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Review article

Mechanical properties of oats and oat products

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The aim of this review is to illustrate how physical properties are important to food processing and quality. Three food products, flakes, porridge and bread, in addition to oat groats are used to show the influence of water and heat-treatments on the mechanical properties. The hydrothermal history of ingredients is shown to affect product quality. Water acts as a plasticiser and solvent in these foods, whilst heat modifies the conformation and interactions of macromolecular components. Structure as well as chemical composition is shown to govern texture.

Key words: glass transition, hardness, texture, water

Oat structure

The floral structure of the oat plant is in the form of an open panicle, with spikelets at the ends of the branches. The spikelets can bear up to three kernels, the largest of which is termed the primary kernel and the smallest the tertiary kernel. Sometimes the primary kernel does not develop this, giving rise to a double or bosom oat (White 1995, Youngs et al. 1982). The oat caryopsis (also called a groat, kernel or grain) is generally covered by the lemma and palae (hull). The hulls are tough and inedible, owing to their high cellulose content. In some cultivars the hull detaches during threshing, these are referred to as naked oats.

The groat is a complex structure, which can be differentiated into at least three distinct regions: bran, germ and endosperm based largely on the fractions obtained during commercial milling (Fulcher 1986). Oat bran, in particular, is rich in mixed-linkage β-glucan and so has in recent years become an important commercial product, based upon the purported ability of oat β-glucan to reduce serum cholesterol (Welch 1995). The oat germ represents only about 3.7% of the groat (Kent 1983, p. 22) but it is particularly rich in lipids and hydrolytic enzymes (Fulcher 1986), and so is important in storage stability. The largest portion (about 80%) of the grain is the endosperm.

Oat endosperm is composed mostly of starch, protein and lipid (Fulcher 1986, White 1995).

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The starch is in the form of compound granules around 20–150 mm in diameter, which are made up of individual polyhedral granules that are 3–10 μm in diameter (Hoseney 1986, Fulcher 1986). The lipid content of isolated oat starch is higher than other cereal starches (Zhou et al. 1998). Oat proteins are present in the form of discreet bodies (Fulcher 1986). The endosperm cells are enclosed in a cell wall, which in the case of oats is rich in β-glucan, protein and pentosans (Fulcher 1986).

Mechanical properties

Mechanical force is applied to food during most processing operations, as well as during chewing and swallowing (Padmanabhan 1995). In fluids, the study of the behaviour in response to force is termed rheology derived from the Greek word for flow. However, for solids this is inappropriate since solids by definition do not flow, but are deformed in proportion to the applied force. Most foods are viscoelastic, in other words they exhibit a combination of fluid-like (viscous) flow and a solid-like elastic responses. Hence, the term "mechanical properties" is used here to refer to the behaviour of a material as a response to an applied force.

The term "material" is used loosely here, not in the strict sense of a material being a homogenous substance. In the case of foods, it is more accurate to think in terms of biologically complex structures. It is necessary then to consider the chemical and physical components of each structure, and how they are arranged. It is also important to consider the types of forces involved during processing, especially with respect to the rate at which they are applied, and their duration. Finally, the processing and storage environment, as temperature and humidity will have a profound effect on the final mechanical properties.

Mechanical properties of food materials have been reviewed elsewhere (Dobraszczyk and Vincent 1999). The main mechanical parameters measured in foods are stress, strain, yield stress, stiffness, Young's modulus, toughness and strength. Normally a small test piece of the food of known geometry is deformed in a controlled manner, usually on a motor-driven machine, and the force applied as a function of distance moved is measured.

Stress is defined as the applied force divided by the cross sectional area over which the force acts, and strain is defined as the ratio of the change in dimensions as a result of the applied deformation. Strain compares the sample dimensions before and after deformation: for example, it could be the change in length divided by the original length during stretching, or the change in thickness divided by the original thickness during compression. The strength of the material can be defined as the rupture force, or the stress at which the material breaks (Fig. 1). This depends not only on the properties of the material, but also on the geometry of the test piece and how the stress was applied.

To enable comparisons between pieces of different sizes it is necessary to convert force into stress and deformation into strain, by taking into account the area over which the force is applied and the length of the piece respectively. The area of the test piece usually changes as a result of the strain, the ratio of lateral to axial strain is known as Poisson's ratio, typical values range between 0.2 and 0.5 in biological materials, 0.5 representing an incompressible material (Mohsenin 1986, Steffe 1996). The stiffness of the material is characterised by the slope of the stress-strain curve (Fig. 1). In the linear region this is referred to as the Young's modulus. The yield stress is defined by the point at which the stress-strain curve significantly deviates from linearity. A closely related concept is toughness, which is the energy required to break the material, and can be calculated from the area under the stress strain curve (Fig. 1).

The idea that energy rather than force is the key to understanding how materials break was advanced by Griffith (1920) it has since been applied to food materials, including cereals (Vin-

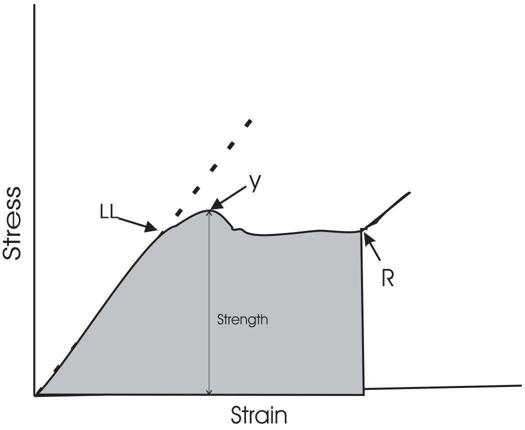

Fig. 1. Stress-strain plot for a possible biological material, showing the linear limit (LL), bioyield point (y) and rupture point (R). The shaded area represents toughness and the slope of the dashed line stiffness or Young's modulus. Adapted from Mohsenin 1986.

cent et al. 1991, Dobraszczyk 1994). Fracture mechanics describes the balance of two energies: the energy required to form new surfaces and the elastic energy stored in the material (Dobraszczyk and Vincent 1999). The theory recognises the importance of local stress concentrations, particularly at the tips of cracks, that substantially weaken the material.

In material science, hardness refers to a surface property referring to the resistance of indentation or abrasion, whereas cereal scientists use it to describe various ill-defined properties of cereals, such as their milling properties, their genetic classification or the sensory perception of biting a grain (Dobraszczyk 2001, Dobraszczyk et al. 2002). This serves as a good example of the difficulty of relating sensory properties with material properties. A combination of mechanical and fracture properties and the way that they are expressed and changed during chewing are essentially what determine the texture of a food (Dobraszczyk and Vincent 1999). However, the same word may be used to refer to different attributes and a single term is often assigned to a sensory perception that results from a number of material properties.

Texture is an important sensory property, especially in bland foods (Szczesniak 1990). Whilst the mechanical properties are obviously involved, the relationship between the mechanical and sensory properties is complex (Guinard and Mazzucchelli 1996, Rosenthal 1999, van Vliet 2002). This is due both to the complexity of human sensory perception and the non-ideal nature of food materials. Texture is not an isolated property but is influenced by other factors such as flavour (van Vliet and Luyten 1995), which is itself influenced by the texture (Hollowood et al. 2002).

Cereal hardness

Hardness is a well-known parameter in cereal quality characterization. However, a definition of hardness is elusive; some see it as a genetic trait, whereas others have tried to measure it mechanically, using a variety of methods (Dobraszczyk 2001). Direct methods have relied either on mathematical models to account for the shape of the grain (Shelef and Mohsenin 1967, Arnold and Roberts 1969), or have involved production of a sample piece with a regular geometric shape (Glenn et al. 1991, Haddad et al. 2001, Dobraszczyk et al. 2002). The small complex geometry of the grain makes the measurement of the mechanical properties of individual grains difficult, and consequently hardness is mostly measured on bulk samples (Glenn and Johnston 1992), usually by correlation of NIR spectra with particle size fractions obtained under standard grinding conditions.

The basis of wheat hardness has been extensively researched, although the findings are often apparently contradictory particularly when the hardness of single kernels is concerned (Stenvert and Kingswood 1977, Dobraszczyk et al. 2002). We will not discuss all the theories here as they have been reviewed elsewhere (Pomeranz and Williams 1990, Dobraszczyk 2001, Turnbull and Rahman 2002). However, the structure of the endosperm, in particular the continuity of the protein matrix and its adhesion to the starch granules seem to be key factors (Stenvert and Kingswood 1977, Dobraszczyk et al. 2002). The continuity of the protein matrix is not only a genetic trait, but is influenced by environmental conditions during growth and by grain drying (Stenvert and Kingswood 1977).

An interesting development has been the Single Kernel Characterization System (SKCS) an instrument which crushes the grains individually, and measures their force-deformation characteristics during crushing. Its use has been reviewed recently (Osborne and Anderssen 2003). This allows a large number of grains to be sampled in a test resembling a milling process, to build up a distribution of the crushing hardness of individual grains, rather than the average figure provided by bulk testing methods. One of the first reported measures of oat hardness involved this instrument (Osborne and Kotwal 1999). Recently Engleson and Fulcher (2002b) used a compression test to measure the mechanical properties of oats along the major axis. They did not observe a brittle-ductile transition but noted that the groats tended to buckle; at low moisture contents (9–10% w.b.) failure was through crushing and plastic compression and at high moisture contents (> 12% w.b.) the groats burst open near the midpoint.

Applications of oat hardness

The hulls must be removed from oats destined for human consumption. This is generally done commercially with an impact huller (Deane and Commers 1986, Ganssmann and Vorwerck 1995). The oats are fed through the hollow shaft of a high-speed rotor to the centre of a horizontal distribution plate. The plate is fitted with fins that guide the grains to the perimeter, where they hit a metal, rubber or composite impact ring (Deane and Commers 1986, Ganssmann and Vorwerck 1995). Hulling efficiency can be improved by grading the oats into homogenous size groups, controlling the moisture content and by adjusting the rotor speed (Ganssmann and Vorwerck 1995).

Groat breakage during dehulling is closely related to the mechanical properties of the grain. A moderate correlation between hardness, as determined by SKCS, and groat breakage was reported by Doehler and McMullen (2000) who also reported a correlation between hardness, bran yield and beta-glucan content. They also found environmental factors to be influential on groat breakage, with crown rust that infected some of the locations in their trial causing an increase in groat breakage. Ferulic acid has been linked to an increase in the stiffness of oat groats (Engleson and Fulcher 2002a) and they suggested that the mechanism for this could be ferulate or diferulate cross-linking. It has earlier been suggested that ferulic acid may increase insect resistance of maize by increasing grain hardness (Classen et al. 1990).

Naked oats lack the protection provided by the hull and are more vulnerable to mechanical damage that may result in reduced germination and grain viability during harvesting and post-harvest handling (White et al. 1999). A study of Finnish naked oats cultivars showed that there was a relationship between the proportion of normally germinated grains and the force required to cut the groat (Peltonen-Sainio et al. 2001): the harder cultivars were more brittle and thus would be more susceptible to damage. There was, however, considerable variation (about 25%) within cultivars.

Oat milling

Grain hardness is known to affect milling performance. In the case of oats, milling generally means flaking. However, with the current demand for β-glucan and other nutrient-enriched products, fractionation is becoming increasingly relevant. In the milling operation the physico-chemical properties of each individual grain interacts with the mill. The resultant fraction characteristics will depend on the size, density and hardness of the grain as well as the mill design and operating conditions (Campbell et al. 2001).

In flaking, the aim is to make the material flow into a uniform shape (Levine 1993), whilst in flour milling the goal is to fracture the grain and separate its components into commercially useful fractions (Gray et al. 2000). Therefore, for flaking the flow properties of the grain in compression will be important, such as yield stress, creep and relaxation (Haddad et al. 2001), whilst in milling the fracture properties will be more relevant.

The moisture content of the grain, and its distribution, also play an important role in determining the behaviour of the material. Haddad et al. (2001) found that with increasing moisture the Young's modulus and yield stress of wheat endosperm decreased, the rupture strength increased and the material tended to flow (Fig. 2). Another study that involved applying soaking and drying cycles to grain and measuring the apparent modulus of elasticity suggested that desorbing grains tend to be softer, and that flour yield was lower for these grains, except at high water activities (> 0.8) (Multon et al. 1981). They concluded that it appeared "necessary to know the hydric history and the sorption characteristics of the product when measuring a rheological property". The softening effect of water on the mechanical properties of oats has been shown (Engleson and Fulcher 2002a, b). The relationship between water content and the mechanical properties can be understood at the macromolecular level using the concept of the glass transition (Matveev et al. 2000) or the brittle ductile transition (Dobraszczyk and Vincent 1999). Whilst the glass transition temperature of various seeds has been determined (Williams 1994, Sun 1997), there are no reported values for oats. The relationship between water content and stiffness (Young's modulus) of various foods has been modelled with the Fermi equation at different temperatures. These studies show that there are two zones with fairly constant stiffness with a sharp decrease between, which has been linked to the glass transition (Peleg 1993, Roos et al. 1998).

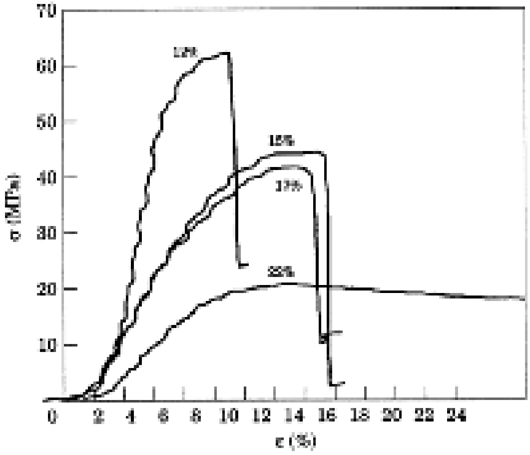

Fig. 2. Increasing moisture content softens wheat endosperm making it more ductile. Reprinted from Haddad et al. (2001) with permission from Elsevier.

The macromolecules in foods are generally in an amorphous state, at low moisture contents and low temperatures they are hard and brittle and are said to be in the glassy state. As the temperature or moisture content increases, the molecules become more mobile and consequently softer as they enter the rubbery state (Roos 1995), and the material can flow, or is ductile. Many food materials are handled in the ductile or rubbery region, or move in and out of the glassy region depending on the surrounding conditions. For example, many cereal-based products such as wafers, biscuits, snacks etc. are expected to be "crisp", or display the characteristics of the brittle, glassy region, but a small increase in water can move them into the rubbery region (Peleg 1994, Roos et al. 1998, Smith 1999). The main factors that affect the glass transition are moisture, temperature and rate. The general effect of effect of rate and temperature on polymers in the brittle and ductile state can be seen in Figure 3. As the temperature decreases, the yield stress and stiffness increase rapid-

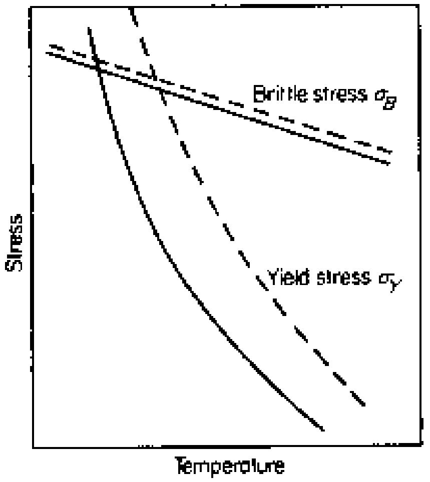

Fig. 3. Effect of strain rate and temperature on the brittle-ductile transition, the dashed line represents a higher strain rate than the solid line. From Ward, I.M. and Hadley, D.W. 1993. Reproduced with permission of John Wiley & Sons Ltd.

ly, until at some point they enter the brittle glassy region, where further decreases in temperature will have much less effect.

Rate dependence is particularly relevant in high-speed operations, such as milling. It is well known that the glass transition temperature is frequency-dependent when measured using mechanical spectroscopic methods (Atkin and Mai 1986, Mark et al. 1984). An increase in strain rate in the ductile region has a major effect on yield stress, with an effect equivalent to decreasing temperature, but has little effect in the brittle glassy region. Brittle fracture, typical of the glassy state, is relatively independent of rate, but ductile fracture is extremely rate sensitive. Hence, deforming a ductile material such as toffee very rapidly (such as hitting it with a hammer) can lead to brittle fracture, but rapid deformation of a material already in the glassy state, such as dry cereal snacks, does not alter their fracture properties.

Size and geometry can also affect the brittle-ductile transition and fracture properties of a material. It is well known that it is easier to break large objects than smaller ones (Atkin and Mai 1986), not only because of the increased probability of finding a crack in a larger object, but also their will be more volume relative to crack area in which to store excess strain energy, making it easier for cracks to grow. Brittle fracture is preferred in a large structure, whereas a small sample of the same material may yield in ductile flow before cracking (Fig. 4). This has important implications for size reduction processes such as milling. The critical size (a_c) at which a transition from brittle to ductile behaviour occurs is given by the relationship:

$$a_c = \alpha E G_c / s_y$$

where α = geometric factor dependent on the shape and size of the specimen, E = Young's modulus, G_c = fracture toughness, s_y = yield stress.

If $a_c < \alpha E G_c / s_y$, the material is in the ductile region and yielding will occur before brittle fracture, and if $a_c > \alpha E G_c / s_y$, then brittle fracture will be preferred (Atkin and Mai 1986, Dobraszczyk and Vincent 1999). The implication here is that below a certain critical size, a material will not fail by brittle fracture but will yield in ductile flow and will therefore have passed from the glassy into the rubbery region. It is therefore possible, if a sample is close to the brittle-ductile transition, to change from the brittle glassy state to the ductile region simply by altering the size and geometry of the material (Dobraszczyk et al. 1987). It is also evident from Figure 4 that brittle fracture is highly dependent on the geometry and size of the sample, due to the sample volume/crack area ratio, whereas ductile failure is independent of size. Therefore, small changes in size and geometry of a cereal grain in the brittle region will have a significant effect on its fracture properties, whereas changes in rate or temperature only have major effects in the ductile region

In oat processing, steam is added to the grains to inactivate lipase and to soften them prior to flaking. Although it is possible to have only one steaming operation, it is more common to have two separate heat treatments: kiln drying and

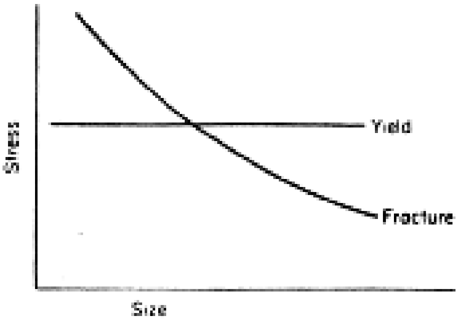

Fig. 4. Effect of size on fracture and yield properties. Large structures are more likely to fail by brittle fracture, whereas small samples yield. From Dobraszczyk, B.J. et al. 1987. Reprinted with permission from Elsevier.

tempering (Ganssmann and Vorwerck 1995). Kiln drying had no significant effect on the mechanical properties of oat flakes (Gates, Dobraszczyk and Salovaara, in press) whereas steam tempering has been shown to decrease the amount of fine, abraded material in oat flakes (Ganssmann and Vorwerck 1995). Steaming also caused permanent changes in the gelatinisation of starch and protein solubility (Oomah 1987, Oeding 1996). The conditions during tempering have been shown to be critical to the quality of sorghum flakes (McDonough et al. 1997).

As mentioned earlier, hardness is an important milling property in wheat. It affects the particle size distribution and amount of damaged starch in flour (Pomeranz and Williams 1990). These characteristics are important in the breadmaking quality of wheat. It has been shown also that roller milling is feasible for oats (Gray et al. 2000). Roller milling allowed separation into fractions with higher levels of β-glucan and antioxidants. This type of mill also allows for more controlled size reduction than most other mills.

Porridge

A common use of oats is in oat porridge. A variation is oat bran porridge fermented with lactic acid bacteria (Salovaara and Kurka 1991), which has been commercially successful in Finland. These are soft solids or viscous liquids, with water contents in excess of 80%. Obviously the main factor affecting the mechanical properties is the amount of water in the porridge. However, heat treatment of the grain has been shown to significantly increase the viscosity of flour slurries. This is attributed to both the inactivation of enzymes and to changes in β-glucan (Doehlert et al. 1997); the type of heat-treatment (roasting or steaming) also had an effect.

As well as modifying the flavour, fermentation can induce changes in the structure of the porridge. Lactic acid bacteria have for example been reported to produce β-glucanases (Jonsson and Hemmingsson 1991) whilst others produce exopolysaccharides that increase viscosity and ropiness (Mårtensson et al. 2002).

From the sensory perspective, the viscosity of the product is important and other factors such as the presence of particulates and adhesion to mouth and teeth have also been found to be involved in the quality of porridge (Lapveteläinen and Rannikko 2000). Differences in the viscosity of porridge prepared in the Amylograph were obtained for different oat cultivars and harvest years, significant interactions were also observed, suggesting that the cultivars responded differently to environmental factors (Lapveteläinen et al. 2001). However, it would be inaccurate to assume that sensory viscosity is same as the shear viscosity, because flow patterns in the mouth are complex and involve elongational flow. The relation between texture and viscosity has been reviewed by van Vliet (2002).

The method of cooking the flakes also affected the texture, as exhibited in porridge made from adding oatmeal to cold water, as compared to that prepared in boiling water (Lapveteläinen and Rannikko 2000). Differences in starch gelatinisation and β-glucan solubility between microwave and conventional cooking have also been reported (Yiu et al. 1991), and these might affect the texture of porridge and similar products. Physical factors such as particle size have also been shown to affect the viscosity of oat slurries (Zhang et al. 1997), which is probably due to increased solubilisation of β-glucan.

At the molecular level, starch and β-glucan are the main contributors to the viscosity of these types of products (Zhang et al. 1997, Zhou et al. 2000), although oat proteins also have a strong water-binding capacity (Jansson and Lindahl 1991) their role in determining the viscosity of oat pastes seems to be minor (Zhou et al. 2000). Whilst the gel-forming properties of starch are well studied, those of β-glucan are less known. It appears that at high concentrations and after extended periods of time β-glucan is capable of forming a gel network, particularly if it is partially hydrolysed (Lazaridou et al. 2003). Starch can interact with other polysaccharides, causing either increases or decreases in viscosity, and starches from different cereal sources do not behave in the same way (Shi and BeMiller 2002), however the study did not include oat starch or β-glucan.

Bread

To achieve an increase in the amount of oats consumed necessitates its incorporation into mainstream food products such as bread. However, most oat bread is currently wheat bread with less than 30% oats added (Ranhotra and Gelroth 1995). Dough containing oats have been reported to have higher water absorption and to have good stability, but the loaf volume was lower (Oomah 1983). The bread was reported to have good keeping properties if the oat addition is below 15%. There is a general consensus that oat flour alone cannot be used to produce bread, as it lacks gluten (Webster 1986, Cauvain 1998). Differences between bread made from roller-milled oat flour and commercial oat flour produced by hammer milling steel-cut groats have been reported (Oomah 1983). The loaf volume of bread produced from the roller-milled flour generally is higher and responds better to improvers than does the hammer-milled flour.

Bread is a very complex structure, consisting of foam that sets during baking to form a sponge. During processing arguably the most important mechanical properties are dough stickiness, consistency, bubble stability and the cutting behaviour of the bread. The properties of wheat bread have recently been reviewed and many of these principles can be applied to oat bread. There are, however, some important differences. The structure of wheat bread is determined largely by extensible, viscoelastic gluten, which is completely lacking in oats. This suggests a comparison with rye breadmaking, where the structure is mostly based on the non-starch polysaccharides (Autio et al. 1996).

Bubble structure and mechanical properties

Bread firmness is considered a good indicator of freshness. In common with other cellular solids, there is a close relationship between bread structure and its mechanical properties, which have been reviewed (Keetels et al. 1996, Scanlon and Zghal 2001, Zghal et al. 2002). Bread firmness has been shown to be affected by both the mechanical properties of the solid phase and the sizes and distribution of the air cells. Many cereal based foods such as bread, cakes, biscuits, snack products etc. have an open cellular foam structure. The mechanical properties of such cellular solids can be described by a theoretical relationship first proposed by Gibson and Ashby (1988), in which foams are modelled as a 3-dimensional array of cubic cells and the cell walls are considered as beams using classical engineering analysis. This work showed that the mechanical properties of such foams (strength, stiffness, toughness etc.) are directly proportional to their relative density (density of foam/density of foam wall material). Linear elastic analysis was used to model the behaviour of foams, considering the cell walls as beams in bending, non-linear elastic behaviour treated the cells walls as Euler struts, and plastic yielding by the creation of plastic hinges at the cell wall intersections. In all cases, the mechanical property of the foam normalised by the wall value scales as a power of the normalised density:

$$s/s_w = C(\rho/\rho_w)^n$$

where s = strength of foam, s_w = cell wall strength, ρ = density of foam, ρ_w = density of cell wall and, C = constant.

In the case of constant cell wall properties this reduces to $s \propto \rho^n$, e.g. the strength rises in direct proportion to a power of the density. Hence a decrease in density brought about by more cells, or increased porosity, will bring about a proportional decrease in strength. Hayter and Smith (1988) showed that these relationships are valid for extruded food foams, and Keetels et al. (1996) showed that Young's modulus, yield and failure stress for starch based foams were well described by the Gibson and Ashby analysis. However, a large variation in the sizes of cells and thickness of beams strongly affects the fracture behaviour of such foams and leads to a lower fracture toughness than predicted by the theory.

The behaviour of the wall material depends on its moisture content, dry breadcrumb will fracture whilst at high moisture contents the wall will buckle and will return to essentially its original shape when the force is removed (Stokes and Donald 2000).

In conclusion, the mechanical properties of food are important during processing and to the sensory quality of the final product. These are determined by the composition and structure of the food. Water is of special importance, as it acts as a plasticiser and is its properties are essential to gel formation. Oats differ from other cereals in their high lipid, β-glucan and protein contents. They must also be heat-treated in the early stages of food processing to prevent rancidity. The effect of heating on the macromolecules has not been studied in concentrated systems, such as are encountered in real foods. The mechanical properties are sensitive to changes in the conformation of macromolecules, and so provide a tool for following the effects of processing.

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