JOURNAL OF MATERIALS SCIENCE **39** (2004) 529–538

The influence of tissue porosity on the material properties of model plant tissues

A. P. ORMEROD, J. D. RALFS, R. JACKSON, J. MILNE, M. J. GIDLEY
Unilever R&D Colworth, Sharnbrook, Beds. MK44 1LQ, UK
E-mail: andrew.ormerod@unilever.com

Plant cell walls are a key determinant of the material properties of vegetable tissue following thermal processing. This study focussed upon the effects of heat on the material properties of model vegetable tissues (Chinese water chestnut and carrot), with particular emphasis on the rate of compression during mechanical testing. In a homogeneous system such as cooked Chinese water chestnut, low strain rate compression (0.2 min^{-1}) produced buckling of the cell walls, steady fluid expression, low stiffness and fractures at high strains. However a high compressive strain rate (>50 min^{-1}), produced a high stiffness and failure by a rapid, brittle fracture at low strain, which propagated by cell rupture causing limited, rapid fluid release. These differences in mechanical behaviour are ascribed to the ability of cellular fluid to flow through the tissue during the timescale of the compressive test. When carrot tissue was heated for short periods of time (<10 min at 100°C), the tissue stiffness again increased with strain rate. For longer heating times (>20 min at 100°C), weakening of the inter-cellular adhesion changed the failure mechanism from cell rupture to cell separation.

These results show that the material properties of processed vegetable tissue depend upon, not only the previously known factor of inter-cellular adhesion and cell wall strength, but also the cell wall porosity and the ease of fluid flow.

1. Introduction

The mechanical properties of a plant-based food determine the textural perception, the release of flavours and the bio-availability of nutrients. The thermal processing of vegetables can radically alter the properties of the material. Raw plant material properties are typically studied at relatively low strain rates (crosshead speeds of between 2 and 200 mm/min [1–5]), with limited work being performed on processed material [6–8]. Thermal processing denatures cell membranes, resulting in a loss of turgor within the plant tissue and enabling the cellular fluid to flow more freely throughout the tissue on the application of strain. The plant cell walls however, are still present and although their properties may be significantly altered at the microstructural and/or molecular level, the plant tissue can still be considered to be a fluid-filled cellular material. The dependence of the flow properties of a fluid on the rate at which strain is applied, made it relevant to study the effects of strain rate on processed plant materials.

Mechanical studies are conveniently carried out using flat plate compression tests to determine stiffness and strength with the mode of failure observed and recorded at the macro level, and examined at the microstructural level using light microscopy. Expression of fluid during mechanical tests can also be observed and measured.

Model systems such as Chinese water chestnuts and carrots were ideal materials for this study, with cooking time being a simple processing parameter. Chinese water chestnuts possess a relatively homogeneous microstructure, which is important for linking mechanical and structural properties. They also retain their textural properties on cooking, primarily due to the thermal stability of the inter-cellular binding, caused by covalent phenolic cross-linking [9–11]. By contrast, carrots soften on cooking and, despite their heterogeneous structure, are a useful system to study, since a whole range of textural qualities can be obtained by varying heating conditions. These two model plant materials are also relatively large, allowing reasonably sized test-pieces to be obtained for mechanical tests.

2. Experimental methods

2.1. Sample preparation

Raw carrots and canned Chinese water chestnuts were purchased from a local supermarket. The chinese water chestnuts would have been subjected to high temperatures during the canning process and their membranes will have been denatured. Subsequently, they will be referred to as processed Chinese water chestnuts to highlight that they are not in their raw, turgid state. The

heating regimes of this study involved immersing ten whole processed Chinese water chestnuts in 500 ml of boiling water for specific times. The samples were then placed in ambient water to cool and ensure that they were at the same temperature for the duration of the mechanical tests. Cubes (10 mm) were then cut from the whole water chestnuts using microtome blades mounted such that material with defined dimensions could be obtained. Similar quantities of heat were applied to the carrots, in order to compare the effects of additional heating on the original materials, though the Chinese water chestnuts will already have received an unknown level of thermal treatment during the canning process. Ten sections of carrot, of a similar size to the whole Chinese water chestnuts (approx. 15 mm high and 20 mm diameter) were immersed in 500 ml of boiling water for specified times, ranging from 5 to 30 min. These were then cooled and cubes (10 mm) cut from the outer region (cortex) of the carrot.

2.2. Mechanical testing

Flat plate compression tests were performed on 10 mm cubes of plant material over a range of strain rates. The speed of the plates ranged from 2 to 500 mm/min using an Instron Universal Testing Machine (Model 4501—Instron Ltd.). An ESH Testing rig (Model 5250—ESH Testing Ltd.) was employed for higher speeds of 1200 and 2400 mm/min. The cubes were compressed during the test to 80% strain. The degree of fluid expression was measured by weighing the material before and after the test, with any expressed fluid being removed, including from the surface of the compressed material. This was repeated for 10 cubes and the average weight loss due to fluid expression calculated. For each heating regime a typical stress/strain plot was chosen to represent an average of the properties and depict the general behaviour of the test pieces. The stiffness, strength and energy to failure of the tissue were then calculated. Further tests were performed with strains of 25% being applied in order to examine the initial failure of the tissue. The failed test pieces were photographed and then placed in fixative for examination by light microscopy.

2.3. Light microscopy

Intact cubes (post-heating), along with failed test pieces (25% or 80% strain), were subjected to a standard histological preparation procedure, prior to examination by light microscopy. Initially, the test pieces were placed in fixative (formol acetic alcohol) for 10 days. A series of increasing alcohol washing steps (70% ethanol to absolute) dehydrated the tissue, before the alcohol was removed using toluene and the tissue was impregnated with wax. The samples were embedded into moulds and 5 μm sections were cut with a microtome (Leica Instruments), before incubation overnight at 56°C. The wax was then removed from the sections using xylene, which were then hydrated using a series of decreasing alcohol steps (absolute ethanol to 70%, then water) and stained with 0.1%. Toluidene Blue in 1% bicarbonate in distilled water (Chinese water chestnut) or 1% Periodic Acid Schiff/1% Light Green (carrot), air dried and mounted in a resinous mountant. Light microscopy examination was then performed in order to assess the tissue microstructure.

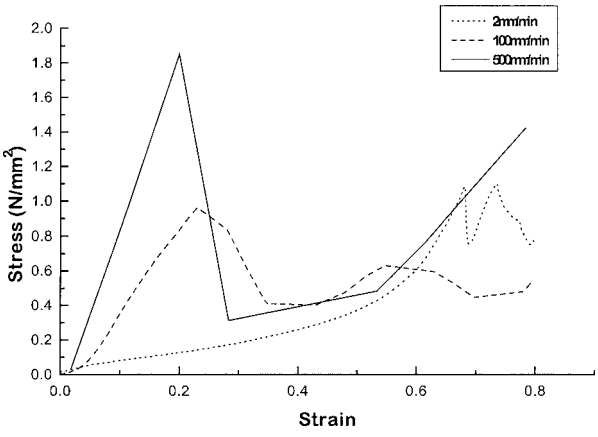


Figure 1 The dependence of the compressive mechanical behaviour of processed Chinese water chestnut tissue on strain rate.

3. Results

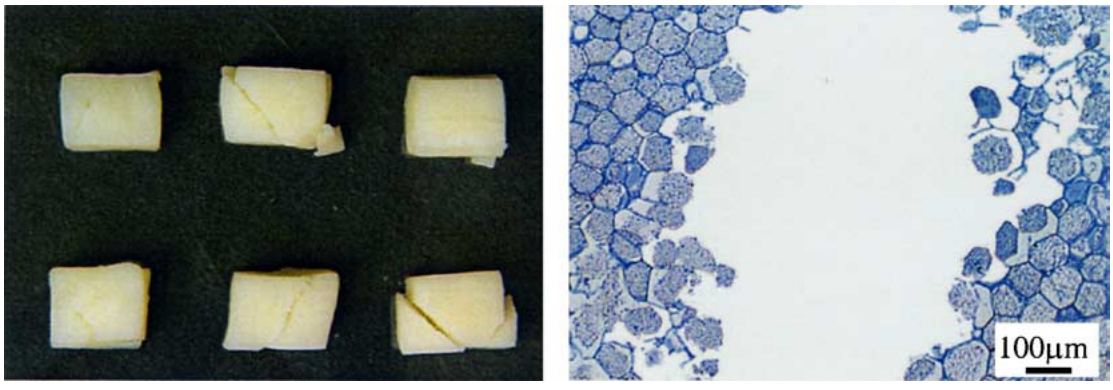
3.1. Chinese water chestnut

The compressive mechanical behaviour of the processed Chinese water chestnuts was highly dependent upon the strain rate at which the test was performed, as shown in Fig. 1.

At 500 mm/min, the tissue has a high stiffness and failure occurs at low strain by a rapid, brittle fracture. The fracture runs at approxiately 45° to the applied strain, propagating through the cells (Fig. 2a and b) and is accompanied by a sharp, acoustic emission. As compression continues to 80% strain, additional fractures occur until the tissue is fragmented into several pieces—this fracture and breakdown of the tissue at high strain was also observed at 100 mm/min (Fig. 3a). During the initial brittle fracture of the material, a small amount of fluid is rapidly expressed, with further fluid being lost in a similar manner towards the end of the test.

The mechanical response of the tissue at 2 mm/min is completely different. The material has a much lower stiffness, with fluid being slowly and continually expressed from the tissue throughout the compression. No fractures are apparent in the sample until relatively high strains have been applied. There is no obvious barrelling of the test piece, which results in the tissue cube being merely compressed in the direction of the applied strain, with the internal cellular structure being buckled rather than fractured (Fig. 4a and b). Therefore, at 80% strain the shape of the test piece is essentially that of a flattened cube (Fig. 3b), with the same cross-sectional area as the original, but surrounded by large quantities of expressed fluid.

Intermediate strain rates, such as 100 mm/min, cause the tissue to have a stiffness that is slightly less than that

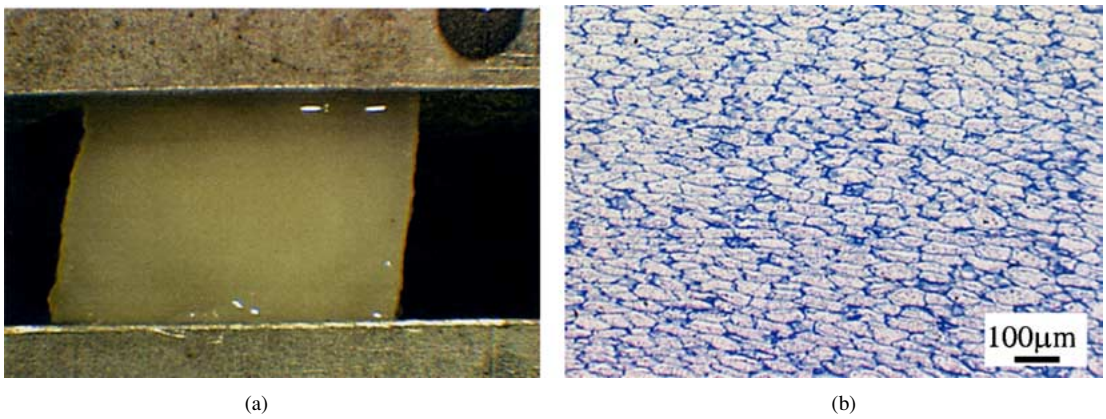


(a) (b)

Figure 2 Chinese water chestnut compressed at 500 mm/min to 25% strain: (a) showing shear, brittle fractures and (b) fracture path through cells.

(a) (b)

Figure 3 Chinese water chestnut compressed at: (a) 100 mm/min to 80% strain—many fragments formed and (b) 2 mm/min to 80% strain—flattened cube (square) formed, with some fracture occurring at high strain.



(a) (b)

Figure 4 Chinese water chestnut compressed at 2 mm/min to: (a) 25% strain—fluid expression, no barrelling and (b) 80% strain—failure by cell wall buckling.

at the higher rates of strain, however the mode of failure is quite different. A slow fracture propagates in the direction of applied strain, through the central region of the test-piece and is therefore apparently tensile in nature (Fig. 5). The fracture does not propagate throughout the whole sample as soon as it is initiated, unlike the brittle fracture that occurs at the higher strain rates (Fig. 2a).

The dependence of the tissue stiffness on strain rate is shown in Fig. 6. Due to the non-linearity of the initial slope of the stress/strain curve, the stiffness of the tissue, for all the strain rates, was calculated from the gradient of the stress/strain curve at a specific strain before failure (10%). The tissue stiffness initially increases

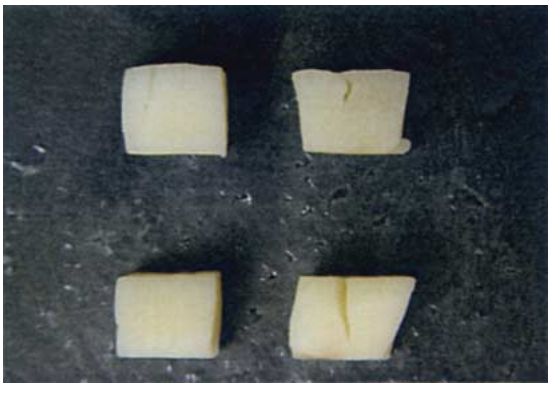


Figure 5 Chinese water chestnut compressed at 100 mm/min to 25% strain—tensile fracture apparent.

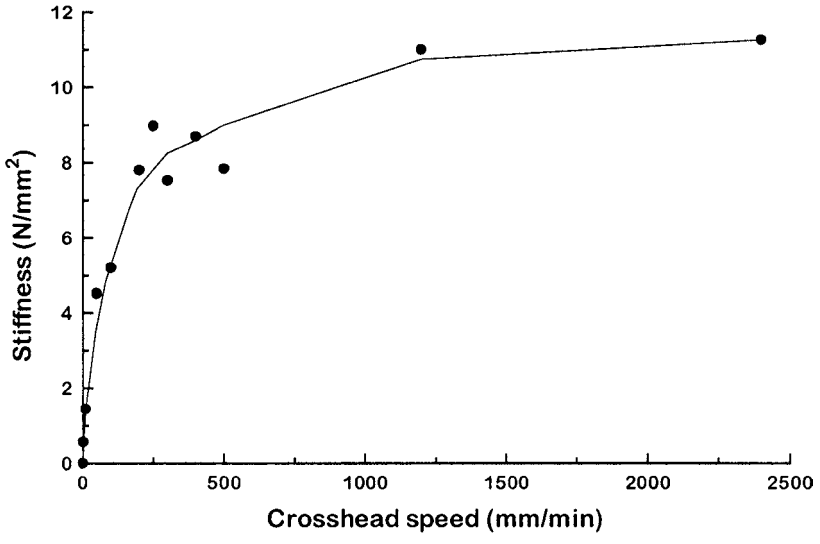


Figure 6 The dependence of the stiffness of processed Chinese water chestnut tissue on strain rate.

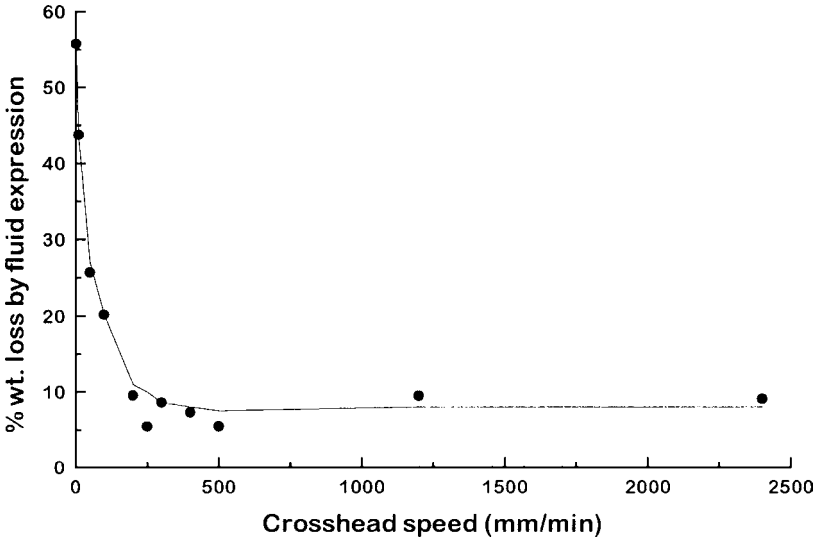


Figure 7 The dependence of the fluid expression during compression from processed Chinese water chestnut tissue on strain rate.

rapidly with strain rate and is then roughly constant at 10 N/mm^2 at the highest strain rates.

The influence of strain rate on the amount of fluid expressed from the tissue during compression to 80% strain is shown in Fig. 7. The fluid expression from the tissue decreases considerably with strain rate, converse to the increase in stiffness (Fig. 6), reflecting the change in failure modes with strain rate.

The potential rehydration and recovery of the processed Chinese water chestnut tissue which had been compressed to 80% strain at 2 mm/min was assessed. Immersion in water at ambient temperature over a period of 24 h resulted in the tissue returning to its original size and shape. The tissue was then re-compressed at 2 mm/min and possessed similar mechanical properties to the original (Fig. 8).

Chinese water chestnuts are well known for retaining their texture on cooking. The mechanical behaviour of the processed Chinese water chestnut tissue was tested following an extended heating time of 30 min in boiling water. There was little change to the mechanical behaviour, which is illustrated in Fig. 9.

3.2. Carrots

The degree of heat applied to carrot strongly influences the strain rate dependence of the mechanical behaviour of the tissue. The properties of the raw material and that which has experienced relatively long heating times, for example 30 min, are essentially unchanged by the strain rates used in this study. However, the behaviour of the tissue that has been heated for short lengths of time is particularly strain rate dependent. These results are shown in Fig. 10.

The raw carrot has a high stiffness and fails with a rapid, brittle fracture for all strain rates investigated. This is very similar to the fracture that occurs when compressing the processed Chinese water chestnuts at high strain rates, since the shear fracture is self-propagating and accompanied by an acoustic emission, along with a small amount of rapidly expressed fluid (Figs 1 and 2).

The mechanical tests that were performed on heated tissue at low strain rates, such as 2 mm/min (Fig. 10a), all indicated that the material had a relatively low stiffness, with failure occurring by shearing and slow

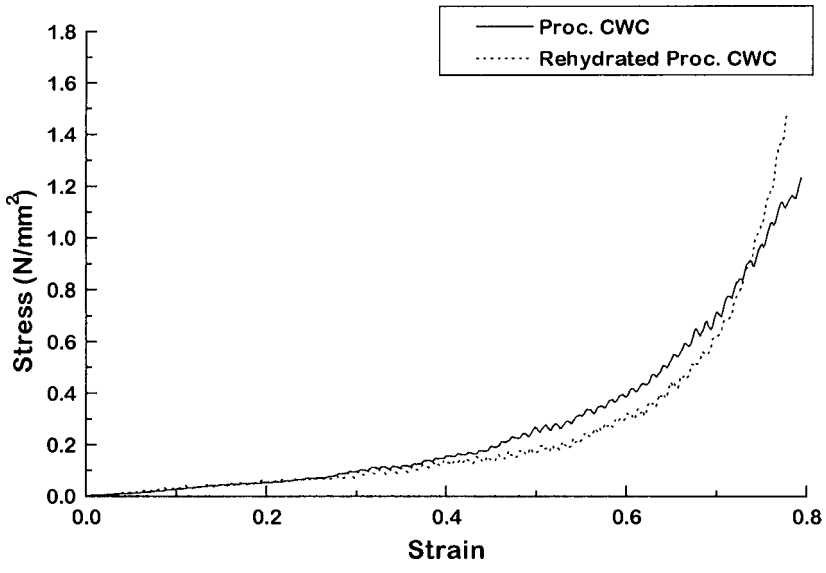


Figure 8 Comparison of the mechanical behaviour at low strain rate of processed Chinese water chestnut tissue (CWC) and compressed tissue following immersion in water.

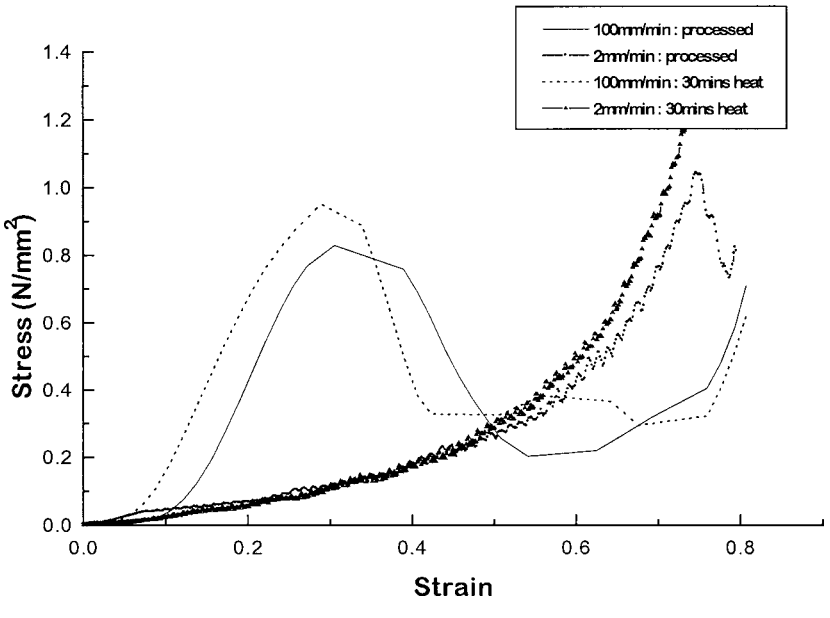


Figure 9 Comparison of the mechanical behaviour of processed Chinese water chestnut tissue and tissue heated at 100°C for 30 min.

fractures, probably due to the heterogeneity of the tissue structure.

At high strain rates, for example 500 mm/min (Fig. 10c), the tissue heated for long periods of time (20 or 30 min) has a low stiffness, and the low peak force indicates that it is relatively weak. Analysis of the microstructure around the failure zone indicates that the fractures propagate between the cells (Fig. 11b). However, tissue subjected to much shorter thermal treatments responds quite differently. This material is significantly stiffer and stronger at the higher strain rates and fails with a fracture that is similar to that which occurs in the raw material, with propagation of a brittle, sound-emitting fracture occurring predominantly by cell rupture (Fig. 11a). Therefore at high strain rates, there appears to be a transition in the fracture mechanism from cell rupture to cell separation, as the heating time increases (Table I), which is accompanied by a decrease in the strength and stiffness of the tissue (Fig. 10c).

The behaviour of the tissue at an intermediate strain rate of 100 mm/min (Fig. 10b) is similar to that at

TABLE I Change in the fracture mechanism of carrot tissue with heating time, when compressed at 500 mm/min

Heating time	Raw	5 min	10 min	20 min	30 min
Fracture Mechanism	Cell rupture	More cell rupture than separation	Mainly cell separation, little rupture	Cell separation	Cell separation

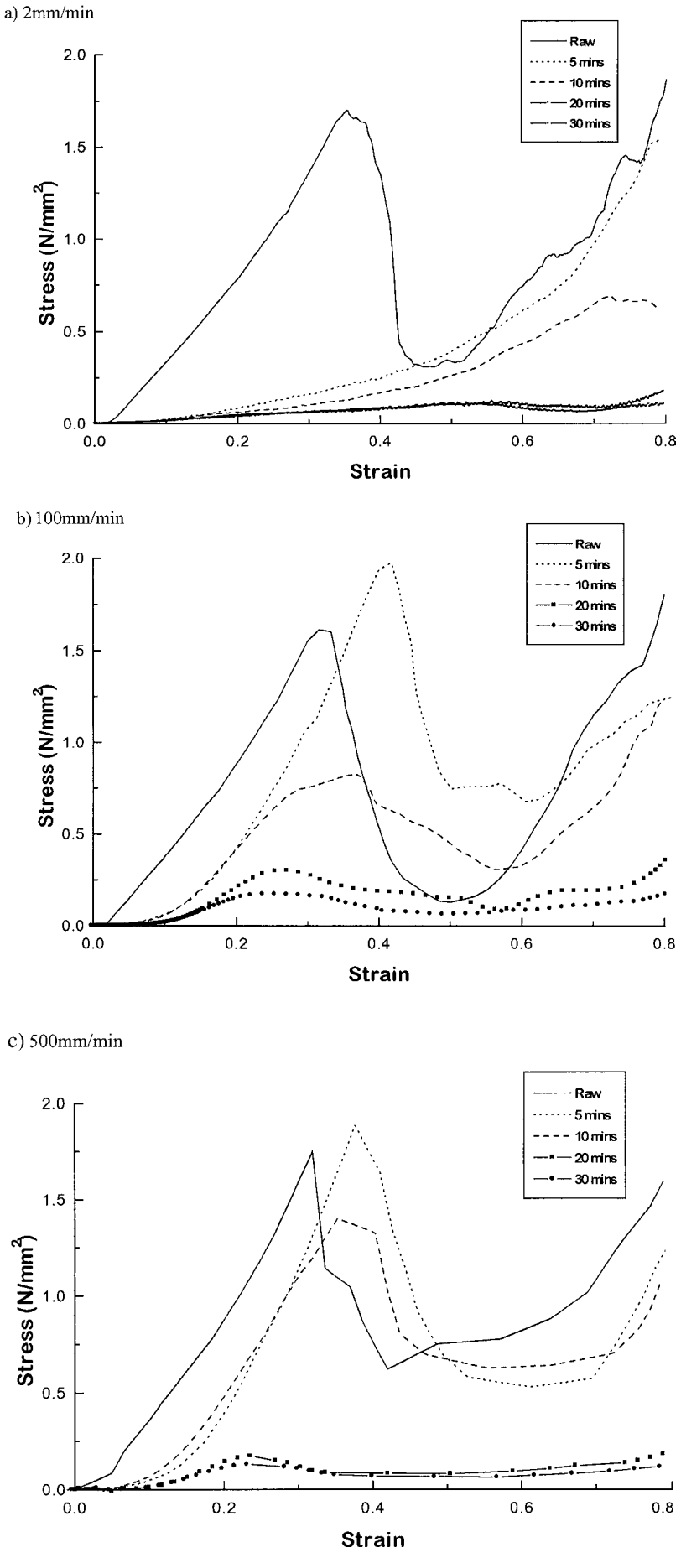
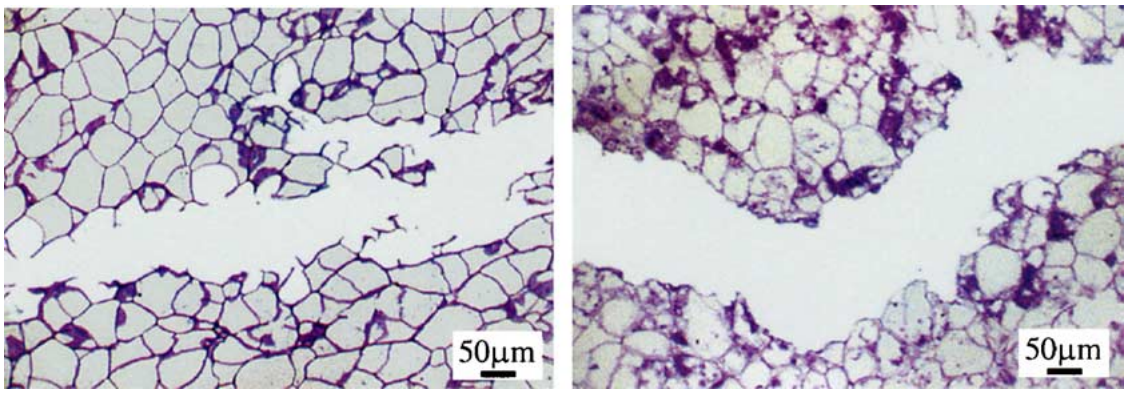


Figure 10 The mechanical behaviour of carrot tissue, subjected to a range of heating times, compressed at: (a) 2 mm/min, (b) 100 mm/min and (c) 500 mm/min.



(a) (b)

Figure 11 Carrot compressed at 500 mm/min to 25% strain: (a) Raw carrot; brittle fracture through cells and (b) Carrot heated for 30 min; fracture occurs between cells.

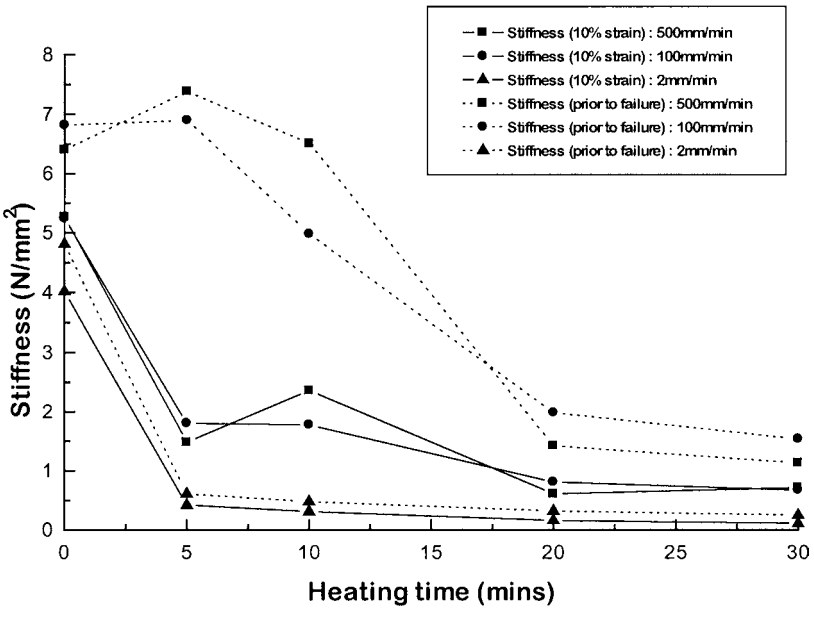


Figure 12 The variation in carrot tissue stiffness (on initial deformation & prior to failure) with heating time, at a range of strain rates.

500 mm/min, though the strength of the tissue following 10 min of heating is notably less, suggesting its behaviour is in between that occurring at 2 and 500 mm/min.

The variation of tissue stiffness with heating time for a range of strain rates is shown in Fig. 12. The stiffness was calculated at two strain values; on initial deformation (10% strain) and prior to failure (25% strain for raw, 5 and 10 min heating times; 15% strain for 20 and 30 min heating times). The decrease in the strength of the tissue and the energy to failure, during compression at 500 mm/min, as the heating time increases, are illustrated in Figs 13 and 14, respectively. The change in displacement at yield, on compression at 500 mm/min, with heating time is shown in Fig. 15.

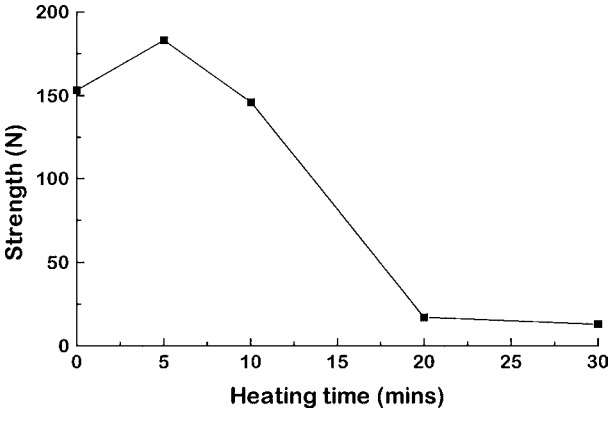


Figure 13 The variation in tissue strength, during compression at 500 mm/min, with heating time.

4. Discussion

4.1. Chinese water chestnuts

The stiffness, failure and degree of fluid expression of processed Chinese water chestnuts are strongly influenced by the strain rate at which the tissue is compressed (Figs 1–7). The contrasting mechanical responses to different strain rates suggest that the flow of fluid within the cellular system may be a dominating factor governing the mechanical behaviour of this and potentially all cellular tissues. Therefore, the porosity of the tissue, particularly the cell walls, and the rheological properties of the fluid would be influential with respect to the mechanics of the tissue.

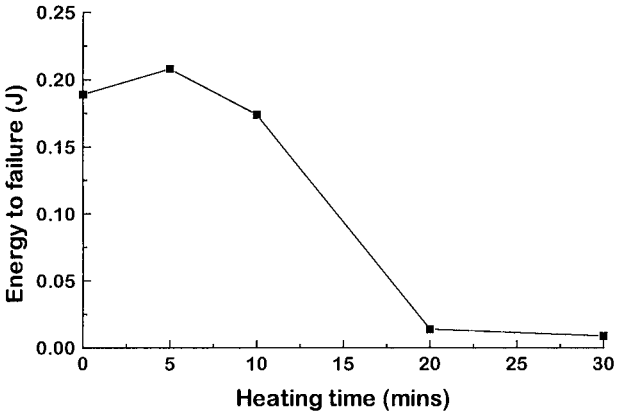


Figure 14 The variation in energy to failure, during compression at 500 mm/min, with heating time.

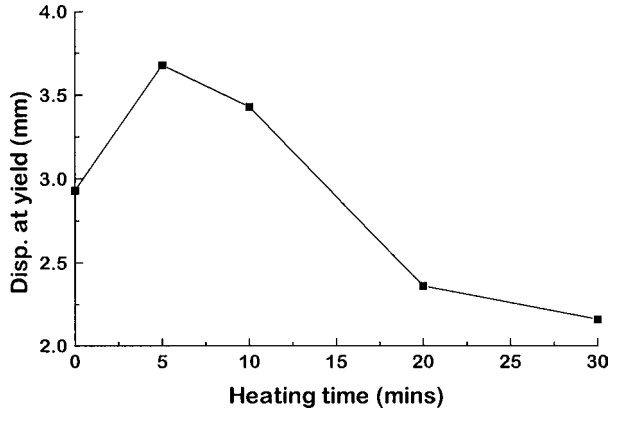


Figure 15 The variation in displacement at yield, during compression at 500 mm/min, with heating time.

At low strain rates, the porosity of the walls is such that cellular fluid is able to flow from thermally processed tissue during the timescale of the compression. The Chinese water chestnuts used in this study will have been subjected to high temperatures during the canning process, destroying the cell membranes and resulting in a non-turgid, cellular material. Therefore, the fluid in the tissue will be relatively free to move within the system, whereas in the raw material the cell membranes would considerably restrict this flow. As slow compression of the processed material occurs, fluid is gradually expressed (Fig. 4a) and the internal cell walls steadily buckle (Fig. 4b). Thus, the original cube of tissue is compressed, with little or no barrelling, until essentially a thin square of tissue results, with only one or two cracks occurring at high strain (Fig. 3b).

The mechanical behaviour at high strain rates can be explained by the restriction of the flow of fluid due to the nature of the test. The rate of compression and the tissue (cell wall) porosity is such that the fluid cannot escape from the system within the timescale of the strain being applied. Hence, the non-compressible fluid is trapped within the cellular structure by the cell walls resulting in high material stiffness. Large tensile forces act on the cell walls due to the entrapment of the fluid, which results in eventual cell rupture. A fracture is effectively initiated which propagates rapidly through other cells (Fig. 2b) causing the material to fail with a rapid, self-propagating, shear fracture (Fig. 2a). Limited fluid is rapidly released from the ruptured cells, due to the high pressure that had been induced and further compression and fractures result in fragmentation (Fig. 3a). The decrease in the weight of the material due to fluid loss is 5–10%, with the fragments therefore retaining the majority of their fluid. This is in contrast to the material which had been compressed slowly, in which up to 50% of the weight is lost due to the gradual expression of fluid during the test (Fig. 7).

It should be noted that the compressive stiffness of the cell walls could be strain rate dependent and therefore this property could control the tissue stiffness. Although the biopolymer matrix of the thin cell walls could have a degree of strain rate dependence, it is considered more likely that the rheology of the fluid and the wall porosity control the material stiffness.

Chinese water chestnuts are unusual compared to most other vegetables, because they retain inter-cellular adhesion and do not soften on cooking (Fig. 9) [9–11]. Commonly in vegetables, the pectin in the middle lamellae between the cells degrades on heating by a chemical β-elimination mechanism, thus reducing the adhesion between the cells and softening the material [12, 13]. However, Chinese water chestnuts contain unusually high levels of thermally stable phenolic cross-links which lead to a retention of strong inter-cellular binding during heating [10, 11, 14]. Therefore, the strong binding between the cells in the processed Chinese water chestnuts is also a factor which leads to the mode of failure at high strain rates being cell rupture, whilst cell wall buckling occurs at low strain rates.

Following compression of the Chinese water chestnut tissue to 80% strain at 2 mm/min, the tissue recovered its size, shape and mechanical properties, when placed in water overnight (Fig. 8). Two possible explanations for this mechanical recovery are: firstly, the water is drawn osmotically back into the tissue, due to the concentrated cell contents and/or starch gel, which subsequently causes the cell wall microstructure to recover. This infers that the walls are plastically deformed and that in terms of their permeability they have a low porosity which is potentially semi-permeable in nature. An alternative explanation for the rehydration recovery is that the cell wall material, coupled with the compressed structure that it forms, is viscoelastic in nature, thus recovering and drawing in water as it does so. Although it is unlikely that the cell wall material is inherently viscoelastic, the curvature of the cell wall material that forms the cells could result in the compressed cellular structure behaving in a viscoelastic manner. Further experiments on the tissue or cell wall material would be necessary to elucidate the mechanism of recovery on rehydration.

4.2. Carrots

The mechanical properties of carrot tissue, such as stiffness, strength and failure mode, are dramatically altered by the extent of heating, which also influences the degree of strain rate dependence of the mechanical behaviour. The properties of the raw material are largely

unaffected by the strain rates used in this study (Fig. 10). For all the carrot systems in this study the stiffness was measured on initial deformation (10% strain) and near to failure (25% or 15% strain depending on the heat regime), due to the J-shaped nature of the stress/strain curves of the heated tissue (Figs 10 and 12). The pre-failure gradient of the stress/strain curve of the raw material is essentially linear which is typical for turgid plant materials [15]. The cell membranes restrict the flow of cellular fluid within the tissue which, coupled with the high fluid pressure due to turgor, causes the material to have a high stiffness at all strain rates (Fig. 12). At low strains, a rapid, brittle fracture is initiated and propagates through the material, by a mechanism of cell rupture (Fig. 11a). This is similar to the behaviour of the processed Chinese water chestnuts at high strain rates (Fig. 2). In both systems the inter-cellular binding is strong, though the limitation of the fluid flow causing failure by cell rupture is produced by different effects—the cell membranes in the raw, turgid carrot, and fluid flow restriction at high strain rates in the non-turgid, processed Chinese water chestnut. The strong inter-cellular binding of the raw carrot ensures that the tissue is strong (Fig. 13) and hence the energy to failure is high (Fig. 14).

On heating the carrot tissue for 5 min in boiling water, the strain rate dependence of the mechanical properties is altered significantly. It would be anticipated that the membranes are denatured and the fluid within the tissue will subsequently be relatively free to flow within and from the system when strain is applied. Consequently, compression of the material at low strain rates produces a low stiffness (Figs 10a and 12), along with some shear and fractures due to the structural inhomgeneities within the tissue. This is in contrast to the raw material when even at low strain rates the tissue was stiff (Fig. 10a). At high strain rates however, the mechanical behaviour of the tissue is similar to the raw, turgid tissue, due to restricted fluid movement (Fig. 10c). At small strain, 10%, the stiffness is low (unlike the raw material), but increases until it is comparable with the raw tissue at 25% strain. Failure then occurs with a fracture similar to the brittle fracture observed in the raw, with the strengths and energies to failure of the heated and raw tissues being comparable (Figs 13 and 14). The tissue that has been immersed in boiling water for 10 min behaves very similarly, though the tissue is slightly weaker at the higher strain rate. The displacement at yield of the tissue heated for 5 and 10 min. is slightly higher than that for the raw (Fig. 15), possibly due to the strength and energy to failure of the tissue being similar to the raw, but the lower initial gradient causing the yield to occur at a higher displacement.

Prolonged heating in boiling water (20 or 30 min) results in a dramatic change to the mechanical properties, particularly at the high strain rates. At the low strain rate, the tissue is similar to that heated for shorter periods of time with the stiffness being low (Fig. 10a). However at the high strain rate, the material is much less stiff and considerably weaker than the raw tissue or tissue heated for a shorter time (Figs 12 and 13). The fractures that occur upon failure are not brittle in nature and propagate relatively slowly through the tissue. The weakening of the tissue is primarily due to the reduction in the strength of the binding between the cells. This is reflected in the mode of failure of the tissue, since the fractures propagate between the cells (Fig. 11b). Hence, as the heating time increases there is a steady transition in the failure mechanism of the tissue, from cell rupture to cell separation (Table I), which leads to a weaker tissue. Thermal degradation of the pectins in the cell wall and middle lamellae weakens the binding between the cells and results in a low energy to failure (Fig. 14) and a decrease in the displacement at which yield occurs (Fig. 15). The lower input of energy into the system would prevent the fractures from being self-propagating or brittle. The thermal degradation of the pectin may also cause the porosity of the tissue to increase, since the pectin matrix is believed to control cell wall porosity [16] and this may be reflected in the lower stiffness of the tissue.

Therefore, as with the Chinese water chestnut system, the ease of fluid flow in the carrot tissue is probably a key determinant of the mechanical behaviour. The strength of the inter-cellular binding is also important, along with the changes that can occur at high temperatures.

4.3. Generic model linking mechanics & structural failure of plant tissue

The factors influencing the mechanical properties of tissue, such as porosity, inter-cellular binding and rate of compression, can be combined to form a generic, qualitative model linking the mechanical, structural and failure properties (Fig. 16). Plant materials that have weak inter-cellular binding fail by cell separation, as illustrated by carrots which have been subjected to prolonged heating at high temperatures. Fluid release as a consequence of failure will be limited, due to the separating cells encapsulating most of the fluid, though some fluid may be released prior to failure, due to the porous nature of heated cell walls following thermal denaturation of the membranes. Tissue with strong inter-cellular adhesion and low porosity would fail by cell rupture, accompanied by an element of fluid expression,

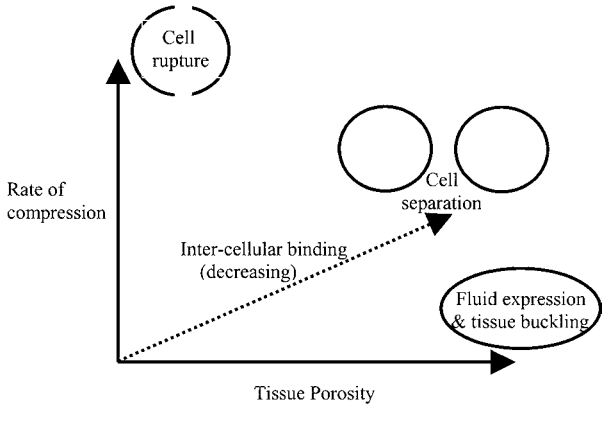


Figure 16 A schematic generic model linking the mechanical, structural and failure properties of plant tissues.

for example the raw carrots or Chinese water chestnuts on rapid compression. However, such tissue when compressed slowly, or tissue with inherently high porosity, would fail by tissue buckling and steady fluid loss. Hence, the three different failure mechanisms and their accompanying mechanical properties would give rise to three characteristic types of fluid release.

5. Conclusions

The key finding of this work is that the mechanical properties and failure of plant materials depend upon the tissue porosity and the ease of fluid flow, which is influenced by strain rate. This, coupled with the known ability of inter-cellular adhesion to affect the material properties, enables a qualitative, generic model to be proposed which illustrates how these key factors influence the failure properties of the tissue. In a simple, homogeneous system, such as canned Chinese water chestnut, a low strain rate leads to compression of the tissue, buckling of the internal cellular structure, a considerable and steady expression of fluid and a low stiffness, with any fractures occurring at high strains. By contrast, the application of a high strain rate produces a completely different behaviour. The tissue has a much greater stiffness, with failure occurring at low strain by a rapid, brittle, sound-emitting fracture that propagates through the tissue by a cell rupture mechanism, causing a limited, but rapid, release of fluid. These differences in the mechanical behaviour are probably caused by the ability of the cellular fluid to flow through and from the tissue during the timescale of the compressive test. Therefore, the ease of fluid flow and the tissue porosity are key factors governing the mechanical behaviour of these fluid-filled, cellular materials.

The application of further heating to the canned Chinese water chestnuts had no significant effect, due to the thermal stability of the strong, phenolic-based inter-cellular binding. The carrot system, a more typical vegetable, was weakened dramatically on heating. The increased heating time leads to a reduction in the thermally labile, pectin-based inter-cellular adhesion which causes the failure mechanism of the tissue to change from cell rupture to cell separation. For the carrot tissue heated for short periods of time, the tissue stiffness was strain rate dependant, due to the heat induced denaturation of the cell membranes enabling fluid flow to occur. This is similar to the behaviour observed in processed Chinese water chestnut. For longer heating times, the weakness of the tissue dominated its mechanical behaviour, which was relatively independent of strain rate.

Plant tissues such as potato and carrot are fluid-filled, cellular materials. The mechanical behaviour of these systems should therefore be related to the properties of cellular solids or foams, as reviewed by Ashby and Gibson [17, 18]. However, as demonstrated above, clearly the properties of the fluid and the porosity of the cell walls are fundamental to the behaviour of the plant material and therefore the ability of the fluid to flow must be accounted for, to fully understand and potentially model the mechanical and failure properties of plant materials. Warner and Edwards [19] and Warner *et al*. [20] extended the approach of Gibson and Ashby to model the influence of fluid flow on the elasticity and failure of filled foams at low strain rates, but did not take into account restricted fluid flow due to high strain rates. This current work suggests that descriptions of tissue behaviour with relevance to real world strain rates need to take fluid flow restriction into account. The studies on Chinese water chestnut described in this paper have since been extended to include turgid and non-turgid potato tissue. This data has subsequently been examined [21] by the Warner and Edwards fluid-filled foam model, and also a model based upon a single, fluid-filled cell, developed by Lui and Jeronimidis [22], which is currently being extrapolated to whole tissue.

Acknowledgements

The authors wish to thank Prof. George Jeronimidis (University of Reading) and Prof. Peter Lillford and Dr. Kathy Burrows (Unilever R&D Colworth) for useful discussions.

References

1. A. A. KHAN and J. F. V. VINCENT, *J. Text. Studies* **24** (1993) 423.
2. C. H. PANG and M. G. SCANLON, *Can. J. Bot.* **74** (1996) 859.
3. M. G. SCANLON and A. E. LONG, *Food Res. Intern.* **28**(4) (1995) 397.
4. K. C. DIEHL, D. D. HAMANN and J. K. WHITFIELD, *J. Text. Studies* **10** (1979) 371.
5. K. C. DIEHL and D. D. HAMANN, *ibid.* **10** (1979) 401.
6. A. A. KHAN and J. F. V. VINCENT, *ibid.* **27** (1996) 143.
7. S. LURIE and A. NUSSINOVITCH, *Int. J. Food Sci. Tech.* **31** (1996) 1.
8. L. C. GREVE, R. N. MCARDLE, J. R. GOHLKE and J. M. LABAVITCH, *J. Agric. Food Chem.* **42** (1994) 2900.
9. G. S. MUDAHAR and J. J. JEN, *J. Food Sci.* **56** (1991) 977.
10. M. L. PARKER and K. W. WALDRON, *J. Sci. Food Agric.* **68** (1995) 337.
11. K. W. WALDRON, A. NG, M. L. PARKER and A. J. PARR, *J. Sci. Food Agric.* **74** (1997) 221.
12. J. P. VAN BUREN, *J. Text. Studies* **10** (1979) 1.
13. J. T. VAN MARLE, A. C. M. CLERKX and A. BOEKESTEIN, *Food Structure* **11** (1992) 209.
14. A. J. PARR, K. W. WALDRON, A. NG and M. L. PARKER, *J. Sci. Food Agric.* **71** (1996) 501.
15. T. LIN and R. E. PITT, *J. Text. Stud.* **17** (1986) 291.
16. N. C. CARPITA and D. M. GIBEAUT, *The Plant Journal* **3**(1) (1993) 1.
17. M. F. ASHBY, *Metal. Trans.* A **14A** (1983) 1755.
18. M. F. ASHBY and L. GIBSON, "The Structure and Properties of Cellular Solids" (Pergammon Press, Oxford) 1988.
19. M. WARNER and S. F. EDWARDS, *Europhys. Lett.* **5**(7) (1988) 623.
20. M. WARNER, B. L. THIEL and A. M. DONALD, *PNAS* **97**(4) (2000) 1370.
21. J. D. RALFS, Ph.D. Thesis, Dept. of Engineering, University of Reading, 2002.
22. G. JERONIMIDIS and J. H. LIU, Structural Mechanics of Parenchyma Tissue, in Technische Biologie und Bionik 4. Bionik-Kongress, München. BIONA Report 12. edited by W. Nachtigall and A. Wisser (1998) p. 65.

Received 26 December 2002
and accepted 18 August 2003