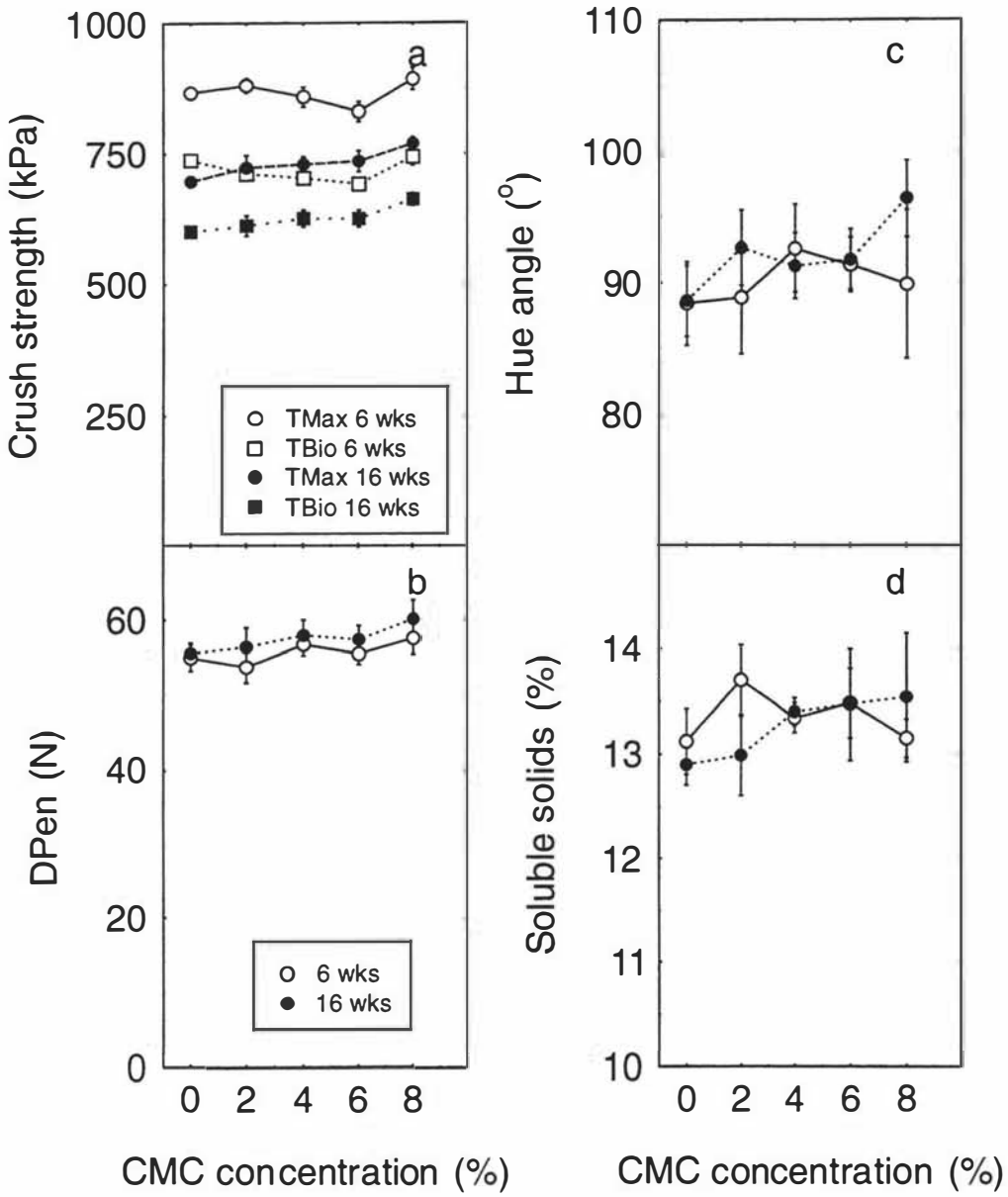


Fig. 6-17 The effect of CMC concentration on fruit firmness (a=TMax & TBio and b=DPen), background colour (c) and soluble solids (d) of 1994 'Fuji' apples stored at 0°C for 6 or 16 weeks.

Table 6-11. The effect of surface coatings on processed fruit quality of 'Fuji' apples made from fruit stored at 20 °C for 5 weeks before processing in 1994.

	CMC concentration (%)					
	0	1	2	3	4	SED
Kramer shear	368	444	451	472	460	34
Compression test						
Slope (N/mm)	14.4	13.6	13.2	14.8	15.3	2.83
Max F (N)	22.2	20.0	19.7	22.0	22.7	4.08
PD (mm)	1.33	1.34	1.35	1.31	1.31	0.033
Juice vol (ml)	48.0	44.6	39.6	50.3	48.4	3.19
SS (%)	8.7	9.0	8.9	9.1	9.0	0.21

For fruit stored at 0 °C none of the texture tests showed any significant differences between coated and non-coated fruit (Table 6-12). However, there were significant differences between the treatments in terms of free-juice volume ($P < 0.002$) and juice soluble solids levels ($P < 0.05$). Length of storage significantly affected Kramer shear ($P < 0.001$), and uniaxial compression ($P < 0.01$-0.02; excl. slope estimates; Table 6-13).

Table 6-12. The effect of surface coatings on processed fruit quality of 'Fuji' apples stored at 0 °C in 1994.

	CMC concentration (%)					
	0	2	4	6	8	SED
Kramer shear	448	473	518	505	448	34
Compression test						
Slope (N/mm)	15.8	17.3	18.3	18.8	19.0	1.96
Max F (N)	23.4	24.9	27.0	27.2	27.9	2.70
PD (mm)	1.33	1.34	1.32	1.33	1.31	0.022
Juice vol (ml)	51.1	42.8	43.2	41.9	45.6	2.84
SS (%)	8.7	9.0	8.9	9.1	9.0	0.19

Table 6-13. The effect of storage duration at 0 °C on processed fruit quality of 'Fuji' apples in 1994.

Measurement	6 wks.	16 wks.	SED
Kramer shear (N)	517	440	22
Compression test			
Slope (N/mm)	18.8	16.8	1.24
Max F (N)	28.1	24.0	1.71
PD (mm)	1.31	1.34	0.014
Juice vol. (ml)	44.4	45.4	1.80
SS (%)	9.0	8.8	0.12

6.3.2 Preharvest application of $CaCl_2$

Preharvest application of $CaCl_2$ did not enhance measured fruit skin permeance values (Table 6-14). At harvest all fruit had similar skin permeances regardless of preharvest treatment. After the first dip application, undipped fruit had significantly higher permeance levels than fruit dipped with either wetter or $CaCl_2$.

Table 6-14. Effect of $CaCl_2$ on fruit skin permeance.

Permeance ($nmol.s^{-1}.m^{-2}.Pa^{-1}$)	Control (dry)	Control (wet)	$CaCl_2$ dip	SED
Time -103 days[x]	17.81	16.31	16.67	0.472
Time 0 days	18.9	19.0	18.7	1.36

[x] number of days before harvest

Freshly harvested fruit were on average 39 % firmer than fruit stored at 0 °C for 20 weeks ($P < 0.001$; Table 6-15). There were no significant interactions between storage temperature and preharvest treatment for any of the variables measured. Preharvest calcium dips slightly enhanced fresh fruit firmness (Table 6-16). This effect of preharvest calcium dips was only significant for the twist test bioyield and penetrometer results. Calcium dipped fruit contained 32 % more calcium than control (dry) fruit ($P < 0.04$).

Table 6-15. The effect of storage on the fresh fruit quality of 'Braeburn' apples at harvest (0 weeks in storage) or after 20 weeks in storage.

		Harvest	20 weeks storage	SED
Twist test	- max force (kPa)	1147	790	45
	- bioyield	908	633	27
Penetrometer (N)		89	75	1.5
Kramer shear (N)		1593	1078	28
Soluble solids (%)		12	13.3	0.20

Table 6-16. The effect of preharvest calcium dips on the fresh fruit quality of 'Braeburn' apples.

		Control (dry)	Control (wet)	$CaCl_2$ dip	SED
Twist test	- max force (kPa)	974	946	986	18
	- bioyield	768	760	785	13
Penetrometer (N)		82	81	84	1.0
Kramer shear (N) (A2)[x]		1060	1045	1111	38
Soluble solids (%)		12.5	12.6	12.8	0.09
Calcium (mg/g dw)(A1)[x]		0.264	0.311	0.349	0.0377

[x] where A1 and A2 are assessment 1 (harvest) and assessment 2 (20 weeks) respectively

Processed slices made from freshly harvested apples were significantly different from those made from stored fruit in terms of texture ($P < 0.0003$); free juice volume ($P < 0.0002$), and juice soluble solids ($P < 0.005$) and pH ($P < 0.001$; Table 6-17). Slices made from freshly harvested apples were 35 % firmer than those produced from stored apples. Preharvest calcium dips produced slices that were 10 % firmer than those that received no treatment (Table 6-18). There were no other significant differences between treatments for any of the other variables measured.

Table 6-17. The effect of storage on the processed fruit quality of 'Braeburn' apples.

	Harvest	20 wks.	SED
Kramer shear (N)	675	501	24
Juice volume (ml)	12.3	34.9	2.99
pH	3.21	3.35	0.027
Soluble solids (%)	10.2	9.8	0.11
Moisture content (%)	88.45	89.14	0.298

Table 6-18. The effect of preharvest calcium dips on the processed fruit quality of 'Braeburn' apples.

	Control (dry)	Control (wet)	$CaCl_2$ dip	SED
Kramer shear (N)	558	586	615	25
Juice volume (ml)	20.5	25.1	26.1	2.75
pH	3.28	3.28	3.28	0.011
Soluble solids (%)	10.0	10.0	10.0	0.10
Moisture content (%)	88.77	88.76	88.89	0.153

6.3.3 Postharvest calcium dips

Postharvest calcium dips slightly retarded textural degradation in fresh 'Braeburn' apple fruit stored at 0 °C for 20 weeks (Table 6-19; IPen $P < 0.06$; FKra $P < 0.03$). However, there were no significant differences between the different levels of calcium concentration used. Despite the slight enhancement in harvested fruit texture, postharvest calcium dips had no effect on processed fruit texture (Table 6-20). Applying calcium as a postharvest dip did improve product quality by reducing the amount of free-juice in the can. An orthogonal contrast comparing the control with the average calcium effect revealed them to be significantly different only at the 5 % significance level. Slice relative density, moisture content and juice pH varied little with calcium concentration. However, the level of soluble solids in the juice of calcium treated fruit was significantly greater than those that received no calcium

treatment ($P < 0.01$). Fruit dipped in 1.0 M calcium contained 52 % more calcium than control fruit ($P < 0.01$), while the overall calcium effect was only significant at $P = 0.06$.

Table 6-19. Effect of postharvest calcium dips on fresh fruit quality.

	Calcium concentration (M)					
	0	0.2	0.6	0.8	1.0	SED
TMax (kPa)	766	752	744	743	767	38
IPen (N)	55	59	61	61	57	2.2
FKra (N)	1012	1154	1138	1243	1140	60
SS (%)	12.4	12.4	12.5	12.3	12.3	0.27
Ca (mg/g dw)	0.280	0.317	0.344	0.347	0.425	0.0446

Table 6-20. Effect of postharvest calcium dips on processed fruit quality.

	Calcium concentration (M)					
	0	0.2	0.6	0.8	1.0	SED
PKra (N)	275	280	262	278	276	18
Juice (ml)	38.6	24.8	27.4	28.9	19.9	5.27
ρ_{rel}^{slice}	1.040	1.035	1.040	1.035	1.033	0.0045
pH	3.36	3.39	3.36	3.38	3.38	0.018
SS (%)	8.9	9.4	9.3	9.4	9.5	0.17
Slice integ.[x]	2.1	2.5	2.1	2	2.1	
Slice app.[x]	2	2	2	2	2	
Moist. cont. (%)	90.49	90.60	90.62	90.60	90.34	0.337

[x] Slice integrity and appearance scales ranging from 1 (excellent) to 5 (poor).

6.4 Discussion

This study has clearly demonstrated the potential for enhancing processed apple slice quality through the use of surface coatings, applied during the postharvest phase to apples destined for processing. For fruit stored at 20 °C, texture was generally superior in slices made from coated apples. In some cases, coating also provided a textural advantage for fruit stored at 0 °C. The level of benefit achieved by the coating was closely linked to the level of atmospheric modification achieved in the fruit. In this study, the degree of atmospheric modification was found to vary with cultivar, storage temperature and coating treatment. Figure 6-18 summarises diagrammatically the factors known to influence $p^i_{O_2}$ and $p^i_{CO_2}$, and provides a platform for discussing the interrelationships between them.

$p^i_{O_2}$ and $p^i_{CO_2}$ values varied considerably with apple cultivar (Figs. 6-1, 6-2, and 6-13). For fruit stored at 20 °C, average $p^i_{O_2}$ values for the cultivars used in this study varied by a factor of between 1.7 and 3.8. These differences may be attributed to natural differences in skin permeance, tissue porosity and respiration rate. 'Braeburn' is known to have a low skin permeance (Dadzie, 1992). Reported values for 'Braeburn' fruit range from 0.098 - 0.294 $nmol.s^{-1}.m^{-2}.Pa^{-1}$, compared with values ranging from 0.270 - 0.588 $nmol.s^{-1}.m^{-2}.Pa^{-1}$ for 'Granny Smith' fruit (Dadzie, 1992). Hence, a cultivar such as 'Braeburn' with low natural skin permeance is likely to have lower and more variable $p^i_{O_2}$ values (and higher $p^i_{CO_2}$ values) compared to cultivars with moderate or high skin permeance, a characteristic that may be exacerbated by surface coating.

Temperature had a marked effect on the internal atmosphere composition of apples, both coated and non-coated. Increasing the temperature from 0 to 20 °C resulted in a decrease in $p^i_{O_2}$ values with a concomitant increase in $p^i_{CO_2}$ (Figs. 6-1, 6-2, 6-7, 6-9, and 6-13). This can largely be attributed to elevated temperatures stimulating respiration, and hence increased O_2 utilisation and CO_2 production. The magnitude

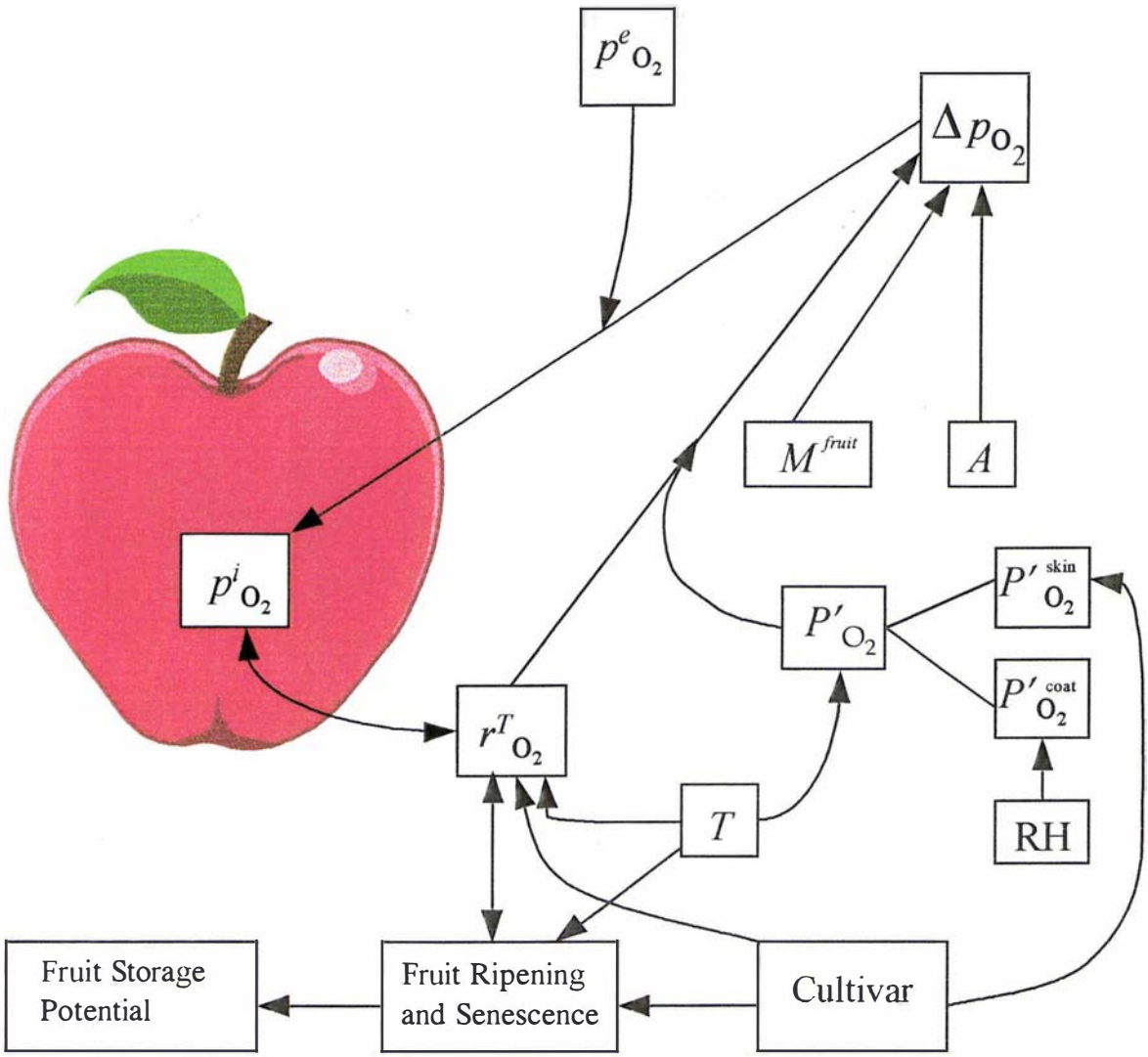


Fig. 6-18 Interrelationships between factors affecting $p^i{}_{O_2}$ in apple fruit (modified from Yearsley, 1996).

of the temperature effect on internal atmosphere composition depends on fruit skin permeance. In fruit in which permeance to O_2 is naturally low, or has been artificially reduced through the application of a surface coating, $p^i_{O_2}$ is depressed more substantially by elevated temperatures. Values for $p^i_{O_2}$ tend to be more affected than those for $p^i_{CO_2}$ because both the cuticle (Banks *et al.*, 1993b) and coating (Hagenmaier and Shaw, 1992) are considerably more permeable to CO_2 than O_2. Temperature also affects coating permeability, with permeability increasing with temperature (Hagenmaier and Shaw, 1991). However despite the relatively substantial increase in coating permeability (estimated to be up to an order of magnitude by Hagenmaier and Shaw, 1991), data presented here would suggest that the overall effect was small and insufficient to offset the large increase in respiratory O_2 demand at elevated temperatures, hence the large depression in $p^i_{O_2}$ at 20 °C.

In this study, coated fruit stored at 20 °C developed $p^i_{O_2}$ values that may be considered close to optimal, with some verging on over-modification. By contrast, levels of modification of the internal atmospheres developed in fruit stored at 0 °C were in the majority of cases sub-optimal and hence provided little benefit over non-coated fruit. Plans for implementing coating of fruit destined for processing would need to consider the potential risks of temperature fluctuations, both in terms of increased variability of ripening and possibly softening, and risk of developing anaerobic conditions inside the fruit. In Hawkes Bay (New Zealand's primary apple producing area and site of J. Wattie Foods) late summer/autumn temperature maximums and minimums range from 16.1 to 23 °C and 6.7 to 14.7 °C, respectively (New Zealand Climate Digest, 1996). Fluctuations in temperature could be partially offset through the use of shade structures and/or cooling stock once a maximum temperature was reached (eg. 20 °C). It may also be that short periods of anaerobic conditions within the fruit resulting from high temperatures are not detrimental to final fruit quality (Nisperos-Carriedo *et al.*, 1990).

The properties of the coating material in terms of pore blocking potential and permeability (in cases where it covers rather than blocks pores) was a key factor in

determining the internal atmosphere composition within the fruit. Work described in this thesis focused on one coating material, CMC, although one of the experiments described (6.2.1) also looked at incorporating calcium into this coating material. Fruit treated with CMC & Ca had average $p^i_{O_2}$ values of between 1.4 and 3.6 times higher than fruit coated with CMC alone. This suggests that adding calcium to the coating substantially decreased the pore blocking ability of the coating or increased its permeance, resulting in a rise in $p^i_{O_2}$. Fruit-to-fruit variability in terms of $p^i_{O_2}$ was similar in both treatments. However, the level of variability in fruit respiration and other physiological processes may be considerably greater in CMC treatments due to the lower absolute values of $p^i_{O_2}$. Values for r_{CO_2} are increasingly suppressed as $p^i_{O_2}$ is decreased; the relationship between the two variables can be described by a Michaelis-Menten function (Andrich *et al.*, 1991; Dadzie, 1992; Banks *et al.*, 1993b; Yearsley *et al.*, 1996). CMC coated fruit had similar levels of variability in $p^i_{O_2}$ but lower absolute values than CMC & Ca coated fruit. This would be likely to result in greater fruit-to-fruit variability with regard to respiration and other associated physiological processes.

One of the objectives of this work was to identify an optimum CMC concentration, at which MA benefits were maximised whilst avoiding the risk of significant off-flavour development and/or physiological disorders. Plots of $p^i_{CO_2}$ versus $p^i_{O_2}$ (Figs. 6-1, 6-2, 6-7, 6-9a, and 6-13) enable visual comparison of the effects of coating treatments on internal atmosphere. These plots reveal considerable fruit-to-fruit variation within a particular coating treatment which would have resulted from variation in respiration rate, skin permeance and fruit mass and surface area (Fig. 6-18). Banks *et al.* (1993b) reported that skin permeance values for fruit within a cultivar may vary by a factor of between 2 and 7. Variations in coating thickness and uniformity may also contribute, despite care being taken to apply a uniform coating. Despite the variation in values for internal atmosphere composition amongst particular treatments, $p^i_{CO_2}$ data generally lay on a consistent curve when plotted against $p^i_{O_2}$ (Figs. 6-1, 6-2, 6-7, 6-9a and 6-13). Initially, as $p^i_{O_2}$ decreased, there was a gradual rise in $p^i_{CO_2}$. This was due to the surface coating decreasing skin

permeance by blocking pores (Banks *et al.*, 1997) resulting in a build-up of $p^i_{CO_2}$ within the fruit. As $p^i_{O_2}$ declined further there was a decrease in $p^i_{CO_2}$, corresponding to a decrease in aerobic respiration, reaching a minimum at a point equivalent to the LOL^i. Beyond this point, anaerobic respiration was initiated resulting in a strong increase in $p^i_{CO_2}$. Overall, average $p^i_{O_2}$ decreased and $p^i_{CO_2}$ increased with coating concentration. These results agree with those of other workers including Trout *et al.* (1952), Banks, (1984), Smith and Stow, (1984), and Smith *et al.* (1987a), who have also reported a coating concentration effect.

Coating optimisation, for a given set of environmental conditions may be achieved by selecting a concentration and/or material that produces $p^i_{O_2}$ values slightly higher than the LOL^i (Banks *et al.*, 1997). The considerable scatter in the plots of $p^i_{O_2}$ vs $p^i_{CO_2}$ makes it difficult to estimate precisely the LOL^i for any of the cultivars. At 20 °C, the LOL^i would appear to be between about 1 and 3 kPa for both 'Braeburn' (Fig. 6-7) and 'Fuji' (Fig. 6-13a). At 0 °C, $p^i_{O_2}$ values did not reach the LOL^i. Based on average $p^i_{O_2}$ values for 'Braeburn' fruit stored at 20 °C, coating concentration appeared to be optimised at about 2 %. However, variability in internal atmosphere composition precluded a firm identification of an optimum coating treatment. It is interesting to note that in 1994 although $p^i_{O_2}$ stabilised at a 2 % CMC concentration, $p^i_{CO_2}$ continued to increase slightly with higher coating concentrations. These results agree with those of Banks *et al.* (1997), who found that in 'Granny Smith' fruit coated with 1-4 % CMC, $p^i_{O_2}$ was largely minimised by the 2 % coating whereas $p^i_{CO_2}$ continued to increase with coating concentration, reaching a maximum value of 56 kPa. For 'Fuji', all concentrations of CMC produced average $p^i_{O_2}$ values greater than the LOL^i, despite some individual values being below it. This highlights the need to look at uniformity of response in conjunction with average $p^i_{O_2}$ and $p^i_{CO_2}$ values when selecting on optimum coating.

In order to determine whether or not surface coatings are a suitable means of enhancing or retaining processed fruit quality we need first to ascertain the level of MA benefit achieved and assess any potential risks. The development of

physiological disorders and off-flavours are the major risks associated with MA. In this study, minimal physiological disorders were observed, and whilst some off-flavour development was detected in a few cans this did not seem to be associated with any particular treatment and it was difficult to determine whether or not this was due to anaerobic respiration, or an alternative reason such as lacquer deterioration. Some fruit ripened unevenly, resulting in blotchy skin colouration (areas of green and green-yellow rather than uniform background colour). Similar results were reported by Meheriuk and Lau (1988) who found that coated 'Bartlett' developed a blotchy appearance when held at ripening temperatures. However, since the fruit in this study were destined for processing, skin colouration was not a major consideration.

In this study, slice texture and free-juice volume were the two processed fruit quality attributes of primary concern. Surface coatings showed the potential to enhance both slice texture and reduce free-juice content. The level of benefit achieved varied considerably with cultivar, storage temperature and grower line, and to a more limited extent with coating concentration. As discussed above, cultivar and storage temperature have a large impact on the degree of atmospheric modification achieved in the fruit and hence the level of MA benefit realised. Slice texture was enhanced and free-juice content reduced in coated 'Granny Smith' and 'Fuji' apples stored at 0 °C. However, in 'Braeburn' apples stored under the same conditions there was only slight evidence of improvement in processed slice quality (1994 compression test results) at low temperature. These cultivar differences were perhaps somewhat surprising since the degree of atmospheric modification at 0 °C was more marked in 'Braeburn' fruit. Slices made from coated apples stored at 20 °C were consistently of a higher standard than those made from non-coated fruit. The effects of coating were perhaps most dramatic for the 'Braeburn' apples in which slices made from coated fruit resisted saucing and produced good quality slices, compared with non-coated fruit that readily sauced and/or produced soft, textureless slices (Fig. 6-19 and 6-20). These MA benefits may be largely attributed to lower respiration rates resulting in a retardation of ripening and fruit softening (Kader *et al.*, 1989).

Fig. 6-19 Slices produced from non-coated 'Braeburn' apples previously stored at 20 °C for 3 weeks.

Fig. 6-20 Slices made from coated 'Braeburn' apples previously stored at 20 °C for 3 weeks.

Considerable benefits were also achieved in terms of fresh fruit quality for coated fruit stored at 20 °C. In these fruit, textural degradation and degreening was in most cases slowed by the coating treatment (Figs. 6-3, 6-5, 6-10, 6-11, 6-16). These results agree with those of Smith and Stow (1984) who found that apples treated post-storage with a 1.25 % sucrose ester formulation showed reduced yellowing and loss of firmness, during a 21 day simulated marketing period. Chu (1986) also found that surface coating with TAL-Prolong delayed loss of texture and ground colour in a 21 day shelf life trial involving controlled atmosphere stored (CA) 'Delicious' and low oxygen (LO) stored 'McIntosh' apples. However, they also found that coating provided no textural advantage for CA stored 'McIntosh' or 'Empire' apples. To account for the differences in softening behaviour of 'McIntosh' apples, between the two storage regimes they proposed that CA stored 'McIntosh' apples may have reached a minimum plateau at the end of their CA storage life, whereas LO stored apples were considerably firmer and hence continued to soften at a rate depending on post-storage treatment. These results exemplify the importance of the need to use fresh, high textural quality fruit if coating treatments are to be relied upon to obtain a textural or quality advantage. The results from the 1994 experiments were perhaps not as clear cut as they might have been due to the comparatively low quality (high maturity, lower initial firmness values) fruit utilised in these experiments. Despite care being taken to remove any hail damaged fruit, some minimally damaged fruit may have been included. Applying a coating to even a slightly damaged apple may have reduced the coating's effectiveness. This would lead to an increased spread in terms of maturity and a greater variability in terms of attribute response. However a reduction in coating effectiveness is not supported by the internal atmosphere data collected from these fruit where the variation in $p^{i}_{O_2}$ values for 'Braeburn' fruit coated with 2 % CMC was not appreciably different between years (1993-1995). Differences in maturity, initial firmness values, respiration and ethylene production rates are therefore more likely to explain both the lower absolute colour and firmness values recorded in these fruit and the increased variability in the 1994 'Braeburn' results (Figs 6-11 and 6-12).

Coated fruit stored at 0 °C showed negligible or modest textural benefits (Figs. 6-4, 6-6, 6-12, 6-17). Other workers have also largely reported modest or negligible textural benefits in coated fruit stored at low temperatures (Smith and Stow, 1984; Santerre *et al.*, 1989; Drake and Nelson, 1990; Chai *et al.*, 1991). Differences between published results may be attributed to differences in cultivars, storage environments (including refrigerated storage temperature), coating materials, firmness determination methods used, and possibly initial fruit maturity and firmness values. The meagre benefits obtained in the current work at 0 °C may be attributed to insufficient modification of the internal atmosphere. MA benefits such as texture retention are largely derived from the depressive effects of low $p^i_{O_2}$ either directly on these processes or on product respiration (Kader *et al.*, 1989). Maximum benefits are achieved when $p^i_{O_2}$ is just above the LOL^i, with increasingly reduced benefits as $p^i_{O_2}$ is increased.

Another interesting consideration is whether or not enhancements in fresh fruit texture are realised in the processed product. In this study, enhancements in fresh fruit quality were generally carried through into the processed product. However, in some cases this did not occur; and in others, there were improvements in processed product quality without corresponding quality enhancement in the fresh product. These results are in general agreement with those of McLellan *et al.* (1990), who found that treatment differences tended to be accentuated in the processed product (in their case, blanched apple slices). They also found, as was the case in this study, that trends in fresh fruit texture were not always carried through into the processed product. These differences may be partially due to use of different methods to measure fresh and processed product texture. In this work, a range of methods have been used to characterise fresh and processed product texture. Not only are the tests measuring different aspects of texture, but some (such as the penetrometer and twist test) are localised tests, whereas others (such as the Kramer shear cell) use a larger volume of tissue, and hence are more likely to reflect the overall texture of the tissue. However, differences in testing methods are likely to provide only part of the answer: thermal processing renders considerable changes in the fruit tissue, including

softening and expansion. Hence, tissue that is tending towards mealiness is more likely to register a considerably lower value following thermal processing than fresh product, accentuating differences in the processed product. Moreover, tough tissue is likely to resist thermal softening, increasing the difference in response between soft and tough tissue. Processors, as outlined in Chapter 5, would ideally like to be able to predict processed fruit quality from measurements made on fresh fruit. However, the considerable changes that occur during thermal processing are likely to make this ideal difficult to achieve. This is apparent in models described by Wiley and Thompson (1960) in which only 66 % of variation in processed slice quality could be accounted for by tests carried out on fresh fruit.

Optimising CMC coating concentration was one of the objectives of this work. Although in some cases increasing coating concentration improved fruit quality, this trend was by no means universal. In terms of fresh fruit quality, there was only a slight hint of textural improvement with increasing coating concentration. In the case of 'Braeburn' fruit stored at 20 °C this was probably due to the 2 % coating depressing average $p^{i}_{O_2}$ values close to the LOL[i]. In the case of fruit stored at 0 °C, the higher coating concentrations did not generally suppress $p^{i}_{O_2}$ sufficiently and hence did not translate into textural and other quality benefits. Other research examining the effect of coating concentration on quality attributes has yielded mixed results. Difficulties arise when trying to compare these research studies as some do not provide internal atmosphere data. Studies by Smith and Stow (1984) and Lau and Meheriuk (1994) found that firmness retention was generally better with higher concentration of 'Prolong' and 'Nutri-Save'. Conversely Santerre *et al.* (1989) found that increasing 'Semperfresh' concentration from 0.6 -1.2 % did not enhance fruit firmness in 'McIntosh' apples and provided some evidence to suggest that lower concentrations (< 1 %) were more effective. Chai *et al.* (1991) also found that for 'McIntosh' apples, stored for 4 months at 0 °C, 'Semperfresh' concentrations < 1.0 % were more effective at delaying textural loss than concentrations > 1.0 %. However, they also found that higher coating concentrations were better for firmness retention during shorter storage periods.

In the case of processed fruit, the results from this study provided some evidence to suggest that higher coating concentrations may enhance slice texture. This effect was particularly evident in slices made from coated 'Braeburn' fruit stored at 20 °C in 1994. In this case, fruit coated with 4 % CMC clearly produced slices of a superior texture (Table 6-9) than those made from fruit coated with 1 % CMC. This effect may be explained by the greater degree of atmospheric modification achieved in 4 % CMC coated fruit. Conversely, only minor differences in level of atmospheric modification were achieved in 1995, and there were no differences between coating concentration treatments in terms of texture. For 'Fuji' apples there were only minor differences in texture between coating concentrations. This is probably due to the degree of atmospheric modification being less marked compared to 'Braeburn' and similar for most of the coating concentrations (Fig. 6-14).

Another objective of this study was to examine the effect of calcium applied pre- or post- harvest on the quality of processed apple slices. Preharvest calcium sprays are the standard approach used by growers to ensure fruit reach calcium levels required to minimise calcium-related storage disorders. Pre-harvest dipping of individual fruit with 0.09 M $CaCl_2$ applied on six occasions interspersed throughout the growing season failed to increase P'_{H2O} (Table 6-14). This contrasts with work described by Davie (1997) where repeated preharvest dipping with $CaCl_2$ increased P'_{H2O} values in kiwifruit by 10 %. It had been anticipated that treatment with $CaCl_2$ would increase P'_{H2O} and thereby enhance fruit transpiration and calcium uptake through the xylem as well as having a direct effect by direct uptake of Ca through the skin. Although there was no evidence for a stimulation of transpiration, fruit calcium levels were slightly higher in treated fruit, presumably because of absorption of calcium through the skin (Table 6-16). Researchers have reported calcium sprays as having both positive (Drake *et al.*, 1979; Hewett and Watkins, 1991; Siddiqui and Bangerth, 1995a) and negligible (Chittenden *et al.*, 1973; Himelrick and Ingle, 1981) effects on fruit calcium status. This apparent disparity may be caused by a number of factors including differences in soil calcium levels and/or spray penetration as a result of coverage level, time of spraying and prevailing environmental conditions. Other

cultural practices such as pruning and thinning are also known to influence fruit calcium status (Tomala and Dilley, 1990). Perhaps not surprisingly, not only are the effects of preharvest calcium sprays on fruit calcium levels inconsistent, but so too are the effects of calcium sprays on fruit firmness (Porritt *et al.*, 1975; Siddiqui and Bangerth, 1995a, 1995b). Differences in other factors such as cell size, airspace volume, fruit development may be responsible for the variability of the firmness-Ca effect. Preharvest treatments such as calcium sprays may induce changes in these factors as well as fruit calcium status. In this study, preharvest calcium application conferred a slight enhancement in both fresh fruit and processed slice texture (Tables 6-16 and 6-18). These results demonstrate that even a small increase in preharvest fruit calcium levels, may result in improved fruit texture.

Postharvest calcium dips also enhanced fruit calcium levels (Table 6-19), but this did not result in an improvement in processed slice texture. These increases in fruit calcium levels, brought about by dipping, were comparable with those of Mason and Drought (1975) and Mason *et al.* (1974). The lack of improvement in processed slice texture may possibly be due to the calcium staying relatively close to the surface and not penetrating deeply into the fruit, resulting in a localised effect, or due to calcium not being incorporated into the cell structure in a way that maintains texture. Studies by Lidster *et al.* (1977) and Mason and Drought (1975) revealed a definite gradient in calcium levels between skin and core, in fruit that had been dipped in calcium. However, this does not appear to be the full story in this study since fresh fruit texture was slightly enhanced and juice volume reduced by calcium treatment. This effect of calcium on juice volume may be due to calcium ensuring that the tissue retains a three dimensional structure that holds juice rather like a sponge. Results from the MA studies (refer 6.3.1.1) also showed that utilising CMC as a thickener substantially increased fruit calcium levels. This agrees with results of Mason (1976) who found that fruit dipped in a solution containing calcium plus thickener contained approx 1.9 times as much calcium as calcium dipped fruit. The enhancement in fruit calcium status brought about by incorporating a food thickener into the dip was probably due to the increased amount of calcium held on the fruit

surface and time that the fruit was in contact with the moist calcium film, enabling more calcium to be taken up by the fruit (Mason *et al.*, 1974; Glenn *et al.*, 1985). Despite the enhancements in fruit calcium levels brought about by incorporating a thickener into the coating, any benefits to processed or fresh fruit texture were small compared to the MA benefits achieved using fruit coatings. This apparent inability of postharvest calcium dips to improve processed slice quality may be due to the comparatively more effective means in which calcium is administered during the processing phase. Here calcium is vacuum infiltrated into the sliced tissue, facilitating rapid flooding of the intercellular air spaces, whilst binding is promoted during the early part of the blanch phase via the stimulation of pectin esterase activity, thereby increasing the demethylation of pectin and increasing Ca^{2+} cross-linking (Van Buren, 1979; Usiak *et al.*, 1995). This rapid incorporation of calcium into the tissue during the processing phase may overshadow any attempts to improve fruit calcium levels during the postharvest phase. Blackler (1992) investigated the effect of increasing the concentration of calcium in the infiltrating solution, and found that calcium levels were substantially raised and slice texture improved. Preliminary work carried out in this study also found that calcium levels were much higher (av. 2.3 mg/g dw) in processed fruit compared to fresh fruit (av. 0.3 mg/g dw). In summary, fruit with a high calcium status tend to process better. Early enhancement of fruit calcium levels (i.e. during pre- or post- harvest phases) is potentially better since it may retard textural degradation during storage. However, in this study, Ca levels were generally not raised sufficiently to provide an additional textural advantage over that provided by vacuum infiltration during the preprocessing phase. Vacuum infiltration provides a more effective means of raising fruit calcium status and if used during the postharvest phase seems likely to result in an additional improvement in product texture.

Results from this study have clearly demonstrated the potential for improving processed slice quality through the use of surface coatings, particularly in situations where fruit are ambient stored prior to processing. Benefits include better firmness retention, greater slice integrity, a reduction in the development of mealiness and in some cases a reduction in the amount of free juice in the can.

Chapter 7

General Discussion

Ultimate quality of processed fruit is influenced by a number of key preharvest, postharvest and processing factors. To achieve consistent production of high quality solid-pack apple slices requires an understanding of the key factors and processes involved and the application of treatments that reduce textural degradation in the fresh product. The work described in this thesis has focused primarily on factors that affect processed apple slice texture and quality. In Chapter 4, factors that affect the effectiveness of the vacuum infiltration process were investigated, whilst Chapters 5 and 6 looked at the effects of a range of pre- and post- harvest factors on slice texture and quality.

Fig. 7-1 provides an overview of preharvest, postharvest and processing factors thought to influence fresh and processed slice texture and quality. The factors or attributes enclosed by boxes indicate those investigated in this study. The first part of this chapter (7.1) reviews key aspects of the individual chapters, highlighting the interrelationships between the various factors investigated. The middle part (7.2-7.4) looks at several key issues in more depth, while the final part (7.5) presents some ideas for further work that could be carried out.

7.1 Project overview

Vacuum infiltration to remove occluded gases from apple tissue is still viewed by processors as a 'bottle-neck' in solid-pack apple slice production. Problems with insufficient deaeration are particularly prevalent early in the processing season and following a cold growing season (J. Wattie Foods, personal communication, 1993). Poor infiltration of slices also tends to result in the production of slices with an inferior texture and overall quality. Work described in this thesis has re-examined ways of assessing the degree of slice infiltration, evaluated each component of the

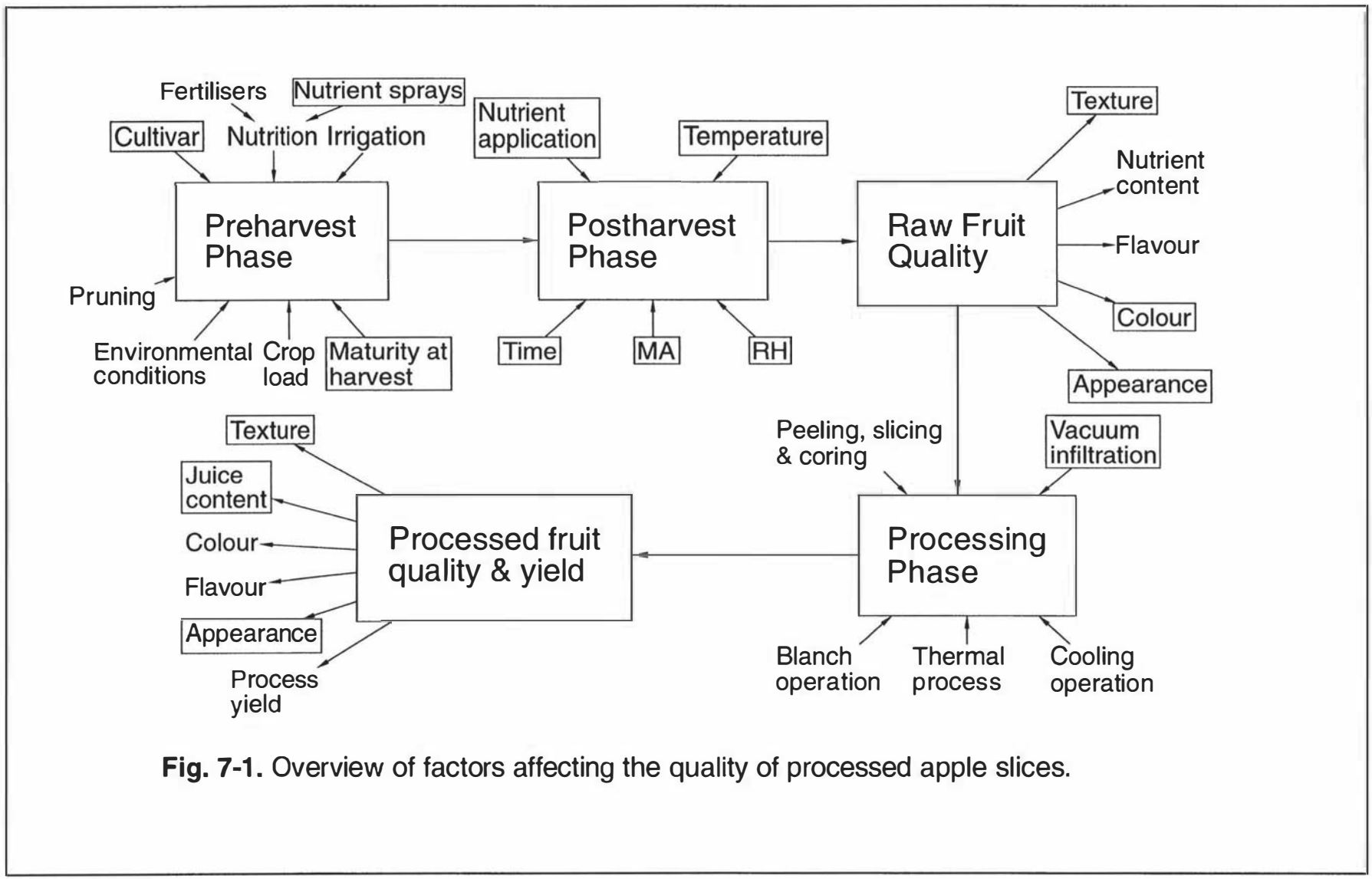


Fig. 7-1. Overview of factors affecting the quality of processed apple slices.

vacuum infiltration sequence, looked at ways of enhancing infiltration through modification of the infiltrating solution and assessed the effect of fruit maturity (as influenced by harvest date) on infiltration.

Accurate assessment of level of infiltration (LOI) is critical for comparison of treatments designed to enhance infiltration in difficult-to-infiltrate fruit. Previous studies looking at level of infiltration achieved during the vacuum process have largely relied on estimates of tissue weight gain to assess infiltration (Hoover and Miller, 1975; Gallander and Kretchman, 1976; MacGregor and Kitson, 1981; and Banaszczyk and Plocharski, 1993), although some have used residual headspace oxygen levels (Hamblin *et al.*, 1987 and Heil *et al.*, 1988). The approach used in this study draws from techniques used to estimate tissue porosity (Reeve, 1953; Kushman and Pope, 1968; Raskin, 1983; Calbo and Nery, 1995; and Yearsley *et al.*, 1996), and hence is able to relate infiltration to the volume of intercellular air space (IAS) in the tissue. This study has demonstrated that $\Delta\rho_{rel}^{slice}$ (Eq. 4-6) is an effective means of assessing level of infiltration. Earlier concerns that $\Delta\rho_{rel}^{slice}$ may not be suitable, since it might not distinguish between wholly infiltrated slices with a smaller IAS and partially infiltrated slices with a large IAS have been largely alleviated. This has been achieved by comparing $\Delta\rho_{rel}^{slice}$ values with DOI (a measure of infiltration that incorporates an estimate of tissue porosity (Eq. 4-2)), which showed that increases in tissue porosity paralleled increases in infiltration (Fig. 4-14b).

Fig. 7-2 is a schematic representation of the factors thought to influence the level of infiltration achieved in apple slices. These factors can be divided into two distinct areas: those that relate to the pre-condition of the tissue before vacuum infiltration; and those that directly affect the vacuum infiltration process. With regard to the pre-condition of the tissue, this study has: characterised the linear relationships between harvest date, ρ_{rel}^{fruit}, and $\Delta\rho_{rel}^{slice}$ (Fig. 4-6); and quantified the significant increase in $\Delta\rho_{rel}^{slice}$ brought about by a short period of storage at 20 °C (Fig. 4-7). From these results, difficult-to-infiltrate fruit can be characterised as those with a low ε, high ρ_{rel}^{fruit}

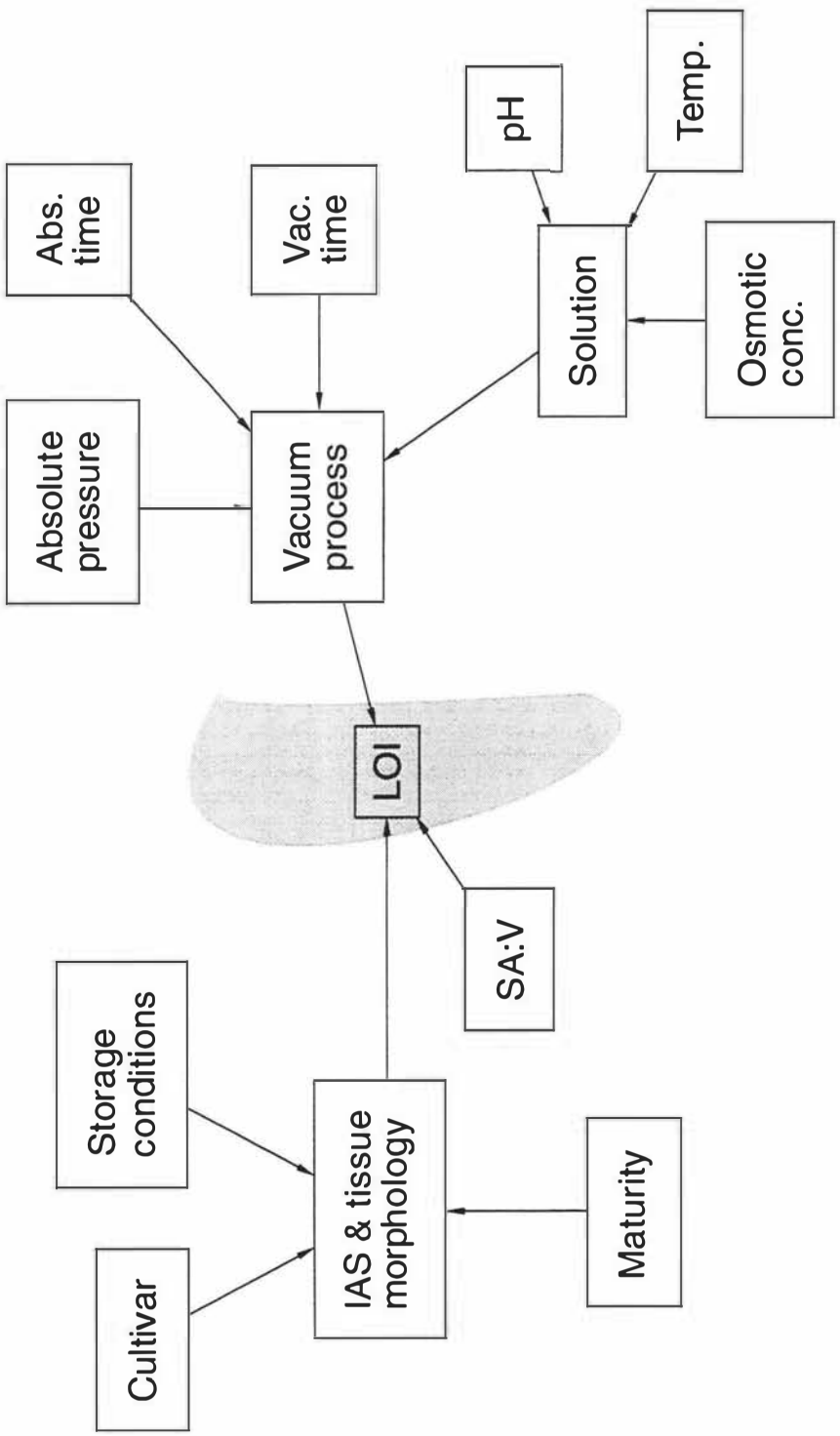


Fig. 7-2 Factors thought to affect apple slice infiltration.

and low maturity level. Opportunities to alter the pre-condition of the fruit include taking fruit from later harvests and pre-storage of fruit for a short period at higher temperatures.

Key aspects of the vacuum infiltration process have also been re-visited and the relationships between vacuum time, absorption time and $\Delta\rho_{rel}^{slice}$ characterised (Figs. 4-8 to 4-10). A previous study by Hoover and Miller (1975) established that lengthening vacuum dwell time resulted in only a slight increase in slice infiltration. They also found that infiltration was significantly reduced at vacuum levels below 91 kPa. However, Hoover and Miller's approach differed in a number of ways from that adopted in this work, including: the use of increase in weight gain to assess level of infiltration; use of a 24 % sucrose solution as the infiltrating medium (considerably higher than that used by the New Zealand industry); and not differentiating between vacuum dwell time and absorption time. The work described in this thesis has furthered Hoover and Miller's work by separating out and quantifying the effects of vacuum level, vacuum dwell time, absorption time and vacuum release speed. Quantifying the relationships between these key variables should enable processors to establish a suitable vacuum infiltration process once the pre-condition of the raw material is ascertained. Results from this current study have shown that to maximise infiltration in 'Braeburn' fruit required: high vacuum levels (preferably >95 kPa); vacuum times (not including pull down period) of approx. 2 min; and absorption times $\geq$ 6 min.

Modification of the infiltrating solution was also an effective means of enhancing infiltration in difficult-to-infiltrate fruit. Earlier studies had pointed to the importance of temperature (Hoover and Miller, 1975; Heil *et al.*, 1988) and osmotic concentration (Hoover and Miller, 1975; Gallander and Kretchman, 1976) of the infiltrating solution. The work described in this thesis used a factorial design to explore further the relationship between solution temperature, osmotic concentration and pH. From this, temperature was identified as the factor with the most potential for enhancing infiltration. A further experiment was carried out to quantify the effect

of solution temperature on infiltration (Fig. 4-12). A quadratic function (Eq. 4-10) adequately described the relationship between the two variables. Heating the solution appears to be a powerful means of enhancing infiltration in difficult-to-infiltrate fruit, which should be feasible to implement in commercial practice.

Level of infiltration also affected ultimate processed slice texture, with insufficient infiltration significantly reducing textural quality (Fig. 4-13). This effect was probably largely due to the thermal expansion of the remaining occluded gases in the tissue during the blanching and cooking phases causing tissue damage that then resulted in sloughing and mushiness. Dougherty *et al.* (1966) noted the beneficial effects of vacuum infiltration on texture but did not investigate the relationship between level of infiltration and textural quality.

The work described in this thesis has largely focused on how postharvest treatment of fresh apples affects the quality, particularly texture, of the processed product. Effects of raw product storage temperature, RH and duration (Chapter 5), and edible surface coatings and calcium application (Chapter 6), on solid-pack textural quality have been examined. The interrelationships between these variables and the response of the fruit to a given set of conditions are quite complex.

Fig. 7-3 draws together the individual factors examined in this thesis and pictorially depicts (through the use of vectors) how each factor affects ripening and texture development in apple fruit. Stage A (Fig. 7-3) represents unripe, cohesive tissue taken from a texturally sound, freshly harvested apple which would be representative of the majority of fruit entering the postharvest phase. This would be particularly true of process grade fruit which, by nature of the grading process, includes a large proportion of immature fruit (J. Wattie Foods, personal communication, 1994). The process of ripening brings about physical changes in tissue morphology which may be caused by degradation in starch or breakdown of the structural integrity of the cell wall and middle lamella (Bartley and Knee, 1982; Tucker, 1993). Stages B_1 and B_2 represent two alternative scenarios for fully ripened fruit, with B_1 and B_2 representing

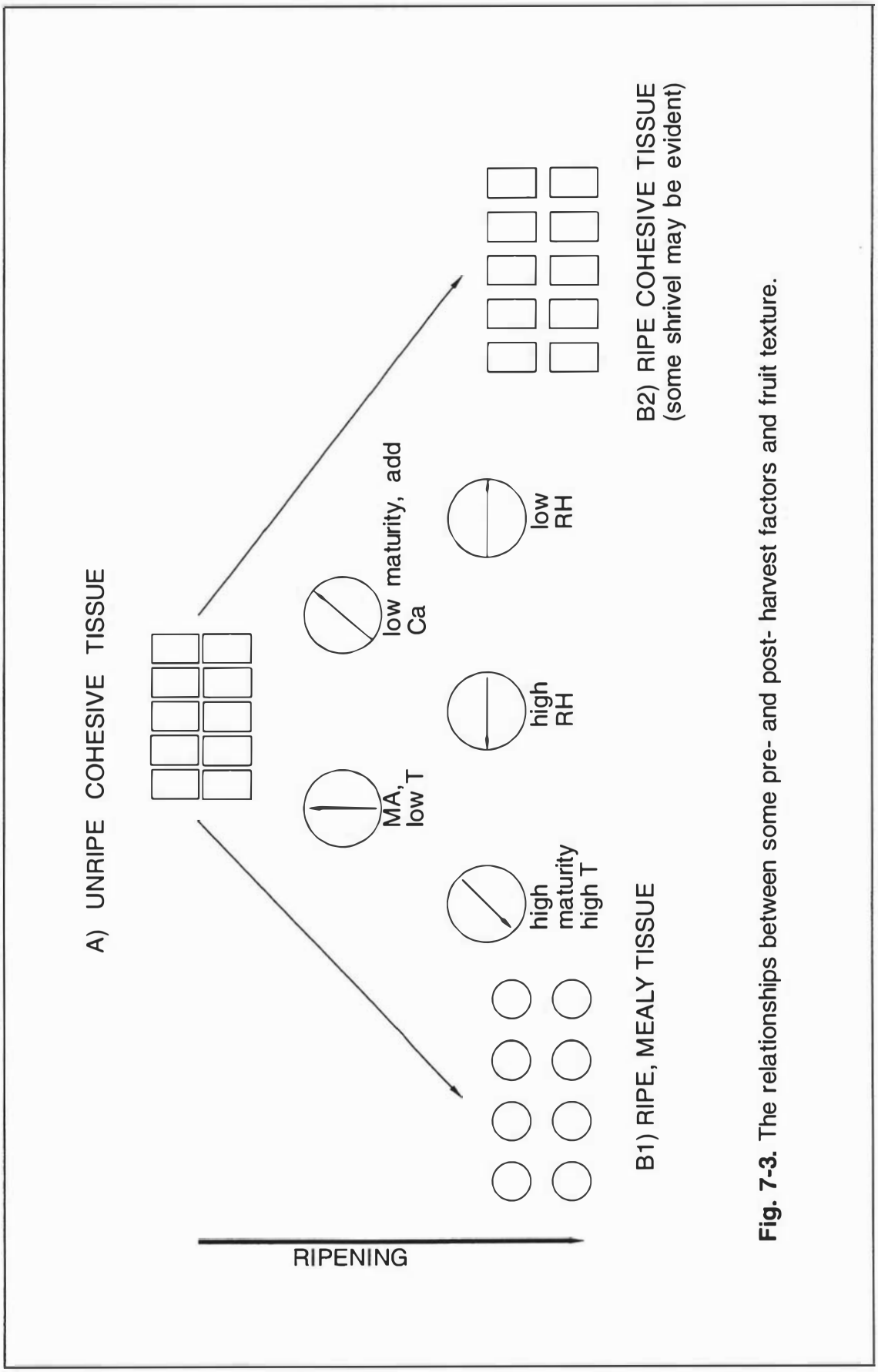


Fig. 7-3. The relationships between some pre- and post- harvest factors and fruit texture.

mealy and non-mealy fruit respectively. Whether or not an apple develops mealiness affects not only the acceptability of the fresh product to consumers, but also its predisposition to processing, as mealy apples have a greater tendency to slough and sauce on heating (Reeve and Leinbach, 1953). In this current study the rapid development of mealiness in 'Braeburn' fruit stored at 10 or 20 °C was particularly detrimental to processed slice quality, resulting in the production of soft, textureless slices with excessive sauce (Fig. 5-5b). The development of mealiness (defined sensorially by Harker and Hallett (1992) as the breakdown of flesh into small pieces in the mouth which tend to be dry) has been associated with an increase in IAS, low adhesion between neighbouring cells and relatively high resistance to cell rupture (Harker and Hallett, 1992; Khan and Vincent, 1993; Tu *et al.*, 1996). Fig. 7-3 draws together schematically factors known to influence raw and processed apple texture, and it is these factors and the interrelationships between them, in conjunction with cultivar differences, that will be discussed over the next few pages.

Cultivar differences featured strongly in this work, with 'Braeburn', 'Fuji' and 'Granny Smith' apples varying quite markedly in terms of textural quality, storage potential, tolerance of ambient temperatures and ultimately in their response to processing. 'Braeburn' apples were particularly sensitive to warm storage temperatures (20 °C), with raw and processed fruit quality deteriorating to an unacceptable level after just 2 weeks. This contrasts with 'Fuji' and 'Granny Smith' apples, that continued to produce slices of an acceptable quality from fruit stored at 20 °C for a considerably longer period. Cultivar differences can be partially attributed to intrinsic differences in morphology, respiration rates and softening behaviour. These large differences between cultivars tend to restrict the development of broad generalisations being made concerning individual extrinsic factors.

Storage temperature and duration had a direct effect on raw apple texture development and corresponding solid-pack texture. Raw apple texture development under cool-storage conditions has been studied extensively (Tijskens, 1979; D'Souza and Ingle, 1989; Ingle and Morris, 1989; Yuwana,1991). However, textural changes

occurring in fruit stored under ambient conditions has received only limited attention (Tu *et al.*, 1996), as have the effects of raw product storage temperatures on processed slice quality (Wiley and Thompson, 1960). Results from the current study have characterised the softening behaviour of 'Braeburn', 'Fuji' and 'Granny Smith' apples at both cool-storage and shelf life temperatures (10 and/or 20 °C), and provided valuable insight into how postharvest storage temperature affects processed slice quality. In general, processed slice firmness decreased with increasing storage temperature and duration. However, this trend was by no means universal, as demonstrated by 'Granny Smith' apples which showed very little change in processed slice quality as a result of higher temperatures or longer storage durations (Fig. 5-5a). This effect was despite raw 'Granny Smith' apples showing significant texture degradation (Figs. 5-1 and 5-2).

The effect of edible surface coatings on raw and processed slice quality formed a key component of the work described in this thesis. The effect of edible coatings on fresh fruit quality has been researched extensively (Trout *et al.*, 1952; Smith and Stow, 1984; Drake and Nelson, 1990; Lau and Meheriuk, 1994). However, the effect of edible surface coatings applied during the postharvest phase on processing quality does not appear to have been studied, at least in apples. In this study, the potential benefits gained from this approach to MA storage varied with cultivar, storage temperature and growing season. In particular, storage temperature had a profound effect on internal atmosphere composition and corresponding relative retardation of texture degradation in raw and processed fruit. Results from this study suggest that edible surface coatings applied to process grade fruit stored under ambient conditions may provide an effective means of enhancing solid-pack slice texture.

The final component of this study looked at the role of calcium in retaining processed slice texture. Calcium applied during the preharvest phase resulted in a slight improvement in processed slice quality (Table 6-16). Postharvest calcium dips did not enhance processed slice texture, despite a slight improvement in raw fruit texture (Tables 6-19 and 6-20). The limited extent of these effects of calcium on

processed slice texture may have been due to the potentially more effective means of incorporating calcium into the tissue via vacuum infiltration and blanching during the processing phase. Vacuum infiltration rapidly floods the tissue with calcium, whilst blanching stimulates pectin esterase activity, thereby increasing the demethylation of pectin and increasing Ca^{2+} crosslinking (Van Buren, 1979; Usiak *et al.*, 1995). The positive textural effects of incorporating calcium into the tissue during the processing phase have been clearly demonstrated by Blackler (1992).

In the preceding chapters (and project overview detailed above), data, ideas and conclusions have been presented concerning the effect of a range of individual factors on vacuum infiltration and raw and process slice texture and quality. The following sections provide the opportunity to integrate and discuss further some of key issues affecting raw and processed slice texture and quality.

7.2 Relationships between raw tissue texture and structure, and their influence on processed slice texture

Textural changes from firm, crisp, juicy tissue to soft, mealy tissue during ripening and storage affect both textural qualities of processed apple products and consumer acceptance of the fresh product. Instrumental tests (twist, penetrometer, Kramer shear, compression) have been used throughout this study to characterise textural changes in fresh and processed tissue, enabling assessment of the potential benefits and risks associated with a number of postharvest treatments and storage regimes. Incidental observations have also been made concerning the response of the unprocessed tissue to heat treatment. To improve both fresh and processed apple texture requires an understanding of the mechanisms underlying these textural changes. Recently, a number of studies have used microscopic techniques in combination with instrumental and physiological tests, and in some cases sensory evaluation, to broaden our understanding of fruit texture and the mechanisms

underlying it. Results obtained from these studies provide insight into some of the possible mechanisms underlying textural changes observed in processed fruit in this study.

Fig. 7-3 (described earlier in this chapter) depicts pictorially the possible extremes of texture development in apple fruit ranging from a fresh, unripe, crunchy texture (Stage A) to dry, mealy, over-ripe texture (Stage B_1). Texture perception of fresh fruit is affected by the way in which cells separate or break open and release their contents (Harker *et al.*, 1997a). Which of these processes occurs (i.e. cell separation or cell rupture) during deformation is determined by the strength of the cell wall relative to the strength of adhesion between neighbouring cells. If the cell wall is the stronger component then cells separate from each other; conversely, if cell adhesion is greater than cell wall strength, cells tend to break open and release their contents. In apples, mealy fruit tend to have low cell-to-cell adhesion but a relatively high resistance to rupture (Harker and Hallett, 1992; Tu *et al.*, 1996). In contrast, fresh fruit and stored but non-mealy fruit tend to maintain relatively high cell-to-cell adhesion, but cells tend to rupture more easily due to a decline in cell wall strength. The tendency for cells to either separate or pull apart also has implications for the textural qualities of processed apple products.

In this study, apples processed at or close to Stage A (i.e. freshly harvested or those cool-stored for a short period) on the whole tended to produce firm, crisp, juicy slices, with a relatively small free juice volume (eg. Tables 6-10 and 6-17). This would suggest that the cell wall and middle lamella integrity has been largely maintained in these slices. Support for this assertion can found in a number of studies (Reeve and Leinbach, 1953; Stanley *et al.*, 1995) including Mohr (1989) who found that the textural quality or 'coarseness' of apple sauce was largely determined by the degree of cell separation. Although these apples (Stage A) tend to process well, there are a couple of processing problems that may arise. For some cultivars (eg. 'Braeburn'), or particularly dense or immature fruit, achieving complete infiltration of IAS may be difficult. Incomplete infiltration may result in

considerable textural damage due to thermal expansion of these gases during blanching and cooking (MacGregor and Kitson, 1981). Infiltration may be enhanced in these slices by: storing the fruit for a short period at 20 °C to allow further ripening to occur (Fig. 4-7); increasing the absorption time (Fig. 4-9); or heating the infiltrating solution (Fig. 4-12). Use of ambient storage of fruit to enhance infiltration needs to be considered carefully as textural quality may decline because of softening associated with ripening. Other problems that may be encountered when processing fruit at this stage (A) include production of slices that: are considered too firm by end users of the product; lack characteristic full apple flavour; or exhibit a pale flesh colour. Each of these may also be overcome by allowing a short period of tempering (warm temperatures).

Processing mealy, overripe apples (Fig. 7-3, Stage B_1) generally results in the production of soft textureless and sometimes saucy slices (eg. Tables 6-6; 6-8; 6-9). Fruit tending towards mealiness often have a greater IAS volume compared to their non-mealy counterparts. Several studies have demonstrated a relationship between large airspace volumes and poor apple texture (Hatfield and Knee, 1988; Vincent, 1989; Harker and Hallett, 1992; Tu *et al.*, 1996). The development of mealy texture and large air spaces is most likely caused by middle lamella degradation, leading to a corresponding reduction in cell-to-cell adhesion. This enables the cells to expand slightly and become more rounded, resulting in an increase in IAS and a corresponding decrease in cell-to-cell contact area. In fruit tending towards mealiness, cell separation is more likely to occur during deformation or tensile testing, vacuum infiltration, or thermal processing. In the current study, 'Braeburn' fruit clearly developed mealiness when stored at warm temperatures (10 or 20 °C) for a short period (2 weeks), as evidenced by an increase in IAS, high maturity (high starch index, low hue angles and firmness values), some sloughing during blanching and the production of soft slices after blanching or canning.

Fruit processed at stage B_2 (ripe, but non-mealy) or at stages of intermediate ripeness tended to produce slices with textures ranging from firm, but not hard, to soft, but

not mushy. Texture decline in these slices (as a result of ripening) could be due to a decrease in cell wall strength and cell-to-cell adhesion, caused by pectin degradation. Postharvest technologies that retard ripening and hence fruit softening (MA, low temperature storage, calcium application) or reduce the likelihood of mealiness (low RH storage, calcium application), enhance both fresh fruit storage life and quality, and processing potential. MA and low temperature storage retard ripening and fruit softening by depressing respiration and hence delaying the utilisation of respiratory substrates and limiting the availability of energy for deteriorative processes. The role of calcium in delaying the onset of fruit softening and mealiness development is thought to be due to its ability to enhance cell wall strength and maintain cell-to-cell cohesion by crosslinking pectin molecules in the middle lamella (Knee and Bartley, 1981; Stow, 1989). Low RH treatments (those that induce a small but significant weight loss (refer Hatfield and Knee, 1988)) may delay mealiness development by restricting the increase in IAS brought about by turgor and hence retaining cell-to-cell contact and enhancing perceived texture (Hatfield and Knee, 1988).

7.3 Prediction of processed slice quality from raw product tests

Prediction of final product texture and quality from raw product tests is of key interest to researchers and processors alike. Using raw product tests in this manner enables the production of both a more consistent final product and the effective scheduling of processing runs. The development of accurate prediction models would assist processors greatly in producing a consistently high quality product and enable them to make suitable changes to the process line based on raw product quality tests (this may be particularly relevant for the vacuum infiltration operation). In this study, 'Braeburn' blanched slice texture was well described by DPen (r^2= 0.91), while for 'Fuji' three variables TMax, TBio and SS accounted for 62 % of the variation in blanched slice quality. Cultivar differences featured strongly in these regression analyses, with substantially more of the variation in blanched

'Braeburn' slice texture being accounted for by raw product tests. This may be partially due to a larger spread in texture values for 'Braeburn' fruit compared to 'Fuji' fruit. Dougherty *et al.* (1966) previously reported that blanched slice firmness was a good predictor of processed slice firmness. In the experiment described in chapter 5, fresh and blanched measurements were made on the same fruit and this may have enhanced the prediction models by removing considerable fruit-to-fruit variation from the error in characterisation of the relationships. Generating prediction models based on fresh and processed data from the same fruit should improve the quality of such models. However, in commercial practice, raw and processed quality estimates would consist of separate samples from the same population of fruit.

7.4 Opportunities in the pre- and post- harvest phases for enhancing apple slice quality

Fig. 7-1 illustrates the diversity of factors thought to affect processed slice quality; many of these have featured in this study. Cultivar selection is an important consideration for processors looking to consistently produce a high quality product. Cultivar differences in processed sauce or slice texture have long been recognised (Reeve and Leinbach, 1953; Williams *et al.*, 1983; McLellan *et al.*, 1984a; 1984b; Mohr, 1989; Wiley and Binkley, 1989). However, little has previously been published about the response of 'Braeburn' and 'Fuji' to processing. The importance of cultivars such as 'Braeburn' and 'Fuji' is likely to increase due to the increased demand for these cultivars on the world fresh fruit market. This study characterised the response of 'Braeburn' and 'Fuji' to processing following exposure to a range of pre-processing conditions. Results from this study suggest that 'Fuji' has the potential to become a top processing apple. 'Fuji' fruit store well, producing good consistent slices throughout the processing season. In this study, fruit stored at 20 °C continued to produce good quality blanched slices for up to 9 weeks storage (Chapter 5). However, 'Fuji' fruit are prone to water loss and shrivel due to their skin and limited amount of natural wax (Kupferman, 1994). This is particularly evident under

low RH conditions. In contrast to 'Fuji', ambient stored 'Braeburn' apples would not appear to be a particularly suitable for apple slice production due to their tendency to develop mealiness after only a short period of ambient storage. 'Braeburn' apples did result in a good product if stored appropriately.

The application of edible surface coatings to ambient-stored, process grade fruit would appear to be a suitable means for extending the storage life and enhancing canned slice quality. Texture development in fresh fruit was also followed in this study, enabling some conclusions to be drawn concerning the use of coatings in the fresh fruit industry. This option has become a lot closer to mainstream fruit handling practice in New Zealand with the dramatic increase in use of waxing for the local market in the last three years. MA benefits observed in fresh fruit included: retention of firmness and chlorophyll and a reduction in the number of fruit developing mealiness. Canned slices produced from coated fruit tended to be firmer, contain a greater number of whole slices and, in some cases, had less free-juice in the can.

The design and optimisation of edible surface coatings requires consideration of a number of important issues including fruit-to-fruit variability, target $p^i_{O_2}$ and $p^i_{CO_2}$ levels, intended storage temperature and end use (i.e. fresh or processing). To maximise the MA benefits achieved by surface coatings requires the selection of a coating material that reduces $p^i_{O_2}$ to a level just above the LOL^i (Yearsley *et al.*, 1996). At this point, respiration and other associated metabolic processes are minimised, without inducing anaerobiosis. Plots of $p^i_{CO_2}$ vs $p^i_{O_2}$ (Banks *et al.*, 1997) can be used effectively to identify the LOL^i for a particular cultivar under a given set of conditions, provided data are available from fruit with a broad spectrum of $p^i_{O_2}$ and $p^i_{CO_2}$ values. Accurate characterisation of LOL^i in these experiments is limited by the often large fruit-to-fruit variability.

Results from the current study (Figs. 6-7, 6-9 and 6-13) and others (Dadzie, 1992; Banks *et al.*, 1997) have demonstrated the considerable variability in $p^i_{O_2}$ and $p^i_{CO_2}$

values that can occur within a particular coating treatment. This variability may be due to inherent differences between individual fruit (in terms of respiration rate, surface area and possibly skin permeance) and/or arise due to differences in the proportion of, or extent to which, pores are blocked. A number of recent studies (Hagenmaier and Baker, 1993; Mannheim and Soffer, 1996 and Banks *et al.*, 1997) have demonstrated that $p^i_{O_2}$ and $p^i_{CO_2}$ are primarily influenced by a coating's pore blocking ability rather than the permeability of the coating material to O_2 and CO_2. Results from the current work show that CMC's pore blocking ability may be altered by incorporating calcium or increasing the concentration and hence viscosity of the solution. However the high level of variability in $p^i_{O_2}$ within a particular coating treatment suggests that CMC can be quite variable in terms of the proportion of, and/or extent of, pore blockage, with some pores being only loosely covered by the coating. Banks *et al.* (1997) also noted that uniformity of response varied quite considerably amongst coating materials. The criteria for selecting suitable coating material therefore needs to include both the average response of the coating material on $p^i_{O_2}$ and the uniformity of that response.

Temperature has a marked effect on internal atmosphere composition due to its dramatic effects on respiration rate. Exposure of a fruit coated with a material optimised at 5 °C to higher temperatures e.g. 25 °C would result in elevated respiration, depression of $p^i_{O_2}$ and increase the risk of anaerobic respiration and off-flavour development. This necessitates coating development and optimisation to be carried out at the maximum temperature the fruit is likely to be exposed to. In the current work, coating optimisation was attempted at 0 and 20 °C. However, despite the use of higher concentrations of CMC at 0 °C, $p^i_{O_2}$ was generally not depressed sufficiently to influence fruit quality characteristics (Figs. 6-1b; 6-2b; 6-9a and 6-13b). Two of these coating concentrations were also used at 20 °C and resulted in the development of $p^i_{O_2}$ values that ranged from super- to sub- optimal. Design and optimisation of a coating at low temperatures (0-5 °C) would require a material that blocked most of the pores in the skin. The lack of an effective means for removing coatings from the cuticle and pores, necessitates the development and optimisation of

coatings at the maximum temperature the fruit is likely to be exposed to and hence largely restricts development of benefits from coatings to those obtained at warm or shelf life temperatures. However, this is not necessarily the case with fruit destined for processing. This is because the peeling process provides an effective means of removing the coating. The potential therefore exists with process grade fruit to optimise the coating at low temperatures (eg. 5 °C) and then process the fruit immediately upon removal from cool-storage hence preventing the development of anaerobic conditions within the fruit that would result from fruit being left for extended periods after removal from cool-storage.

7.5 Recommendations for further research

This study has investigated the effects of a range of preharvest, postharvest and processing factors on processed slice texture and quality. While it has provided answers to some of the questions posed in this study, it has raised a number of other questions that could form useful avenues for further research.

This study has demonstrated that the effectiveness of vacuum infiltration may be enhanced in difficult-to-infiltrate fruit by subjecting these fruit to a short period of storage at warm temperatures (20 °C) prior to processing. Immaturity is one of the main characteristics of such fruit and so it would be interesting to know whether or not treatment with a ripening promoter, such as ethylene, would also enhance infiltration. Another aspect that could be investigated further is the potential trade-off between enhanced infiltration and reduced texture in these fruit.

Development of a model to predict ease of infiltration from raw product tests would greatly assist processors in devising infiltration regimes or applying pre-processing treatments. In addition, processors do not currently have a quick, easy and reliable test to distinguish between well and poorly infiltrated slices. They currently rely on visual assessment of the infiltrated product. Development of such a test could reduce product line variability and enable quick establishment of a suitable vacuum

infiltration sequence for a given line of fruit.

This study has characterised the softening and processing behaviour of two relatively new cultivars to processing: 'Braeburn' and 'Fuji'. As the world fresh fruit market demands change and with the development of new cultivars, the mix of varieties available to processors will also change. To keep processors abreast of these changes, further research on new cultivars will be required to establish how they respond to storage and processing, and in particular to ascertain which type of processed apple product they are most suited to.

The potential for utilising surface coatings to preserve quality attributes of fruit destined for processing warrants further research. This could involve screening, selection and ultimately optimisation of coating materials at low temperatures (eg. 5 °C). Further work could also be carried out on the use of coatings at 20 °C. In this study, $p^i_{O_2}$ values in 'Braeburn' and 'Fuji' fruit coated with CMC were close to and significantly higher than the LOL^i, respectively. Large fruit-to-fruit variation was also evident in both cultivars. Further work could involve screening a range of coating materials to find potentially more suitable compounds that produced a more uniform response and $p^i_{O_2}$ values within an acceptable range for each cultivar. Such materials could then be used in small commercial trials to assess the commercial feasibility of such an operation. This study should also incorporate a sensory evaluation component to establish whether or not any off-flavour development in the fresh product is detectable in the processed product.

Ultimate processed slice texture is closely tied to tissue structure; it would be useful to relate changes in process slice texture to changes in tissue morphology. This could be achieved by using fruit from a range of maturity classes and relating changes in fresh fruit tissue morphology, as viewed using electron microscopy, to processed slice texture and morphology.

Canned apple texture is also influenced by an array of processing factors including blanch temperature. Recent studies with canned green beans and carrots (Stanley *et al.*, 1995) point to the positive influence of low temperature blanching on final product texture. The potential benefits of such a regime for canned apple slice texture should be assessed.

7.6 Conclusion

The study described in this thesis had two primary objectives:

1) to identify potential techniques for enhancing infiltration in difficult-to-infiltrate fruit;
2) to ascertain the effects of a range of pre- and post- harvest factors including temperature, surface coating and calcium treatments on processed slice texture and quality.

The level of infiltration achieved in apple slices was affected by the pre-condition of the tissue (eg. maturity, porosity, whole fruit density) and by variables that relate directly to the vacuum infiltration process (eg. vacuum time, absorption time, solution temperature). Infiltration was enhanced in difficult-to-infiltrate fruit by either modifying the pre-condition of the tissue (eg. inducing further ripening by storing fruit for a short period at 20 °C) or altering the vacuum infiltration process (eg. by heating the infiltrating solution)

Processed slice quality and texture are affected by the quality of the unprocessed slices and the way in which the unprocessed flesh responds to the canning process. This study has investigated the effects of cultivar, storage temperature, storage duration, MA storage and calcium treatments on processed slice texture and quality. Cultivars utilised in this study varied markedly in terms of texture (expressed as absolute firmness, softening rate or variability in firmness), storage potential, tolerance of ambient temperatures and in their response to processing. In general, fresh and processed slice texture declined with increasing storage temperature and storage duration. Application of edible surface coatings to process grade fruit has the

potential to enhance apple slice texture and quality. Development of coating materials that optimise $p^i_{O_2}$ at 0 and 20 °C should result in enhanced slice quality without the deleterious effects associated with anaerobic respiration. This study has attempted to characterise the relationships between these postharvest variables and process slice texture and quality and, whilst these relationships were not always clear cut, progress has been made in identifying key factors and possibilities put forward for enhancing the textural quality of this product. It is hoped that subsequent studies will investigate further some of the potential areas identified for enhancing product quality.

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