MECHANICAL PROPERTIES AFFECTING SLICING PERFORMANCE OF POTATOES

By

Miruna Laza

A Thesis

Submitted to the Faculty

Of

Graduate Studies

In Partial Fulfillment of the

Requirements for the Degree

Of

MASTER OF SCIENCE

Food Science Department

University of Manitoba

Winnipeg, Manitoba

THE UNIVERSITY OF MANITOBA

FACULTY OF GRADUATE STUDIES

*****

COPYRIGHT PERMISSION PAGE

Mechanical Properties Affecting Slicing Performance of Potatoes

BY

Miruna Laza

A Thesis/Practicum submitted to the Faculty of Graduate Studies of The University of Manitoba in partial fulfillment of the requirements of the degree of Master of Science

I hereby declare that I am the sole author of this thesis.

I authorize the University of Manitoba to lend this thesis to other institutions or individuals for the purpose of scholarly research.

Miruna Laza

I further authorize the University of Manitoba to reproduce this thesis by photocopying or by other means in total or in part, at the request of other institutions or individuals for the purpose of scholarly research.

Miruna Laza

The University of Manitoba requires the signature of all persons using or photocopying this thesis. Please sign below, and give address and date.

Good, better best,
Never rest,
Till good be better and better best.

Anonymous

ACKNOWLEDGEMENTS

I wish to express my gratitude to my advisor, Dr. Martin Scanlon, who believed in me and chose me to be his student. Appreciation is extended to Dr. G. (Joe) Mazza for always having the right answers to my countless questions. I had the opportunity to conduct my research at Pacific Agri-Food Research Centre (PARC), Summerland, BC. For this chance I also need to thank Dr. Scanlon and Dr. Mazza. Special thanks are also given to Dr. Cenkowski for his valuable advice and participation on the thesis examination committee.

The cooperation and friendship of the entire staff at PARC are gratefully acknowledged. Special thanks to Rod Hocking, John Hall, Sandra Stewart, David Goodfrey, Peggy Watson, Michael Weis, Dr. Sabina Stan and Dr. Dave Oomah.

Sincerest gratitude to my parents who taught me never to give up, and to my husband whose support I could always count on.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF APPENDICES

ABSTRACT

In the processing of potatoes into french fries the slicing operation is critical to both yield and quality of the fries. Slicing performance is not constant throughout the tuber storage season, with changes in mechanical properties (due to cell wall or turgor changes) affecting the amount of feathering that occurs on the fry surfaces. This results in a poor surface quality of the french fry, causing subsequent degradative reactions such as breakage of the strip and discoloration. To improve efficiency and quality of the slicing operation some processors will pre-heat the tubers prior to slicing. The purpose of this work was to examine the effect of thermal treatment and artificial turgor adjustment on various mechanical properties of potatoes throughout the storage season. The relationship between the parameters of interest was analyzed in order to see if the size reduction of the tuber could be viewed as a brittle fracture phenomenon. Specimens taken from two potato cultivars (Russet Burbank and Shepody) of two different solids contents were subjected to small strain oscillatory shear tests, wedge fracture tests and notched-specimen tensile tests. The degree of feathering on the two new surfaces following the wedge fracture test was quantified. The specimens were prepared from control (8°C) and pre-heated (33, 47 or 60°C) samples of Russet and Shepody potatoes with both high and low solids content. Prior to testing, specimens were osmotically adjusted in a mannitol solution of 3%, 5% or 7%. The small strain oscillatory shear tests were performed at 1 Hz frequency and stresses ranging between 10 and 100 Nm^{-2}. The wedge-penetration fracture tests and the tensile tests were both performed at cross-head speeds of 20 mm min^{-1}. All the measurements were performed at room temperature (23±1°C). The tests were repeated every month from November to June. Measurements of turgor pressure and

specific gravity were also performed during the storage time, for both Russet and Shepody potatoes. The results showed that turgor pressure slightly decreased, while the solids content slightly increased throughout the storage period. Control (8°C) and pre-heating temperatures of 33 and 47°C had little or no influence on dynamic shear storage modulus, fracture toughness, amount of feathering, tensile stiffness and tensile strength. The highest pre-heating temperature (60°C) caused an increase in the amount of feathering, while all the other measured mechanical parameters decreased. Two types of feathering were observed to occur depending on pre-heating temperature. Storage time had only a slight effect on the parameters of interest. As mannitol concentration increased (and so turgor pressure in the potato cells decreased), all the mechanical properties investigated decreased for the control, as well as for 33 and 47°C pre-heating treatments. Mannitol concentration had no effect on any of the mechanical parameters for tubers that had been pre-heated at 60°C. For Shepody potatoes solids content had a significant effect on shear modulus, feathering and stiffness. For Russet potatoes, only stiffness was significantly affected by solids content. All the mechanical parameters were positively correlated to each other, but only two significant correlations were found: one between stiffness and shear modulus and one between stiffness and strength. The conclusions of this research work were: (1) the size reduction of the potato tubers cannot be viewed as a classic brittle fracture phenomenon, and (2) pre-heating of the potato tubers prior to slicing does not improve the surface quality of the french fries based on the results of the wedge fracture test.

1. INTRODUCTION

The potato is one of the oldest sources of human food. Historians have traced *Solanum tuberosum* back to at least 200 A.D. at which time it was being cultivated by the Indians of Peru (Talburt, 1967; Reeve, 1967). In our days, potato ranks as the fourth major food crop of the world, after wheat, rice and maize (Salunkhe and Kadam, 1991). The trends in the global consumption of potato have shown an increased popularity of french fries, whose quality is critical to customer acceptability (Anonymous, 1988). The principal quality parameters that describe french fries are: colour, flavour, appearance and texture (Talburt, 1967), of which the mechanical properties of the tubers affect the latter two (Burton, 1989; Anonymous, 1998).

One consequence of the mechanical properties of potato parenchyma is that newly harvested tubers tend to be very brittle. They are prone to impact damage which ranges from internal black spot bruising through shatter bruising to tissue cracking (Bajema *et al.*, 1998b). Because of their high brittleness, potato tubers also cause problems in the slicer in french fry processing plants. As a result, low quality fries with "feather" cuts along their length are obtained. This results in a poor quality appearance to the fries (Anonymous, 1998). Feathering behaviour is influenced by the mechanical properties of the cell walls, as well as the adhesion between cells and the turgor pressure within the cells. The effect of tuber temperature on impact sensitivity is known to be significant (Bajema *et al.*, 1998b), so that some french fry processing plants pre-heat their tubers in an attempt to overcome the feathering problems.

Storage conditions play a vital role in determining the processing quality of the potato tuber. It has been suggested that the optimum storage temperature for french frying cultivars is about 7°C (Mazza *et al.*, 1983). During prolonged storage at this temperature potato tubers are subject to both physiological changes (Smith, 1967) and water losses (Schippers, 1976; Mazza *et. al.*, 1983). Physiological changes affect the integrity of the structural components of the potato cell (membranes, middle lamella, cell walls), while water losses lead to differences in turgor pressure. Theoretical and experimental results suggest that both cell wall modifications and turgor changes are expected to affect the mechanical properties of potatoes (Nilsson *et al.*, 1958; Niklas, 1989; Scanlon *et al.*, 1996).

This study was therefore undertaken to determine the effects of pre-heating temperature, turgor pressure and storage time on various mechanical properties of potatoes, using large-scale, as well as small-scale deformation techniques. The relationship between the rheological parameters obtained was analyzed in order to see if the size reduction of the tuber during the slicing operation could be viewed as a brittle fracture phenomenon. The project also aimed to quantify the amount of feathering in the wedge fracture test for potatoes pre-heated at different temperatures.

2. LITERATURE REVIEW

2.1 Potato Tuber: Structure and Chemical Composition

2.1.1 Potato Anatomy

Morphologically, a potato tuber is a modified underground stem of a potato plant (Artschwager, 1924) representing its only edible part. The longitudinal section of a mature potato tuber showing the organization of its principal internal tissues is presented in Figure 1. The outer skin is called periderm and it is comprised of 10 to 11 layers of dead cells with thick cell walls made of cellulose and lignin (Fedec *et al.*, 1977). These cells do not contain starch or proteins. The role performed by the periderm is to retard loss of moisture and also to resist attack by fungi (Schwimmer and Burr, 1967). The layer underneath the periderm is called cortex. It contains large cells (the largest in the tuber), with dimensions up to 189 μm (Fedec *et al.*, 1977). These cells have very thin cell walls and contain numerous round and oval-shaped starch grains. Underneath the cortex lies the vascular storage parenchyma, which is also rich in starch content (Schwimmer and Burr, 1967; Kadam *et al.*, 1991a). Xylem and external phloem are conducting or vascular tissues which, together, form the vascular ring. Adjacent to the vascular ring, the perimedullary zone is located. It accounts for about 75% of the total tuber volume and contains starch granules similar in size to those of the cortex (Fedec *et al.*, 1977). Numerous internal phloem strands are distributed within the perimedullary zone. The pith, also called the medulla or the water core, occupies the central part of the tuber radiating narrow branches to each of the eyes. The cells in the pith are smaller and have a lower starch content than those in the vascular storage parenchyma and the cortex

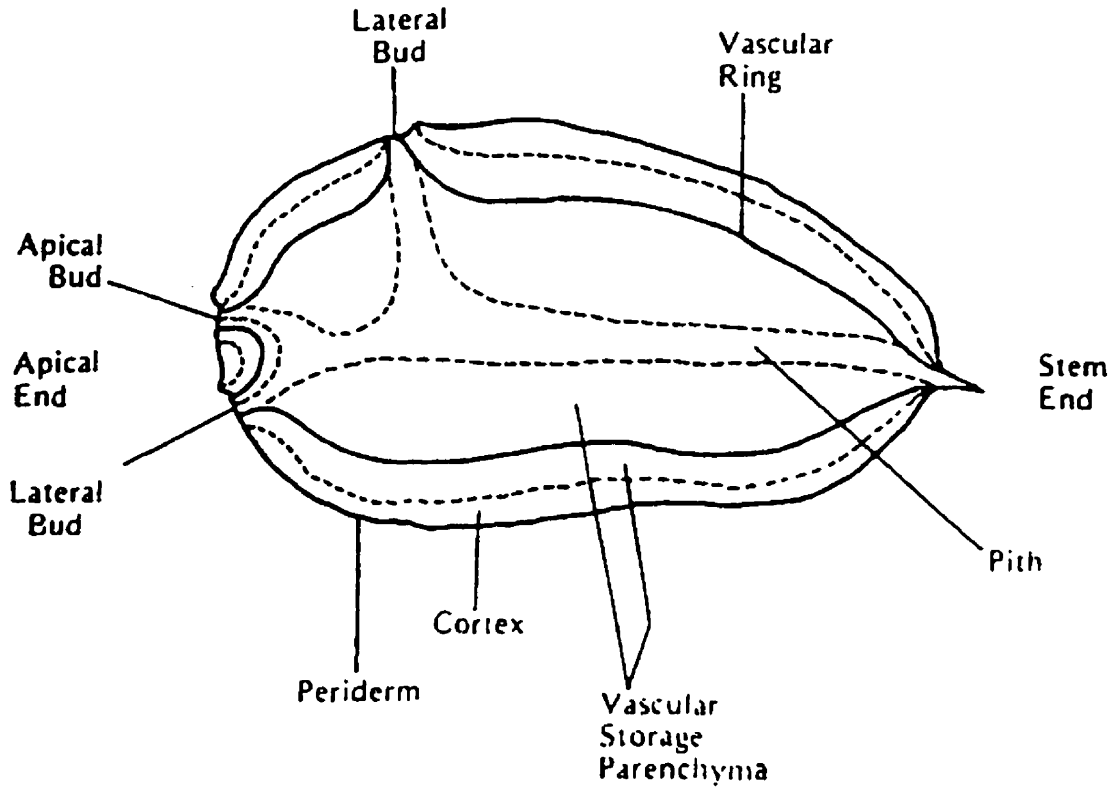

Figure 1. Anatomical structure of a potato showing principal features (adapted from Kadam *et al.*, 1991a)

(Artschwager, 1924). The pith is known to have higher moisture content than the other tissues (Anzaldua-Morales *et al.*, 1992).

2.1.2 Cell Structure

The parenchyma cells are the main component of the plant tissues. These cells, capable of growth and division (Mohsenin, 1986), are responsible for manufacturing and accumulation of food materials such as sugar and starch. Parenchyma cells are held together by cementing agents (mostly pectic substances) to form parenchyma tissues (Mohsenin, 1986). Unlike other plant materials where parenchyma cells are believed to be separated by large intercellular spaces filled with air or water, potato parenchyma is characterized by a very strong cellular adhesion (Khan and Vincent, 1993).

The structure and content of a parenchyma cell of potato as compared with a generalized parenchyma cell is presented in Figure 2 (a and b). The two major components of the cell are the wall and the protoplast, the latter involving the cytoplasm, the nucleus and the vacuole (Brown, 1960). The presence of the starch granules in the cytoplasm is very noticeable for the parenchyma cells of potato compared to other plant materials.

The cell wall is mainly comprised of cellulose microfibrils embedded in an amorphous matrix made of hemicelluloses, pectic substances, proteins and lipids (Van Buren, 1979). The cellulose microfibrils give rigidity and resistance to tearing to the cell wall, while the hemicelluloses and the pectic substances confer plasticity to it and allow it to stretch (Van Buren, 1979). The lipoproteic component is believed to determine the permeability of the wall (Ramana and Taylor, 1994). The middle lamella, which lies

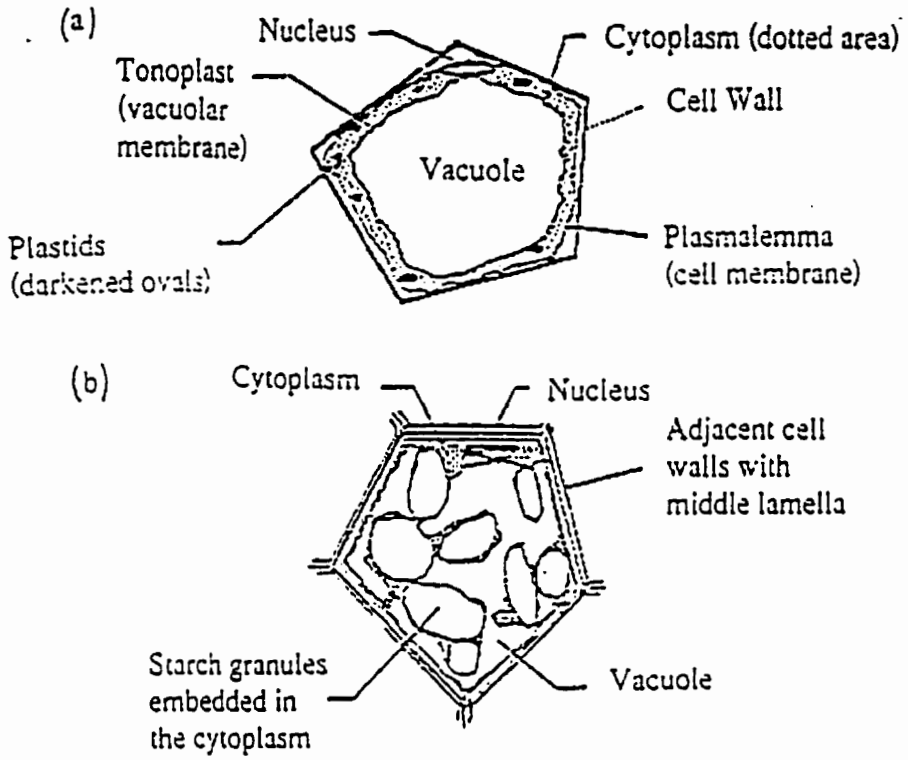

Figure 2. **The structure and content of a parenchyma cell; (a) a generalized parenchyma cell showing cell wall and major barriers to water movement; (b) a parenchyma cell of a potato showing starch granules in the cytoplasm (Adapted from Brown, 1960)**

outside the cell wall, is composed mainly of pectic material and plays an important role in intercellular adhesion (Van Buren, 1979).

Within the cell wall, the nucleus and the cytoplasm are the structures which carry the metabolic and hereditary characteristics of the organism (Brown, 1960). However, the cytoplasm is the main component of the protoplast. Little droplets called vacuoles are scattered throughout the cytoplasm of young cells (Devlin, 1967). In mature cells, these small vacuoles fuse together to form one big vacuole, which may fill almost the entire cavity of the cell (Devlin, 1967). The vacuole is filled with an aqueous fluid (cell sap) which is known to be responsible for exerting a pressure (turgor pressure) on the cell walls keeping them in a state of elastic stress (Nilsson *et al.*, 1958; Ramana *et al.*, 1997). It is the combination between the effects of turgor pressure exerted by the cell sap and elasticity of the cell walls which gives biological materials their viscoelastic character (Mohsenin, 1986).

2.1.3 Osmotic Relationships in Living Cells

As it was stated before, it is generally agreed that the elasticity of plant tissues derives from the elasticity of cell walls (Nilsson *et al.*, 1958; Mohsenin, 1986). On another hand, the important role of the cell sap on viscoelastic properties of plants is also recognized (Nilsson *et al.*, 1958). In order to understand the combined effect of cell walls and cell sap on mechanical properties of biological materials it is necessary that the basic relationships of the plant cell are known.

The cell sap is a solution of sugars, acids and salts dissolved in water. It is surrounded by a semi-permeable membrane called the tonoplast (Figure 2a). This membrane allows water to pass through, but restricts the movement of the other

components (sugars, ions, salts). In the same way, the plasmalemma, the cellular membrane (Figure 2a), is permeable to water, but impermeable to the solutes (Devlin, 1967). The differential permeability of these membranes is vital to the cell, since the cell wall is not capable of performing this function. If the cell possessed no other barrier for the unwanted materials but the cell wall, then its life would be hazardous (Devlin, 1967).

When a living plant cell is placed in a solution with a higher concentration than that of its own cell sap (hypertonic), water diffuses outwardly from the cell into the exterior solution. As a result, turgor pressure decreases, the vacuole shrinks and the plasmalemma contracts and separates itself from the cell wall. This condition in a cell is called 'plasmolysis' (Miller, 1931; Devlin, 1967). The cell itself is said to be 'flaccid'.

A different situation develops when a living plant cell is placed in a solution with a lower concentration than that of its own cell sap (hypotonic). In this case, water is drawn into the cell causing its turgor pressure to increase. The cell is said to be 'turgid'. Since the cell wall is elastic to a certain extent, a slight increase in the volume of the cell will also occur (Devlin, 1967).

In view of the osmotic relationships outlined above, the potato samples used in this study were osmotically equilibrated in mannitol solutions of different concentrations. Since the plasmolysis of potato parenchyma cells is known to occur in 0.4M mannitol solutions (Lin and Pitt, 1986), the concentrations chosen were lower than this value.

2.1.4 Chemical Composition

Dry matter is considered to be the most important quality parameter for potato products (Smith, 1967; Dull *et al.*, 1989; Kadam *et al.*, 1991b). It describes the amount of material left after all water is removed from the potato. The textural changes that occur

during storage and cooking are especially related to physico-chemical changes which take place in the cell wall, middle lamella and membranes. On another hand, starch content also plays an important role in terms of textural quality (Schwimmer and Burr, 1967). The dry matter content has often been equated to starch content, since starch is the largest component of the dry matter of potatoes (60-80 %). However, within the potato industry, the terms 'dry matter' and 'solids content' have become synonymous with 'specific gravity' and are used almost interchangeably (Lulai, 1986). The distribution and composition of dry matter in the potato tuber is outlined below.

2.1.4.1 Starch

Starch is the main carbohydrate of the potato tuber. The size of the starch granules varies from 5 to 189μm, while the shape of the granules can be round, oval (Fedec *et al.*, 1977) or ellipsoidal (Schwimmwer and Burr, 1967). It has been suggested that the larger starch granules are located close to the vascular ring, while the smaller ones can be found in the inner pith (Damir, 1989).

Starch consists of two chemically and physically distinct fractions: amylose and amylopectin. Amylose is a linear α(1,4)- linked glucan which is the principal component of the amorphous region of the starch molecule. Amylopectin contains both α(1,4) and α(1,6) glycosidic linkages and represents the main component of the crystalline region. Highly branched amylopectin molecules are usually located in the amorphous region. The order in the crystalline zone is determined by double helices which occur in pairs and are held together by inter- and intramolecular hydrogen bonds (Segal, 1992). It is believed that the crystalline zone, which is more stable, is embedded in the amorphous zone,

which is more prone to water absorption (Izydorczyk, 1997). Therefore, the amorphous region and not the crystalline one, was suggested to promote swelling and solubility of starch (Izydorczyk, 1997).

2.1.4.2 Pectins

Pectins make up about 55% of the dry substances of the potato cell wall (Jarvis *et al.*, 1981). Also, they represent the main component of the middle lamella. The basic structure of pectins consists of a main chain of galacturonic acid residues linked by β(1,4) glycosidic bonds. Side chains made of neutral sugars such as galactose, xylose and arabinose frequently attach to the main chain (Van Buren, 1979). The carboxyl groups of the galacturonic acid are esterified to different degrees (Segal, 1992).

Generally, the pectic substances can be divided into three categories: protopectin, soluble pectin and pectic acid (Schwimmer and Burr, 1967). Protopectin is insoluble and can be found in large amounts in freshly harvested potatoes. Upon storage, the protopectin content decreases and the soluble pectin content increases (Reeve, 1967). The pectic acid is usually present in middle lamella in the form of calcium and magnesium salts (Schwimmer and Burr, 1967; Warren and Woodman, 1973). The pectic polysaccharides provide mechanical strength to the cell walls and also act as intercellular adhesives (Burton, 1989).

2.1.4.3 Cellulose

Cellulose represents 10-20% of the non-starch polysaccharides in the potato (Schwimmer and Burr, 1967) and about 30% of the dry matter of the cell wall (Jarvis *et al.*, 1981). Chemically, it consists of glucose residues combined through β(1,4) linkages

and stabilized by inter- and intramolecular hydrogen bonds (Lineback and Inglett, 1982). Cellulose occurs naturally as microfibrils which contain crystalline and amorphous regions (Lineback and Inglett, 1982). It is believed that the amorphous portion of cellulose is flexible, giving strength to the cell walls without rendering them rigid (Mohsenin, 1986).

2.1.4.4 Hemicellulose

Hemicellulose represents 7-10% of the dry weight of the potato cell wall (Jarvis *et al.*, 1981). It usually contains glucuronic acid, xylose, galacturonic acid and arabinose, plus their combinations (Schwimmer and Burr, 1967; Kadam *et al.*, 1991). Xyloglucan is considered to be the major hemicellulosic polymer of the potato cell wall (Ryden and Selvendran, 1990). Of particular importance is the ability of xyloglucan to complex with cellulose fibrils, thus attaching them to the matrix material (Van Buren, 1979; Ryden and Selvendran, 1990).

2.1.4.5 Proteins and Lipids

The proteins of the potato represent about 0.6-1.2% of the fresh weight of the tuber. Chemical analysis has shown that proline, hydroxyproline and serine are the major proteic components of the cell walls (Van Buren, 1979). It is believed that most of the proteic fraction is bound to polysaccharides, contributing to the structure of the cell wall (Mohsenin, 1986). Also, proteins can be found in the cell membranes (Devlin, 1967; Stanley, 1991).

The lipids of the potato tuber represent about 0.1% of the fresh weight (Schwimmer and Burr, 1967) and occur either as impregnations in the cell walls or in the

membranes of the cells (Stanley, 1991). Generally, the cell membranes have a bimolecular lipid center bordered by monomolecular layers of protein (Devlin, 1967). The lipid fraction mainly consists of phospholipids and glycolipids with linoleic, linolenic, palmitic and stearic acids in its composition (Knowles and Knowles, 1989).

2.1.4.6 Phenolics

The phenolic components are usually associated with undesirable discoloration in raw and cooked potatoes (Schwimmer and Burr, 1967). Also, they may interact to pectic substances and act as a cementing agent in older plants (Mohsenin, 1986). Chlorogenic acid and tyrosine are responsible for after cooking blackening and non-enzymatic browning, respectively (Burton, 1989; Kadam, *et al.*, 1991b). Lignin is believed to replace water in the cell wall matrix, thus increasing the rigidity and cohesion of the walls (Van Buren, 1979). Some other phenolic substances such as: ferulic and coumaric acids, which may play a role in the maintaining of cell wall integrity, can also be found in the potato tuber (Parker and Waldron, 1995).

2.1.4.7 Sugars

The sugar content of potatoes may vary from very low amounts up to 10% of the dry weight (Burton, 1989). Glucose, fructose and sucrose are the main components of the sugar fraction in potatoes (Smith, 1967). Besides those, traces of maltose, xylose, sugar phosphates, raffinose, melibiose, and melezitose can also be found (Burton, 1989). There are two main factors that affect sugar content in potatoes after harvesting: specific gravity and temperature. Varieties with low specific gravity accumulate more sugar than varieties with high specific gravity (Burton, 1989). The optimum storage temperature suggested

for french frying cultivars is about 7°C (Mazza *et al.*, 1983). Potatoes that are harvested chemically immature, usually accumulate a greater amount of reducing sugars than mature tubers during storage (Mazza *et al.*, 1983; Pritchard and Adam, 1994). The maximum level of sucrose accepted in potatoes for processing as french fries must be no more than 1.5-2.8 mgg^{-1} fresh tissue at harvest, to minimize accumulation of reducing sugars during long term storage (Mazza *et al.*, 1983; Pritchard and Adam, 1992).

2.2 Comparison Between *Russet Burbank* and *Shepody* Potatoes

Burbank was one of the first potato varieties developed in North America (Thompson, 1967) and is considered to be 'the long time holder of the crown for french fry excellence' (Anonymous, 1992). *Shepody* is a relatively new variety developed at Agriculture and Agri-Food Canada Research Centre, Federicton, New Brunswick. Since its release in December 1980, *Shepody* potato has mounted the biggest challenge ever to *Russet Burbank*. *Shepody* matures earlier, grades better, grows more evenly and yields higher than *Russet* (Anonymous, 1992). Also, it makes good quality french fries. In terms of shape of the tubers, color of flesh and specific gravity, *Russet Burbank* and *Shepody* potatoes do not show significant differences; *Shepody* potatoes are quite resistant to hollow heart (Young *et al.*, 1983).

2.3 Changes During Storage

2.3.1 Membranes Disintegration

The cellular membranes of the potato tubers are susceptible to disintegration during storage, especially at low temperatures (Burton, 1989). It has been proven that the changes in the starch and sugar contents, which occur during storage of the tubers below

7°C, can be correlated with damage to the plastid membrane (Ohad *et al.*, 1971). Experimental results showed that storage for 8 weeks at 5.5°C induced increased amyloplast membrane permeability, compared with storage at 15.5°C (Shekhar *et al.*, 1979). It has been suggested that low temperatures cause a physical change in the membranes of amyloplasts, from a crystalline state to a solid gel state (Shekhar *et al.*, 1979). The latter state is believed to be more permeable, causing an increased breakdown of starch to sugar (Burton, 1989). The vacuolar membrane is believed to be even more susceptible to disintegration during storage than the amyloplast membrane, causing significant cation leakage from the tuber cells (Turnbull and Cobb, 1992). Experimental results showed that the overall pattern of cation efflux over 36 weeks of storage was similar in tubers stored at 5 and 10°C. However, the increase in leakage was observed to occur later and more gradual in potatoes stored at 10°C, suggesting that disruption of membranes is less pronounced at this temperature (Turnbull and Cobb, 1992).

The degradation of the lipoproteic structure of cell membranes is catalyzed by lipolytic acyl hydrolase (LAH) (Turnbull and Cobb, 1992). It is believed that disruption of tonoplast membrane (especially during cold storage) is responsible for the release and activation of LAH from the vacuole, where it normally exists in an inactive form (Galliard and Matthew, 1973). LAH attacks various glycolipids and phospholipids from the membrane, to transform them to polyunsaturated acids, which later become substrates for lipoxigenases (LOX). The membrane disintegration is initiated by the incorporation of oxygen into the fatty acids, which is catalyzed by LOX (Turnbull and Cobb, 1992). Indicative of disintegration of the vacuolar membrane is the decrease in fatty acid content

of tubers, which was observed over a 10-month storage period at 9°C (Spychalla and Desborough, 1990).

One of the most important consequences of vacuolar membrane denaturation is related to cell turgidity which decreases when the cell sap is released from the vacuole (Devlin, 1967). Sucrose and inorganic phosphate from the cell sap accumulate in the cytoplasm (Spychalla and Desborough, 1990). Sucrose is converted to reducing sugars which affect the color of french fries (Mazza *et al.*, 1983; Pritchard and Adam, 1994), while inorganic phosphate influences starch breakdown by phosphorolysis (Burton, 1989). Apart from the sensory quality losses that can be attributed directly to membrane deterioration, there is an increased concern regarding the possibility of toxicity that may be induced by some of the oxidation products (secondary lipid peroxides) (Stanley, 1991).

2.3.2 Changes in Turgor Pressure and Dry Weight Losses

Changes in turgor pressure during storage are caused by the combined effect of water loss through evaporation and water gain through respiration (Brusewitz *et al.*, 1989). The degree of evaporation depends on the drying effect of the surrounding air, the temperature, the permeability of the skin of the tubers and the duration of storage (Smith, 1967). The most important factor is the first of the four (Schippers, 1976): the greater the vapour pressure deficit in the surrounding air, the greater the water loss (Burton, 1989). In other words, the higher the relative humidity, the better. Evaporative loss of water is often the most serious cause of loss of weight during storage (Schippers, 1976; Burton, 1989).

Respiratory loss of dry weight is the least important storage loss on the quantitative side (Smith, 1967; Schippers, 1976; Burton, 1989). Respiration utilizes carbohydrates such as starch and sugars, converting them into carbon dioxide and water (Smith, 1967). The respiration rate of potato increases with increase of temperature and it is usually higher in immature and wounded tubers (Smith, 1967; Burton, 1989).

Although the weight loss is likely to be considered more as a quantitative change which occurs in potatoes during storage, it is also a quality factor that affects the appearance of the tubers. For weight losses higher than 5% the tubers become increasingly soft. Beyond this point, when the weight losses reach 8-9%, the skin starts to wrinkle (Schippers, 1976). On the quantitative side, the weight loss is a very important economic consideration for the storage operator and/or producer.

2.3.3 Changes in Cell Walls and Middle Lamella Components

It has been suggested that changes in cell wall and middle lamella components are negligible during long term storage (Burton, 1989). However, pronounced pectic changes over time and an accompanying decrease in hemicelluloses have also been reported (Wittenberger, 1952; Sharma *et al.*, 1959; Buch *et al.*, 1961; Reeve, 1967; Van Buren, 1979).

During storage, water-soluble pectins increase, while both oxalate-soluble and acid-soluble pectins decrease (Reeve, 1967). Water soluble pectins are obtained as a result of the partial depolymerization of protopectin (Schwimmer and Burr, 1967). It is believed that this process represents the theoretical basis of tissue softening (Van Buren, 1979; Segal, 1992). Sharma *et al.* (1959) reported that hard-cooking potatoes became

soft-cooking potatoes upon storage due to an increase in water-soluble pectin. However, the percent esterification of the pectins from the cell wall and middle lamella is also related to the softening process (Buch *et al.*, 1961). It has been suggested that a lower degree of esterification of the pectin is related to firming of snap beans during blanching (Van Buren *et al.*, 1960). An increase in firmness of cherries during storage has also been related to demethoxylation of the pectin to the less soluble pectic acid (Wittenberger, 1952; Buch *et al.*, 1961).

2.3.4 Changes in Starch and Sugars

Usually, during prolonged storage, the starch content of potatoes decreases, while the sugar content increases (Smith, 1967; Burton, 1989). However, if potatoes are stored at high temperatures (15-20°C), the ratio of starch to sugar content increases due to increased respiration and conversion of sugars (Smith, 1967, Schippers, 1976).

Loss of starch is of great importance in the potato processing industry and can occur in three ways: respiration, conversion to sugars and translocation to the sprouts (Burton, 1989). Sugar accumulation, on another hand, strongly affects the color and flavor of french fries and results from two main events: prolonged storage of tubers (senescent sweetening) and storage of tubers at low (4-5°C) temperatures (low temperature sweetening) (Burton, 1989). While low temperature sweetening is a reversible process, senescent sweetening is not (Schippers, 1976).

In senescent sweetening both phosphorolysis and hydrolysis of starch may be involved (Burton, 1989). However, in low temperature sweetening, phosphorolysis must be the main process since amylase activity (implicated in hydrolysis) is drastically

reduced at low temperatures (Arreguin-Lozano and Bonner, 1949). It is currently hypothesized that greater permeability of the amyloplast membrane that occurs at low temperatures causes a reduction in the starch content, while the level of free sugars increases (Ohad *et al.*, 1971).

Upon prolonged storage starch grains decrease in size and show less gloss (Smith, 1967). Also, there is an increase in the total number of small granules, due to enzymatic hydrolysis of large granules (Reeve, 1967; Fedec *et al.*, 1977).

Tubers harvested at chemical immaturity are more susceptible to sugar accumulation during storage (Pritchard and Adam, 1992). For *Russet Burbank* and *Shepody* potatoes stored at 8°C, glucose was shown to be more closely associated to fry color than fructose, sucrose, total reducing sugars or total sugars (Mazza *et al.*, 1983; Pritchard and Adam, 1994). It has been suggested that the increase in sugar content becomes noticeable after 5-6 month of storage at 10°C (Burton, 1989).

2.3.5 Sprouting

Sprouting is a physiological process that occurs during storage and represents loss of usable weight in potato tubers. Senescent sweetening (and consequently starch loss) is associated with the start of sprout growth (Burton, 1989). It has been suggested that the accumulation of sugars in the potato tuber occurs only when the total mobilization of starch outstrips the translocation of the sugars to the sprouts (Burton, 1989). If the sprouts are continuously removed, than translocation cannot occur and the accumulation of sugars in the tuber is greater (Isherwood and Burton, 1975). Losses of proteins, thiamin

and ascorbic acid have also been reported to occur upon sprouting (Burton, 1989; Mazza *et al.*, 1983).

The start of sprout growth was also related to an increase in respiration rate (Schippers, 1977). It has been suggested that the respiration of a sprouting tuber comprises both the respiration of the tuber itself and that of the sprouts (Isherwood and Burton, 1975). At the same time it is also possible that the presence of the sprouts themselves may maintain a higher rate of metabolism in the tuber, therefore increasing the rate of respiration (Isherwood and Burton, 1975).

Sprouting in potato tubers can be prevented chemically by applying sprout suppressants such as chloro-isopropyl carbamate (CIPC) during storage or maleic hydrazide during the growing season (Jadhav *et al.*, 1991). Also sprouting can be suppressed by irradiation (Burton, 1989).

2.4 Effect of Thermal Treatment on Potato Tissue

2.4.1 Effect of Heat Treatment on Potato Cell Wall, Middle Lamella and Membranes

The softening phenomenon that occurs in plant materials upon heating is partly due to the loss of turgor, but also to a variety of chemical changes in the cell wall and middle lamella polysaccharides (Van Buren, 1979). A reaction of particular importance with regard to the texture of processed fruits and vegetables is the depolymerization of pectic substances by β elimination. The reaction involves splitting of the glycosidic bonds of esterified pectins at a pH above 4.5 (Andersson *et al.*, 1994). Occurrence of the reaction can be detected by an increased solubility of pectic materials, which results in

separation of the cells and weakening of the cell walls (Van Buren, 1979; Andersson *et al.*, 1994).

Two different viewpoints have been formulated regarding the physical effect of heat treatment on the structure of the cell walls. Some researchers believe that tissue softening is caused by cell separation (Personius and Sharp, 1938a; Sterling, 1955; Shomer, 1995). Some other scientists however, observed that cell rupture generally attends the heating process (Reeve, 1954; Roberts and Proctor, 1955; Reeve, 1967; Reeve, 1977). It is expected that cell wall and middle lamella components (especially pectic substances) play an important role for both cell separation and cell wall rupture (Andersson *et al.*, 1994).

It has been reported that pectin content of potato decreases by cooking (Andersson *et al.*, 1994). Roberts and Proctor (1955) heated potato tissue in water and observed that a slight increase in temperature up to 30°C did not affect either the pectic content or the structure of the middle lamella and the cell wall. At 45±5°C the structure of the middle lamella started breaking, while the structure of the cell wall became less compact. At 60±5°C the pectic content of the middle lamella was altered. Even if the cellulose content of the walls was not significantly affected at this temperature, the local decrease in the amount of pectin caused the walls to fracture easily. Reeve (1967) agreed with the theory that the dissolution of non-cellulosic components during heating weakens the cell wall. However, he suggested that cell rupturing begins in those naturally thin areas of the cell wall, which contain fewer cellulose microfibrils.

A study published in 1955 by Sterling reported softening of carrot, apple and potato tissues upon cooking, with no breakage of the cell walls. It has been suggested that

the hydration of the cell wall and middle lamella components during cooking can reduce the cohesiveness of the matrix, softening the cell wall, but also can decrease the intercellular adhesion, causing cell separation (Warren and Woodman, 1974; Van Buren, 1979).

Generally, the texture of cooked potatoes varies from mealy to firm (Van Marle *et al.*, 1992). While mealy potatoes are easily broken down upon cooking, firm potatoes retain their form (Warren and Woodman, 1974). Therefore a mealy texture is preferred for mashed potatoes, while a firm texture is suitable for the production of salads. Van Marle *et al.* (1992) investigated the texture of raw and steam-cooked potatoes using cryo-scanning electron microscopy (Cryo-SEM). For non-cooked potatoes, the results showed that fracturing took place through cells. In contrast, fracturing of steam-cooked potatoes seemed to take place between cells. Mealy and firm potatoes showed clear differences with respect to intercellular contact, cell shape and cell surface. In mealy potatoes fracturing between cells took place easily, resulting in intact cell surfaces. In firm potatoes, ruptured cell walls were observed in the fracture planes. The authors suggested that different breakdown of the middle lamella or the cell wall could explain the differences that occur during cooking between mealy and firm potatoes.

Ramana *et al.* (1992) investigated cellular integrity during heating by microscopic examination. The changes occurring in carrot protoplasts, cells, cell walls and whole tissues during heating from 20 to 90°C were recorded on videotape. It was observed that the protoplasts were disrupted around 60°C, the cells lost their integrity between 50 and 65°C and the cell wall thickened around 68°C. The whole tissue lost rigidity at very similar temperatures (~60°C). Personius and Sharp (1938b) also indicated a major change

in the permeability of potato plasmalemma around 60°C. The degradation of the protoplasmic membranes, which control the composition of cells by their selective activity, would make the cell wall the sole partition between the intracellular medium and the outer medium (Shomer *et al.*, 1993).

Shomer *et al.* (1993) studied the rheological behaviour of suspensions of potato tuber cells at different temperatures. The effect of enzymatic degradation of cellulose (with cellulase) was also observed. The results showed that below 40-50°C the cell wall was thoroughly swollen, while starch was swollen moderately. Above 40-50°C the gelatinized starch was swollen to such an extent that it actually pushed the cell wall outwards making the cells become more elastic. Cellulase activity resulted in the removal of the cell wall, which caused the breakdown of the cell structure.

The important role of the cell wall in maintaining the structure of the cells was also investigated by Ramana and Taylor (1994). The authors evaluated the effect of heat treatment on rheological properties of suspensions of carrot cells and carrot protoplasts previously treated in different ways. The treatments involved modification of the lipid/protein components in the cell walls/membranes using enzymes (protease/lipoprotein lipase). The cells and the protoplasts used in this experiment were isolated from thin sections of carrot using enzymatic and mechanical methods as described by Ramana and Taylor (1992b). The results showed that cells were more rigid and lost rigidity more slowly on heating than protoplasts. Both lipid and protein components of protoplast membranes affected rigidity, whereas only the protein component of the cell wall seemed to be important in controlling the rigidity of the cell. Since both control and lipase-treated cells behaved in the same way when analyzed on the

Bohlin rheometer, it has been suggested that either lipase could not attack the lipid component of the cell wall or that lipid did not affect cell rigidity (Ramana and Taylor, 1994). The experiment proved the vital role that the cell wall plays in maintaining cell structure, as its removal rendered the protoplasts susceptible to heat damage.

2.4.2 Effect of Thermal Treatment on Starch

When potato tissue is heated above 50°C, water passes from the non- starchy parts of the cell into the starch granule, which starts to swell and subsequently gelatinizes (Schwimmer and Burr, 1967). The tissue cells become distended by the swollen gel and tend to separate, since the components of middle lamella and cell wall are also disrupted (Reeve, 1967).

Some researchers believe that cell separation is accompanied by a 'rounding off' of the cells, which causes the walls of adjacent cells to be pushed apart (Reeve, 1972). Swelling of starch granules induces a so called starch swelling pressure, analogous to turgor pressure in raw tissues (Jarvis *et al.*, 1992). This swelling pressure was estimated to have a value around 100 kPa, increasing non-linearly with starch concentration (Jarvis *et al.*, 1992). It has been suggested that variation in starch swelling pressure, for cultivars having different starch content, is the main cause of variation in texture of these potatoes when they are cooked (Jarvis *et al.*, 1992).

On the contrary, other researchers suggest that the observed 'rounding off' of the cells is 'the result, rather than the cause of cell separation' (Warren and Woodman, 1974). These latter scientists believe that the 'swelling pressure theory' requires a practically inextensible cell wall (Warren and Woodman, 1974).

More recent results were in support of the swelling pressure hypothesis, even though no evidence of cell separation was observed (Jarvis and Duncan, 1992; Agblor and Scanlon, 1998). Examination of the microstructure of blanched potato strips revealed a 'balloon-like' appearance for the cells at the periphery of the strips, which had received the most heat treatment and contained mostly gelatinized starch. This appearance was less evident in the inner part of the strips, which contained mainly ungelatinized starch granules (Agblor and Scanlon, 1998).

Excessive swelling may cause cell rupture and leakage of starch (Reeve, 1967; Swimmer and Burr, 1967), which may explain the decrease in the starch content during cooking, as suggested by Bettelheim and Sterling (1955). Shomer (1995) also noticed starch leakage from potato tubers upon boiling. However, his microscopic observations showed intact cell walls. It has been hypothesized that starch molecules smaller than 600 kDa were allowed to leak through cell wall pores (Shomer, 1995). This hypothesis was not surprising, knowing that the permeability of potato tissue increases during heating (Personius and Sharp, 1938b).

Huang *et al.* (1990) investigated by scanning electron microscopy (SEM) tissue characteristics and starch granule variations of potatoes after microwave and conductive heating. It was observed that swelling patterns of starch granules in potatoes were different using the two heating processes. However, after both microwave and conductive heating, potatoes were softer outside than inside.

It has been suggested that the gelatinization temperature of starch is influenced by the proportions of amylose and amylopectin, the two main fractions of the starch granule (Segal, 1992). Generally, starch gelatinization occurs over a range of temperature, which

can be determined with different techniques. Van Beynum and Roels (1985) considered that the loss of birefringence was the most accurate method for measuring the gelatinization temperature range for potato starch (58-68°C). Lamberg and Hallström (1986) used the DSC techniques and showed that gelatinization starts at 55°C and ceases at 75°C, with an optimal temperature of 66°C. Huang *et al.* (1990) used SEM on cooked potatoes and observed that gelatinization first occurred in end regions of the tubers between 46 and 65°C. The starch granules with the lowest gelatinization temperature usually swell quickly, so that a smaller quantity of water will be available for the swelling of granules with higher gelatinization temperatures (Svegmark and Hermansson, 1991).

If a potato tissue is heated and then cooled, the crystallinity of the starch molecule lost during gelatinization is partially regained during the cooling step (Andersson *et al.*, 1994). This phenomenon is known as starch retrogradation. The new crystalline structure will prevent swelling of starch during subsequent processing. It has been shown that potato starch starts to retrograde at 50°C, the process being accelerated at 25°C. However, starch may also retrograde at pre-heating temperatures between 60 and 75°C (Andersson *et al.*, 1994). It has been suggested that the modification of cooked potato texture brought about by starch retrogradation can substantially improve its cutting performance (Jankowsky, 1992).

2.5 Mechanical Properties of Biological Materials

Mechanical properties of foods can be defined as 'those having to do with the behaviour of the food material under applied forces' (Mohsenin, 1986). In addition to affecting the behaviour of the product during handling, transportation and processing, the

mechanical properties form the basis of textural attributes of foodstuffs (Szczesniak, 1983). Some researchers use interchangeably the terms 'mechanical properties' and 'rheological properties', which is only approximately correct, since all rheological properties are mechanical properties, but not all mechanical properties are rheological properties (Szczesniak, 1983). Rheology can be defined as 'the science concerned with deformation and flow of matter' (Tung, 1986). Since certain mechanical properties do not involve deformation (drag coefficient, the rebound coefficient in impact), they can not be classified as rheological properties (Szczesniak, 1983).

The most common tests used in evaluating the textural properties of foods involve large deformation (puncture, compression, tension) which leads to the breakdown of the test-piece (Vincent, 1990; Jackman and Stanley, 1992; Khan and Vincent, 1993; Scanlon and Long, 1995). Some researchers consider failure during testing desirable, their theory being that mechanical parameters of foods, which are important in defining texture, manifest themselves under large stresses (Szczesniak, 1983). Generally, large deformation methods are used to determine rheological parameters associated with failure properties (Alvarez and Canet, 1998). Identification of failure mechanisms is extremely important in developing strategies to optimize the quality of fruits and vegetables through handling and processing (Jackman and Stanley, 1992). Some other researchers, however, prefer to use non-destructive methods such as dynamic tests, which allow continuous monitoring of textural attributes (Ramana and Taylor, 1992a, b; Pang and Scanlon, 1996). Small-scale deformation methods are generally used to evaluate microstructural changes (Alvarez and Canet, 1998); there is also the advantage that the sample remains essentially unperturbed during testing (Jackman and Stanley, 1992). The information obtained from

the small scale deformation methods may be useful in complementing and better defining the force deformation behaviour predicted by large scale deformation testing techniques (Jackman and Stanley, 1992).

2.5.1 Viscoelastic Nature of Biological Materials

From the rheological point of view, condensed materials can be divided into solids, which deform, and fluids, which flow (Szczesniak, 1983). Classical theory describing the mechanical properties of matter was developed based on ideal elastic solids, which follow Hooke's law and ideal viscous fluids, which follow Newton's law. Both ideal solids and ideal fluids are considered to be homogenous and isotropic (Tung, 1986).

When a Hookean solid is subjected to small deformations, stress (σ = applied force/area) is always proportional to strain (ε = deformation/original size). That is (Tung, 1986):

$$\sigma = k\ \varepsilon \qquad (1)$$

where σ = stress (Nm^{-2})

ε = strain (dimensionless)

k = proportionality constant which relates stress to strain (Nm^{-2})

A solid material can be described by different moduli, depending upon the method of stress application. When a tensile (or compressive) stress is applied, the proportionality constant that relates stress to strain is called the modulus of elasticity or Young's modulus (E). The storage modulus, or modulus of rigidity (G) relates shear stress to shear strain, while the bulk modulus (K) relates hydrostatic stress to volumetric

strain (Tung, 1986). An ideal elastic body returns to its initial shape instantly upon the removal of stress. All the stored strain energy from the applied stress is recovered during the returning process (Tung, 1986).

When a Newtonian fluid is subjected to shear stress, deformation and flow begin as soon as the shear stress is applied, but there is no elastic recovery when the stress is removed (Mohsenin, 1986). In ideal viscous fluids, stress is directly proportional to rate of strain (shear rate) rather than strain, that is (Mohsenin, 1986):

$$\tau = \eta \dot{\gamma} \qquad (2)$$

where τ = shear stress (Nm^{-2})

η = shear viscosity ($Nm^{-2}s$)

$\dot{\gamma}$ = shear rate (s^{-1})

In reality, most biological materials (foodstuffs included) exhibit simultaneously viscous and elastic properties. In rheological terms, such behavior is called viscoelasticity (Tung, 1986). A viscoelastic material will return to its original shape after releasing the deforming stresses, but the viscous resistance to deformation will delay the response of the material (Barbosa-Canovas *et al.*, 1996). It has been suggested that the turgor pressure exerted by the cell sap against the cell walls, combined with the elasticity of the cell walls, may be responsible for the viscoelastic character of cellular biomaterials (Mohsenin, 1986).

2.5.2 Models of Failure in Biological Materials

Fracture involves failure or cracking of a material, which does not necessarily refer to the breaking up of that material into pieces (Vincent, 1990). In order that failure

occurs, a crack must be first initiated. It has been suggested that small imperfections inside a material can act as initiators, as long as they are above a critical size for a given level of stress (Griffith, 1920; Vincent, 1990; Hiller and Jeronimidis, 1996).

Fracture of molecular bonds at the tip of a crack depends on the strength of these bonds. Also, the shape of the crack tip is important (especially if it is sharp) because it has the effect of concentrating the stress, thus mediating the propagation of the crack (Vincent, 1990). However, in order that a crack can be propagated, energy in the form of strain (stretching or shearing) must be provided (Vincent, 1990). The amount of energy required to propagate a fracture through a material is a measure of the toughness of that material (Schoorl and Holt, 1983). For example, glass, which is very brittle and requires relatively little energy to fracture, has a toughness of about 1-10 Jm^{-2}, compared to that of wood (much less brittle) whose toughness is about 10^{4} Jm^{-2} (Vincent, 1990). Potatoes are known to possess a fracture toughness lower than wood (Schoorl and Holt, 1983; Fahloul and Scanlon, 1996; Hiller and Jeronimidis, 1996).

Three modes of tissue failure have been proposed for biological materials: cell wall rupture, intercellular debonding and cell relaxation due to migration of the fluids out of the cells (only for compression) (Diehl *et al.*, 1979; Holt and Schoorl, 1983; Lin and Pitt, 1986; Jackman and Stanley, 1992; McGarry, 1993). Holt and Schoorl (1983) reported both cleavage (intercellular debonding) and slippage (cell wall rupture) occurring in whole potato tubers subjected to compression. Cleavage is a normal force phenomenon, while slippage is a shear stress phenomenon occurring along planes at 45° to the direction of loading. Lin and Pitt (1986) confirmed the earlier finding of Diehl *et al.* (1979) that cell rupture is the only mode of failure in potato tubers subjected to

compression. McGarry (1993) found that splitting in carrots also propagates by cell breakage, as opposed to cell separation. It is not always clear what dictates the mode of failure. However, it has been suggested that the adhesion between cells controls whether the fracture path goes between cells or through cells (Vincent, 1990). Tensile fracture tests on potato showed that cell walls break rather than separate from each other, the reason being that the potato cells are very cohesive (Vincent, 1990).

Water status has also been suggested to play a key role in determining the fracture properties of biological materials, splitting in carrots being more prevalent under conditions promoting high root turgor (McGarry, 1993). The work of fracture is lower in turgid carrots than it is in flaccid ones (Atkins and Vincent, 1984).

2.5.3 Mechanical Properties of Biological Materials Tested by Large-Scale Deformation Techniques

Various instruments and techniques have been used to define the texture of biological materials. Among them fracture tests are relevant, especially for sensory evaluation of fruits, vegetables and meat (Volodkevich, 1938; Vincent, 1990; Vincent *et al.*, 1991; Jackman and Stanley, 1992). The concepts of fracture mechanics are fundamental to the understanding of fracture processes, allowing us to distinguish between the resistance to fracture (e.g., fracture toughness) and geometrical factors such as flaw size, which also affect such parameters as tensile strength (Andrews, 1974). It has been suggested that the textural characteristics of foods can be described by the stiffness, strength, toughness and the coefficient of friction (Kamyab *et al.*, 1998). Two of these parameters (toughness and stiffness) control crack initiation (Hiller and Jeronimidis,

1996). Therefore, in order to assess the susceptibility of a plant material to fracture, knowledge of the parameters of strength, stiffness and toughness is essential.

2.5.3.1 Fracture Toughness

Fracture toughness is usually associated organoleptically with 'the ease with which the teeth initially penetrate the product and the ease with which the product breaks into smaller fragments' (Finney, 1969). Since both penetration and breakdown are destructive operations, evaluation of toughness always involves a definite destruction of the cellular tissue (Finney, 1969). There are various ways of measuring fracture toughness (simple compression, wedging, tension on a notched specimen etc.), each of them making specific assumptions about both the material and the method (Vincent, 1990).

2.5.3.1.1 Toughness of Biological Materials Tested by Simple Compressive Fracture Tests

In compressive fracture tests, failure can be initiated by imperfections in the test material (Griffith, 1920; Vincent, 1990; Hiller and Jeronimidis, 1996). As a result, failures can occur remote from the site of the eventual fracture, giving too high an estimate for toughness ('apparent fracture toughness') (Vincent, 1990). For this reason, simple compression tests, which are useful for estimation of the fracture stress, are less reliable for estimating the work of fracture (Vincent, 1990).

Schoorl and Holt (1983) investigated cracking in *Sebago* and *Pontiac* potatoes by compressing whole tubers between flat plates at low compression rates. The results

showed that cracking occurred when the stored energy exceeded a critical value. It was suggested that the extent of cracking was determined by the fracture toughness of the tubers. The energy necessary to form new crack surfaces was calculated to be 1350 Jm^{-2} for *Sebago* and 1230 Jm^{-2} for *Pontiac.*

In another work published in the same year, Holt and Schoorl (1983) subjected potatoes and apples to slow and fast compression tests. For both quasi-static and impact loading, the results suggested two modes of failure for potatoes (slippage in the interior and cleavage around the periphery), but only one mode of failure for apples (bruising). Microscopical results suggested that bruising was the result of cell bursting. The distortion of the parenchyma cells under compression causes the cell walls to stretch, leading to their fracture. The fracture toughness of *Sebago* potatoes was calculated at 208 Jm^{-2} for cleavage failures and 770 Jm^{-2} for slip failures. For apples, the apparent fracture toughness was calculated at 5.4 Jm^{-2} for quasi-static compression and 6.2 Jm^{-2} for impact (Holt and Schrool, 1983).

Bajema *et al.* (1998a and 1998b) investigated the effects of turgor and temperature on selected failure properties of *Russet Burbank* and *Atlantic* potatoes. The tissue samples were tested to impact failure using a rigid pendulum designed by the authors (Bajema *et al.*, 1998c). The experiments were conducted at 5, 10 and 15°C on samples with 4 turgor levels. The results showed that tissue toughness increased significantly with increasing temperature and decreasing turgor for both cultivars. However, *Russet Burbank* potato was found to be much tougher than *Atlantic*, a result which agrees with industrial observations that *Atlantic* bruises more easily than *Russet Burbank* does (Bajema *et al.*, 1998a and 1998b).

2.5.3.1.2 Toughness of Biological Materials Tested by Wedge-Penetration Fracture Tests

Wedging is another standard fracture test and involves crack opening (Vincent, 1990, Vincent *et al.*, 1991). In this test, strain energy is fed into the sample by a wedge which forces apart the two 'halves' of the specimen (Figure 3) (Atkins and Mai, 1985; Vincent, 1990; Vincent *et al.*, 1991). It must be emphasized that the wedge cuts the test-piece only in the first part of the test. At some point during the penetration of the wedge, sufficient strain energy has been stored within the material to initiate and maintain a free running crack within the test-piece (Vincent, 1990; Vincent *et al.*, 1991).

The amount of strain applied to the test piece depends on the included angle of the wedge: the larger the angle, the greater the strain energy stored in the specimen. Also, the strain energy depends on the stiffness of the material: stiffer materials store more energy for the same amount of strain (Vincent, 1990).

Once the crack has started to propagate ahead of the tip of the wedge, the amount of energy required to be fed into the material drops. The advancing crack tip now uses up the strain energy stored in the specimen. The sequence of events as the wedge enters the test-piece is presented in Figure 4.

The control of the stability of the crack propagation is essential to the correct measurement of fracture energy. This requires that the rate of penetration of the wedge should be kept constant (Vincent *et al.*, 1991). Also, it is recommended that the test is performed slowly, so that the energy fed into the specimen is partitioned only between elastic strain energy and fracture energy. If the test is performed quickly, then excess

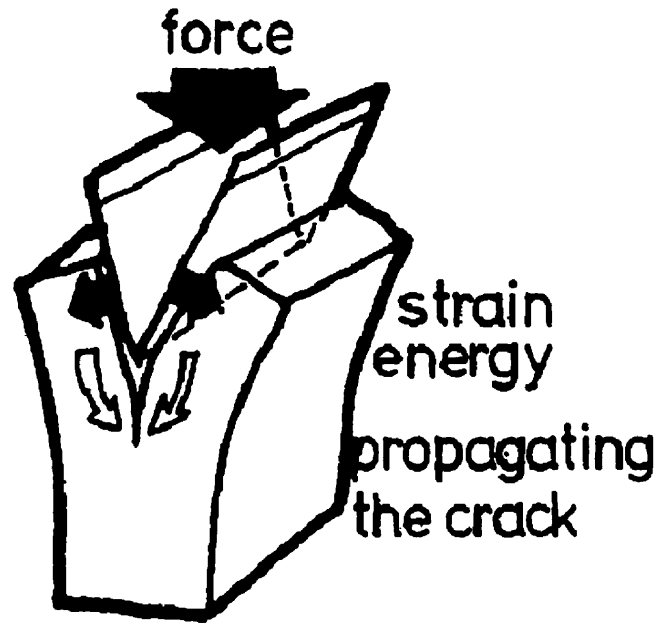

Figure 3. Diagram representing the propagation of the crack in the wedge fracture test. The black arrows on the specimen represent the force which is transmitted from the wedge to the two 'halves' of the specimen, forcing them apart such that they store strain energy. The white arrows refer to the stored strain energy which can be fed to the advancing crack once the failure stress has been reached. (Adapted from Vincent, 1990)

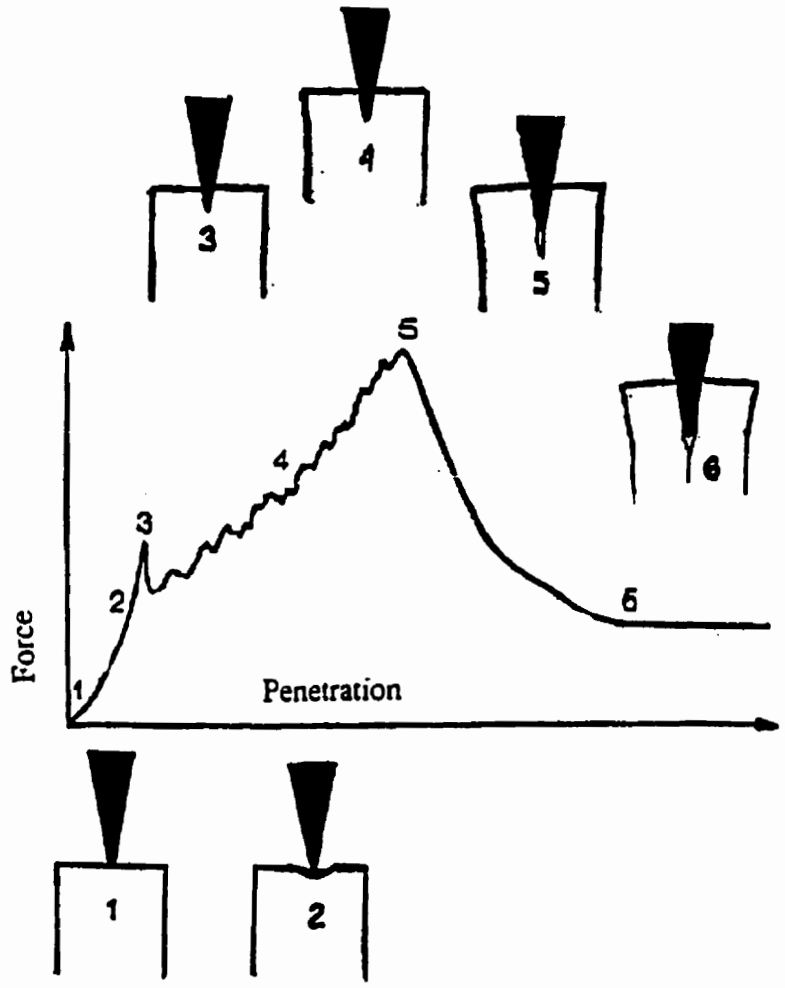

Figure 4. Sequence of events as the wedge enters a fracture test-piece: (1) the wedge is just about to enter the specimen, (2) the top of the specimen deflects storing elastic energy, (3) the wedge cuts into the specimen; the elastic strain energy is fed to the cut surface and the force drops, (4) as the wedge enters further the two halves of the specimen are forced apart storing strain energy, (5) sufficient strain energy is available to start a free-running crack propagating ahead of the wedge: the force falls, (6) propagation of the crack stabilizes and it propagates at the same velocity as the wedge (Adapted from Vincent *et al.*, 1991)

strain energy may be dissipated as kinetic energy or sound energy (Vincent *et al.*, 1991).

In the wedge test, the work of fracture may be estimated by measuring the area beneath the graph (Figure 4) and equating this work with the area of fracture surface produced (Vincent *et al.*, 1991). This is the so called 'work-area method' (Hiller and Jeronimidis, 1996).

The wedge test described above was used by different authors to measure fracture toughness of apples and cheese (Vincent *et al.*, 1991), potatoes (Hiller and Jeronimidis, 1996) and polysaccharide gels (Oates *et al.*, 1993).

Vincent *et al.* (1991) used a wedge penetration technique to analyze fracture properties of apples and Gouda cheese. The results showed a highly significant anisotropy of apple flesh depending on the orientation of the air spaces. For three different varieties of apples tested with a 30° wedge, the fracture toughness was significantly higher in those samples where the wedge was orthogonally oriented relative to the air spaces. A lower included angle for the wedge (10°) provided insufficient energy to start a running crack. For the cheese samples, the fracture properties were tested by sensory, tensile and simple compression tests, as well as the wedge test. The experiments showed that the results obtained in the wedge test (10°) were very similar to the results obtained in the sensory test by 10 panelists (the term 'results' refers to the distance the wedge/teeth had penetrated into the sample before the crack started to propagate freely). A higher force had to be applied to produce crack propagation in old Gouda compared to young Gouda.

Oates *et al.* (1993) subjected gels of different polysaccharide concentrations to quasistatic tests by driving a 40° included angle wedge into intact specimens in order to

determine their fracture toughness. The work of fracture for alginate and agar gels varied from 4 to 32 Jm^{-2}. The results showed that agar gels behave in a manner typical for starch gels: as gels became firmer (i.e. more solid-like, due to a higher concentration) they also became tougher. For alginate gels the reverse was true.

Hiller and Jeronimidis (1996) investigated the effect of turgor pressure on fracture properties of potato tubers. For calculation of fracture toughness they used a technique based upon the wedge test described by Vincent (1990) with two modifications: (a) the wedge (45°) was advanced into the sample to increasing depths on successive cycles and then withdrawn completely between each advance, prior to the initiation of the next cycle; (b) the fracture toughness was calculated using only the energy dissipated by the crack, and not the energy represented by the total area beneath the force deflection curve (i.e. a toughness value that would include energy irreversibly lost in plastic flow and hysteresis). Because of the way that fracture toughness was calculated, the results reported by Hiller and Jeronimidis (1996) showed much lower values (34-78 Jm^{-2} for potatoes cv. *King Edward* and *Record*) compared to those obtained by other researchers, which used the 'work-area method' (389 Jm^{-2} for potatoes cv. *Record*, as cited by Vincent, 1990). In accordance with the work on carrots (Atkins and Vincent, 1984), the mean work of fracture for potatoes was found to be significantly higher in flaccid tissue, compared to both fresh and turgid tissues (Hiller and Jeronimidis, 1996). The authors suggested that once cell turgor pressure exceeds a certain threshold value, mechanical properties are little influenced by further increase of turgor pressure.

2.5.3.1.3 Toughness of Biological Materials Tested by Tensile Tests on Notched Specimens

Fahloul and Scanlon (1996) measured the fracture toughness of *Shepody* potatoes using a tensile test on a notched specimen. This test involves crack opening and it is considered to be the analogue of the wedge test in tension (Vincent, 1990). In their work, Fahloul and Scanlon (1996) showed that the generalized fracture mechanics theory, originally applied to polymers and metals, was also applicable to potatoes. The authors performed tensile tests on specimens with different initial crack lengths. Their results showed that the critical apparent energy release rate ($T = 2650\ Jm^{-2}$) was independent of the initial crack length and the applied load. The fracture toughness (T_0) derived from this value of T was 212 Jm^{-2} and was regarded as a material property. Despite variability in the mechanical properties of potatoes, the value of fracture toughness obtained by Fahloul and Scanlon (1996) was comparable with those obtained by other researchers using different techniques.

2.5.3.2 Stiffness and Strength

Stiffness and strength influence both the perceived texture of foods, and the magnitude of mechanical damage that occurs in biomaterials during and after harvesting (Finney, 1969; Szczesniak, 1983; Mohsenin, 1989; Bajema *et al.*, 1998a, 1998b). Of all the types of measurement used in evaluating changes in stiffness and strength, compressive tests are the most common (Mohsenin, 1986), but tensile tests have also been performed (Huff, 1967, 1971; Niklas, 1988).

2.5.3.2.1 Stiffness and Strength of Biological Materials Determined by Compressive Tests

Lin and Pitt (1986) performed compressive failure tests on apple and potato specimens in order to quantify the effects of turgor pressure on tissue stiffness and strength. For apples, two modes of failure were observed, the mode being dependent on turgor pressure and rate of loading. When the dominant mode of failure was cell rupture, tissue strength decreased with an increase of turgor pressure or strain rate. When the dominant mode was cell debonding, an increase in turgor pressure or strain rate caused an increase in tissue strength. Apple tissue stiffness increased with increased turgor, except in the range of plasmoptysis, where it decreased. The term plasmoptysis refers to the rupture of the cells caused by a high turgor pressure which creates unsustainable cell wall stress (Lin and Pit, 1986). For McIntosh apples, plasmoptysis occurred in a narrower range of mannitol concentrations (0.0-0.1 M) than for Ida Red apples (0.0-0.5 M). For potatoes the sole mode of failure observed was cell rupture. As turgor pressure increased, the compressive stiffness of potato parenchyma generally increased, while the strength decreased. No plasmoptysis occurred in potato tissue.

Canet and Sherman (1988) subjected potato samples to compressive failure tests and investigated the influence of sample dimensions, rate of compression, surface friction and lubrication on the failure stress and apparent modulus of elasticity. It was observed that the failure stress generally decreased with increasing sample length/diameter ratio, increasing rate of compression and with sample lubrication. Use of emery paper on the compression platens generally increased failure stress. For the apparent modulus of elasticity, the same trends were observed. The results obtained in this test were similar to

those obtained by Culioli and Sherman (1976) on Gouda cheeses, with the difference that surface lubrication had a much smaller effect on fracture strength of potatoes. A possible explanation suggested by the authors was that the release of cellular fluid from the damaged potato flesh, which would reduce frictional forces, may reduce the difference in behavior between non-lubricated and lubricated samples.

Brusewitz *et al.* (1989) investigated the effect of storage time and static preloading on the rheology of potato tissue. It was reported that failure stress and tissue stiffness, as well as cell turgor pressure, were significantly affected by storage time. Increasing turgor reduced failure stress and increased tissue stiffness, results which are consistent with earlier theoretical models and experimental work (Nilsson *et al.*, 1958; Lin and Pitt, 1986). It was also observed that statically preloaded tissues exhibited a reduction in tissue stiffness and an increase in failure stress.

Although it has been well recognized that plant tissues are highly inhomogeneous (Van Buren, 1979; Mohsenin, 1986; Vincent, 1990), most of the studies either focused on a certain region of the plant or considered it isotropic (Lin and Pitt, 1986; Canet and Sherman, 1988; Brusewitz *et al.*, 1989). Khan and Vincent (1993) studied compressive mechanical properties of apple and potato parenchyma, assuming apple flesh to be anisotropic and potato flesh to be isotropic. The results showed two modes of failure in apples and one mode of failure in potatoes. When apple flesh was compressed along the rows of cells (radially), the fracture took place through a single layer of cells at right angles to the force. When apple flesh was compressed at right angles to the rows of cells (tangentially) the fracture occurred in shear. Radial specimens of apple were reported to be stiffer than tangential ones. However, there was no significant difference in the failure

stress between the two orientations. Potatoes, which only failed in shear, were reported to have a higher stiffness and a higher strength than apples.

Later studies by Pang and Scanlon (1996) and Scanlon *et al.* (1996) investigated mechanical properties of potato tissue at two physiological ages tested under uniaxial compression. The results indicated that potato flesh is not isotropic in nature, although, the extent of anisotropicity may depend on turgor pressure. It was observed that stiffness was much greater in tubers stored for one month, than in tubers stored for ten months. The authors suggested that a contributing factor to the greater stiffness of the tubers stored for a shorter period of time may be greater turgor in the cells. Movement of fluids from cells during repeated compressive loading was reported to ameliorate the differences in stiffness between short and long term stored tubers during subsequent loadings (Pang and Scanlon, 1996).

It was also reported (Scanlon *et al.*, 1996) that longitudinal stiffness was very much affected when osmotic adjustment was applied to potato parenchyma cells. The hypotonic treatment (3% mannitol) caused the load-deformation curves for long-term stored tubers to resemble those of short-term stored tubers. Similarly, the hypertonic treatment (7% mannitol) caused the short-term stored tubers to appear as though they had been stored for ten months (Scanlon *et al.*, 1996).

The importance of water content on stiffness and strength of potato was also emphasized by Hiller and Jeronimidis (1996) who tested under compression potato cylinders in three different turgor states (turgid, fresh and flaccid). It was observed that decreasing the turgor pressure to very small values (flaccid tissues), caused a decrease in compressive stiffness. Fresh and turgid tissues were reported to differ insignificantly with

regard to stiffness. The mean failure stress as measured in the compression test was reported to be significantly higher for flaccid tissues than for either fresh or turgid tissues.

Bajema *et al.* (1998a and 1998b) reported that turgor pressure did not have a significant effect on impact failure stress. However, increasing temperature from 5 to 15°C increased failure stress in two potato cultivars (*Russet Burbank* and *Atlantic*) subjected to impact testing.

2.5.3.2.2 Stiffness and Strength of Biological Materials Determined by Tensile Tests

An early work by Huff (1967) investigated the tensile strength and the failure modulus (i.e. tensile strength over strain to failure) of *Kennebec* potatoes (stored for different storage times) for specimens taken from three locations in the tuber. The results showed that over 4 months of storage, the tensile strength increased in the specimens taken from the center of the tuber and decreased in the specimens taken just below the skin. The tensile strength did not change with time for samples taken halfway between skin and center, nor did failure modulus at any location. In a later work, Huff (1971) added to the experiment two more variables: *Russet Burbank* potatoes were tested as well as *Kennebec*, and two temperatures (6°C and 21°C) were employed during testing. The results showed great variation of both strength and stiffness with location in the tuber. The pith (center) and the skin-cortex region were stronger and stiffer than the perimedullary zone (halfway). It was also observed that stiffness generally increased when temperature decreased. Storage time affected properties in the perimedullary zone much less than just below the skin and in the center.

Niklas (1988) performed uniaxial tensile tests on potato parenchyma samples in order to determine the effect of turgor pressure on the tensile modulus of elasticity. The results indicated that the elastic modulus decreased as turgor pressure decreased (mannitol concentration increased). The explanation given by the author for such a behavior was that mannitol penetrated the plasmalemma of cells 'plasticizing' the tissue, and hence reducing the tensile modulus.

2.5.4 Mechanical Properties of Biological Materials Tested by Small-Scale Deformation Techniques

2.5.4.1 Basic Concepts

Small-scale deformation tests can be used to gain information on the microstructural organization of a system, or to predict behavior on a macroscopic scale (Tung, 1986). In a dynamic shear test, the specimen is subjected to a small amplitude sinusoidal stress or strain, the mode depending on the type of the instrument. The resulting shear strain or stress is then measured as a function of the wave cycle. The small stresses or strains employed in the dynamic tests permit the application of linear viscoelastic theories to predict overall stress-strain behavior (Jackman and Stanley, 1992).

For a test piece subjected to a sinusoidal stress (σ) at a frequency (ω), the responding sinusoidal strain (γ) may be expressed as (Tung, 1986):

$$\gamma = \gamma_0 \sin(\omega t) \qquad (3)$$

where γ_0 = maximum strain amplitude (dimensionless)

ω = oscillatory frequency ($rads^{-1}$ or Hz)

t = time (s)

The strain rate (γ) is the first derivative of strain with respect to time:

$$d\gamma/dt = \dot{\gamma} = \omega \gamma_0 \cos(\omega t) \quad (4)$$

For a Hookean solid, stress is directly proportional to strain and may be expressed as (Tung, 1986):

$$\sigma = k \gamma_0 \sin(\omega t) \quad (5)$$

where k = proportionality constant.

For a Newtonian fluid, stress is directly proportional to shear rate and may be expressed as (Tung, 1986):

$$\sigma = \eta \omega \gamma \cos(\omega t) \quad (6)$$

where η = shear viscosity ($Nm^{-2}s$).

For perfect elastic bodies, the shear stress wave is in phase with the shear strain wave, whereas for perfect viscous fluids, the stress and strain waves are 90° out of phase. In a viscoelastic body, the resulting shear strain will lag behind the applied shear stress by an angle (δ) intermediate between 0 and 90° (Figure 5). The angle is usually referred to as the phase angle and is considered to be a measure of the viscoelastic characteristics of a given material. Generally, the stress function for viscoelastic materials may be written as:

$$\sigma = \gamma_0 [G'\sin(\omega t) + G''\cos(\omega t)] \quad (7)$$

where G' = dynamic shear storage modulus (Nm^{-2})

G'' = loss modulus (Nm^{-2})

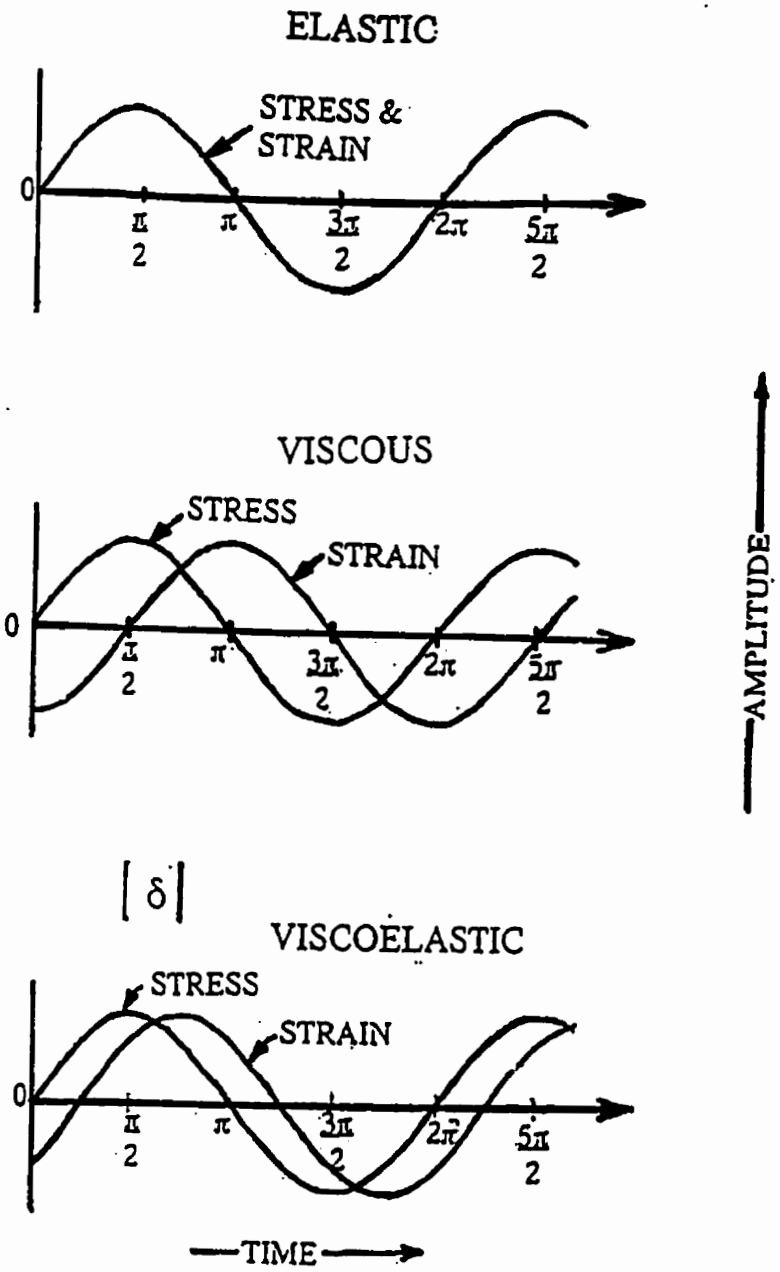

Figure 5. Stresses and strains of elastic, viscous and viscoelastic bodies subjected to dynamic tests by a controlled stress rheometer (Adapted from Pang, 1995)

The dynamic shear storage modulus is an estimate of the energy recovered per cycle of sinusoidal shear deformation, and is defined as the stress in phase with the strain divided by the strain (elastic component). The loss modulus is a measure of the energy dissipated as heat per cycle of sinusoidal shear deformation, and is defined as the stress out of phase with the strain divided by the strain (viscous component) (Tung, 1986). The ratio of the loss and storage moduli is numerically equal to the tangent of the phase angle and is called the loss tangent:

$$\tan \delta = G''/G' \tag{8}$$

A phase angle approaching 0° indicates only negligible energy being lost as heat, and therefore a material has a predominantly elastic character. A phase angle approaching 90° indicates only negligible energy recovered, and therefore a material with a predominantly viscous character. The complete information of the viscoelastic properties of materials is given by the complex dynamic modulus G^*, which includes both the elastic and the viscous components:

$$\vec{G^*} = \vec{G'} + \vec{G''} \tag{9}$$

where G*, G' and G" are represented as vectors.

2.5.4.2 Effect of Temperature on Mechanical Properties of Biological Materials Tested by Small-Scale Deformation Techniques

Non-destructive rheological methods have been used for a long time to characterize plant tissues. Peterson and Hall (1974) were among the first showing that potato behaves as a viscoelastic material. They used an electro-mechanical vibration exciter in order to determine the effect of temperature on dynamic mechanical properties

of potatoes. Their results showed that complex dynamic modulus, storage modulus and phase angle were all independent of temperature in the range between 2 and 30°C. This was an intriguing finding since previous studies had reported a high correlation between temperature and impact sensitivity (Lutz *et al.*, 1952; Johnson and Wilson, 1969). The effect of thermal treatment on the rheological properties of plant tissues is still uncertain to this date (Ramana and Taylor, 1992b). Therefore, different researchers have continued to focus their work on this area of study.

Ramana and Taylor (1992a) performed dynamic oscillatory shear measurements on fresh vegetables (parsnip, swede, yam, potato, turnip, mooly and radish), in an attempt to establish the applicability of this method for monitoring textural changes of vegetable tissues during commercial cooking. Using a modified Weissenberg rheogoniometer, the authors found that the apparent storage modulus G' either remained constant or rose slightly in the range between 20 and 50°C and then dropped sharply around 60°C. Frozen tissues showed a higher apparent G' than raw tissues, but cooking of frozen samples caused a rapid reduction in G'. Thawed tissues exhibited similar G' values as did cooked tissues. The authors suggested that cellular damage brought about by freezing might be equivalent to the damage caused by heating. In both cases, the consequence of the structural damage appeared as a loss of turgor pressure.

A similar pattern for the decline in storage modulus upon heating was reported by Ramana *et al.* (1992) for heated carrot tissues subjected to dynamic shear tests. The sharp decline of G' around 60°C was associated with disruption of the plasmalemma and loss of cellular integrity. For a better understanding of the mechanisms that occur during heating, Ramana and Taylor (1992b) evaluated the rheological properties of carrot cells

and cell wall material (rather than whole tissues) during typical cooking. The tests were performed using a Bohlin controlled-stress rheometer. For the cell wall material, the elevation of temperature from 25 to 90°C caused a steady increase in the complex modulus (G^*). The phase angle (δ), showed no clear trend as temperature increased. Carrot cells showed an increase in G^* from 25 to 75°C, when a decrease was noted. Tan δ stayed constant up to 60°C and then showed a rapid rise up to 90°C. The different behaviour of tan δ upon heating of cells compared to cell-walls was not unexpected. Initially, cells were solid-like structures due to turgor pressure. Upon heating, cells became less turgid and lost their solid-like characteristics. Tan δ increased at the point where the turgor pressure was released. For cell-wall material, there was no distinct change between the elastic and the viscous states, since the structure has already been broken during preparation of the cell-wall material. Therefore, no significant change in tan δ was observed.

In the attempt to shed more light on the textural changes which occur in potato upon heating, Shomer *et al.* (1993) studied the dynamic rheological properties of potato cell suspensions during thermal treatment and enzymatic degradation of cellulose. Their results showed that elevating temperature from 20 to 70°C caused storage modulus (G') to increase, while loss modulus (G") decreased. The authors attributed this behaviour to the gelatinized starch which swelled to such an extent that the cell wall was pushed outwards. As a result the cell became more elastic and less plastic, which was shown as an increase in G' and a decrease in G". Enzymatic treatment by cellulase caused both G' and G" to decrease. It has been suggested that cellulase removed the cell wall, which resulted in breakdown of the cell structure and dispersion of starch.

2.5.4.3 Effect of Turgor Pressure on Mechanical Properties Tested by Small-Scale Deformation Techniques

The effect of turgor pressure on rheological properties of plant materials tested by small deformation techniques is not as extensively documented as that of temperature. However, it is well known that both rheological properties and cell turgor pressure are affected by storage time (Brusewitz *et al.*, 1989).

Pang and Scanlon (1996) used a Bohlin rheometer to investigate mechanical properties of raw potato tissues at two physiological ages (1 month and 10 months). The results indicated that the shear storage modulus was greater in short-term stored tubers compared to long-term stored tubers. The authors suggested that the difference in shear stiffness might have been caused by a greater turgor pressure of the tubers that had been stored for a shorter time. In order to separate the actual effect of water loss on mechanical properties from the effect of physiological changes which occur during storage, Scanlon *et al.* (1996) adjusted the turgor pressure of potato parenchyma cells with mannitol solutions in a later study. For these new tests, the results showed that storage modulus was much higher for hypotonic treated samples (3% mannitol), than for hypertonic treated samples (7% mannitol), regardless of whether the crop was old or new. As mannitol concentration decreased, the turgor pressure increased and imposed an internal pressure on the cell walls, causing them to stiffen (Niklas, 1989). This effect was seen as an increase in storage modulus. The results obtained by Pang and Scanlon (1996) and Scanlon *et al.* (1996) indicate the importance of water content when analyzing mechanical properties of both fresh and stored potatoes.

2.5.4.4 Effect of Density on Mechanical Properties Tested by Small-Scale Deformation Techniques

Many of the rheological studies that have been performed on plant materials have assumed that plant tissues are continuous and isotropic (e.g., Lin and Pitt, 1986; Canet and Sherman, 1988). On the contrary, Vincent (1989) reported that the variations in cell size and density make apple parenchyma inhomogeneous and anisotropic, affecting significantly the behaviour of the flesh during mechanical tests. In his study, Vincent (1989) analyzed the density-stiffness relationship for nine varieties of apple using a modified Deer rheometer. The results showed that the torsional stiffness was largely dependent on the average density, both within and between varieties. At a given density, the outer parenchyma was found to be stiffer than the inner. During storage, apple flesh increased in permeability causing the density and the stiffness to decrease. Combining the results of mechanical tests with a simple model for cell packing, the author suggested that stiffness of apple parenchyma is a function of the area of contact between adjacent cells.

As noted in 2.1.4.1, one component contributing to heterogeneity in potatoes is starch, and greater starch content increases the density of potato tubers. Scanlon *et al.* (1998) studied the density-stiffness relationship for potato parenchyma, using a Bohlin VOR rheometer to determine whether stiffness was affected by density. The experiments were performed on both control (normal turgor) and osmotically adjusted (flaccid or turgid) specimens. The results showed that a positive relationship does exist between shear stiffness and density, but only for the osmotically adjusted specimens. No such relationship was observed for the control specimens. The authors suggested that the slight

variability in turgor pressure between the control specimens affected shear stiffness independently of the effect of density. As a result the effect of density itself on shear stiffness was masked.

The results obtained by Vincent (1989) and Scanlon *et al.* (1998) suggest that anisotropy and density/stiffness relationship should be taken into consideration in any mechanical testing of plant tissues.

2.6 Cutting Properties of Biological Materials

Cutting of biological materials is one of the most frequently used operations in food processing. It can be defined as a size reduction technique in which the fracture of the body is initiated and propagated along a predetermined line by a cutting tool (Persson, 1987). For french fry manufacture, the cutting operation plays an important role in terms of yield, as well as quality of the fries (Feustel and Kueneman, 1967; Anonymous, 1998). Generally, the overall yield of french fry cuts (after peeling, trimming and cutting) is expected to fall in the range of 50 to 75% of the weight of potatoes processed (Feustel and Kueneman, 1967). The quality of the cut can be viewed in terms of surface damage and the length of the cut (Scanlon, 1997).

2.6.1 Surface Damage

Surface damage refers to the disruption of the cells caused by the cutting operation in the vicinity of the cut. A particular form of surface damage is the so-called feathering, which applies to the rupturing of the cells along the length of the cut strip (Anonymous, 1998). It is believed that feathering may lead to subsequent degradative

reactions such as breakage of the strip and discoloration. Also, oil may be trapped and held in the ruptures during the frying operation (Anonymous, 1998).

There are a number of factors which can contribute to the surface damage during the cutting operation: the condition of the tuber, the blade thickness and sharpness, the blade surface finish, and the flow velocity.

2.6.1.1 Condition of the Tuber

Potato tubers are not the best of objects to submit to a slicing operation, especially when they are freshly harvested and tend to be brittle (Anonymous, 1996). Slicing performance is not constant throughout the tuber storage season. Changes in mechanical properties over time (due to cell wall or turgor changes) affect the amount of feathering that occurs on the cut strip. This condition may also vary with potato variety, as well as solids content (Anonymous, 1998). Thermal treatment is believed to decrease the brittleness of the tubers (Andersson *et al.*, 1994) and consequently the amount of feathering. This is the reason why some processors pre-heat their tubers prior to slicing.

2.6.1.2 Blade Thickness

Generally, the cutting edge of a knife should be thin enough so that the yield stress of the material is surpassed. However, for too thin blades, the yield stress of the steel is exceeded during cutting and blunting occurs (Scanlon, 1997). Blades that are too thick cause an increase in the energy consumption (Visvanathan *et al.*, 1996), as well as a higher yield of feathered strips (Anonymous, 1998). It has been suggested that a cutting edge with a thickness between 50 and 150μm would be optimal for traditional type cutters (Persson, 1987). Most recently there has been much interest in tensioned cutters,

which involve a new style of ultra-thin tension blades. This new system has been reported to give virtually no feathered potato strips (Anonymous, 1998).

2.6.1.3 Blade Sharpness

Most of the cutting tools are known to become dull or contaminated after use of several hours. Dull blades increase the force needed to push the tubers through the cutter, causing unacceptable degrees of feathering or even breakage of the potato strips (Anonymous, 1998).

In order to minimize these problems, the blades must be replaced and sharpened often. Some processors use inbuilt control systems, which can detect a dull knife and then switch it with a new one, without interrupting the production flow (Anonymous, 1995). Another option may be the use of bladeless cutting machines which do not require periodic sharpening or cleaning. It has been reported that water jet slicing systems give a high quality, clean and precise cut (Day, 1995). However, some other researchers believe that sharp blade cutting is preferable over water jet cutting, in terms of surface damage (Becker and Gray, 1992).

2.6.1.4 Blade Surface Finish

It has been suggested that one of the main reasons for feathering may be the friction from surface contact at the intersection of two blades (Figure 6). When the blades have "mirror-finished" surfaces, the drag friction across the blade is reduced and therefore the feathering phenomenon is diminished (Anonymous, 1998).

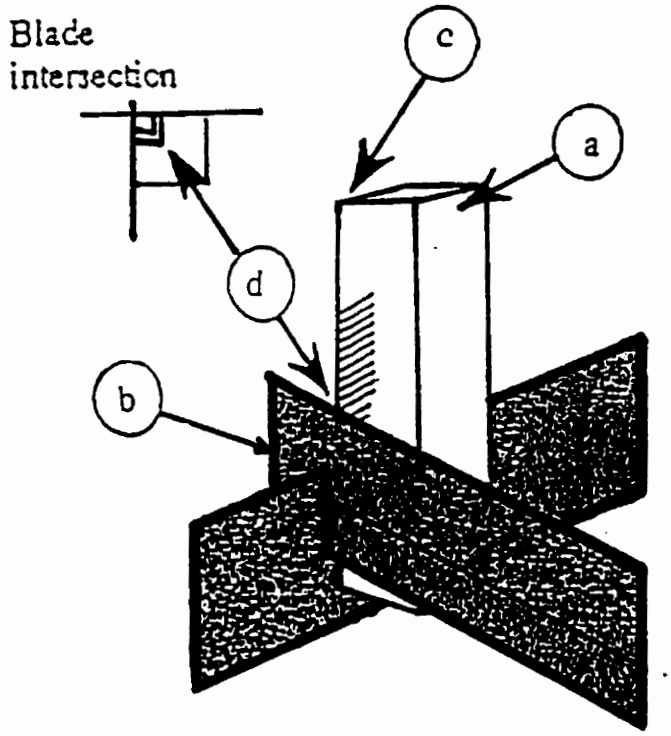

Figure 6. Graphical representation of the feathering phenomenon as it occurs on the potato strip at the intersection of two blades; (a) cut potato strip; (b) blade intersection; (c) strip corner where most friction exists; (d) feathering (Adapted from Anonymous, 1998).

2.6.1.5 Flow Velocity

Theoretically, the slower the potato can be run through a conventional cutter, the better the quality of the strips is. Unnecessarily high velocities are known to result in feathering and breakage of the fries (Anonymous, 1998). In practice however, too slow a velocity may result in plugging the cutter and consequent shutting-down of the line (Anonymous, 1998).

2.6.2 The Length of The Cut

In potato processing manufacture the length of the cut is particularly important, since the customers find longer french fries more desirable (Feustel and Kueneman, 1967). In the last few decades, there has been much interest in the hydro-cutting technology, which is still believed to be the most efficient and cost-effective method of mass-producing cut fruit and vegetable (Anonymous, 1998). In a hydro-cutting system, the tubers are "shot" lengthwise through a so called "water gun", which forces the through a tubular cutter at tremendous hydraulic pressure (Livingston, 1962). During this operation, each individual potato tuber is sliced longitudinally with a set of fixed cutting blades. To customers this means an extra long french fry that has a uniform cross-sectional area from end to end (Livingston, 1962).

2.6.3 Efficiency of the Cutting Operation

The efficiency of the cutting operation, along with the quality of the cut defines the performance of the cutting process. The efficiency can be viewed in terms of energy consumption, which is very much affected by the mechanical properties of the food

material (Sitkei, 1986). It has been suggested that total energy consumed in the cutting process of plant materials varies markedly with the turgor pressure of the tissue (Atkins and Vincent, 1984) and the maturity of the plant (Scanlon, 1997). Experimental results showed that an increase in turgor pressure may cause an increase in the cutting energy of potatoes (Hiller and Jeronimidis, 1996). One possible explanation is increased interaction between the lateral surfaces of previously-cut potato parenchyma and the sides of the knife blade, caused by a greater bending stiffness of the turgid tissue (Hiller and Jeronimidis, 1996). Over time in storage, both turgor pressure (Brusewitz *et al.*, 1989) and stiffness (Pang and Scanlon, 1996) of the potato tuber may decrease. These changes, however, do not necessarily translate into a decrease of cutting energy (Scanlon, 1997), since the fracture toughness of the tuber may increase over storage time (McGarry, 1993). This observation suggests that a strong knowledge of the mechanical properties of the food material is required in order to get a full appreciation of energy consumption.

2.7 Objectives

In view of the research that has been outlined above, the objectives of this study were:

1. To investigate the effect of thermal treatment and artificial turgor adjustment on the mechanical properties of potato parenchyma;
2. To quantify the amount of feathering in potato tubers pre-heated at different temperatures;
3. To examine the effect of storage on the mechanical properties of the potato tuber;

4. To determine the influence of solids content and cultivar on the mechanical properties of the potato tissue;
5. To investigate whether size reduction of the tuber can be viewed as a brittle fracture phenomenon.

3. MATERIALS AND METHODS

3.1 Materials

Potatoes of the cultivars *Russet Burbank* and *Shepody* were commercially grown near Carberry, Manitoba and were supplied by Midwest Food Products (Nestle-Simplot). The potatoes were harvested in late September to early October 1997 and arrived at Summerland in mid November 1997. Upon arrival the potatoes were stored at 7.5±1°C and 90% relative humidity (R. H.). Neither *Russet Burbank* nor *Shepody* potatoes were sprout-inhibited. Sprouting was first noticed to occur in *Shepody* potatoes (late January 1998) and then in *Russet* potatoes (late April 1998).

D-mannitol was obtained from Fisher Scientific Ltd. (Ottawa, ON). Miracloth was procured from Calbiochem-Novabiochem Corp. (La Jolla, CA). Emery paper with grain 50μ and cyanoacrylate bonding agent were bought from a local store.

The Bron slicer (model Mandoline) was procured from J. B. Prince Co. (New York, NY). The double blade cutting device ('cuber') as well as the core borer of 40 mm diameter and the attachments for the tensile test were all manufactured by the Food Engineering workshop at Pacific Agri-Food Research Centre, Summerland, B. C. The stainless steel wedge used in the fracture test was manufactured by the Physics Workshop at the University of Manitoba. The Mitutoyo Digimatic caliper was purchased from Prince and Markle Equipment Ltd., Penticton, B. C.

3.2 Methods

3.2.1 Overall Experimental Design

The project consisted of three main parts:

1. Examination of the effect of thermal treatment and artificial turgor adjustment on dynamic shear storage modulus using small strain oscillatory rheometry.

2. Examination of the effect of thermal treatment and artificial turgor adjustment on toughness and 'feathering' using a wedge-penetration fracture test.

3. Examination of the effect of thermal treatment and artificial turgor adjustment on stiffness and strength using a tensile test performed on a notched test specimen.

All the above tests were performed monthly, in triplicate, on two potato cultivars (*Russet Burbank* and *Shepody*) of two different specific gravities each (high and low). Prior to testing the tubers were pre-heated for at one of three pre-heating temperatures (33, 47 and 60°C). Then the samples were taken and soaked in one of three mannitol concentrations (3, 5 or 7%). Unheated samples (8°C) were also soaked in mannitol solutions and were used as control specimens. The total number of samples per test per month was 144: 3 replicate tubers * 2 cultivars * 2 specific gravities * 4 temperatures * 3 mannitol concentrations.

Two auxiliary tests were done every month: specificÿgravity measurements and turgor pressure measurements. At the end of each month the interrelationship between the mechanical properties obtained was analyzed. The tests were repeated over a period of eight months (from November to June) to examine the effect of storage time on the mechanical properties of potato tissue.

All tests were performed at room temperature (23 ± 1°C).

3.2.2 Sample Preparation

A number of potato tubers were removed from storage, washed and left to air dry overnight at room temperature (23 ± 1°C). The tubers were then immersed in a waterbath at either 33, 47 or 60 °C and pre-heated for 90 minutes. Potatoes were then removed and allowed to cool and dry for another night at room temperature. The control samples (8°C) were also left at room temperature overnight, after being brought out of storage. For these samples the pre-heating step was omitted.

In order to facilitate slicing, equal portions of flesh (in length) were discarded with a knife from the stem (S) and the bud (B) ends (Figure 7). The slicer was set at a clearance of 5 mm between the sliding plate and the blade. The potato tuber was then manually pulled onto the blade on the direction of its longitudinal axis. Since mechanical properties vary with location in the tuber (Huff, 1971; Pang, 1995; Agblor, 1997), the samples were consistently taken from the same histological regions. Out of each tuber, slice 1 was discarded and slice 2 was used to obtain the sample for the tensile test. The actual dimensions of the tensile specimens were 60 mm length, 10 mm width and 5 mm thickness, so that the ends could be attached to aluminum grips with cyanoacrylate adhesive as shown in Figure 8. The gauge length of the specimen (40 mm) was chosen in conformity with the recommendations of ASTM-E8-1993 (ASTM, 1993). A single edge notch of 5 mm was cut into the specimens halfway along their length and perpendicular to the tensile axis (Fahloul and Scanlon, 1996).

After the tensile specimen was removed, the potato tuber was transversally cut with a knife into two equal pieces (see arrow in Figure 7). One half of the tuber was used to obtain a cube with sides of 20 mm, which was used as the specimen in the wedge-

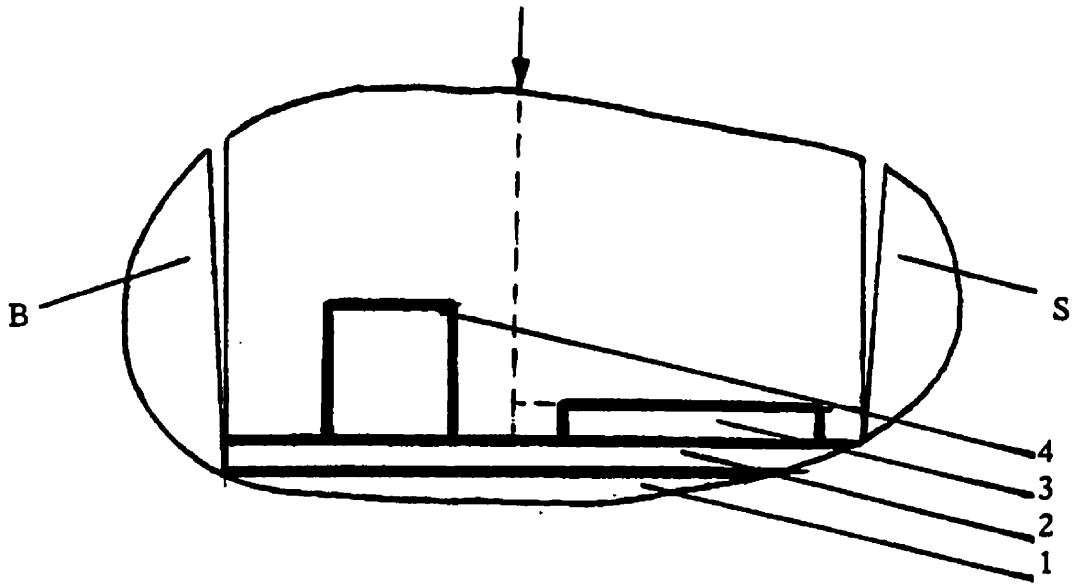

Figure 7. Original location in the tuber of samples used in different tests; B- bud end, S- stem end, 1- discarded slice, 2- tensile test specimen, 3- small strain dynamic shear test specimen, 4- wedge-penetration fracture test specimen.

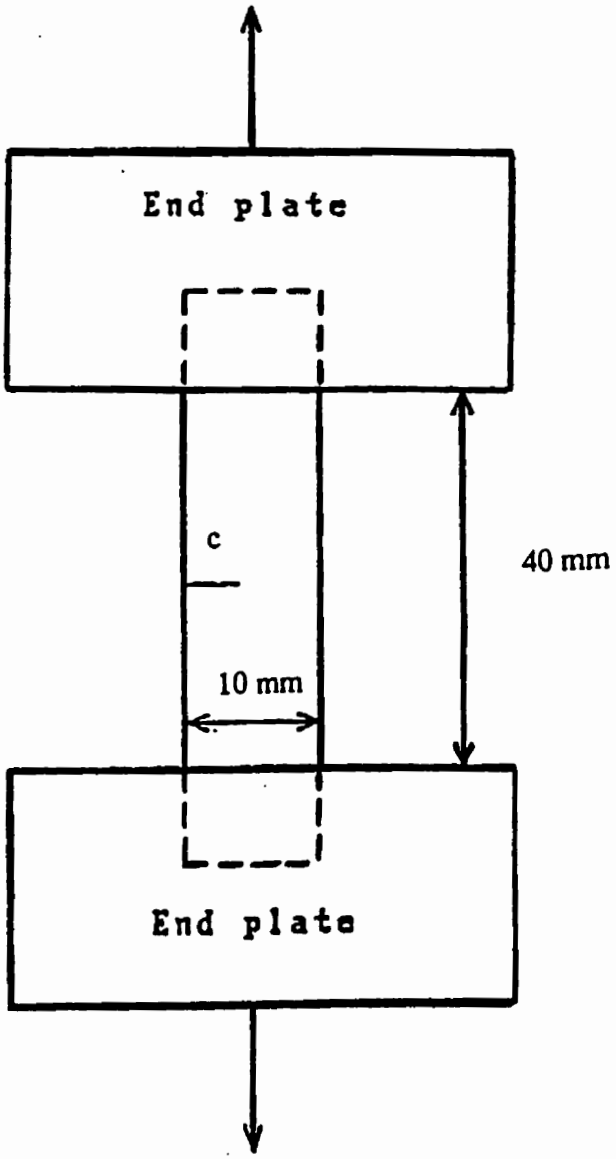

Figure 8. Dimensions and experimental set-up of potato specimen used in tensile test (Adapted from Fahloul and Scanlon, 1996).

penetration fracture test. The tool used to excise the specimen was 'the cuber', a double blade cutting device shown in Figure 9. The clearance between the two blades (which were rigidly fixed on the plastic handle) was 20 mm. From the other half of the potato tuber, the test-piece used in the oscillatory shear test was taken (Figure 7). In order to obtain this specimen, the tuber was first pulled onto the blade of the slicer, so that a slice of 5 mm thickness was obtained. Then, a core borer was used to punch the slice and to obtain a 40 mm diameter disc.

All the above samples were soaked in a chosen mannitol solution immediately after they were taken from the potato tuber so that they would not dry out. One of three mannitol concentrations was employed: 3, 5 or 7% (w/v), to create for potato flesh hypotonic, approximately isotonic and hypertonic conditions, respectively. The three different types of specimens taken out from each tuber were soaked all together in one labeled plastic dish containing approximately 120 ml of mannitol solution of a given concentration. This amount of mannitol solution was carefully calculated, so that the decrease in concentration brought about by the potato specimens (which contain about 80% water) would not affect the concentration of mannitol solution by more than 10%. Based on the work of Lin and Pitt (1986), the samples were soaked over two nights (about 40 hours) prior to testing. On the first night the samples were kept in the fridge to prevent microbial growth. On the second night the samples were kept at room temperature to allow thermal equilibration.

3.2.3 Experimental Methods for Small Strain Shear Testing

A controlled stress rheometer (CVO Bohlin, Bohlin Instruments Ltd., Gloucestershire, UK) with a parallel plate geometry was used for small strain oscillatory

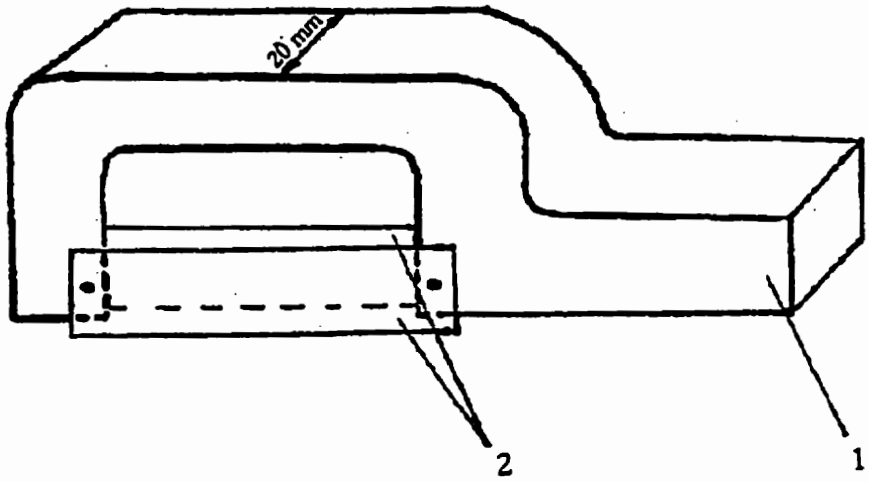

Figure 9. The cutting device ('cuber') used to take samples for the wedge-penetration fracture test; 1- plastic handle, 2- metallic blades.

shear testing. The diameter of the plates was 40 mm. In order to prevent slippage of the sample during testing, precut discs of emery paper of grain size 50 μ were attached to the upper and lower plates. The thickness of emery paper discs was measured at 1.74 mm by lowering the plates until they just touched. Also, compression of the slice provided better contact between the slice and the plate, preventing slippage. Based on preliminary experiments, the maximum compression applied was a distance of 2.5% of sample height.

Prior to testing in the rheometer, the samples obtained as described in section 3.2.2 were taken from the mannitol solution and dried with clean paper towel. The thickness of the specimens after soaking in mannitol was measured with a caliper in three spots and the average was calculated. For each specimen, the gauge of the rheometer was set at a value equal to the difference between the actual thickness of the specimen measured with the caliper (the average) and the compression factor (2.5% of the thickness).

Rheological measurements were obtained in oscillatory mode at 23±1°C and a frequency of 1 Hz. For samples pre-heated at 60°C, the measurements were performed at stresses ranging between 10 and 35 Pa. For all the other samples (8, 33 and 47°C), the applied stresses ranged between 35 and 100 Pa. Values of the dynamic shear storage modulus (G') were obtained directly from the software analysis program of the Bohlin Rheometer. In all measurements, the sample was subjected to four full cycles of oscillation for conditioning (Ramana and Taylor, 1992; Pang and Scanlon, 1996), the reading from the fifth cycle being recorded. The conditioning was necessary to ensure that there was no mechanical constraint on the system (Pang and Scanlon, 1996). The

measurements were done as a part of a stress sweep where 25 values of G' were obtained for each sample. The average of these 25 values was taken in subsequent calculations.

3.2.4 Experimental Methods for Wedge-Penetration Fracture Testing

The technique for fracture testing was based upon those used by Vincent *et al.* (1991), Oates *et al.* (1993) and Hiller and Jeronimidis (1996). An Instron Universal Testing instrument M-4201 (Canton, MA, USA), with a sharp 30° (included angle) steel wedge attached to a 500 N capacity load cell was used. The sample cube of tissue (dried as above) was placed upon a stationary horizontal metal platen within the Instron. Based on preliminary research, the cross-head was lowered at a speed of 20 mm min^{-1} until the crack had propagated through three quarters of the sample depth (15 mm). Then the cross-head was reversed. Preliminary research showed that for lower cross-head speed values little or no brittle fracture occurred in the test-piece. The force-deflection curve was scanned with an AGFA scanner (Model Arcus II) and processed with Adobe Photoshop 4.0 software. The area under the force-deflection curve, which gives the total work done, was corrected for energy losses (Oates *et al.*, 1993) and was calculated with NIH Image 1.6/ppc software system. The new crack surface area (A_0) was calculated as the product of the depth of the crack and the width of the cube, which were both measured with the caliper in two spots and then averaged. When 'feathering' occurred, the surface area of each individual 'feather' (A_i, mm^2) was estimated and was added to the new crack surface (A_0, mm^2). The total new crack surface area was therefore calculated with the equation:

$$A_{total} = 2A_0 + \sum_{i=1}^{n} A_i \ (mm^2) \qquad (10)$$

where i = number of 'feathers' per specimen total surface.

The amount of feathering was calculated as a percentage of the total new surface area. The work of fracture (toughness) was given by the total work done divided to the total new crack surface area (Oates *et al.*, 1993). This general approach of determining the toughness of a material is known as the 'work-area' method (Vincent *et al.*, 1991).

3.2.5 Experimental Methods for Tensile Notch Testing

It has been suggested that the wedge-penetration fracture test described in 3.2.4 and the tensile test in a notched specimen are geometrically identical (Vincent *et al.*, 1991). Therefore, the tensile test was conducted on the same machine which was used in the wedge fracture test (Instron Model 4201), at the same cross-head speed (20 mm min^{-1}). The sample taken as described in 3.2.2 was glued to aluminum plates as shown in Figure 8. Then the plates were attached to the Instron and were pulled apart. The force deflection curve was recorded by the Instron chart recorder until the specimen failed. When the recorded force dropped to zero, the cross-head was manually reversed. The fracture stress was calculated by dividing the maximum recorded force (Figure 10) by the cross-sectional area of the specimen (50 mm^2). The stiffness (Young's modulus) of the notched specimen of the material was obtained from the slope of the tangent to the recorded curve (Figure 10).

3.2.6 Experimental Methods for Specific Gravity Measurements

Specific gravity of potatoes was measured using the weigh in air/ weigh in water method, which is considered to be the most popular for this purpose (Lulai, 1986). A

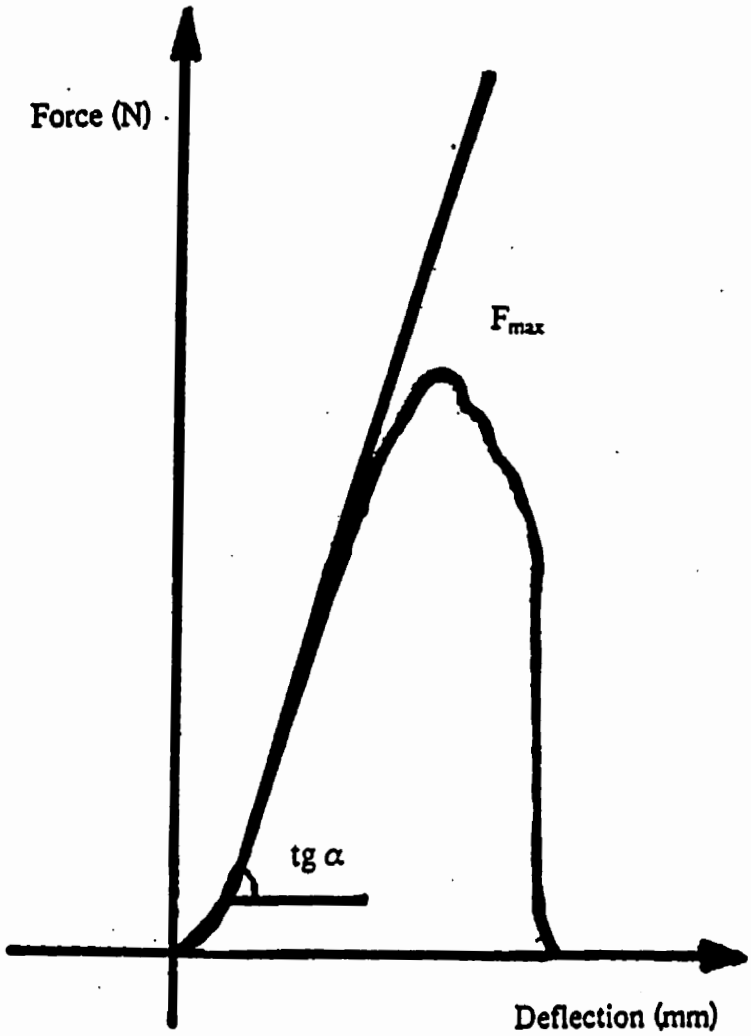

Figure 10. Typical force-deflection curve obtained in the tensile test.

number of potato tubers of each cultivar and specific gravity were taken out from the storage at the beginning of every month, washed and let to air dry overnight at room temperature (23±1°C). The next day each potato tuber was weighed in air and in water, by placing it in a basket suspended by a string from the weighing balance into a bucket of water. Prior to the measurements, water was allowed to reach room temperature. Specific gravity was calculated by dividing the weight of the tuber in water by the difference between the weight in air and the weight in water (Lulai, 1986; Dull *et al.*, 1989). Ten tubers of each cultivar and solid content (*Russet Burbank* high/low and *Shepody* high/low) were analyzed and the average for each treatment was calculated every month.

3.2.7 Experimental Methods for Turgor Pressure Measurements

The technique used to determine the turgor pressure of potato flesh was based upon those used by Lin and Pitt (1986) and Mc Garry (1993). A number of potato tubers of known specific gravities were peeled and chopped one by one in small pieces. The chopped flesh obtained from each tuber was separated into three parts, and each third was immersed in a plastic dish containing 120 ml of 3, 5 or 7% mannitol solution. The amount of mannitol solution used in each plastic dish was carefully calculated, so that the decrease in concentration brought about by the potato flesh (which contains about 80% water) would not affect the concentration of mannitol solution by more than 10%. After a soaking time of about 65 hours in the fridge, the mannitol solutions from each dish were discarded and the samples were frozen by pouring liquid nitrogen over the potato flesh. The samples were left to thaw for about 45 minutes and then were crushed in a mortar with a pestle. The sap was expressed by squeezing the mash through a double layer of

cheese-cloth and Miracloth, and was subsequently used for osmolality measurements performed with a Vapour Pressure Osmometer, Model 5500 (Wescor Inc., Logan, UT). For each sample four readings were taken and the average was calculated.

Turgor pressure was calculated as the difference between the water potential (Ψ) and the osmotic potential (Π). Both water and osmotic potentials in the cells after soaking were estimated using the ideal gas law (Lin and Pitt, 1986):

$$\Psi = - M R T \quad (11)$$

$$\Pi = -M_l R T \quad (12)$$

where: M= molarity of mannitol solution (mol L^{-1})

M_l = molality of potato sap (mol L^{-1})

R = the gas constant = 0.008314 (L MPa) (mol K)$^{-1}$

T = temperature (K)

For water potential, molarity was given by the molar concentration of mannitol solution used for soaking the specimen. For osmotic potential, molarity was calculated from the osmolality of the potato sap measured with the osmometer.

The whole experiment was performed in triplicate (three tubers each), on both *Russet* and *Shepody* potatoes with both high and low solids contents.

3.2.8 Statistical Analysis

Statistical analysis was performed using SAS statistical analysis software program package (SAS Institute, Version 6.12, 1996). The General Linear Model (GLM) Procedure was used for the analysis of variance. Significant differences between treatments ($P \leq 0.05$) were determined with Duncan's multiple range test.

4. RESULTS

4.1 Preliminary Experiments

4.1.1 Determination of Linear Viscoelastic Region For Potato Parenchyma in Small Strain Oscillatory Shear Test

Small strain oscillatory shear tests are known to furnish unambiguous results only if the potato tissue displays a linear viscoelastic region (Pang, 1995; Pang and Scanlon, 1995). If the sample is 'over-strained', then the elastic structure of the material is destroyed and the results obtained are more difficult to understand. Therefore, preliminary experiments were performed to establish the linear viscoelastic region of potato parenchyma. Slices of 5-mm thickness and 40-mm diameter, taken out of one-month-old potatoes, were tested in oscillatory mode at 1Hz frequency. The storage (G') and the loss (G") moduli were measured across a range of stress between 5 and 500 Nm^{-2}. From Table 1, it can be seen that G' was substantially greater than G" for all the extreme treatments, which proves that G' is the dominant modulus contributing to shear stiffness (Pang and Scanlon, 1996). Table 2 shows the effect of different stresses and the corresponding strains on G' for unheated *Russet Burbank* potatoes. The linear viscoelastic region was considered to lie between 41.3 and 88.9 Nm^{-2}, as G' showed little variability in this range. Below 41.27 Nm^{-2} the pattern of G' was rather inconsistent. Beyond 88.89 Nm^{-2} G' dropped relatively sharply indicating that considerable irreversible damage had occurred in the tissue. Therefore, a range of stress between 35 and 100 Nm^{-2} were chosen to be applied to potato samples. Subsequent experiments, however, showed that this level of applied stress held true for samples pre-heated at 33 and 47°C, but it was too high for samples pre-heated at 60°C. The mechanical behaviour

Table 1. Effect of extreme thermal and osmotic treatments on storage modulus (G'), loss modulus (G") and tan δ (phase angle) for low solids content *Russet Burbank* potatoes in the first (November) and the last (June) months of storage

Mannitol concentration (% w/v)	Temperature (°C)	Month	G' (kNm^{-2})	G" (kNm^{-2})	Tan δ
3	8	November	536.3	72.6	0.14
7	8	November	175.0	23.8	0.14
3	60	November	89.8	17.0	0.19
7	60	November	82.8	14.6	0.18
3	8	June	434.8	57.9	0.13
7	8	June	147.3	29.8	0.20
3	60	June	106.1	19.0	0.18
7	60	June	104.4	20.4	0.20

1 Values were averaged over 3 replicates.

Table 2. Effect of different stresses on storage modulus (G') of unheated *Russet Burbank* potato tissue (low solids content)

Stress (Nm^{-2})	Strain (%)	G' (kNm^{-2})
5.0	0.0009	576.6
6.0	0.0007	687.6
7.3	0.0015	476.0
8.9	0.0018	434.4
10.8	0.0018	586.2
13.1	0.0024	546.7
23.2	0.0040	568.3
28.1	0.0055	508.7
41.3	**0.0075**	**541.1**
50.0	**0.0091**	**545.3**
60.6	**0.0113**	**542.8**
73.4	**0.0139**	**543.9**
88.9	**0.0165**	**545.6**
107.7	0.0209	509.9
130.5	0.0263	481.4
191.6	0.0400	450.7
281.2	0.0623	380.9
412.7	0.0960	301.5
500.1	0.1188	280.6

1 Values were averaged over 3 replicates.

of potato specimens was drastically changed by the heat treatment, and therefore stresses lower than 35 Nm^{-2} were required to be applied in order to obtain a linear viscoelastic response. Indeed, Figure 11 shows that both heated and unheated samples display fairly consistent linear viscoelastic regions when subjected to different applied stresses. Therefore, in subsequent experiments G' was measured across 2 ranges of stress: 10-35 Nm^{-2} for samples pre-heated at 60°C, and 35-100 Nm^{-2} for all the other samples. The corresponding ranges of strain were 0.011-0.023 % and 0.008-0.017 %, respectively.

4.1.2 Determination of Time for Pre-Heating

Preliminary work was carried out to determine the heating time required for the tubers to reach a given target. Three big potato tubers (~200/125/65 mm) were immersed in water at 60°C, as this was the highest temperature chosen for pre-heating in subsequent tests. Figure 12 shows the time-temperature dependence in the pre-heating process. As can be seen, the temperature in the centre of the tuber increased sharply in the first 60 minutes, but tended to level off over the next 30 minutes. Therefore, for all subsequent tests the tubers were pre-heated for 90 minutes.

4.1.3 Comments

The experiment was supposed to begin in October, as soon as both *Russet* and *Shepody* potatoes were harvested. However, for different reasons, the potatoes did not arrive from Manitoba until late November. In an attempt at starting the experiment on schedule, *Russet Burbank* potatoes from British Columbia (BC) were bought from the market and analyzed in October and November. Then the results from the tests performed

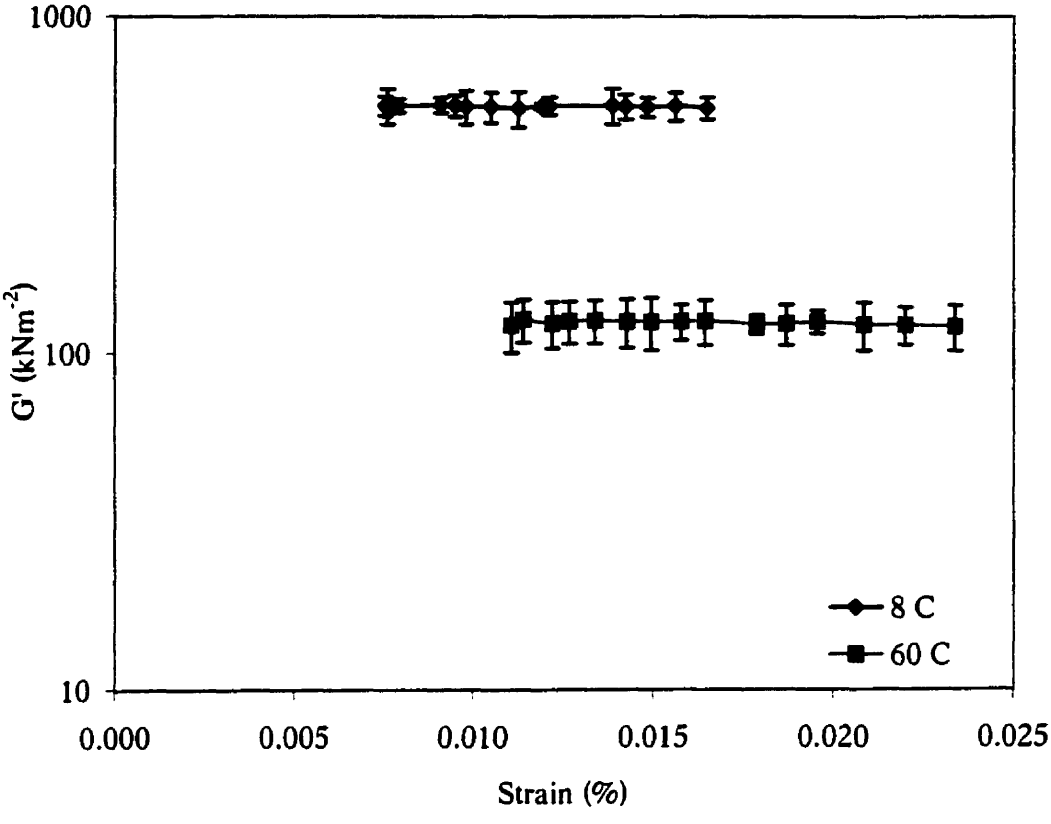

Figure 11. Effect of oscillatory shear strain on the storage modulus (G') of new *Russet Burbank* potatoes (low solids content) stored at 8°C and pre-heated at 60°C (Error bars refer to the standard deviation of the 3 replicates)

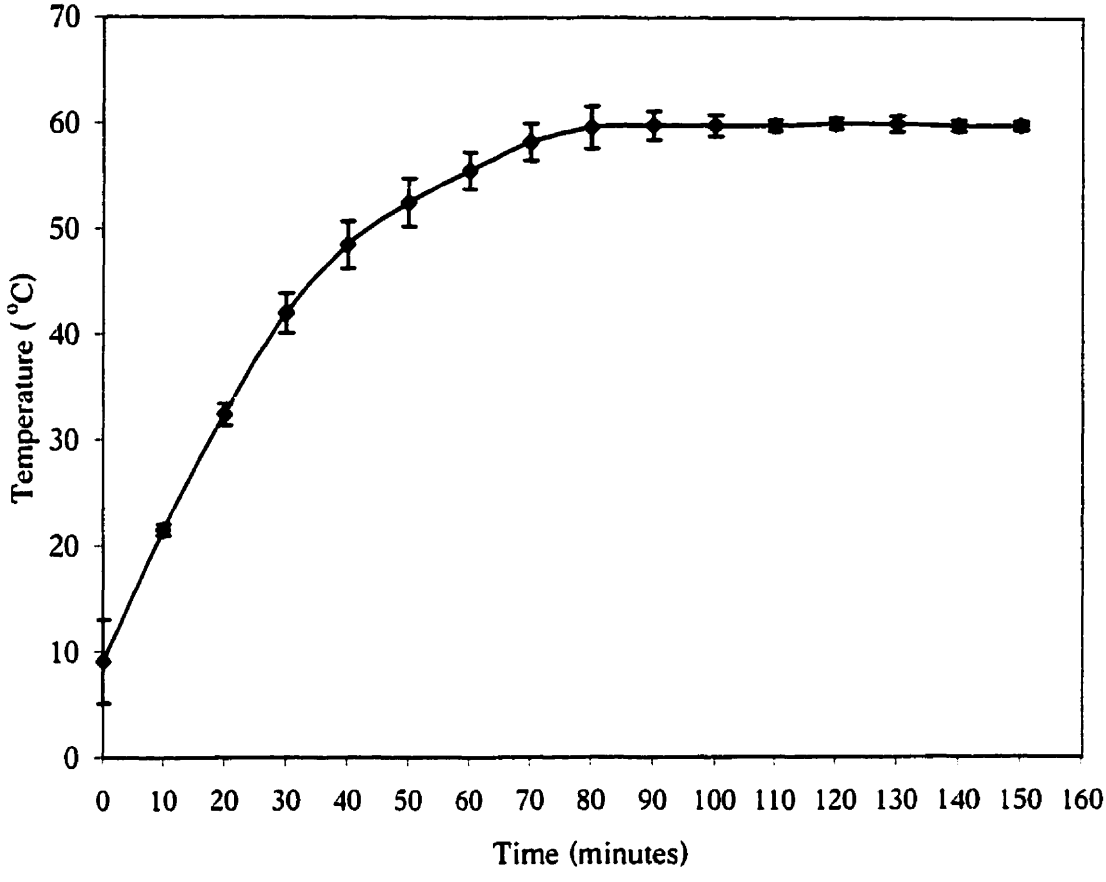

Figure 12. Time-temperature dependence in the process of potato pre-heating (Error bars refer to the standard deviation of the 3 replicates)

in November on Manitoba and BC potatoes were compared. Statistical analysis showed that most of the parameters of interest were not significantly different for the two locations (Appendix 1). However, because of the significant difference in strength, the results obtained in October were not included in subsequent statistical analyses.

4.2 Specific Gravity

Specific gravity was measured every month using the 'weigh in air/ weigh in water' method and the results were plotted against time. Trend-lines in Figures 13 and 14 show that specific gravity slightly increased over time for both *Russet* and *Shepody* potatoes, indicating a slight increase in percentage solids in the tubers (Terman *et al.*, 1950). This increase was considered to be due to a greater loss of water by evaporation in comparison to loss of solids by respiration (Smith, 1967). *Russet* potatoes had a higher specific gravity than *Shepody* potatoes, but the difference was not significant. This was in agreement with the results reported by Young *et al.* (1983).

The review of literature showed that the change in specific gravity over time is strongly related to the storage conditions (relative humidity (RH) and temperature). It has been reported that potatoes stored at temperatures of 40-50°F (4.4-10°C) and RH of 83-84 % increased in specific gravity (Heinze *et al.*, 1952). Increasing the RH to 90 % in the same temperature range caused specific gravity to remain unchanged over time. On the other hand, a slight decrease in specific gravity of commercially stored potatoes with time has been reported by Mazza (1983). Since the potatoes used in this research work were stored at temperatures of 7.5±1°C and RH of 80-90 %, it can be concluded that the results obtained were generally in agreement with results reported in the literature.

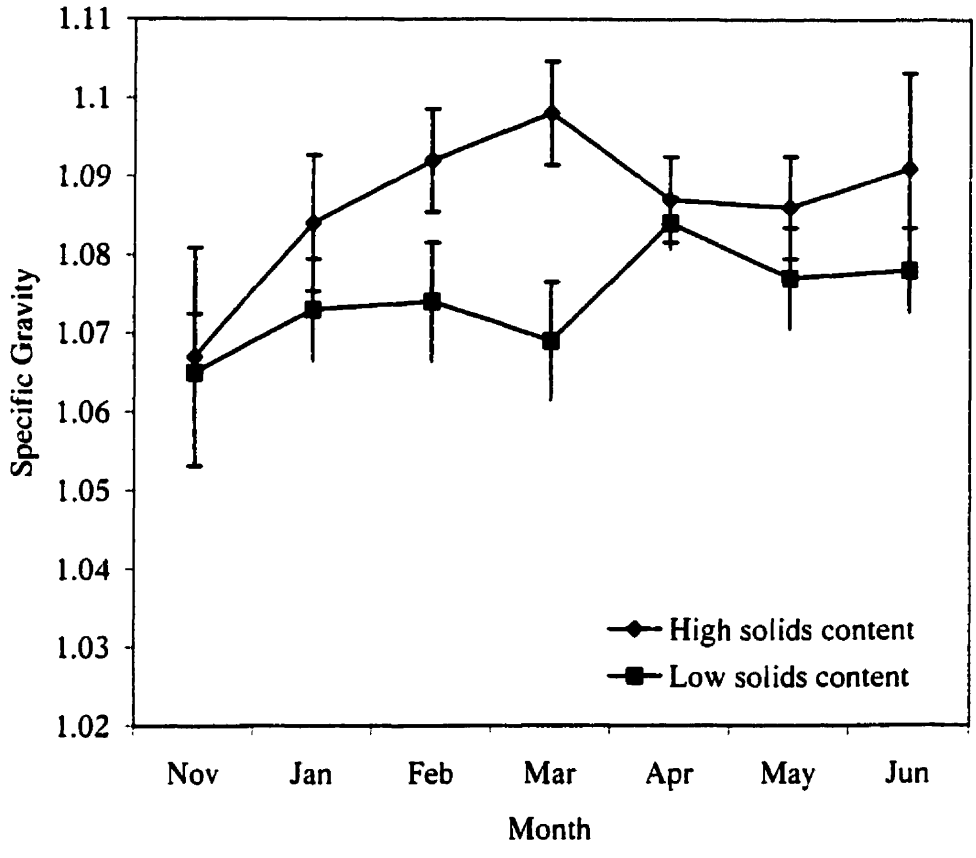

Figure 13. Variation of specific gravity with time for *Russet Burbank* potatoes (High = *Russet* potatoes with high solids content; Low = *Russet* potatoes with low solids content) (Error bars refer to the standard deviation of the 10 replicates)

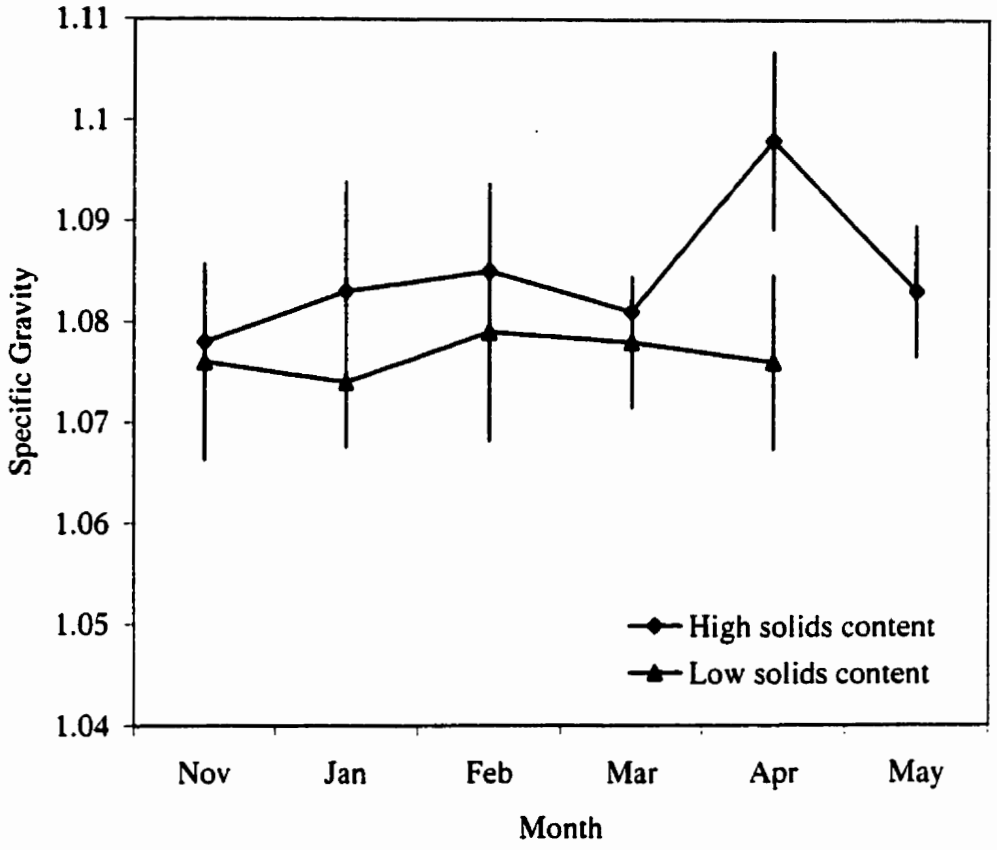

Figure 14. Variation of specific gravity with time for *Shepody* potatoes (High = *Shepody* potatoes with high solids content; Low = *Shepody* potatoes with low solids content) (Error bars refer to the standard deviation of the 10 replicates)

4.3 Turgor Pressure

Changes in turgor pressure over time are believed to be due to respiration and transpiration, the two physiological processes which take place in potato parenchyma during storage (Schippers, 1976; Brusewitz *et al.*, 1989). Stress relaxation in the cell walls is also known to influence turgor pressure of stored potatoes (Brusewitz *et al.*, 1989). During the present experiment turgor pressure was measured every month for both cultivars, both specific gravities and all three mannitol concentrations. The trend-lines in Figures 15 to 18 show a slight decrease in turgor pressure over time. This behavior may be due to a higher rate of transpiration and a lower rate of respiration during storage, which is in agreement with the slight increase in specific gravity reported in the previous section. The structural disruption of the cellular membranes of the potato cells during storage (Turnbull and Cobb, 1992) also caused turgor pressure to decrease.

4.4 Small Strain Oscillatory Shear Test

Statistical analysis revealed that storage modulus (G') was affected by pre-heating temperature, mannitol concentration and storage time (Appendix 2). Also, a number of interactions at the 0.05 level were observed for G' (Appendix 3). For both *Russet* and *Shepody* potatoes, unheated (8°C) or pre-heated at 33 or 47°C, G' decreased as mannitol concentration increased. However, for samples pre-heated at 60°C, mannitol concentration had no effect on G' (Figure 19). This differentiated effect of mannitol concentration on G' depending upon the pre-heating temperature of the tubers, explains the mannitol*temperature interaction indicated in Appendix 3. For all mannitol concentrations, as pre-heating temperature increased from 8°C to 47°C there was no

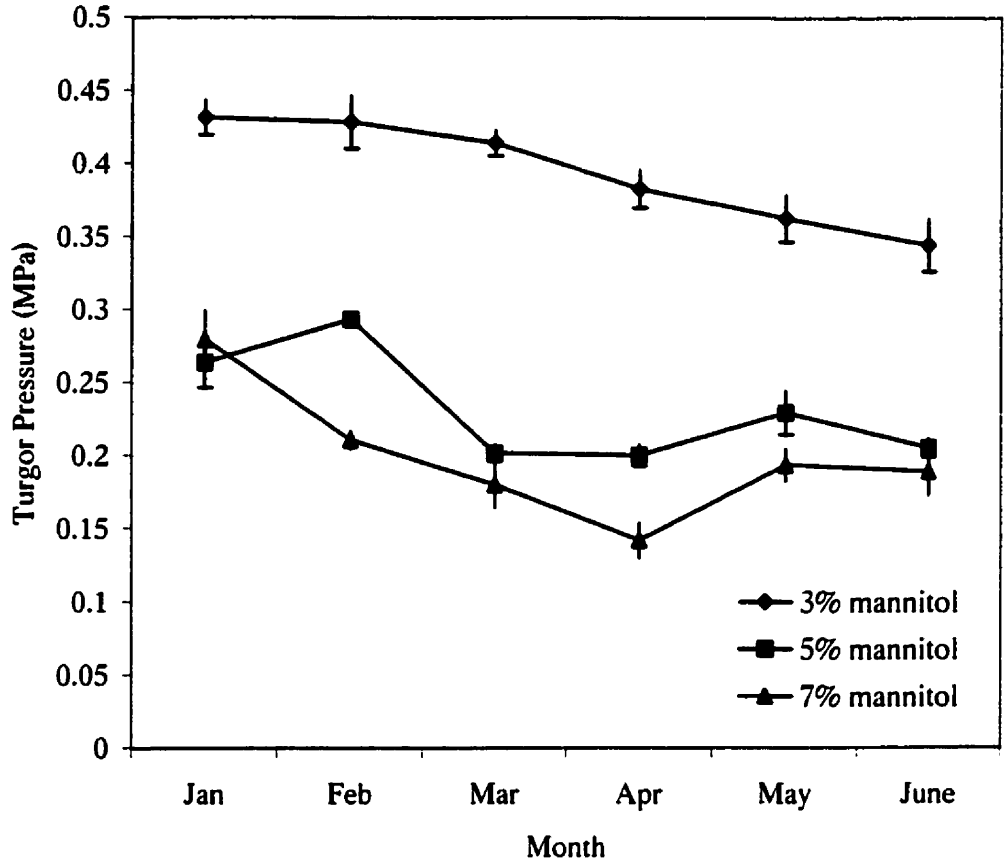

Figure 15. Changes in turgor pressure over time for high solids content *Russet Burbank* potatoes soaked in mannitol solutions of different concentrations (Values were obtained for unheated potato tubers (8° C) Error bars refer to the standard deviation of the 3 replicates).

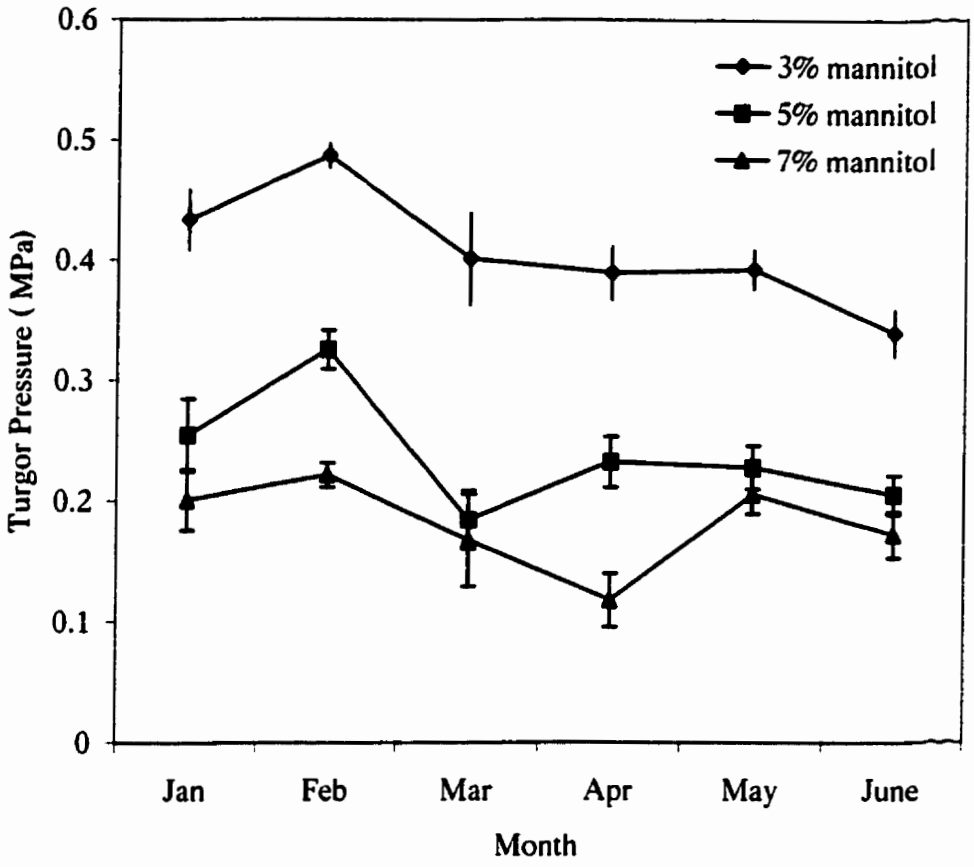

Figure 16. Changes in turgor pressure over time for low solids content *Russet Burbank* potatoes soaked in mannitol solutions of different concentrations (Values were obtained for unheated potato tubers (8°C); Error bars refer to the standard deviation of the 3 replicates).

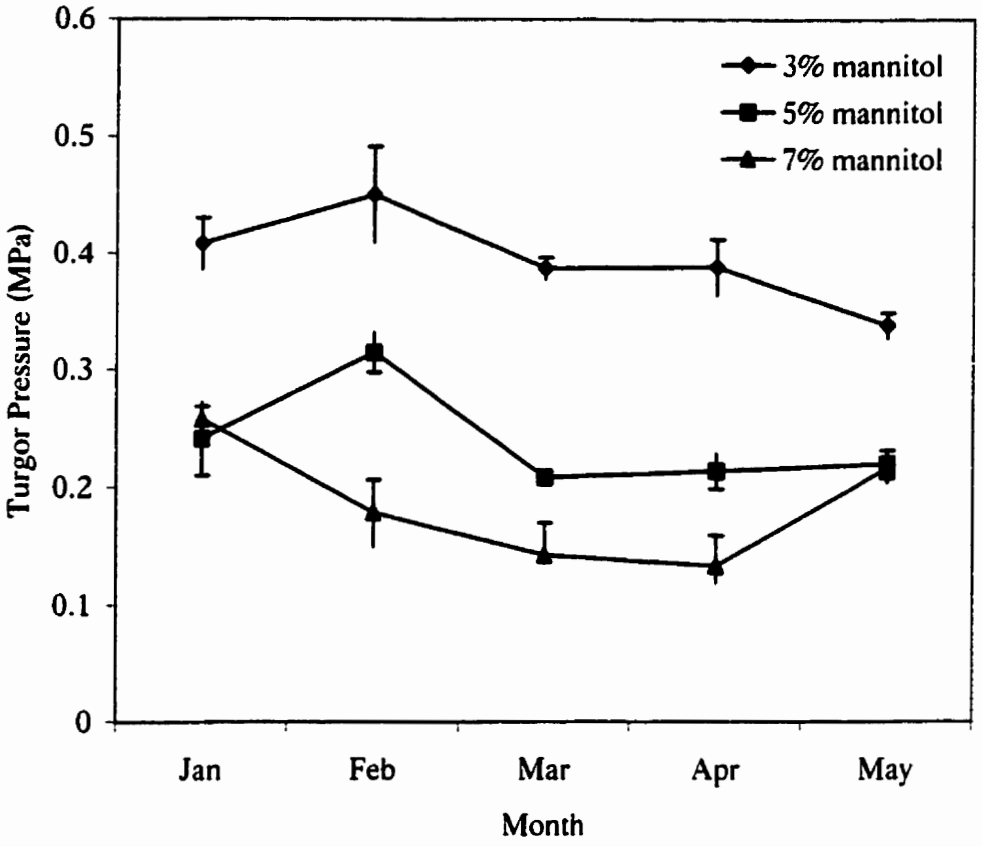

Figure 17. Changes in turgor pressure over time for high solids content *Shepody* potatoes soaked in mannitol solutions of different concentrations (Values were obtained for unheated potato tubers (8°C); Error bars refer to the standard deviation of the 3 replicates).

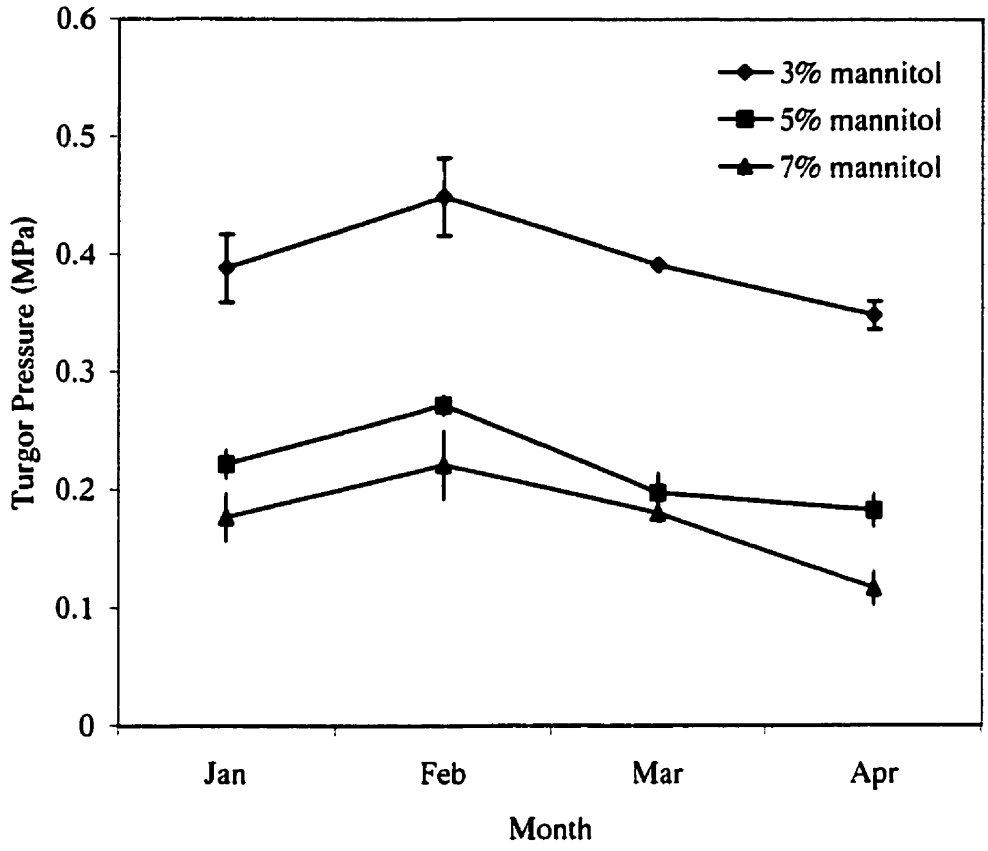

Figure 18. Changes in turgor pressure over time for low solids content *Shepody* potatoes soaked in mannitol solutions of different concentrations (Values were obtained for unheated potato tubers (8°C); Error bars refer to the standard deviation of the 3 replicates).

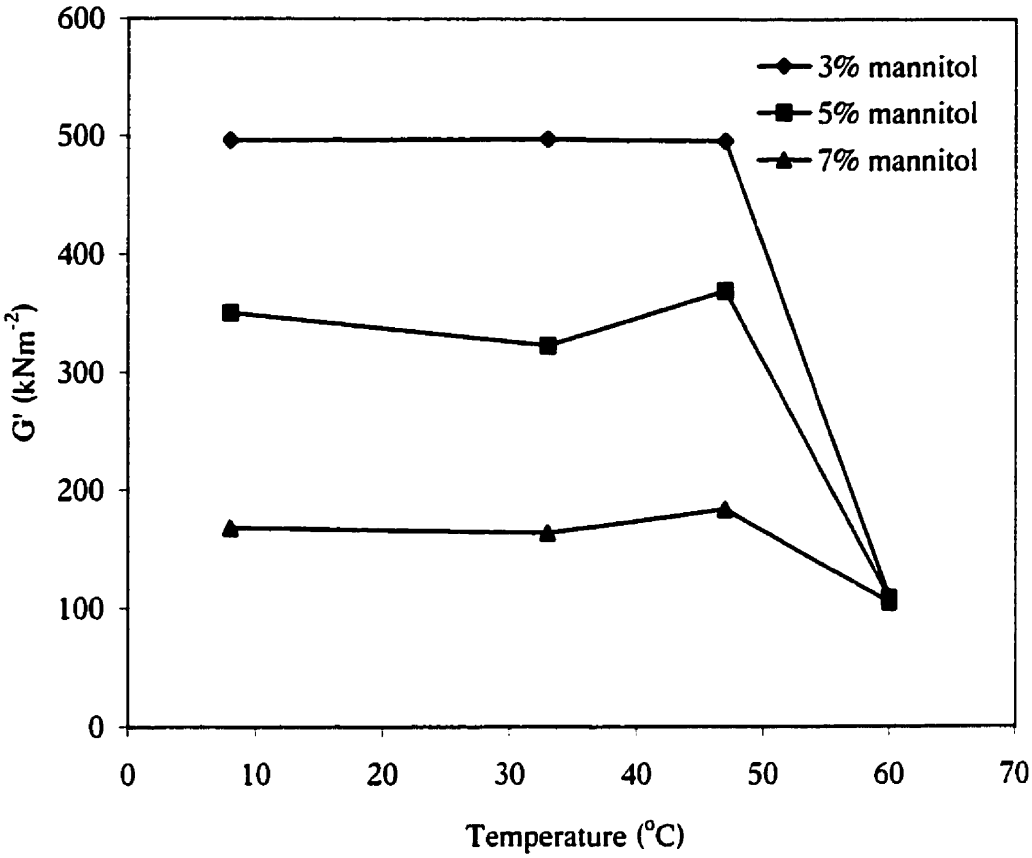

Figure 19. Effect of tuber pre-heating temperature and mannitol concentration on storage modulus (G') (Values were averaged over 3 replicates * 2 cultivars * 2 solids contents * 8 months storage).

change in G'. When the pre-heating temperature was higher (60°C), G' dropped sharply especially for samples soaked in 3% and 5% mannitol solutions. For hypertonic treated samples, the decrease in G' was not as drastic.

Solids content did not have any effect on G' for *Russet* potatoes, but for *Shepody* potatoes G' increased as solids content increased (Figure 20). This behaviour explains the cultivar*solids content interaction which was seen as an overall result.

Over 8 month of storage (November to June) G' did not change markedly with mannitol concentration either for *Russet* or for *Shepody* potatoes. However, the 3-way interaction month*mannitol*cultivar (Appendix 3) may be attributed to the slight decrease in G' seen in the last month of storage for both *Russet* and *Shepody* potatoes (Figures 21a and 21b). Figure 22 confirms the above mentioned pattern of G' for samples at 8, 33 and 47°C; for samples pre-heated at 60°C, G' remained rather constant during the whole storage period (month*temperature interaction). It should be noted however, that the actual values for G' at 60°C were much smaller than those obtained for lower temperatures.

Generally, the actual values obtained for storage modulus every month were in the range 105-500 kNm^{-2}, depending on both mannitol and heat treatments. These results agreed with those reported by Pang (1995) and Scanlon *et al.* (1996).

4.5 Wedge Test

Statistical analysis revealed that toughness was affected by temperature, mannitol concentration and storage time (Appendix 2). An interaction significant at the 0.05 level also occurred (Appendix 3).

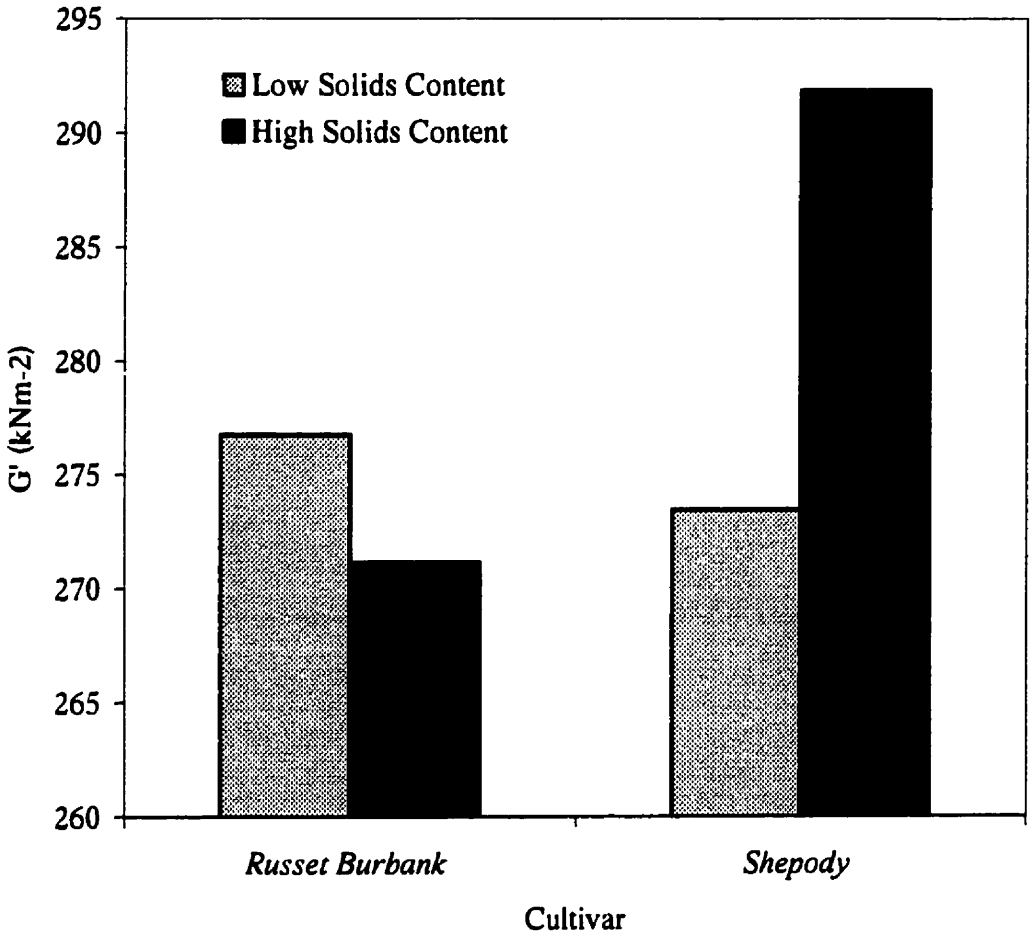

Figure 20. Effect of cultivar and solids content on storage modulus (G') (Values were averaged over 3 replicates * 3 mannitol concentrations * 4 temperatures * 8 months storage).

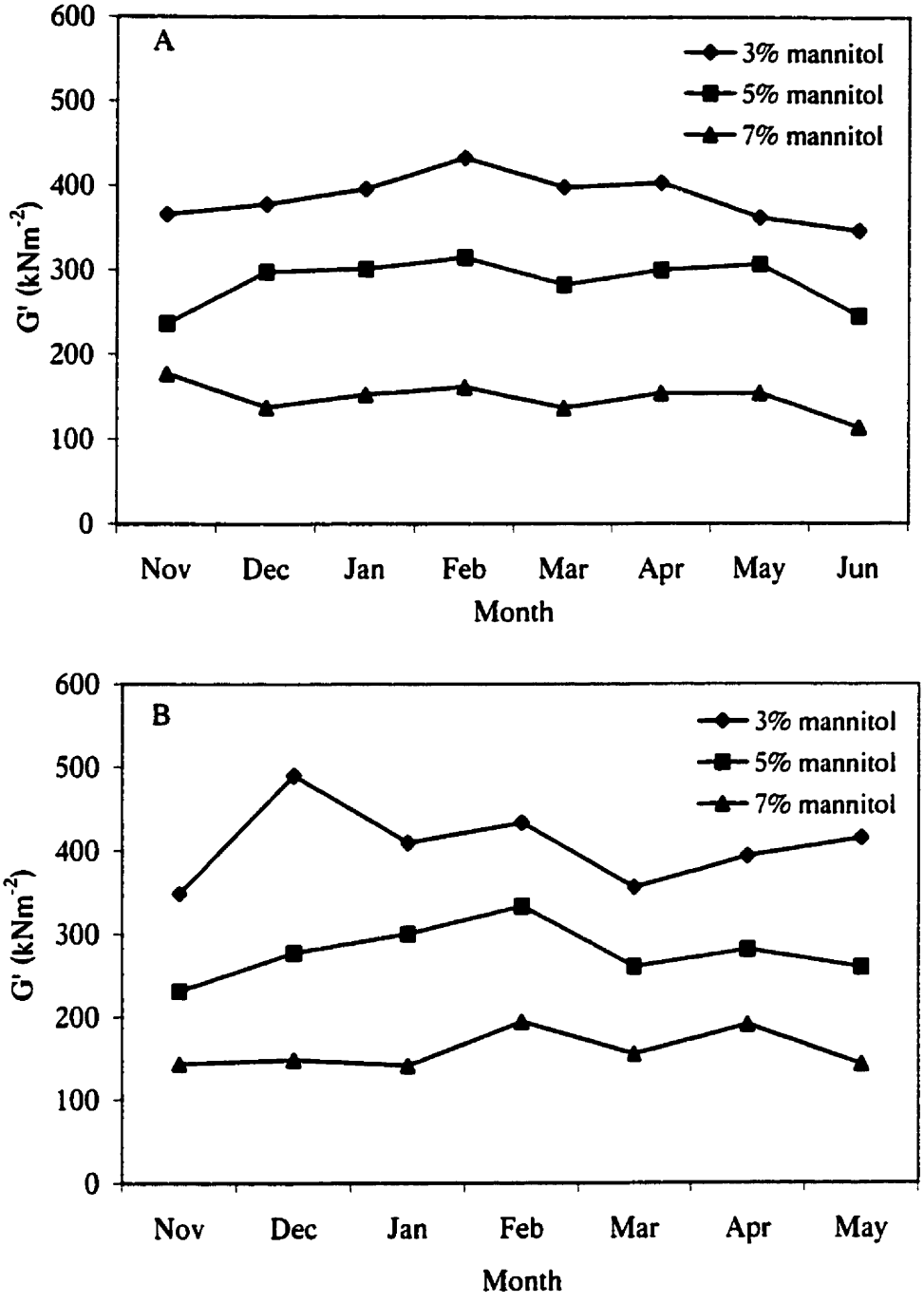

Figure 21. Effect of mannitol concentration and storage time on storage modulus (G') for *Russet Burbank* (A) and *Shepody* (B) potatoes (Values were averaged over 3 replicates * 2 solids contents * 4 temperatures).

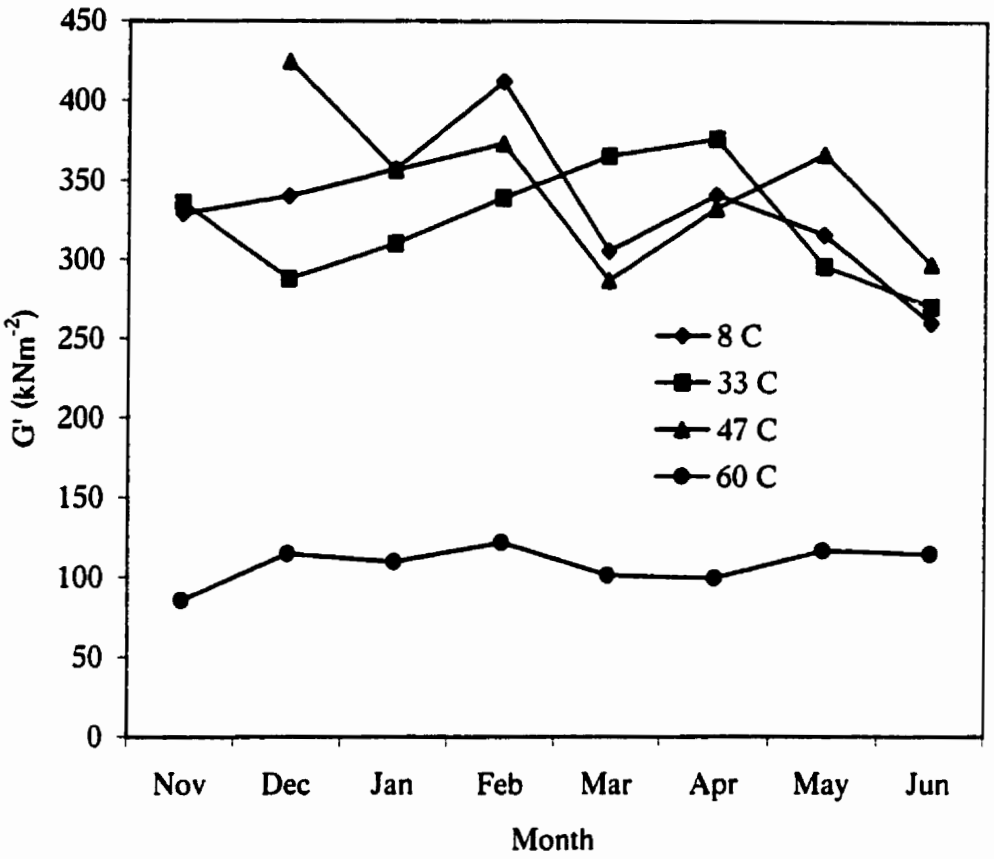

Figure 22. Effect of tuber pre-heating temperature and storage time on storage modulus (G') (Values were averaged over 3 replicates * 2 cultivars * 2 solids contents * 3 mannitol concentrations).

For samples pre-heated at 8, 33 and 47°C toughness declined with the increase in mannitol concentration (Figure 23). For higher pre-heating temperatures (60°C) mannitol concentration had no effect on toughness. When the samples were soaked in 3% and 5% mannitol solutions, toughness slightly decreased as pre-heating temperature increased. The decrease was more accentuated in specimens pre-heated at 60°C, and less visible for those pre-heated at lower temperatures. For samples soaked in 7% mannitol solutions, toughness remained almost constant for all pre-heating temperatures.

Although Appendix 3 indicates that there were interactions involving solids and cultivar, neither specific gravity nor cultivar affected toughness significantly (Table 3).

Over the whole storage period toughness decreased from about 363 Jm^{-2} in November to about 247 Jm^{-2} in June (Figure 24). These values were slightly lower than those reported by Hiller *et al.* (1996) and Vincent (1990), but were definitely in agreement with Schoorl and Holt (1983) who suggested that potatoes posses a fracture toughness less than 10^{4} Jm^{-2}. The values obtained for toughness during the present wedge test were of the same order of magnitude as those reported by Fahloul and Scanlon (1996) in a tensile test. Hiller and Jeronimidis (1996) obtained much lower values for toughness of potato tuber parenchyma. A possible reason for this difference may be due to a different way of calculating the fracture energy from the total area beneath the force/deflection curve (Hiller and Jeronimidis, 1996). It may also be worthy to mention that the results obtained during the present wedge test were averaged over temperature and mannitol, including 60°C and 7% concentration, which lowered the toughness values from those obtained by others.

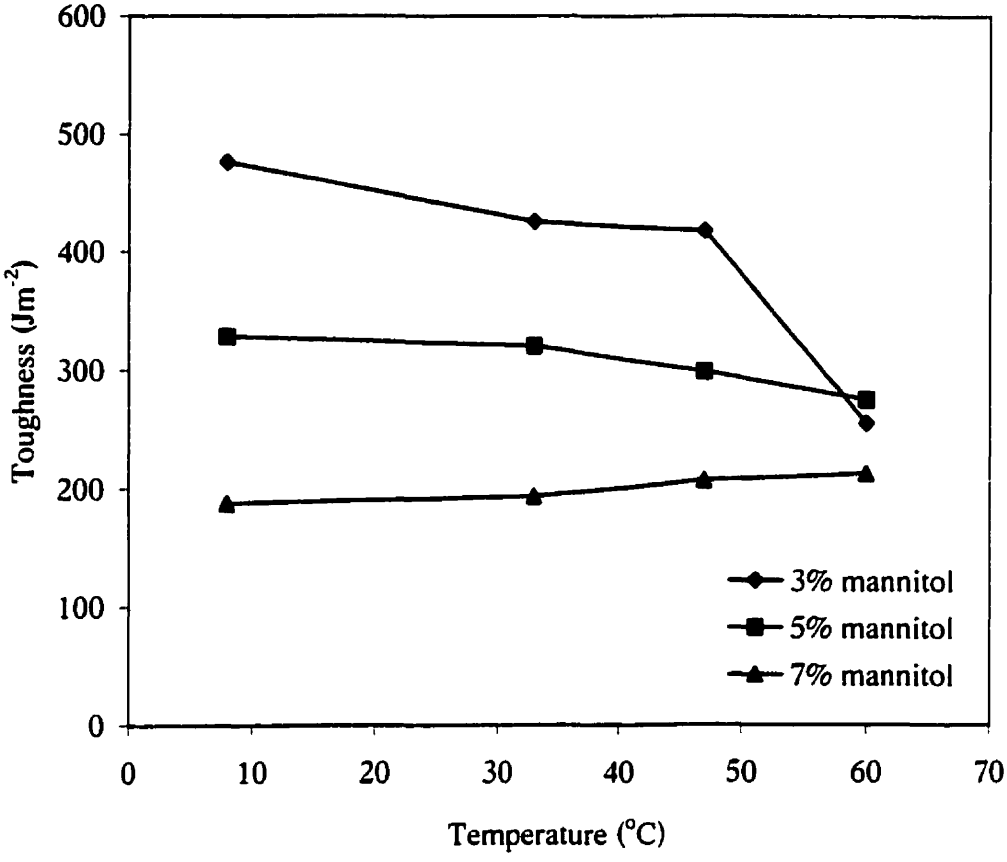

Figure 23. Effect of tuber pre-heating temperature and mannitol concentration on toughness (Values were averaged over 3 replicates * 2 cultivars * 2 solids contents * 8 months storage).

Table 3. Effect of cultivar and specific gravity on toughness and strength

Mechanical Parameter	Cultivar[1]		Specific Gravity[2]	
	Russet Burbank	*Shepody*	Low	High
Toughness (Jm^{-2})	296.5	317.2	296.0	314.8
Strength[3] (kNm^{-2})	143.3[a]	131.8[b]	137.7	138.5

[1] Values were averaged over 3 replicates * 3 mannitol concentrations * 4 temperatures * 2 solids contents * 8 months storage.

[2] Values were averaged over 3 replicates * 3 mannitol concentrations * 4 temperatures * 2 cultivars * 8 months storage.

[3] Values followed by different letters are significantly different at 0.05 level.

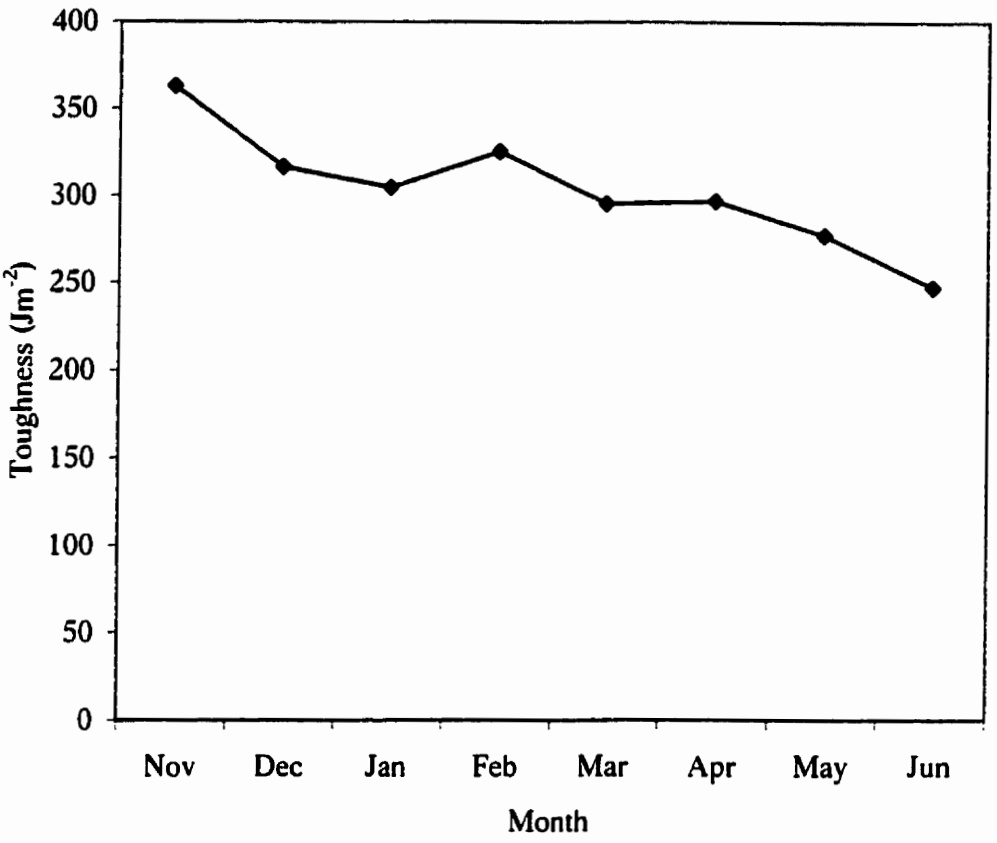

Figure 24. Effect of storage time on toughness (Values were averaged over 3 replicates * 2 cultivars * 3 mannitol concentrations * 4 temperatures).

Two types of feathering were noticed during the cutting process: 'brittle' feathering and 'soft' feathering. The first one appeared for samples pre-heated at 33 and 47°C or unheated, while the other appeared for the samples pre-heated at 60°C. Statistical analysis showed that temperature, mannitol concentration, solids content, variety and storage time affected feathering (see Appendix 3 for the significant interactions between the main effects).

At 8, 33 and 47°C feathering declined as mannitol concentration increased, but for pre-heating at 60°C mannitol concentration had no effect on feathering (Figure 25). An increase in pre-heating temperature up to 47°C did not affect feathering at a given mannitol concentration, but at the higher temperature feathering increased. Solids content made no significant difference to the amount of feathering for *Russet* potatoes, but for *Shepody* potatoes feathering decreased as solids content increased (Figure 26).

Over time, feathering did not show any particular trend under 8°C storage or when pre-heating up to 47°C (Figure 27), but for pre-heating at 60°C it decreased markedly. It may be worth mentioning that every month the actual values of feathering at 60°C were higher than those obtained at lower temperature.

4.6. **Tensile Test**

Statistical analysis revealed for both stiffness and strength a number of 2 way and 3 way interactions between the significant main effects: temperature, mannitol concentration, solids content, cultivar and storage time (Appendices 2 and 3). For unheated samples (8°C), as well as for samples pre-heated at 33 and 47°C, stiffness and strength decreased as mannitol concentration increased (Figures 28 and 29). For samples

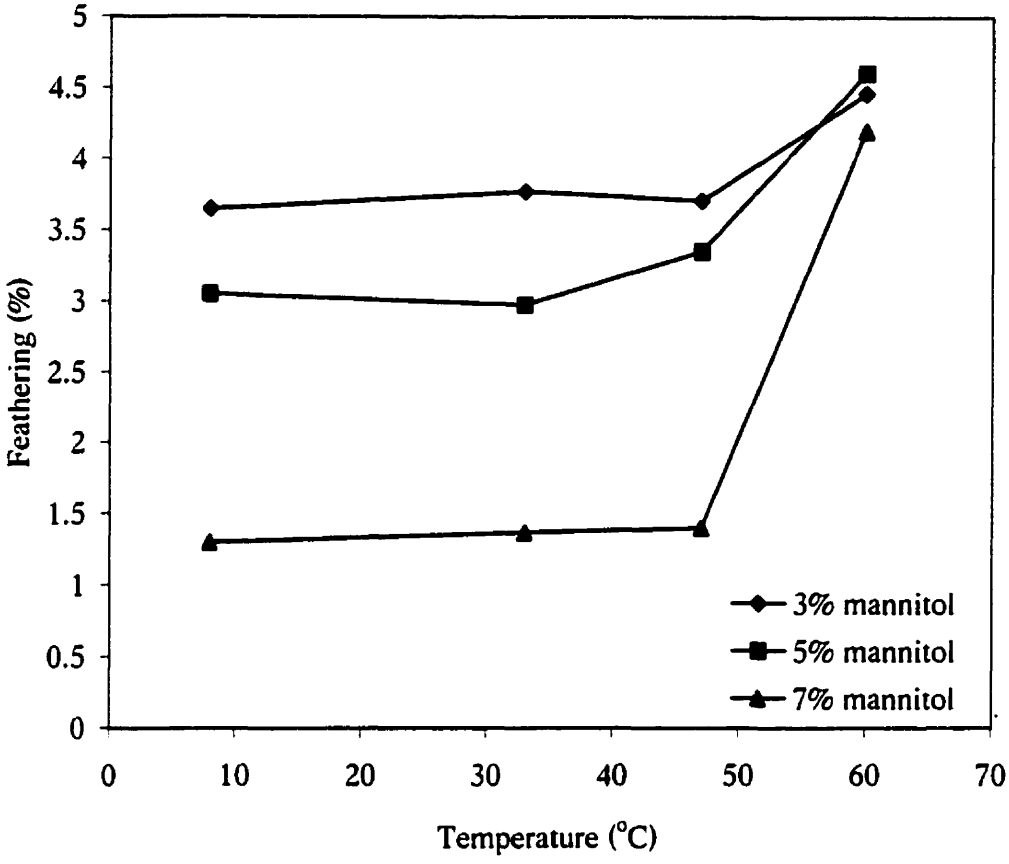

Figure 25. Effect of tuber pre-heating temperature and mannitol concentration on the amount of feathering (% of total new crack surface area) (Values were averaged over 3 replicates * 2 cultivars * 2 solids contents * 8 months storage).

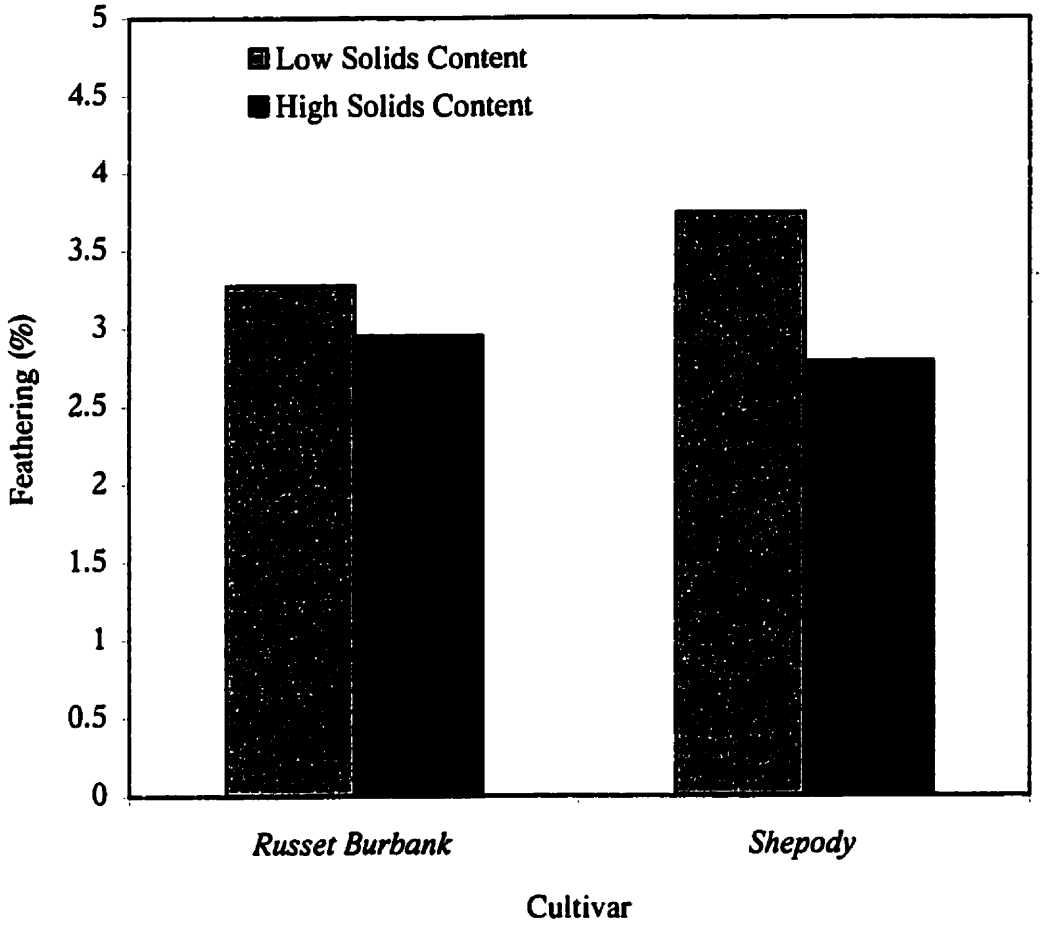

Figure 26. Effect of cultivar and solids content on the amount of feathering (% of total new new surface area) (Values were averaged over 3 replicates * 3 mannitol concentrations * 4 temperatures * 8 months storage).

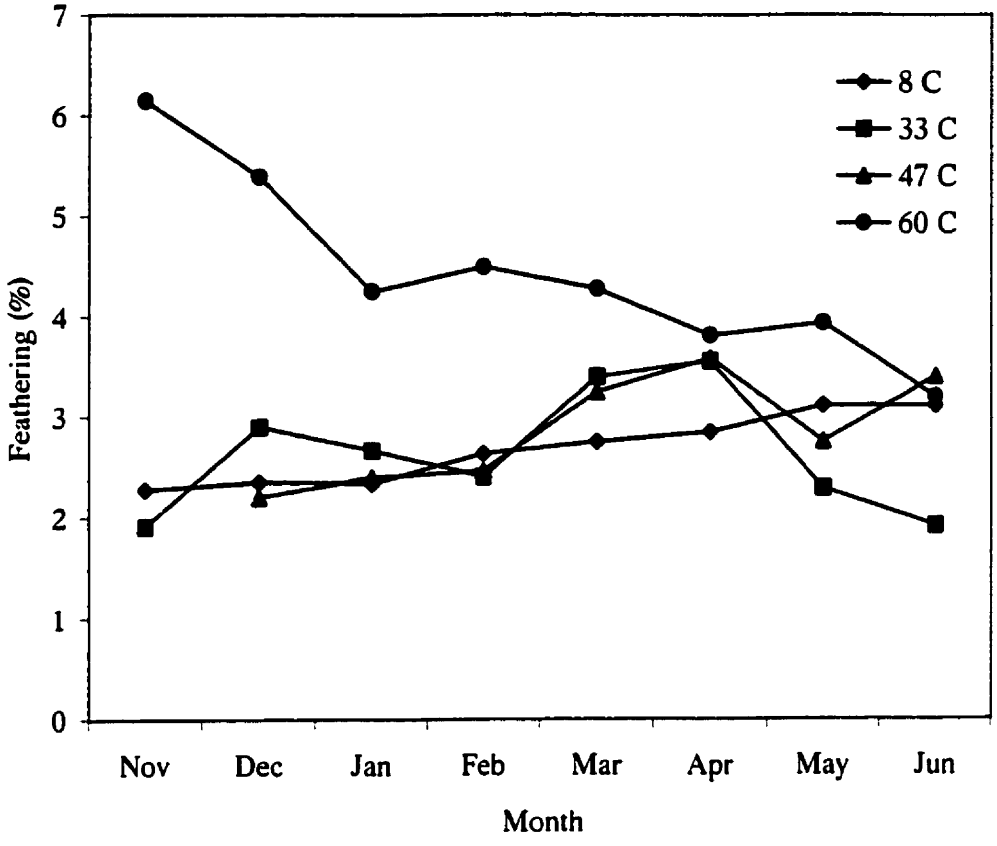

Figure 27. Effect of tuber pre-heating temperature and storage time on the amount of feathering (% of total new crack surface area) (Values were averaged over 3 replicates * 2 cultivars * 2 solids contents * 3 mannitol concentrations).

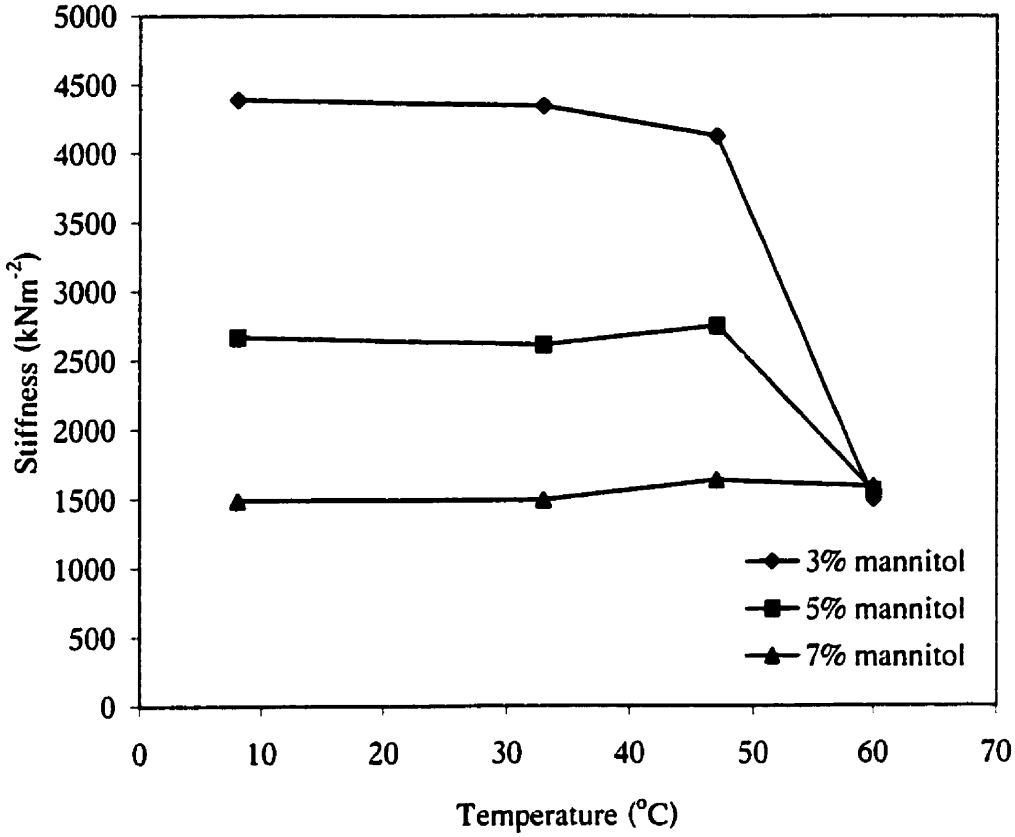

Figure 28. Effect of tuber pre-heating temperature and mannitol concentration on stiffness (Values were averaged over 3 replicates * 2 cultivars * 2 solids contents * 8 months storage).

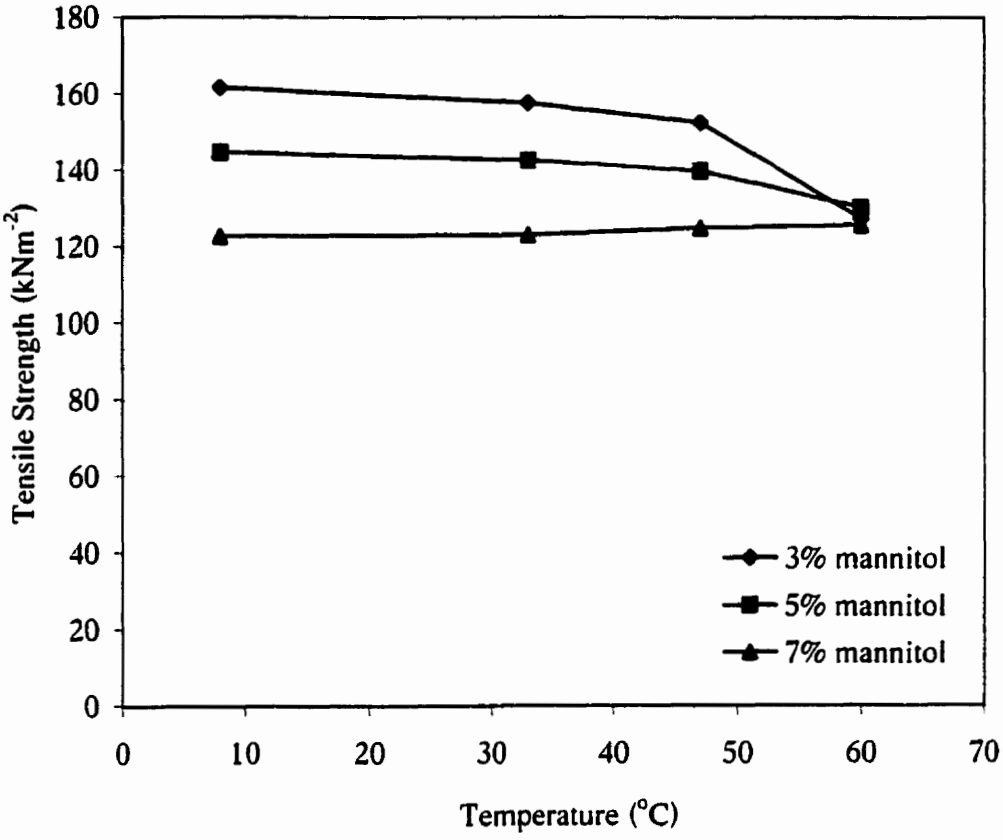

Figure 29. Effect of tuber pre-heating temperature and mannitol concentration on tensile strength (Values were averaged over 3 replicates * 2 cultivars * 2 solids contents * 8 months storage).

pre-heated at 60°C, neither stiffness nor strength were affected by mannitol concentration. For samples soaked in 3% and 5% mannitol solutions both stiffness and strength remained almost constant as pre-heating temperature increased from 8°C to 47° C. For 7% mannitol concentration both stiffness and strength remained almost unchanged for the whole heating range. The actual value of stiffness was higher for *Russet* potatoes than for *Shepody* potatoes, for both high and low solids contents, at all temperatures (Figures 30a and 30b). For samples pre-heated up to 47°C, stiffness was higher for lower solids content (Figure 31). For samples pre-heated at 60°C, solids content had no effect on stiffness. Both these results were surprising since potato tubers with high solids content have been found to be firmer after cooking than those with low solids content (Sharma *et al.*, 1959).

Strength was not significantly affected by solids content (Table 3). However, *Russet* potatoes were shown to be significantly stronger than *Shepody* ones (Table 3).

Over time, stiffness did not show any particular trend (Figure 32), but it should be noted that the values obtained at 8, 33 and 47°C were higher than those at 60°C. Strength increased from January to June, after a slight decrease in the first two months (Figure 33).

The actual values obtained for stiffness lay in the same range as those reported by Alvarez and Canet (1998). For strength however, the results obtained during the present tensile test were lower than those reported by Scanlon and Long (1995). This may be due to differences between experimental settings, but also to the fact that the strength values were calculated on the basis of having a crack cut into the samples.

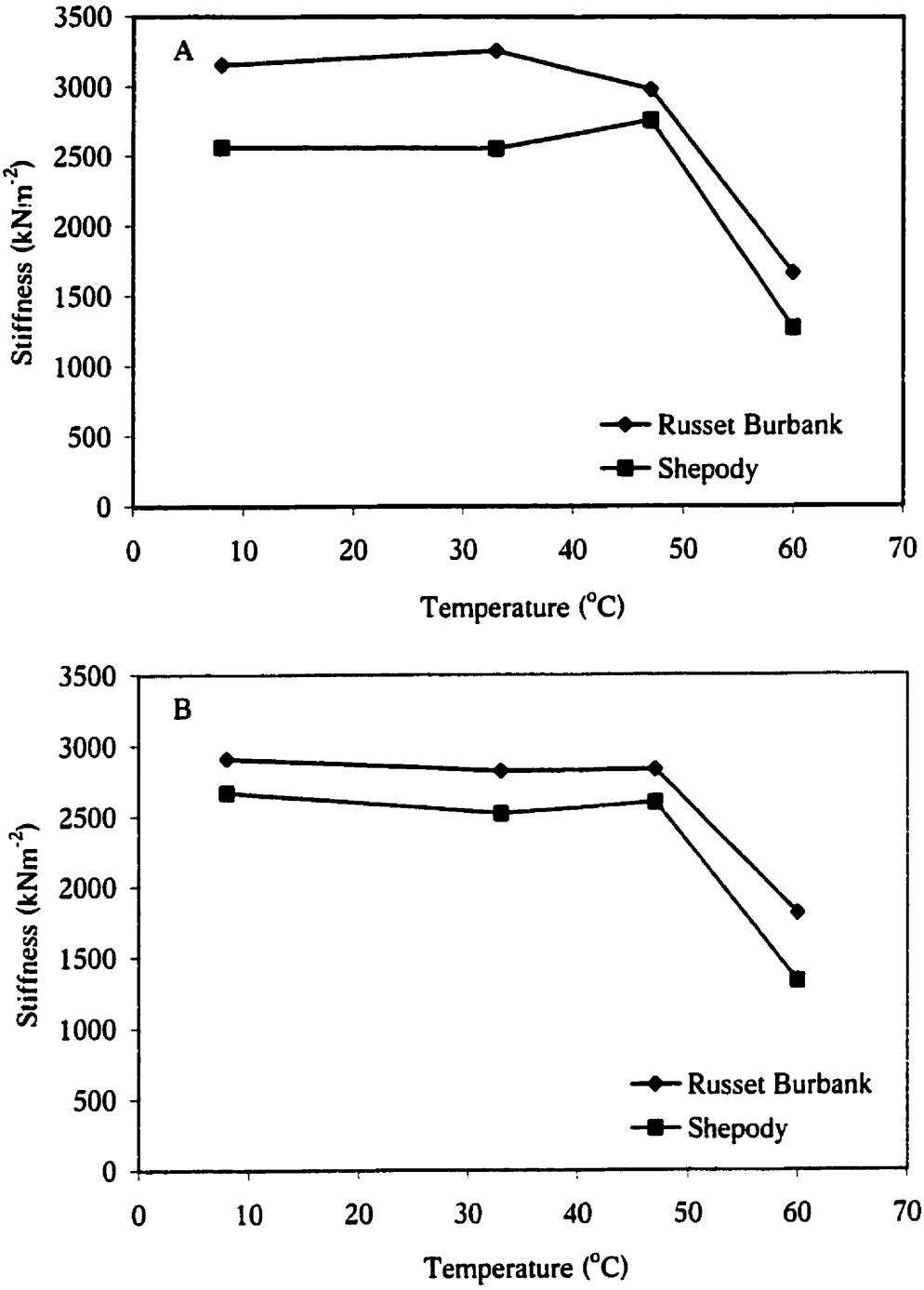

Figure 30. Effect of tuber pre-heating temperature and cultivar on stiffness for potatoes with low (A) and high (B) solids content (Values were averaged over 3 replicates * 3 mannitol concentrations * 8 months storage).

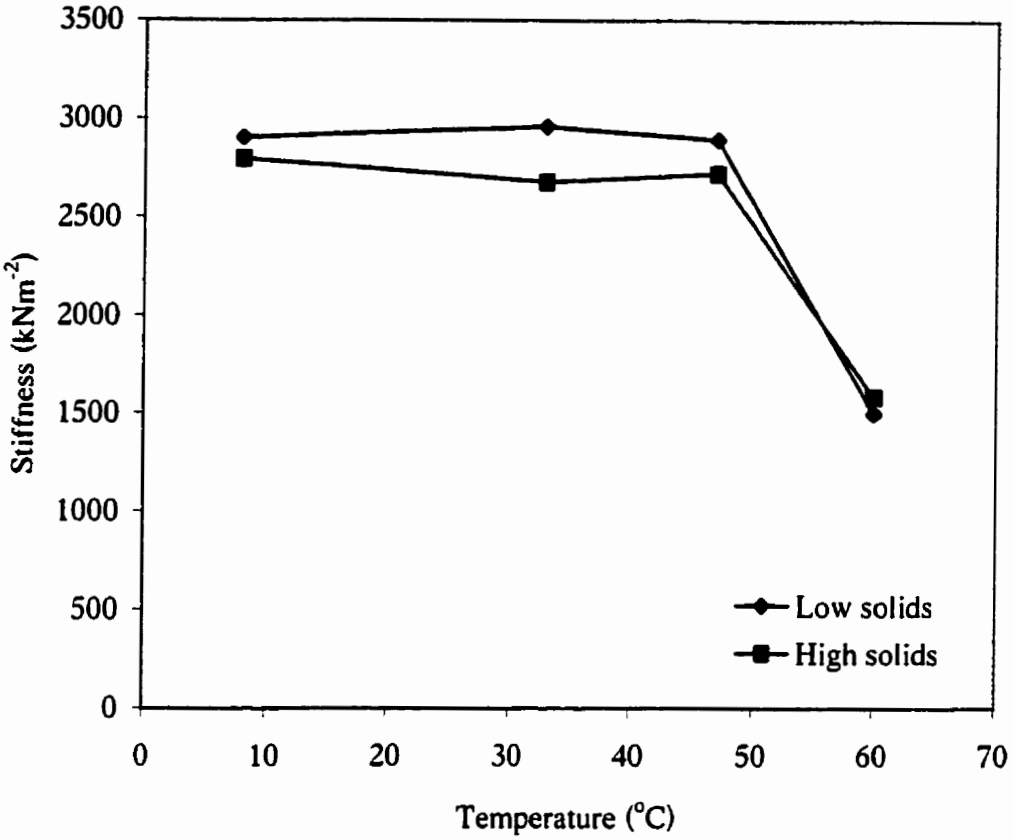

Figure 31. Effect of tuber pre-heating temperature and solids content on stiffness (Values were averaged over 3 replicates * 2 cultivars * 3 mannitol concentrations * 8 months storage).

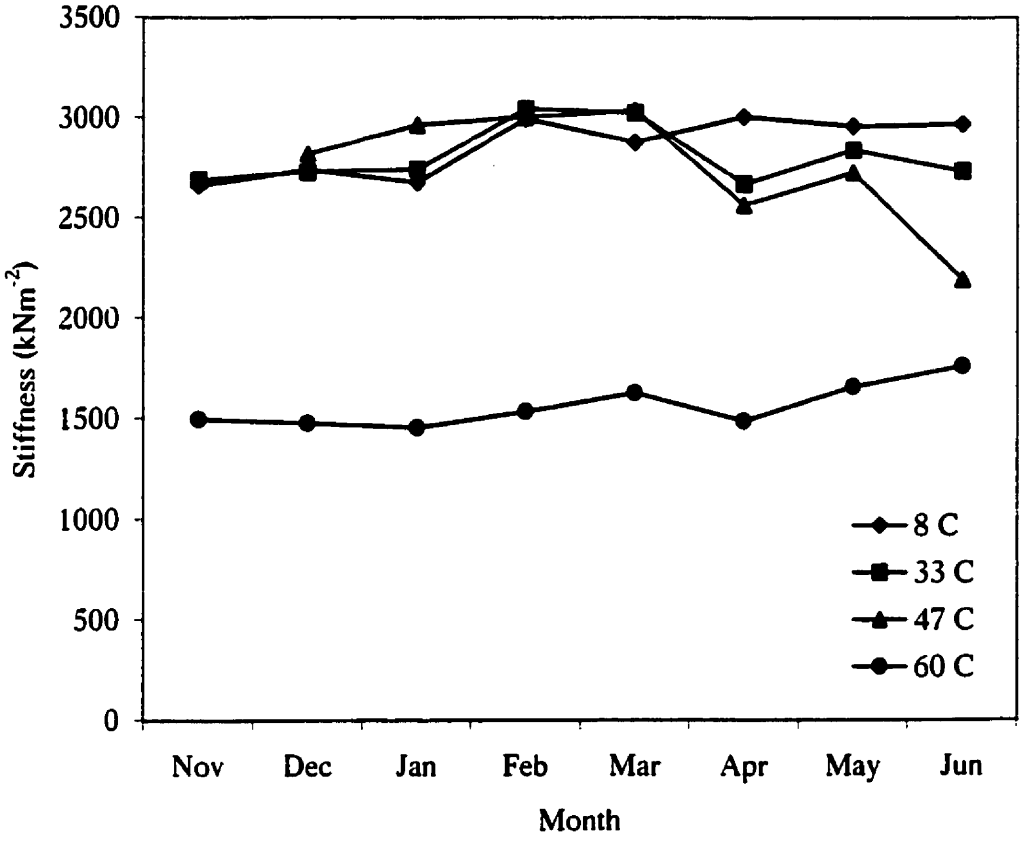

Figure 32. Effect of tuber pre-heating temperature and storage time on stiffness (Values were averaged over 3 replicates * 2 cultivars * 2 solids contents * 3 mannitol concentrations).

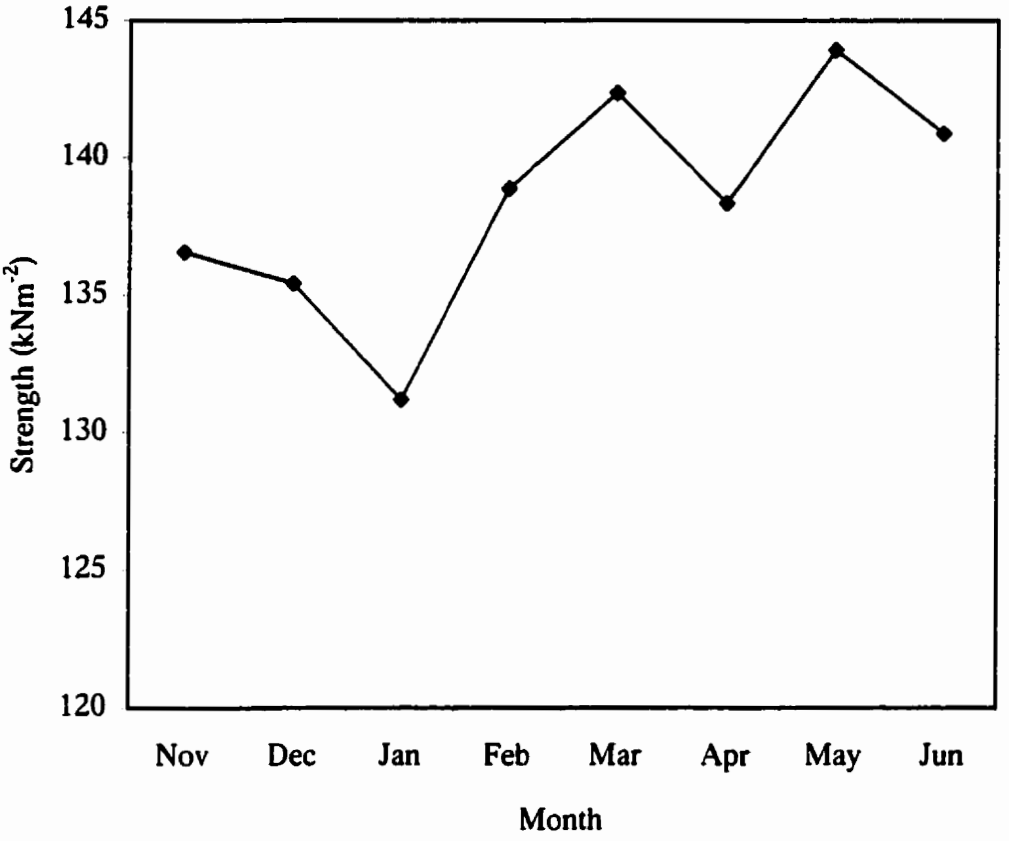

Figure 33. Effect of storage time on strength (Values were averaged over 3 replicates * 2 cultivars * 3 mannitol concentrations * 4 temperatures).

5. GENERAL DISCUSSION

5.1 Inter-Relationship of Various Mechanical Properties in Potatoes

The manner in which the tuber can be reduced in size during the slicing operation is strongly affected by the mechanical properties of potato parenchyma. In the present work, mechanical properties were investigated by studying dynamic shear storage modulus (G'), toughness (work of fracture), stiffness (Young's modulus) and fracture stress (strength). The relationship between these parameters was analyzed in order to see if the size reduction of the tuber could be viewed as a brittle fracture phenomenon, and if the pre-heating treatment (which is commonly employed in potato processing plants) would affect tuber brittleness.

Storage modulus of a material dictates its fracture properties, determining the ability of the material to transmit strain energy to a crack tip (Scanlon, 1997). Toughness represents the amount of energy required to create a new crack surface, while stiffness determines the amount of energy stored per unit volume under a given strain (Hiller and Jeronimidis, 1996). Fracture stress is the maximum force per unit area sustained by the specimen before failure (Huff, 1971). In an isotropic material storage modulus and stiffness are linearly related (Mohsenin, 1986). The initial hypothesis which was to be tested was that the fracture stress could be predicted by the formula below, if toughness and Young's modulus were known (Williams, 1984):

$$\sigma_{fr} = \sqrt{\frac{2ER}{\pi L_c}} * \frac{1}{Y} \qquad (13)$$

where: σ_{fr} = fracture stress (Nm^{-2})

E = Young's modulus (Nm^{-2})

R = toughness (Jm^{-2})

L_c = critical crack length (m)

Y = correction factor (dimensionless)

Y ≈ 2.826 for a 5 mm crack in a 10 mm specimen (Williams, 1984)

It should be noted that the critical crack length refers to the size of a flaw that must be obtained in the material so that the fracture can occur. The above equation holds true only for brittle materials, for which plastic yielding in the area of the tip of the crack is negligible (Hiller and Jeronimidis, 1996).

The theoretical value of fracture stress was calculated with equation (13) using the parameters obtained in the tests performed. The Young's modulus was calculated from the storage modulus obtained in the small strain oscillatory shear test. The reason for calculating the Young's modulus instead of taking it directly from the tensile test results was that all tensile tests were performed on notched specimens. For elastic, homogenous and isotropic materials the relationship between the Young's modulus and the storage modulus is given by equation (14) (Mohsenin, 1986). In reality, however, perfect elasticity, homogeneity and isotropy may not exist in any food material (potato included) (Reiner, 1960).

$$E = 2G(1 + \mu) \tag{14}$$

where E = Young's modulus (Nm^{-2})

G = Storage modulus (Nm^{-2})

μ = Poisson's ratio (dimensionless)

The value of toughness (R) used in equation (13) was that obtained from the wedge test. For the critical length (L_c) the value of the notch from the tensile test was used. The theoretical strength calculated with equation (13) was plotted against the actual strength results obtained from the tensile test. Although a set of 4 plots (one for each cultivar and for each solids content) was drawn every month, only the two extremes of storage are presented, since the plots for all eight months look similar. The treatments that gave non-brittle results, namely 7% mannitol (Hiller and Jeronimidis, 1996; Scanlon *et al.*, 1996) and 60°C pre-heating (Ramana and Taylor, 1992a), were eliminated from the brittle analysis.

Figures 34 and 35 show that most of the actual values of fracture stress were higher than the theoretical values. This difference was not unexpected since the actual stiffness obtained from the tensile test was much greater than the one derived from storage modulus. An explanation for this behaviour may be the fact that in pure shear there is no volume change and therefore the stiffness of the cellular fluids does not influence G', as it does in tensile stretching. If the initial hypothesis would have held true, than the scattered points from the charts would have fallen on the Y=X line (45° angle to the baseline). This did not happen, therefore it was concluded that equation (13) could not be used to describe accurately the relationship between the parameters of interest. However, statistical analysis revealed that correlations do exist between the various mechanical properties studied (Table 4).

Storage modulus, toughness, amount of feathering, stiffness and strength were all positively correlated to each other, but the correlation coefficients varied widely (r = 0.03

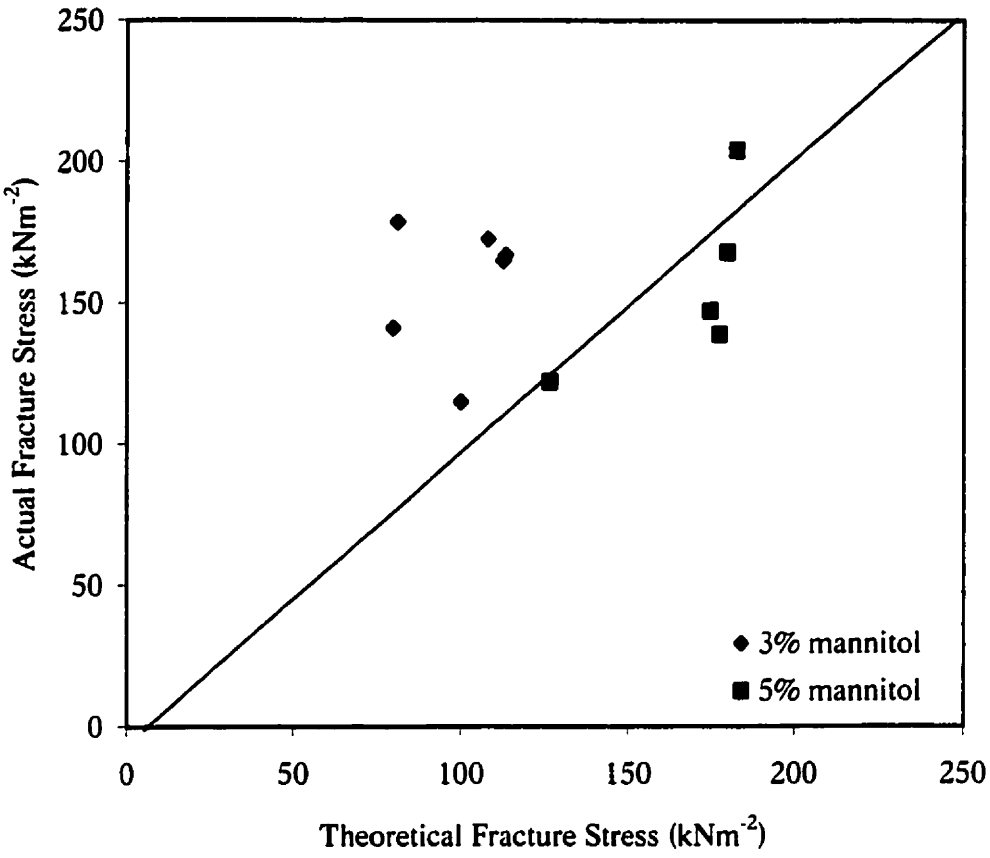

Figure 34. Actual versus theoretical fracture stress for high specific gravity *Russet Burbank* potatoes, one month old, at different mannitol concentrations.

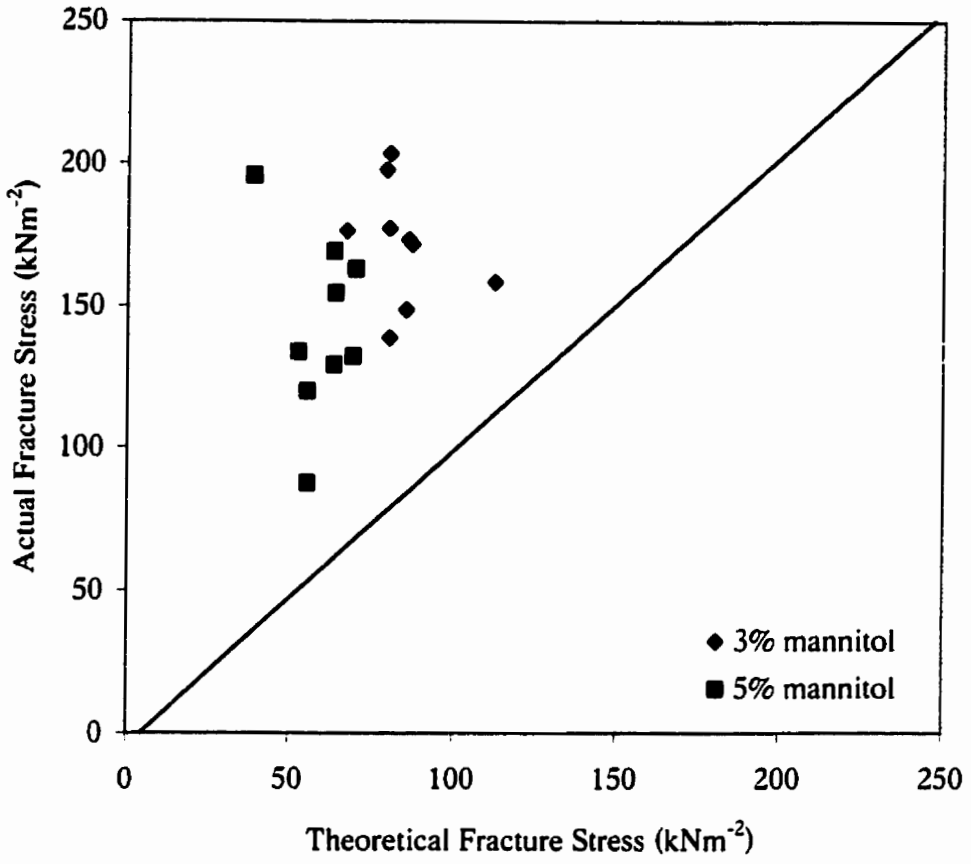

Figure 35. Actual versus theoretical fracture stress for high specific gravity *Russet Burbank* potatoes, eight months old, at different mannitol concentrations .

Table 4. Correlation coefficients among different parameters which describe the mechanical properties of potatoes

Parameter	Storage modulus	Toughness	Feathering	Stiffness	Strength
Storage modulus	1.00	0.38**	0.03	0.76**	0.42**
Toughness		1.00	0.09*	0.40**	0.22**
Feathering			1.00	0.11**	0.11**
Stiffness				1.00	0.67**
Strength					1.00

* $p<0.01$; ** $p<0.001$

to 0.76). Storage modulus was poorly correlated to toughness, feathering and strength (r = 0.003-0.42), but it was highly correlated to stiffness (r = 0.76). This was not unexpected (as can be seen from equation 14) since both stiffness and storage modulus define the elastic response capacity of a body, only measured by different methods (tension vs. shear). Toughness and feathering were not significantly correlated to each other, to stiffness or to strength (r = 0.09-0.40). However, as expected, a reasonably high correlation (r = 0.67) was found between stiffness and strength. The stiffer a material is, the higher is the stress required to cause fracture, assuming that fracture occurs at the same strain value.

In conclusion, only two significant correlations were found: one between stiffness and storage modulus and the other between stiffness and fracture stress. Feathering showed the lowest correlation coefficients (r = 0.03–0.11) in relation to all the other parameters. This was surprising, since feathering was believed to be related to storage modulus and toughness which dictate and control fracture properties. Further work would be needed to investigate the relationship which exists between the amount of feathering and other mechanical properties of potatoes.

5.2 Influence of Temperature and Turgor Pressure on Mechanical Properties

The effect of temperature and turgor pressure on storage modulus, toughness, stiffness and strength are shown in Figures 19, 23, 28 and 29, respectively. Both temperature and turgor pressure (mannitol concentration) significantly affected all the parameters studied. Increasing pre-heating temperature up to 47°C had no effect on storage modulus, stiffness and strength, but caused a slight decrease in toughness. Pre-

heating at 60°C caused all the parameters to decrease. The review of literature has indicated both support and contradiction of these findings. Peterson and Hall (1974, 1975) reported that small strain properties were independent of temperature in a range from 2°C to 30°C. Similarly, Ramana and Taylor (1992a) and Ramana *et al.* (1992) found that the apparent storage modulus for intact plant tissues either remained constant or rose slightly up to 50°C, but decreased markedly around 60°C. However, in a later work Ramana and Taylor (1992b) also found that the storage modulus for isolated cells increased as temperature rose from 25°C to about 80°C. The differences in their results might be caused by differences in properties of a cellular assembly versus those of isolated cells.

In an early research work Personius and Sharp (1938) reported that no reduction in tensile strength was found at temperatures lower than 50°C. Later, Huff (1971) showed that an increase in temperature in the range 6-21°C did not significantly affect failure modulus, but caused a slight decrease in tensile strength. The results agree with those shown in Figures 28 and 29, respectively. However, Bajema *et al.* (1998a, 1998b) reported that an increase in temperature from 5°C to 20°C caused a slight decrease in stiffness, but also an increase in strength. The differences between the results obtained by Huff (1971) and Bajema *et al.* (1998a, 1998b) might be due to great variability of mechanical properties with location in the tuber. Huff's results referred to samples taken halfway between skin and centre, while Bajema's results referred to samples taken just below the skin. In the present research work, as described in section 3.2.2, the tensile specimen was taken just below the skin, while the wedge and the small oscillation test specimens were taken from the perimedulary zone towards the pith. The differences

between the results obtained in the present project and those reported by Bajema and co-workers (1998a, 1998b), for the same location in the tuber, may be due to different pre-heating temperatures. The pre-heating regime used by Bajema *et al.* (5, 10, 15 and 20°C) was less severe than the one used in the experiments presented here (33, 47 and 60°C).

For pre-heating temperatures higher than 47°C, the results obtained in terms of stiffness and strength agreed with those found in the literature (Mohsenin, 1986; Alvarez and Canet, 1998). In contrast, the finding regarding the decrease in toughness with the increase in pre-heating temperature was in disagreement with the results reported by Tuomy *et al.* (1963) and Bajema *et al.* (1998a, 1998b). The difference might be due to different experimental equipment. The wedge fracture test that was used during this research work is a relatively newly introduced method for measurement of food texture (Vincent, 1990; Vincent *et al.*, 1991). No published data was found regarding the influence of temperature on toughness measured by this method.

Generally, upon heating, two typical structural changes occur inside the potato cells: starch granules absorb cellular water and swell to form a gel and pectic substances from the middle lamella and cell walls are degraded (Shomer, 1995). In addition, the cell membranes lose their integrity resulting in a loss of turgor pressure and the free diffusion of the cellular contents throughout the tissue (Andersson *et al.*, 1994). The pre-warming temperatures which were used in the present research were chosen so that they had meaningful values in terms of transformations which occur at the cellular level during heating. Thus, pre-warming the samples at 33 and 47°C caused the pectic substances from middle lamella to degrade slightly (Roberts and Proctor, 1955), while starch was swollen moderately (Shomer *et al.*, 1993). The results that were obtained for the present

tests showed that the changes which occur at a cellular level in this range of temperature did not have much influence on any of the parameters studied. Even if some partial gelatinization of starch may have occurred at these temperatures (Huang *et al.*, 1990), the strong cell walls (characteristic for potato cells) maintained their integrity. The pectic material from the cell walls, associated with cellulose, was not denatured by the mild heat treatment, therefore a strong cohesion was still maintained in the potato tissue. As a result, potato samples pre-heated at 33 and 47°C behaved essentially the same as did unheated samples (8°C).

In samples pre-heated at 60°C, the middle lamella (Roberts and Proctor, 1955), the cell wall (Ramana *et al.*, 1992) and the plasmalemma (Personius and Sharp, 1938b) were all degraded, while the partially gelatinized starch (Briant *et al.*, 1945; Van Beynum and Roels, 1985) was swollen (Shomer *et al.*, 1993). The net result of these changes was a softer tissue. Therefore, it was not unexpected to obtain much lower values for all the mechanical properties studied, as temperature increased.

Turgor pressure is much harder to measure, predict and control than temperature (Bajema *et al.*, 1998a, 1998b). When samples are treated in hypotonic conditions (3% mannitol concentration) water from the surrounding medium is drawn into the cells (Miller, 1931). Consequently, the turgor pressure that is normally exerted against the protoplasm and the cell walls increases, and the cells become 'turgid'. When samples are treated in hypertonic conditions (7% mannitol solution) cellular water diffuses outwardly, in order for the cell sap to attempt to reach osmotic equilibrium with the external solution (Miller, 1931). As a result, turgor pressure decreases and the cells become 'flaccid'.

In the present tests, at pre-heating temperatures of 8, 33 and 47°C, the storage modulus, toughness, stiffness and strength decreased as mannitol concentration increased (Figures 19, 23, 28 and 29). The decline in storage modulus and stiffness with increasing mannitol concentration was definitely in agreement with the results reported by other researchers (Falk *et al.*, 1958; Nilsson *et al.*, 1958; Lin and Pitt, 1986; Niklas, 1988; Brusewitz *et al.*, 1989; Pang, 1995; Hiller and Jeronimidis, 1996; Scanlon *et al.*, 1996; Bajema *et al.*, 1998a, 1998b). The lessened mechanical properties may be attributable to the loss of water from the cell during the hypertonic treatment. Another explanation may be that the tissues were 'plasticized' as more concentrated mannitol solutions penetrated the plasmalemma of cells (Niklas, 1988), therefore it was expected that both elastic and shear moduli decreased.

Regarding toughness, the present results were in contradiction to those found in the literature. In 1984 Atkins and Vincent reported that toughness was appreciably higher in 'flaccid' than in 'turgid' carrot phloem parenchyma. Later on, Hiller and Jeronimidis (1996) and Bajema *et al.* (1998a, 1998b) confirmed this finding. The results obtained during the present research work showed that toughness was higher in 'turgid' than in 'flaccid' samples. One possible explanation is increased interaction between the lateral surfaces of previously-cut cube-halves and the sides of the cutting wedge, as it penetrated further through the cubic sample (Hiller and Jeronimidis, 1996). The higher load imposed by the more turgid samples on the sides of the cutting wedge caused a larger area to be created beneath the specimen's force/deflection curve. Since this total area was used as energy in the calculations, it was not unexpected that toughness had higher values for 'turgid' than for 'flaccid' samples. Another reason for the difference between the results

presented here and those found in the literature may be a different way of calculating the work of fracture. In the present experiments toughness was calculated using the energy represented by the total area beneath the force/deflection curve (including energy lost in hysteresis and plastic flow) (Vincent, 1990), as opposed to the bare energy required solely for the propagation of the fracture (Hiller and Jeronimidis, 1996).

In terms of fracture stress, the results agreed with those found in 1978 by De Baerdemaeker *et al.* who reported that tensile strength increased with increasing turgor pressure. However, more results were reported for compression tests where the compressive strength decreased with increasing turgor (De Baerdemaeker *et al.*, 1978; Lin and Pitt, 1986; Brusewitz *et al.*, 1989; Hiller and Jeronimidis, 1996; Bajema *et al.*, 1998a, 1998b). In terms of tensile stiffness, the results were in agreement with those of Niklas (1988) who indicated that the elastic modulus decreased as turgor pressure decreased (mannitol concentration increased).

Since turgor pressure of the cell basically refers to the inwardly directed pressure of the cell wall against the cell sap (Miller, 1931), the integrity of the cell wall and the cell membranes is crucial if turgor pressure is to be maintained. It is also well known that an increase in temperature affects the integrity of both the cell wall and the cell membranes. Therefore, it is not surprising that an interaction between temperature and turgor pressure occurred consistently during the present experiment (Appendix 3). As a result, samples pre-heated at 60°C were not influenced by mannitol concentration. The high temperature caused the breakdown of the cell structure, as both cell wall and cellular membranes were denatured (Personius and Sharp, 1938b; Ramana *et al.*, 1992). As a result, the additional contribution of structural disruption brought about by the mannitol

treatment was negligible. Figures 19, 23, 28 and 29 show that either high mannitol concentrations or high temperatures led to a decrease in the magnitude of the mechanical properties investigated. However, it should be noted that high temperatures (60°C) only affected samples soaked in 3% and 5% mannitol solutions. An explanation may be that during the hypertonic treatment there was so much fluid removed from the cell, that the additional contribution of the temperature to the decrease in all the parameters studied was negligible. The results that have been obtained confirm the importance of water content and heat treatment, as well as their combined effect, when analyzing mechanical properties of potato.

5.3 Influence of Temperature and Turgor Pressure on Feathering

Although feathering is a phenomenon quite often met in the potato processing industry, the review of literature did not reveal any research work focused on solving this problem. Feathering is an important drawback which affects slicing performance in potatoes. It is believed to occur when brittle potato tubers are cut and a free-running crack propagates for a certain distance to cause so called feathers along the length of the fry. The present research work attempted to predict feathering using the wedge test. However, the strain rates used during the wedge test (20 mm min^{-1}) were much lower than the tremendous cutting speeds used in the potato processing industry (15-25 m sec^{-1}; Anonymous, 1998). It is the author's opinion that even with the difference in strain rates, the results obtained during this project are meaningful and may represent a starting point for the understanding of the feathering phenomenon, as it occurs at higher speeds.

The initial hypothesis which was assumed at the beginning of the present project was that feathering might be overcome by pre-warming the potato tubers. (This is what some french fry processing plants do.) However, the results that have been obtained showed that pre-heating temperatures up to 47°C did not affect feathering at all (Figure 25). Even more, increasing pre-heating temperature up to 60°C caused more feathering to happen. However, it was noticed that feathering occurring at 60°C was of a different nature than that occurring at lower temperatures. At the lower temperatures, when the sample was brittle, and the wedge of the knife penetrated it, the specimen was cut only in the first part of the test. At a certain point during the penetration a free-running crack propagated (Vincent *et al.*, 1991) and caused 'brittle feathering' to occur (Figure 36a and 36b). When the sample was soft (60°C pre-heating), there was much more deformation occurring at the surface of contact with the wedge of the knife before the knife actually penetrated through the potato cube (Figure 36c). The specimen was squeezed and the cut surface obtained showed 'soft feathers' which were more numerous, much smaller and differently shaped than the 'brittle' ones (Figure 36d). It is the author's opinion that 'soft feathers' were not obtained as a result of brittle fracture propagation.

So far, it was believed that feathering in general depends on structural integrity of the potato, as well as the pre-heating temperature of the tubers. The results, however, suggested that only 'soft' feathering was related to temperature. 'Brittle' feathering was only affected by the structural integrity of the tubers related to turgor pressure within the cells. For pre-heating temperatures up to 47°C, feathering decreased as mannitol concentration increased, but for 60°C mannitol had no effect on feathering (Figure 25).

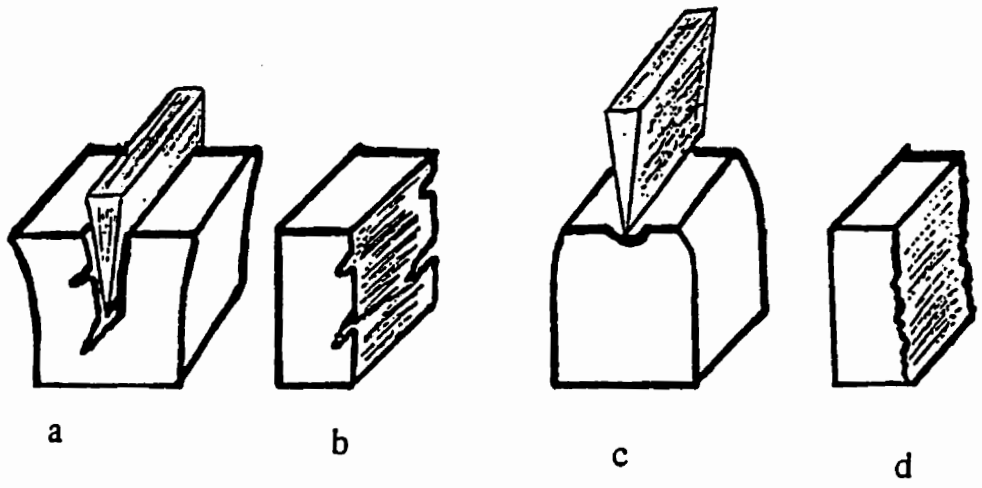

Figure 36. Propagation of fracture and types of feathering in potato cubes; (a) propagation of fracture through a 'brittle' potato cube, (b) half of potato cube with signs of 'brittle' feathering, (c) deflection of the top of a 'soft' potato cube as the wedge of the knife tries to penetrate it, (d) half of potato cube with signs of soft feathering.

For pre-heating temperatures up to 47°C, the structural changes which occurred at the cellular level were not drastic. Neither the thermal stress on the cell wall and membranes (Personius and Sharp, 1938b; Ramana *et al.*, 1992), nor the partial gelatinization of starch (Huang *et al.*, 1992) affected 'brittle' feathering. The decrease of turgor pressure as mannitol concentration increased, caused the samples to become less rigid, therefore less fracture occurred and less 'brittle' feathering was visible. When the samples were pre-heated at 60°C, feathering was not affected by turgor pressure. At this temperature, because of its low stiffness, potato tissue was unable to store sufficient strain energy to start a free-running macroscopic crack. The wedge only ever cut through the sample (Vincent *et al.*, 1991). Therefore the 'soft' feathers were not caused by the same mechanism of free-propagating fracture, as were 'brittle' feathers. Further work would be required to clarify the differences between the two mechanisms of feathering propagation.

5.4 Effects of Storage on Potato Parenchyma

5.4.1 Effect of Storage on Mechanical Properties

Compared with the information available for other plant materials, less is known about the effect of storage on mechanical properties of potatoes (Brusewitz *et al.*, 1989). However, it is known that during storage the tubers are subject to both physiological changes and water losses (Scanlon *et al.*, 1996).

When potatoes are brought into storage, they are still alive and respiring. As a result, they lose dry matter, mainly carbohydrates such as starch and sugars, which are converted into carbon dioxide and water (Smith, 1967). The rate of respiration is closely

linked to physiological shrinkage during storage. At the same time, transpiration of potatoes causes loss of water which is often the most serious cause of weight loss during storage (Schippers, 1976; Burton, 1989). Therefore, changes in mechanical properties of potatoes over time must be always related to both transpiration and respiration.

The influence of storage time on storage modulus, toughness, feathering, stiffness and strength are shown in Figures 21a and 21b, 24, 27, 32 and 33. With the exception of toughness and strength which both showed obvious trends of modification over time, all the other parameters did not change much during a storage period of 8 months.

Storage modulus did not change markedly from November to May, for any mannitol concentration, but in the last month of storage it decreased (Figures 21a and 21b). This result is in agreement with those of Pang and Scanlon (1996) and Scanlon *et al.* (1996) who found that potatoes stored for ten months had lower shear moduli than potatoes stored for one month. During storage, the cellular membranes of potato cells underwent structural disruptions (Turnbull and Cobb, 1992) which mainly resulted in water losses (Scanlon *et al.*, 1996). This caused turgor pressure to decrease and cells to become more 'flaccid'. Therefore, it was not unexpected that storage modulus decreased at the end of the storage period. Figure 22 supports the explanation given above. However, for potatoes pre-heated at 60°C G' was not affected by storage time. No significant drop in storage modulus was seen in the last month of storage for these samples, but the overall values of G' were much lower during the whole storage period. The reason might be that the cellular membranes were so drastically denatured by the heat treatment (Personius and Sharp, 1938b), that the additional contribution of structural disruptions which occurred over time was negligible.

Similarly, stiffness and feathering did not change much over the eight months of storage. The review of literature revealed conflicting results for this matter. Thus, Huff (1971) reported that tensile stiffness is not significantly affected by storage time over a three-four month period. However, Brusewitz *et al.* (1989) reported that compressive stiffness of cell walls increases with storage time. In contrast, Pang and Scanlon (1996) and Scanlon *et al.* (1996) found that compressive stiffness is lower in crops stored for ten months compared to crops stored for one month. These differences among the results obtained might be due to different potato storage time, as well as different experimental techniques. For feathering, no published data was found related to the present results.

The overall increase in fracture stress during storage was not surprising since early works showed that firming in cherries is actually a matter of aging (Whittenberger, 1952; Buch *et al.*, 1961; LaBelle *et al.*, 1964). It is believed that the aging of tissues results in the strengthening of the intercellular cement, but the actual physiological process involved is not adequately understood (Wittenberger, 1952; Mohsenin, 1986). Similar results were obtained by Huff (1971) who reported an increase in tensile strength over time for specimens taken from the center of the potato tuber. For the same test however, he reported a decrease of strength with time, for specimens taken just below the skin. This latter result was in agreement with those reported by Brusewitz *et al.* (1989).

The decrease in toughness over time was believed to be caused by irreversible decrease in cell membrane integrity during storage. Turnbull and Cobb (1992) subjected potato tissues to cation analysis and observed a significant increase in sodium and calcium leakage during storage time. Both sodium and calcium are believed to be involved in the structural functions of the cellular membranes, as well as cell wall

synthesis and cohesion (Van Buren, 1979). The disruption of the cellular membranes resulted in water losses, which caused turgor pressure to decrease. Therefore, it was not unexpected for the toughness to decrease as well.

In conclusion, it can be said that the trend of mechanical properties over time was strongly dependent on the biochemical changes which occurred in the potato tissue. It is also worthy to mention that the changes occurring in the mechanical properties over time were much less pronounced than the changes caused by mannitol treatment. Therefore, it can be concluded that mannitol treatment is not the best choice if 'artificial' aging is to be induced. In other words, much more water is withdrawn from potato tissues during hypertonic treatment than during natural aging.

5.4.2 Other Effects of Storage on Potato Parenchyma

In the last 3 month of storage some discoloration was noticed for both heated and unheated samples. However, the blackening process was more pronounced for specimens which were pre-heated at 60°C. Non enzymatic browning was believed to have caused the pigmentation.

Non enzymatic browning was due to Maillard reaction based on carbonyl-amino interactions (Burton, 1989). Since the change in the amino fraction during storage was rather random (Talley *et al.*, 1964; Burton, 1989), it can be concluded that the extent of pigmentation was largely controlled by the amount of reducing sugars (Kadam *et al.*, 1991). In general, sugar accumulation is believed to begin to be noticeable after about 5-6 months of storage (Burton, 1989). Therefore, it was expected that pigmentation occurred around that time. Another reason for the discoloration might have been the formation of

melanins from tyrosine in disrupted cells (Burton, 1989). It is possible that oxidation of tyrosine occurred while the samples were cut from the tuber before they were dropped in mannitol solutions.

Another major physiological process which occurred during storage was sprouting (Schippers, 1976). Losses of proteins, reduced sugars and ascorbic acid (Burton, 1989; Jadhav *et al.*, 1991), as well as increases in the rate of respiration (Burton, 1989) have been previously reported to occur in sprouting tubers. During the present experiment, sprout growth was noticed to appear in January and in April for *Shepody* and *Russet Burbank* potatoes, respectively (Table 5). The reason for the delay in sprout growth between the two cultivars is not known. It is possible that *Russet Burbank* potatoes are more resistant to sprouting than *Shepody* potatoes.

5.5 Effect of Solids Content and Cultivar on Mechanical Properties

Solids content and cultivar affected most of the parameters studied, either as main effects or in interactions (Appendix 3). Generally, the mechanical properties of *Shepody* potatoes were more frequently affected by solids content than were those of *Russet* potatoes (Figures 20, 26, 31). Thus, an increase in solids content caused storage modulus to increase and feathering to decrease in *Shepodies*, while in *Russets* neither storage modulus, nor feathering were significantly affected (Figures 20 and 26). These results were quite intriguing since Scanlon *et al.* (1996) also reported an increase in storage modulus with solids content, but for *Russet* potatoes.

Similarly, stiffness had higher values at lower solids contents. However, the differences in stiffness caused by different solids content disappeared in samples pre-

Table 5. Sprout growth in *Russet Burbank* and *Shepody* potatoes over eight-month storage

Month	Approximate sprout length (mm)	
	Russet Burbank	*Shepody*
November	0	0
December	0	0
January	0	5
February	0	10
March	0	15
April	5	20
May	10	35
June	20	NA

heated at 60°C (Figure 31). As it was already discussed, starch (which mostly accounts for solids content) was gelatinized at this high temperature. Therefore, the drop in stiffness independently of the actual amount of starch (and implicitly of solids content) was not unexpected. For strength, solids content made no significant difference (Table 2). This was in agreement with Huff's opinion (1971) that 'strength is determined by cell wall properties and thickness' and consequently it is not directly related to starch. For both stiffness and strength *Russet* potatoes showed higher values than *Shepodies* (Figures 30a and 30b and Table 2). Toughness was not significantly affected either by solids content or by cultivar.

In conclusion, for *Russet* potatoes, only stiffness was significantly affected by solids content. For *Shepody* potatoes, solids content had a significant effect on storage modulus, feathering and stiffness. For both *Russets* and *Shepodies*, toughness and strength were not significantly affected by solids content. Little has been published so far about *Shepody* potato characteristics, therefore it is difficult to make a comparison between them and *Russets*. It has been suggested that *Shepodies* have a lower specific gravity than *Russets* (Young *et al*, 1983), but the difference was very small. Further research would be required to see if this little difference in solids caused *Russet* and *Shepody* potatoes to have different mechanical properties.

6. CONCLUSIONS

The present study was undertaken to characterize the mechanical properties of potatoes using large-scale deformation techniques (wedge-penetration fracture test, tensile test in a notched specimen), as well as small-scale deformation techniques (small strain oscillatory shear tests). The relationship between the various rheological parameters obtained was analyzed in order to see if the size reduction of the tuber during the slicing operation could be viewed as a brittle fracture phenomenon. The experiments were designed to: (1) investigate the effect of thermal treatment and artificial turgor adjustment on the mechanical properties of the potato parenchyma; (2) quantify the amount of feathering in the wedge fracture test for potatoes pre-heated at different temperatures; (3) examine the effect of storage on the mechanical properties, as well as solids content and turgor pressure of the potato tuber; (4) determine the influence of solids content and cultivar on the mechanical properties of the potato tissue.

Although pre-heating temperatures up to 47°C had little or no effect on dynamic shear storage modulus, fracture toughness, tensile stiffness and tensile strength, pre-heating at 60°C caused all the parameters above to decrease (especially for samples soaked in 3% and 5% mannitol solutions). This latter behaviour (i.e. pre-heating at 60°C) was thought to be related to structural changes which occur in the potato tissue upon heating: degradation of pectic substances from cell walls and middle lamella, swelling and gelatinization of starch, and degradation of the lipo-proteic structure of the membranes. For samples pre-heated up to 47°C, a decrease in turgor pressure caused all the parameters of interest to decrease. However, manipulation of turgor had no effect on

samples pre-heated at 60°C. An explanation for this behavior could be related to the importance of the cell membranes in maintaining turgidity of the cells.

An increase in the pre-heating temperature up to 47°C did not affect either the occurrence or the amount of wedge test feathering. Pre-heating at 60°C increased the amount of feathering. This result was surprising since some of the french fries manufacturers pre-heat the tubers in order to overcome the feathering phenomenon. Two types of feathering were noticed to occur depending upon the temperatures at which the tubers were pre-heated: 'brittle feathering' (up to 47°C) and 'soft feathering' (60°C). It is the author's opinion that two different mechanisms may be involved in the occurrence of the two types of feathering noticed. Further work is needed to investigate this hypothesis.

Throughout the storage period the solids content slightly increased, while turgor pressure slightly decreased. Storage time had little or no effect on dynamic shear storage modulus, amount of feathering and tensile stiffness. However, aging caused fracture toughness to decrease and tensile strength to increase.

The fact that the changes occurring in the mechanical properties over time were much less pronounced than the changes caused by mannitol treatment indicates that less water was withdrawn from the potato parenchyma during natural aging than during artificial turgor adjustment. This observation proves that good humidity conditions during storage prevent the potato tubers from losing moisture and therefore maintain their processing quality.

Solids content had a significant effect on the dynamic shear storage modulus, amount of feathering and tensile stiffness of *Shepody* potatoes. For *Russet* potatoes, only tensile stiffness was significantly affected by solids content.

The initial hypothesis which was to be tested in the present study was that fracture stress could be predicted by equation (13), if toughness and stiffness were known (Griffith, 1920; Williams, 1984; Hiller and Jeronimidis, 1996). The results showed that equation (13) could not be used to describe accurately the relationship between the parameters of interest. However, statistical analysis revealed that correlations do exist between the various mechanical properties studied. Although all the parameters were positively correlated to each other, only two significant correlations were found: one between stiffness and storage modulus and one between stiffness and strength.

This research has demonstrated that pre-heating of the potato tubers prior to slicing does not improve the surface quality of french fries. However, for the first time, two different types of feathering were noticed. This information may be used as a starting point for another research work aiming to explain fully the differences in the mechanisms which caused the two types of feathering mentioned.

REFERENCES

Agblor, A. 1997. Measurement of Physical Properties During Processing of French Fries. Ph.D. Thesis, University of Manitoba, Winnipeg, MB.

Agblor, A. and Scanlon, M. G. 1998. Effects of blanching conditions on the mechanical properties of french fry strips. Am. J. Potato Res. 75: 245-255.

Alvarez, M. D. and Canet, W. 1998. Rheological characterization of fresh and cooked potato tissues (cv. Monalisa). Z Lebensm Unters Forsch. 207: 55-65.

ASTM. 1993. Standard test methods for tension testing of metallic materials. Annual Book of ASTM Standards, ASTM-E8-93, Vol.03.01, pp. 130-149, American Society for Testing Materials, Philadelphia.

Andersson, A., Gekas, V., Lind, I., Oliviera, F. and Oste, R. 1994. Effect of pre-heating on potato texture. Crit. Rev. Food Sci. Nutr. 34: 229-251.

Andrews, E. H. 1974. A generalized theory of fracture mechanics. J. Mat. Sci. 9: 887-894.

Anonymous. 1988. Frozen french fries lead resurgence in potato sales. Farmline. 9: 4-7.

Anonymous. 1992. *Shepody* potato fries around the world. Agvance. 2 (2): 6.

Anonymous. 1995. Sharp practices. Potato Business World. 3 (2): 10-12, 14, 16.

Anonymous. 1996. A cut above. Potato Business World. 4 (2): 17-20, 22, 24.

Anonymous. 1998. Profitable size reduction. Potato Business World. 6 (2): 21, 22, 24, 26-30.

Anzaldua-Morales, A., Bourne, M. C. and Shomer, I. 1992. Cultivar, specific gravity and location in tuber affect puncture force of raw potatoes. J. Food Sci. 57: 1353-1356.

Arreguin-Lozano, B. and Bonner, J. 1949. Experiments on sucrose formation by potato sugar as influenced by temperature. Plant Physiol. Lancaster 24: 720-738.

Artschwager, E. 1924. Studies on the potato tuber. J. Agric. Res. 27: 809-835.

Atkins, A. G. and Mai, Y. -M. 1985. Elastic and Plastic Fracture: Metals, Polymers, Ceramics, Composites, Biological Materials. Ellis-Horwood, Chichester.

Atkins, A. G. and Vincent, J. F. V. 1984. An instrumented microtome for improved histological sections and the measurement of fracture toughness. J. Mat. Sci. Lttr. 3: 310-312.

Bajema, R. W., Hyde, G. M. and Baritelle, A. L. 1998a. Temperature and strain effects on the dynamic failure properties of potato tuber tissue. Trans. ASAE. 41: 712-732.

Bajema, R. W., Hyde, G. M. and Baritelle, A. L. 1998b. Turgor and temperature effects on dynamic failure properties of potato tuber tissue. Trans. ASAE. 41: 733-740.

Bajema, R. W., Hyde, G. M. and Peterson, K. 1998c. Instrumentation design for dynamic axial compression of cylindrical tissue samples. Trans. ASAE. 41: 747-754.

Barbosa-Canovas, G. V., Kokini, J. L., Ma, L. and Ibartz, A. 1996. The rheology of semiliquid foods. Adv. Food Nutr. Res. 39: 2-69.

Becker, R. and Gray, G. M. 1992. Evaluation of a water jet cutting system for slicing potatoes. J. Food Sci. 57: 132-137.

Bettelheim, F. and Sterling, C. 1955. Factors associated with potato texture. I. Specific gravity and starch content. Food Res. 20: 71-78.

Briant, A. M., Personius, C. J. and Cassel, E. G. 1945. Physical properties of starch from potatoes of different culinary quality. Food Res. 10: 437-444.

Brown, R. 1960. The plant cell and its inclusions. Pages 3-129 in: Plant Physiology. Vol I A: Cellular Organization and Respiration, ed: F. C. Steward. Academic Press. New York and London.

Brusewitz, G. H., Pitt, R. E. and Gao, Q. 1989. Effects of storage time and static preloading on the rheology of potato tissue. J. Texture Stud. 20: 267-284.

Buch., M. L., Satori, G. K. and Hills, C. H. 1961. The effect of bruising and aging on the texture and pectic constituents of canned red tart cherries. Food Technol. 15: 526-531.

Burton, W. G. 1989. The Potato. 3rd edition. Longman Scientific and Technical, UK.

Canet, W. and Sherman, P. 1988. Influence of friction, sample dimensions and deformation rate on the uniaxial compression of raw potato flesh. J. Texture Stud. 19: 275-287.

Culioli, J. and Sherman, P. 1976. Evaluation of Gouda cheese firmness by compression tests. J. Texture Stud. 7:353-372.

Damir, A. A. 1989. Effect of heat penetration during cooking on some physico-chemical properties and microstructure of sweet potatoes. Food Chem. 34: 41-55.

Day, B. 1995. New developments in cutting and slicing. Food Manuf. 70 (4): 49, 51-52.

De Baerdemaeker, J. G., Segerlind, L. J., Murase, H. and Merva, G. E. 1978. Water potential effect on tensile and compressive failure stresses of apple and potato tissue. ASAE Paper No. 78-3057. St. Joseph, Michigan.

Devlin, R. M. 1967. Plant Physiology. Reinhold Publishing Corporation. New York, Amsterdam, London.

Diehl, K. C., Hamann, D. D. and Whitfield, J. K. 1979. Structural failure in selected raw fruits and vegetables. J. Texture Stud. 10: 371-400.

Dull, G. G., Birth, G. S. and Leffler, R. G. 1989. Use of near infrared analysis for the nondestructive measurement of dry matter in potatoes. Am. Potato J. 66: 215-225.

Fahloul, D. and Scanlon, M. G. 1996. A fracture mechanics analysis of the texture of potatoes. J. Texture Stud. 27: 545-557.

Falk, S., Hertz, H. and Virgin, H. 1958. On the relation between turgor pressure and tissue rigidity I. Experiments on resonance frequency and tissue rigidity. Physiol. Plant. 11: 802-817.

Fedec, P., Ooraikul, B. and Hadziyev, D. 1977. Microstructure of raw and granulated potatoes. J. Inst. Can. Sci. Technol. Aliment. 10: 295-306.

Feustel, I. C. and Kueneman, I., C. 1967. Frozen french fries and other frozen potato products. Pages 340-373 in: Potato Processing. 2nd edition. The Avi Publishing Company, Inc., Westport, Connecticut.

Finney, E. E. 1969. To define texture in fruits and vegetables. Agric. Eng. 50: 462-465.

Galliard, T. and Matthew, J. A. 1973. Lipids of potato tubers. II. Lipid-degrading enzymes in different varieties of potato tuber. J. Sci. Food. Agric. 24: 623-627.

Griffith, A. A. 1920. The phenomena of rupture and flow in solids. Phil. Trans. Roy. Soc. Lond. A221: 163-198.

Heinze, P. H., Craft, C. C., Mountjoy, B. M. and Kirkpatrick, M. E. 1952. Variations in specific gravity of potatoes. Am. Potato J. 29: 31-37.

Hiller, S., Bruce, D. M. and Jeronimidis, G. 1996. A micro-penetration technique for mechanical testing of plant cell walls. J. Texture Stud. 27: 558-587.

Hiller, S. and Jeronimidis, G. 1996. Fracture in potato tuber parenchyma. J. Mat. Sci. 31: 2779-2796.

Holt, J. E. and Schoorl, D. 1983. Fracture in potatoes and apples. J. Mat. Sci. 18: 2017-2028.

Huang, J., Hess, W. M., Weber, D. J., Purcell, A. E. and Huber, C. S. 1990. Scanning electron microscopy: tissue characteristics and starch granule variations of potatoes after microwave and conductive heating. Food Struct. 9: 113-122.

Huff, E. R. 1967. Tensile properties of Kennebec potatoes. Trans. ASAE. 10: 414-419.

Huff, E. R. 1971. Tensile properties of potato tuber. Am. Potato J. 48: 148-158.

Isherwood, F. A. and Burton, W. G. 1975. The effect of senescence, handling, sprouting and chemical sprout suppression upon the respiratory quotient of stored potato tubers. Potato Res. 18: 98-104.

Izydorczyk, M. S. 1997. Lecture notes for course 78.716 Food Carbohydrates for 1996-1997 session. Department of Food Science, University of Manitoba, Winnipeg, MB.

Jackman, R. L. and Stanley, D. W. 1992. Failure mechanisms of tomato pericarp tissue suggested by large and small deformation tests. J Texture Stud. 23: 475-489.

Jadhav, S. J., Mazza, G. and Desai, U. T. 1991. Postharvest handling and storage. Pages 70-110 in: Potato: Production, Processing and Products, ed. D. K. Salunkhe, S. S. Kadam and S. J. Jadhav. CRC Press.

Jankowsky, T. 1992. Influence of starch retrogradation on the texture of cooked potato tuber. Int. J. Food. Sci. Technol. 27: 637-642.

Jarvis, M. C., Hall, M. A., Threlfall, D. R. and Friend, J. 1981. The polysaccharide structure of potato cell walls: Chemical fractionation. Planta. 152: 93-100.

Jarvis, M. C. and Duncan, H. J. 1992. The textural analysis of cooked potato. 1. Physical principals of the separate measurement of softness and dryness. Potato Res. 35: 83-91.

Jarvis, M. C., Mackenzie, E. and Duncan, H. J. 1992. The textural analysis of cooked potato. 2. Swelling pressure of starch during gelatinisation. Potato Res. 35: 93-102.

Johnson, E. F. and Wilson, J. B. 1969. The effect of soil temperatures at harvest on the bruise resistance of potatoes. Am. Potato J. 46: 75-82.

Kadam, S. S., Dhumal, S. S., Jambhale, N. D. 1991a. Structure, nutritional composition and quality. Pages 9-37 in: Potato: Production, Processing and Products, ed. D. K. Salunkhe, S. S. Kadam and S. J. Jadhav. CRC Press.

Kadam, S. S., Wankier, B. N. and Adsule, R. N. 1991b. Processing. Pages 111-155 in: Potato: Production, Processing and Products, ed. D. K. Salunkhe, S. S. Kadam and S. J. Jadhav. CRC Press.

Kamyab, I., Chakrabarti, S. and Williams, J.G. 1998. Cutting cheese with wire. J. Mat. Sci. 33: 2763-2770.

Khan, A. A. and Vincent, J. F. V. 1993. Compressive stiffness and fracture properties of apple and potato parenchyma. J. Texture Stud. 24: 423-435.

Knowles, N. R. and Knowles, L. O. 1989. Correlations between electrolyte leakage and degree of saturation of polar lipids from aged potato (Solanum tuberosum L.) tuber tissue. An. Bot. 63: 331-338.

LaBelle, R. L., Woodams, E. E. and Bourne, M. C. 1964. Recovery on Montmorency cherries from repeated bruising. Proc. Am. Soc. Hortic. Sci. 84: 103-109.

Lamberg, I. and Hallström, B. 1986. On the possibility of modifying the gelatinization properties of starch by lipid surface coating. Stärke. 33: 231-235.

Lin, T. T. and Pitt, R. E. 1986. Rheology of apple and potato tissue as affected by cell turgor pressure. J. Texture Stud. 17: 291-313.

Lineback, D. L. and Inglett, G. E. 1982. Food Carbohydrates. AVI, Westport, CT.

Livingston, L. J. 1962. Lamb-Weston packs Dehydro-frozen mashed and long-cut French potatoes by new methods. Canner/Packer. 131(6): 28-29.

Lulai, E. C. 1986. Potato specific gravity. Chipper/Snacker. August. pp. 28-29.

Lutz, J. M., Edgar, A. D. and Glaves, A. H. 1952. Reducing injuries in grading stored potatoes. Am. Potato J. 29: 234-240.

Mazza, G. 1983. Correlations between quality parameters of potatoes during growth and long term storage. Am. Potato J. 60: 145-159.

Mazza, G., Hung, J. and Dench, M. J. 1983. Processing/nutritional quality changes in potato tubers during growth and long term storage. Can. Inst. Food Sci. Technol. J. 16: 39-44.

Mc Garry, A. 1993. Influence of water status on carrot fracture properties. J. Hortic. Sci. 68: 431-437.

Miller, E. C. 1931. Plant Physiology. With reference to the green plant. McGraw-Hill Book company, Inc. New York and London. pp: 69-75.

Mohsenin, N. N. 1986. Physical Properties of Plant and Animal Materials. 2nd edition. Gordon and Breach Science Publishers, New York, NY.

Niklas, K. J. 1988. Dependency of tensile modulus on transverse dimensions, water potential and cell membrane of pith parenchyma. Am. J. Bot. 75: 1286-1292.

Niklas, K. J. 1989. Mechanical behaviour of plant tissues as inferred from the theory of pressurized cellular solids. Am. J. Bot. 76: 929-937.

Nilsson, S. B., Hertz, H. and Falk, S. 1958. On the relation between turgor pressure and tissue rigidity II. Theoretical calculations on model systems. Physiol. Plant. 11: 818-837.

Oates, C. G., Lucas, P. W. and Lee, W. P. 1993. How brittle are gels? Carbohydr. Polym. 20: 189-194.

Ohad, I., Friedberg, I., Newman, Z. and Schramm, M. 1971. Biogenesis and degradation of starch. I. The fate of the amyloplast membranes during maturation and storage of potato tubers. Plant Physiol. 47: 465-477.

Pang, C. H. and Scanlon, M. G. 1996. Mechanical properties of parenchyma of potato (Solanum tuberosum cv. *Russet Burbank*). Can. J. Bot. 74: 859-869.

Pang, C. H. 1995. The Mechanical Properties of Raw Potato Tissues as Measured by Uniaxial Compression and Small Strain Oscillatory Shear Tests. M.Sc. Thesis, University of Manitoba, Winnipeg, MB.

Parker, M. L. and Waldron, K. W. 1995. Texture of Chinese water chestnut: Involvement of cell wall phenolics. J. Sci. Food. Agric. 68: 337-346.

Personius, C. J. and Sharp, P. F. 1938a. Adhesion of potato tuber cells as influenced by temperature. Food Res. 3: 513-524.

Personius, C. J. and Sharp, P. F. 1938b. Permeability of potato-tuber tissue as influenced by heat. Food Res. 3: 525-538.

Persson, S. 1987. Mechanics of cutting plant material. ASAE. Monograph No. 7 St. Joseph, Michigan, pp. 3-19.

Peterson, C. L. and Hall, C. W. 1974. Thermorheological simple theory applied to the *Russet Burbank* potato. Trans. ASAE. 17: 546-556.

Peterson, C. L. and Hall, C. W. 1975. Dynamic mechanical properties of the *Russet Burbank* potato as related to temperature and bruise susceptibility. Am. Potato J. 52: 289-312.

Pritchard, M. K. and Adam, L. R. 1992. Preconditioning and storage of chemically immature *Russet Burbank* and *Shepody* potatoes. Am. Potato J. 71: 59-68.

Pritchard, M. K. and Adam, L. R. 1994. Relationships between fry color and sugar concentration in stored *Russet Burbank* and *Shepody* potatoes. Am. Potato J. 69: 805-815.

Ramana, S. V. and Taylor, A. J. 1992a. Dynamic measurement of tissue rigidity during freezing and cooking of vegetables. J. Sci. Food. Agric. 58: 261-266.

Ramana, S. V. and Taylor, A. J. 1992b. Development of a method to measure rheological properties of carrot cell and cell wall materials. J. Sci. Food. Agric. 60: 39-45.

Ramana, S. V., Wright, C. J. and Taylor, A. J. 1992. Measurement of firmness in carrot tissue during cooking using dynamic, static and sensory tests. J. Sci. Food. Agric. 60: 369-375.

Ramana, S. V. and Taylor, A. J. 1994. Effect of various agents on rheological properties of carrot cells and protoplasts. J. Sci. Food. Agric. 64: 519-525.

Ramana, S.V., Stengel, E., Wolf, W. and Spiess, W. E. L. 1997. A simple technique to improve the firmness of cooked potato tissue. J. Sci. Food. Agric. 74: 340-346.

Reeve, R. M. 1954. Histological survey of conditions influencing texture of potatoes. I. Effects of heat treatments on structure. Food Res. 19: 323-333.

Reeve, R. M. 1967. A review of cellular structure, starch and texture qualities of processed potatoes. Econ. Bot. 21: 294-308.

Reeve, R. M. 1972. Pectin and starch in pre-heating firming and final texture of potato products. J. Agric. Food Chem. 20 (6): 1282.

Reeve, R. M. 1977. Pectin, starch and texture of potatoes: some practical and theoretical implications. J. Texture Stud. 8: 1-17.

Reiner, M. 1960. Deformation, Strain and Flow. H. K. Lewis and Co., Ltd., London.

Roberts, E. A. and Proctor, B. E. 1955. The comparative effect of ionizing radiations and heat upon the starch containing cells of the potato tuber. Food. Res. 20: 254-263.

Ryden, P. and Selvendran, R. R. 1990. Structural features of cell wall polysaccharides of potato (*Solanum tuberosum*). Carbohydr. Res. 195: 257-272.

Salunkhe, D. K. and Kadam, S. S. 1991. Introduction. Pages 1-7 in: Potato: Production, Processing and Products, ed. D. K. Salunkhe, S. S. Kadam and S. J. Jadhav. CRC Press, Boca Raton, FL.

Scanlon, M. G. and Long, A. E. 1995. Fracture strength of potato tissue under compression and tension at two rates of loading. Food Res. Int. 28: 397- 402.

Scanlon, M.G., Pang, C. H. and Biliaderis, C. G. 1996. The effect of osmotic adjustment on the mechanical properties of potato parenchyma. Food Res. Int. 29: 481-488.

Scanlon, M. G. 1997. Lecture notes for course 78.709 Unit Process Operations for 1996-1997 session. Department of Food Science, University of Manitoba, Winnipeg, MB.

Scanlon, M. G., Day, A. J. and Povey, J. W. 1998. Shear stiffness and density in potato parenchyma. Int. J. Food Sci. Technol. 33: 461-464.

Schippers, P. A. 1976. Biological characteristics of the potato in relationship to storage. Pages 47-62 in: The Potato Storage, ed. B. F. Cargill. Michigan State University, East Lansing, MI.

Schippers, P. A. 1977. The rate of respiration of potato tubers during storage. II. Results of experiments in 1972 and 1973. Potato Res. 20: 189-206.

Schoorl, D. and Holt, J. E. 1983. Cracking in potatoes. J. Texture Stud. 14: 61-70.

Schwimmer, S. and Burr, H. 1967. Structure and chemical composition of the potato tuber. Pages 12-44 in: Potato Processing. 2nd edition. The Avi Publishing Company, Inc., Westport, Connecticut.

Segal, R. 1992. Biochimie (Biochemistry). Universitatea 'Dunarea de Jos'. Vol 1. Galati, Romania.

Sharma, K. N., Isleib, D. R. and Dexter, S. T. 1959. The influence of specific gravity and chemical composition of hardness of potato tubers after cooking. Am. Potato J. 36:105-112.

Shekhar, V. C., Iritani, W. M. and Magnuson, J. 1979. Starch-sugar interconversion in *Solanum tuberosum L.* II. Influence of membrane permeability and fluidity. Am. Potato J. 56:225-235.

Shomer, I., Rao, M. A., Bourne, M. C. and Levy, D. 1993. Impact of temperature and cellulase treatments on rheological behavior of potato tuber cell suspensions. J. Sci. Food Agric. 63: 245-250.

Shomer, I. 1995. Swelling behaviour of cell wall and starch in potato (Solanum tuberosum L.) tuber cells-I. Starch leakage and structure of single cells. Carbohydr. Polym. 26: 47-53.

Sitkei, G. 1986. Mechanics of agricultural materials. Elsevier Science Publisher, Amsterdam, The Nederlands, pp. 439-440.

Smith, O. 1967. Effect of transit and storage conditions on potatoes. Pages 167-217 in: Potato Processing. 2nd edition. The Avi Publishing Company, Inc., Westport, Connecticut.

Spychalla, J. P. and Desborough, S. L. 1990. Fatty acids, membrane permeability, and sugars of stored potato tubers. Plant Physiol. 94: 1207-1213.

Stanley, D. W. 1991. Biological membrane deterioration and associated quality losses in food tissues. Crit. Rev. Food Sci. Nutr. 30: 487-553.

Sterling, C. 1955. Effect of moisture and high temperature on cell walls in plant tissues. Food Res. 20: 474-479.

Svegmark, K. and Hermansson, A.-M. 1991. Distribution of amylose and amylopectin in potato starch pastes: effects of heating and shearing. Food Struct. 10: 117-129.

Szczesniak, A. S. 1983. Mechanical properties. Pages: 20-41 in: Physical Properties of Foods. Micha Peleg and Edward B. Bagley, ed. The AVI Publishing Co., Inc. Westport, CT.

Talburt, W. F. 1967. History of potato processing. Pages 12-44 in: Potato Processing. 2nd edition. The Avi Publishing Company, Inc., Westport, Connecticut.

Talley, E. A., Fitzpatrick, T. J. and Porter, W. L. 1964. Chemical composition of potatoes IV. Relationship of the free amino acid concentrations to specific gravity and storage time. Am. Potato J. 41: 357-366.

Terman, G. L., Goven, M. and Cunningham, C. E. 1950. Effect of storage temperature and size of French-fry quality, shrinkage and specific gravity of Maine potatoes. Am. Potato J. 27: 417-424.

Thompson, N. R. 1967. Potato Varieties. Pages 44-68 in: Potato Processing. 2nd edition. The Avi Publishing Company, Inc., Westport, Connecticut.

Tung, M. 1986. Some concepts in food rheology. Lecture notes from unknown course. Department of Food Science, Technical University of Nova Scotia.

Tuomy, J. M., Lechnir, R. J. and Miller, T. 1963. Effect of cooking temperature and time on the tenderness of beef. Food Technol. 17: 1457-1460.

Turnbull, N. D. and Cobb, A. H. 1992. A study of tuber cell integrity and ultrastructure during prolonged potato storage. Aspects Appl. Biol. 33: 113-188.

Van Beynum, G. M. A. and Roels, J. A. 1985. Starch conversion technology. New York: Marcel Dekker Inc.

Van Buren, J. P., Moyer, J. C., Robinson, W. B. and Hand, D. B. 1960. Control of firmness in canned snap beans. Farm Res. 26: 9.

Van Buren, J. P. 1979. The chemistry of texture in fruits and vegetables. J. Texture Stud. 10:1-23.

Van Marle, J. T., Clerkx, A. C. M. and Boekestein, A. 1992. Cryo-scanning electron microscopy investigation of the texture of cooked potatoes. Food Struct. 11: 209-216.

Vincent, F. V. J. 1989. Relationship between density and stiffness of apple flesh. J. Sci. Food. Agric. 47: 443-462.

Vincent, F. V. J. 1990. Fracture properties of plants. Adv. Bot. Res. 17: 235-287.

Vincent, J. F. V., Jeronimidis, G., Khan, A. A. and Luyten, H. 1991. The wedge fracture test. J. Texture Stud. 22: 45-57.

Visvanathan, R., Sreenarayan, V. V. and Swaminathan, K., R. 1996. Effect of knife angle and velocity on the energy required to cut cassava tubers. J. Agric. Eng. Res. 64: 99-102.

Volodkevich, N. N. 1938. Apparatus for measurements of chewing resistance of tenderness of foodstuffs. Food. Res. 3: 221-225.

Warren, D. S. and Woodman, J. S. 1973. Distribution of cell wall components in potato tubers: A new titrimetric procedure for the estimation of total polyuronide (pectic substances) and its degree of esterification. J. Sci. Food Agric. 24: 769-777.

Warren, D. S. and Woodman, J. S. 1974. The texture of cooked potato: a review. J. Sci. Food Agric. 25: 129-138.

Williams, J. G. 1984. Fracture Mechanics of Polymers. Ellis-Horwood: Chichester.

Whittenberger, R. T. 1952. Factors which affect the drained weight and other characteristics of heat-processed red cherries. Food. Res. 17: 299-306.

Young, D. A., Tarn, T. R. and Davies, H. T. 1983. *Shepody*: a long, smooth, white-skinned potato of medium maturity with excellent french fry quality. Am. Potato J. 60: 109-113.

APPENDICES

Appendix 1. Effect of location on mechanical properties of *Russet Burbank* potatoes

Location	G' (kNm^{-2})	Toughness (Jm^{-2})	Feathering (%)	Stiffness (kNm^{-2})	Strength (kNm^{-2})
Pr>F[1]					
Manitoba	315.22	358.79	3.24	2885.68	142.62
BC	315.67	307.14	1.98	2536.48	113.13
Pr>F	0.999	0.221	0.358	0.233	0.003

1 Pr>F refers to the level of significance of the test statistic.

Appendix 2. Main effects which significantly[1] affect the mechanical properties of potatoes every month and overall

Month	Storage Modulus (G') (kNm^{-2})	Toughness (Jm^{-2})	Feathering (%)	Stiffness (kNm^{-2})	Strength (kNm^{-2})
November	temp man	man	temp	cv temp man	cv man
December	cv temp man	temp man	temp man	cv temp man	cv temp man
January	temp man	sol temp man	man	cv temp man	cv man
February	temp man	sol temp man	temp man	cv temp man	cv temp man
March	temp man	temp man	sol temp man	cv temp man	cv temp man
April	temp man	man	man	cv temp man	cv temp man
May	temp man	solid temp man	sol man	cv sol temp man	cv temp man
June	temp man	temp man	man	temp man	temp man
Overall	temp man month	temp man month sol	temp man sol	temp man month sol cv	temp man month cv

[1] $p<0.05$

Note: temp = tuber pre-heating temperature; man = mannitol concentration; cv = cultivar; sol = solids content.

Appendix 3. Significant[1] interactions between the main effects for every month and overall

Month	Storage Modulus (G') (kNm^{-2})	Toughness (Jm^{-2})	Feathering (%)	Stiffness (kNm^{-2})	Strength (kNm^{-2})
November	temp*man	NA[2]	NA	temp*man	temp*man*sol temp*cv
December	temp*man cv*man	temp*man	NA	temp*man	NA
January	temp*man	temp*man*sol	NA	temp*man	NA
February	temp*man	temp*man*sol cv*sol	temp*cv sol*cv*man	temp*man	temp*man
March	temp*man	temp*man*cv	temp*man*sol	temp*man	temp*man
April	temp*man	temp*man*cv sol*man	NA	temp*man	temp*man
May	temp*man	temp*man temp*sol man*sol	temp*man temp*sol	temp*man temp*sol temp*cv	temp*man
June	temp*man	temp*man	NA	temp*man	temp*man
Overall	temp*man temp*month month*man*cv sol*cv	temp*man	temp*man temp*month sol*cv	temp*man temp*month temp*sol temp*cv*sol	temp*man

[1] $p<0.05$

[2] Not Available (No interaction between the main effects, as obtained from SAS statistical analysis program)

Note: temp = tuber pre-heating temperature; man = mannitol concentration; cv = cultivar; sol = solids content.