# Solid Food Foams

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## 1 Introduction

The words 'cell' and 'cellular' came to English (via French) from the Latin *cella*, a store room or chamber. In modern usage, they have several very different meanings. The two that are pertinent to food structure and texture have to do with the cells in edible tissues of plants, fungi and animals or with the open spaces, filled with air or another gas, enclosed by a liquid or solid matrix that forms the 'cell walls'. 'Solid', rheologically speaking, is a term that needs to be used with caution. An albumen foam and whipped cream, under most circumstances, do not flow under their own weight and are therefore solid in a certain sense. Yet, upon disintegration, they leave behind a liquid. This is in contrast with puffed cereals and snacks, pieces of freeze-dried vegetables or chicken and agglomerated, spray dried or instant coffee particles. These, if ground, would leave a powder made of solid particles. But what about fresh bread, cakes, marshmallows and popcorn? We'll consider them solids despite that their cell wall material is plasticized.

There are different ways to classify cellular solid foods. Here are some:

a. Structural: Open and/or closed cells, thick vs. thin walls (relative to the cell's size), 'solid' walls or walls that themselves have tiny bubbles, isotropic vs. directional structures, uniform vs. non-uniform bubble size distribution, single or layered array.
b. Method of formation: Fermentation and baking, extrusion and puffing, aeration or gas release ($CO_2$) followed by heat setting, agglomeration, freeze drying.
c. Texture: 'Soft' (i.e., easily deformed) vs. brittle, (i.e., a material that shatters upon impact or compression), weak or strong (disintegrates easily or only under a considerable stress), elastic (springs back to its original shape) or plastic (maintains its deformed shape).

d. Physically stable under 'normal' humidity conditions or hygroscopic.
e. Unit size scale: Consumed or handled as individual units (a bread slice, snack) or as an assembly (puffed breakfast cereals, instant coffee).

None of the above categories is sharply defined and there can be other classifications. One can easily contemplate solid cellular foods that can move between otherwise mutually exclusive groups, fresh and toasted or dried bread crumbs is a good example and so is ice cream, although for very different reasons. Moreover, with the above classifications, the number of possible combinations must be enormous even without considering the food's chemical composition. Yet, most cellular solid foods share a small number of common features and hence can be discussed as belonging to two major categories; 'soft' and brittle; keeping in mind that within the two, there might be numerous sub-classifications. Examples are given in the following table.

| **Food** | **Density** ($g\ cm^{-3}$) | **Wall density** ($g\ cm^{-3}$) | **Void Fraction** (%) | **Type** |
|---|---|---|---|---|
| Popcorn | 0.07 | 1.40 | >95 | Soft |
| Puffed Rice | 0.13-0.17 | 1.35-1.40 | 88-90 | Brittle |
| Extruded Products | 0.10-0.33 | 1.25-1.40 | 75-90 | Soft or Brittle |
| Meringue | 0.17-0.18 | 1.55 | 88-90 | Mixed |
| Baked Bread Loaf | 0.20-0.35 | ~1.25 | 72-85 | Soft |
| Sponge Cake | 0.25-0.35 | ~1.25 | 70-80 | Soft |

Adapted from Campbell and Mougeot (1999).

## 2 Mechanical Properties of 'Soft' Cellular Foods

Pictures of bread slice specimen, intact and at three levels of compressive deformation, are presented in Fig. 1 (top). When only slightly deformed, the open structure is characterized by bending of the cells' walls. At progressively higher compressive deformations the cell walls buckle, some may even rupture – see below, until much of the volume is occupied by the collapsed cell wall material. When this occurs, the deformation is to a large extent of the solid material itself. As could be expected, the dense compacted structure offers stronger resistance to deformation than the original open structure. Since the collapsed solid matrix primarily fills open spaces, the compressed specimen's cross-sectional area hardly changes, even under strains on the order of up to about 75%. This is in contrast with incompressible solids, like cheese or ham– see Fig. 1 (bottom), whose cross-sectional expansion is considerable. When the volume of a solid is preserved, or almost preserved, the product of its cross-sectional area multiplied by its height is constant, or approximately constant. Hence, any reduction in the specimen's height leads to a corresponding area expansion, a factor that needs to be taken into account in the interpretation of such materials' force-displacement or stress-strain relationships.

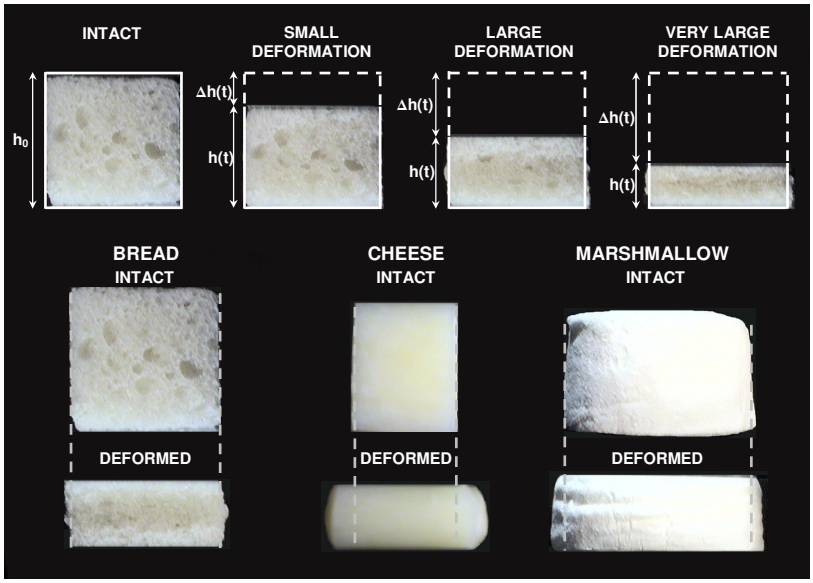


**Fig. 1.** Top: The compressibility of bread crumbs. Notice the cell walls' collapse. Bottom: Comparison of the compressibility of bread crumbs, cheese and marshmallows. Notice that the bread crumb 'collapses on itself' and hence the specimen does not expand laterally.

Cellular solids with thick walls and very small air bubbles can exhibit similar compressibility patterns - see the discussion of marshmallows below. Marshmallows, however, are an exception, as far as cellular foods are concerned. A structural collapse unaccompanied by significant lateral expansion is a characteristic of the majority of solid food foams, regardless of whether their cells are open or closed and whether their cell wall material is brittle or complying ("soft").

## 2.1 The Compressive Stress-Strain Relationships of "Typical" Cellular Solids

The mechanics of solid foams has been extensively studied, theoretically and experimentally. Many of the important and influential results can be found in the works of Ashby and in the by now classic book of Gibson and Ashby (1997) "Cellular Solids: Structure and Properties". Briefly, the compressive force-deformation curves, when converted into a engineering stress-strain relationship, has the typical shape shown in Fig. 2. [The engineering stress, $\sigma_E$, is the force divided by the specimen's original cross-sectional area, which, as stated, remains fairly constant as long as the deformed specimen still maintains a cellular structure]. The engineering strain, $\varepsilon_E$, is the absolute deformation ($\Delta h$) divided by the original specimen's height, ($h_0$) - see Fig. 1. The classic stress-strain curve, $\sigma_E$ vs. $\varepsilon_E$, of cellular solids has three discernible regions. They correspond to the deformed specimen's states depicted in Fig. 1 (top).

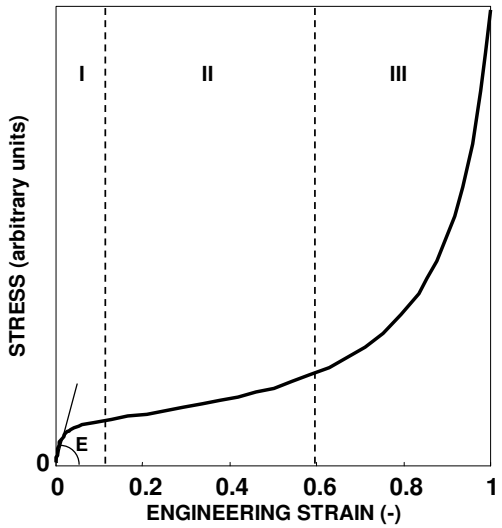


**Fig. 2.** Schematic view of the three regions of the force-displacement curve of a typical cellular solid: I-small deformation of the intact structure, II- buckling and fracture of cell walls and III-compaction of what is increasingly collapsed cell wall material.

At low strains, according to Ashby (1983), Gibson and Ashby (1997) and others, the specimen's deformability can be characterized by a 'modulus of elasticity', E, defined as the slope of the stress-strain curve, i.e., the stress divided by strain. This modulus is related to the foam's density by the equation:

$$\frac{E}{E_s} = k\left(\frac{\rho}{\rho_s}\right)^n \tag{1}$$

where Es is the cell wall material's modulus, ρ and ρs are the densities of the foam and of the cell wall material, respectively, and k and n constants. The constants k and n, according to Ashby, are determined by the cellular structure, i.e., by whether the cells are open or closed, the relative thickness of the wall (which determines the wall's tendency to buckle), etc. This formula has been used to characterize cellular foods too (e.g., Aguilera and Stanley 1999) but it is still unclear whether all solid foods indeed exhibit true elasticity even under small strains. One of the implications of Eq. 1 is that the plot of log E vs. log ρ is a straight line. Thus, in principle, if $\rho_s$ and Es are known, can be measured or estimated, this plot's slope and "intersect" (i.e., where $\rho/\rho_s = 1$) will yield the parameters k and n, from which the foam's structure characteristics would be inferred. In practice, attempting to change a food's density, even when the ingredients composition remains unchanged, may also induce structural changes that might complicate the interpretation of the E vs. ρ plot. Also, in contrast with theoretical models in which the cells are uniform and their geometry well defined, the bubbles of real solid food foams have varying cell wall thickness as well as a size distribution that is not always known, let alone uniform. Moreover, in

solid food foams, some of the cells can be open while others are closed, i.e., they belong to groups that according to Eq.1 would have a different exponent, n. This is in contrast with synthetic solid foams, like the familiar polystyrene and polyurethane, whose cells are either closed or open. Still, the equation can probably be used to characterize cellular foods if and when they exhibit distinct elastic response at low strains and conform to the theoretical classifications of Ashby (1983) and Gibson and Ashby (1997).

The central region of the stress-strain curve, typically, is characterized by a constant or almost constant low stress level over a large range of strains – see figure. This ability of solid foams to undergo considerable deformation while the stress remains low makes them ideal for cushioning sensitive items to protect them against mechanical damage. The presence of air bubbles also makes them excellent thermal insulators. This characteristic also influences the processing of cellular foods where heat transfer plays an important role.

In the third phase of the deformation, see Fig. 2, there is a steep stress rise as the number of still 'un-collapsed cells' rapidly diminishes and the compact's density approaches that of the cell wall's material.

The textural implications of the above characteristics of the stress-strain relationships are not always clear. When one examines a bread loaf or a roll with the fingers to evaluate its freshness, it seems obvious that the perceived mechanical stimulus is associated with the first region of the curve. Yet, in mastication, the compact's resistance to *tearing* probably plays a more significant role than the first and second stages of the compression. At the point where the bread crumb is torn, however, the specimen might have already been wetted by saliva so that the relationship between the stress-strain characteristics of the dry sponge and its perceived textural properties is usually obscured.

## 2.2 Mathematical Characterization of the Compressive Stress-Strain Relationship of Polymeric Foams, Breads and Cakes

Typical sigmoid compressive stress-strain relationships of both synthetic foams and bakery products can be expressed mathematically by a variety of empirical models among them (Swyngedau, Nussinovitch, Roy, Peleg, and Huang 1991):

$$\sigma = \frac{C_1\varepsilon}{(1+C_2\varepsilon)(C_3-\varepsilon)} \tag{2}$$

$$\sigma = C_1\varepsilon^{n_1} + C_2\varepsilon^{n_2} \qquad (n \le 1 \text{ and } n > 1) \tag{3}$$

$$\sigma = C_1\left(\frac{\varepsilon}{C_2-\varepsilon}\right)^n \tag{4}$$

$$\sigma = \frac{\log_e(1-\frac{\varepsilon}{C_1})^{\frac{1}{n}}}{C_2} \tag{5}$$

where σ is the engineering stress, ε is either the engineering or Hencky's (natural) strain and the C's and n's are constants. Hencky's strain preserves the relative magnitude of the deformation by taking into account the continuously changing specimen's height. For this reason it is commonly used to describe systems where the deformations are large. Mathematically, the compressive Hencky's strain, $\varepsilon_H$, is defined by:

$$\varepsilon_H = \log_e\left(\frac{h_0}{h_0 - \Delta h}\right) \tag{6}$$

Obviously, the magnitude of the C's and n's in Eqs. 2-5 will not be the same if the strain is Hencky's, $\varepsilon_H$, or the engineering, $\varepsilon_E$. The fit of the four models is demonstrated in Fig. 3.

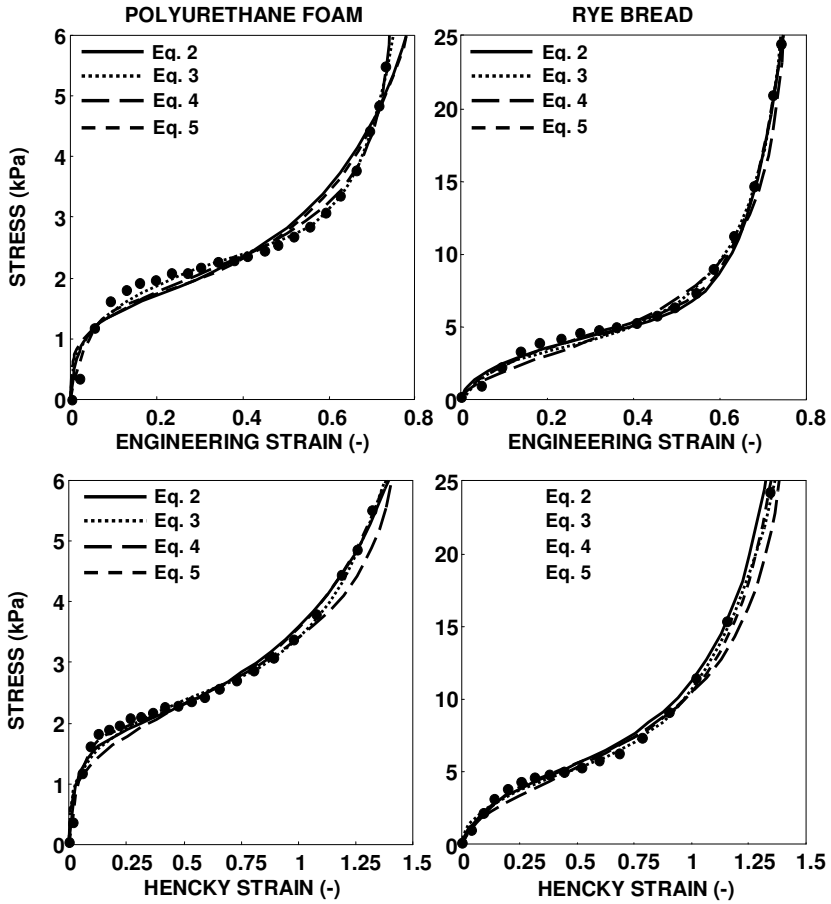


**Fig. 3.** The stress-strain relationship of a polyurethane and bread crumb foams fitted with four empirical models (see text). From Swyngedau et al. (1991).

The advantage of Eq. 2 as a model is that C1, serves as a sort of a scale factor, C2 as a measure of the flat region's (shoulder's) prominence (when C2=0 the shoulder disappears altogether) and C3 is a marker of the strain where the densification (stage three) becomes the dominant deformation mechanism (when $\varepsilon \rightarrow C3$, $\sigma \rightarrow \infty$). The advantage of Eq. 3 is that it identifies two compressive mechanisms, one dominated primarily by buckling with a scaling factor of less than one (downward concavity) and one by compaction with a scaling factor of more than one (upper concavity). The only advantage of Eqs. 4 and 5 is that they have an analytic inverse, i.e., one can express $\varepsilon$ as a function of $\sigma$ algebraically. This characteristic can be exploited in the calculation of the mechanical properties of layered arrays - see below.

### *Breads*

Had all food sponges been truly elastic over a large range of strains, repeated compression-decompression cycles would have produced identical stress-strain relationships, perhaps with a small hysteresis as shown schematically in Fig. 4. Since the area under stress-strain curves has energy per volume units, the area enclosed by the hysteresis loop would reflect the energy loss as a result of internal friction. In reality though, successive compression-decompression cycles can produce stress-strain relationships that are *qualitatively different*. The stress-strain curves of a white bread crumb repeatedly compressed (Fig. 5) is an example. Notice that the 'shoulder', which was quite prominent in the first compression, totally disappeared in all successive cycles. A possible interpretation of this observation is that the initial compression caused the burst of closed cells, turning the cellular crumb into an open"spongy" structure, whose deformability pattern was quite distinct (Peleg, Roy, Campanella, and Normand 1989). Similar observations were recorded in other breads so the phenomenon cannot be uncommon.

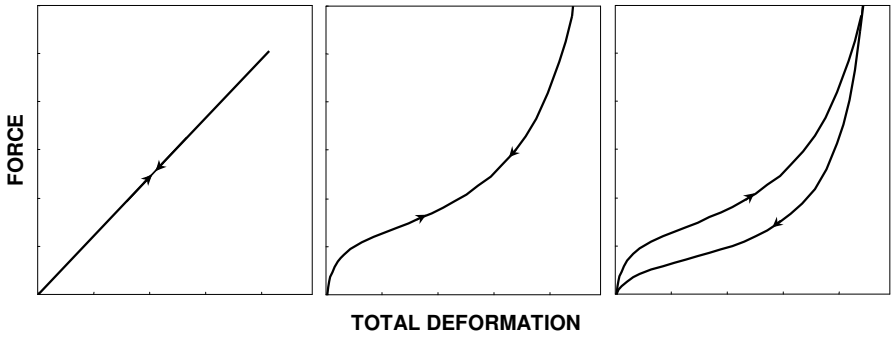


**Fig. 4.** Schematic view of reversible and irreversible stress-strain relationships in a compression-decompression cycle. Left - ideal linear elasticity (small deformation), center-nonlinear elasticity and right - a relationship showing a hysteresis loop.

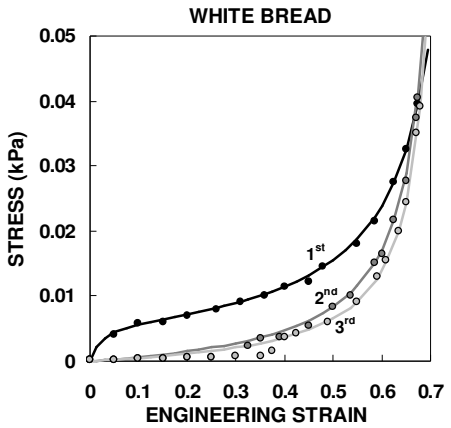


**Fig. 5.** The stress-strain relationships of a bread crumb in successive compression-decompression cycles. Notice the disappearance of the 'shoulder' in the 2nd and 3rd cycles, probably an indication of closed cells rupture. After Peleg et al. (1989).

## *The Deformability of Marshmallows*

Although marshmallows are by all means cellular solids, they exhibit a deformability pattern that is atypical to cellular solids of the kinds classified by Ashby (1983). The marshmallow deformability is characterized by the *absence* of a prominent shoulder in the stress-strain relationships as shown schematically in Fig. 6 (top).

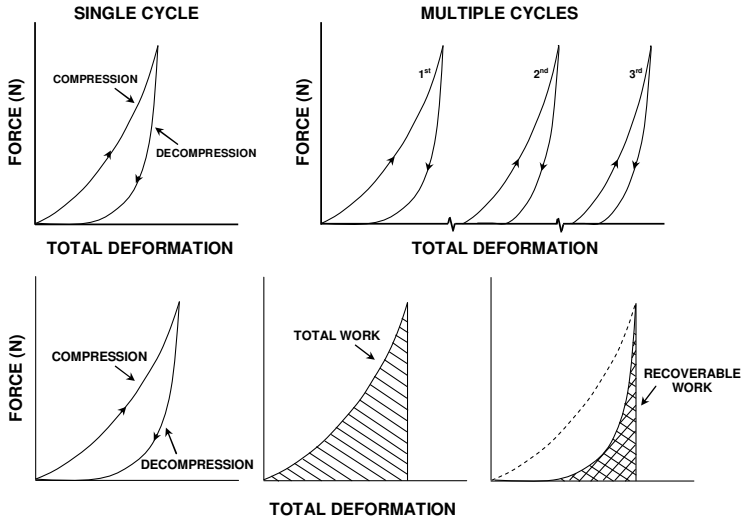


**Fig. 6.** Top: Schematic view of the force-deformation relationships of marshmallows. Notice the absence of 'shoulder'. After Kaletunc et al. (1992). Bottom: Schematic view of how the 'degree of elasticity' can be assessed from a compression-decompression curve. (Notice that the area under the stress-stress strain curve has work per unit volume units and that the 'degree of elasticity' can be defined as the recoverable/total work ratio.)

Apparently, because of the plasticized and relatively thick cell walls, buckling, let alone gross fracture and collapse, simply do not occur. But large deformation does affect the mechanical response of marshmallows. This becomes evident when they are subjected to repeated compression-decompression cycles. If their 'degree of elasticity' can be assessed in terms of the relationship between the recoverable to total work (after reaching a given strain) – see Fig. 6 (bottom), then there is a clear loss of elasticity upon repeated deformation as shown in Fig. 7 (Kaletunc, Normand, Nussinovitch, and Peleg 1991;1992). The extent to which this loss of elasticity occurs is different in marshmallows of different brands, an observation supported by other measures obtained from stress relaxation tests (Kaletunc et al. 1992).

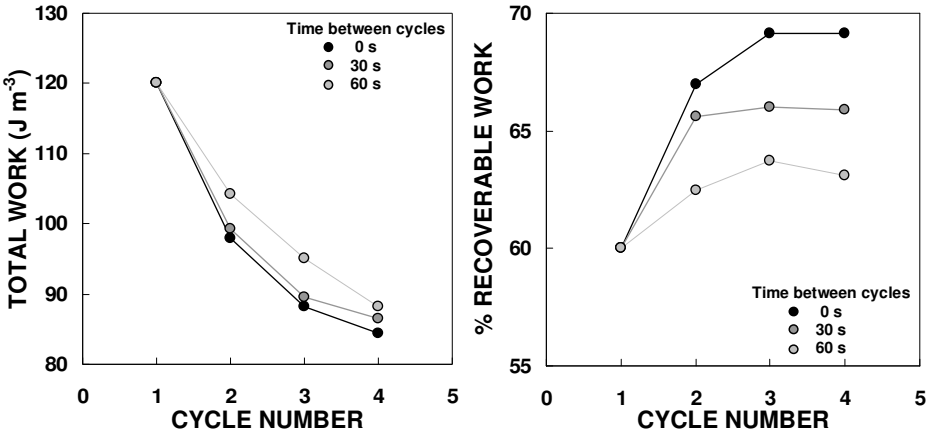


**Fig. 7.** Degree of elasticity of marshmallows. From Kaletunc et al. (1992).

## *Popcorn*

The force-displacement of stress-strain curves of puffed popcorn, compressed individually or in bulk, do not have a prominent 'shoulder' (Nussinovitch, Cohen, Peleg 1991). Like in marshmallows, this can be explained by the plasticity and relative thickness of the cell walls. Support for this view comes from the comparison of their deformability pattern with that of "synthetic popcorn" (polystyrene), which is used for the cushioning of transported goods. The stress-strain curve of polystyrene foam particles not only shows evidence of at least a "weak" shoulder but it also indicates an overall stress level that is by far lower than that of natural popcorn, as shown in Fig. 8. It ought to be remembered though that in both the natural and the synthetic products, the puffed particles morphology and orientation play an important role in shaping of the force-displacement curve. This is regardless of whether they are tested individually or in bulk. Thus, although the cellular structure is still largely responsible for the cushioning properties of such particles, geometry is also an important factor.

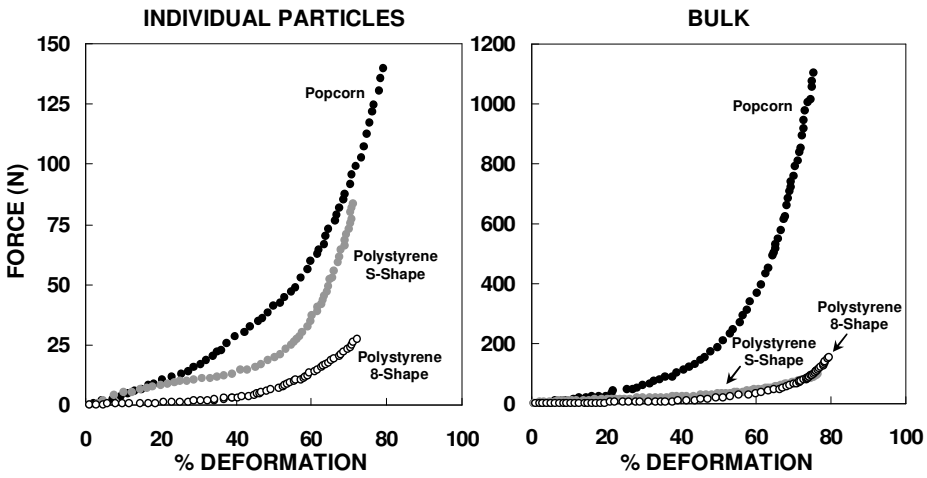


**Fig. 8.** Comparison of the force-displacement curves of synthetic (polystyrene) and natural puffed popcorn, tested individually and in bulk. After Nussinovitch et al. (1991).

## 2.3 Layered Arrays

### *Arrays of Cellular Solids Only*

A schematic view of a layered array of "typical" cellular solids is given in Fig. 9 (left). When compressed uniaxially, the force in all the layers is the same and their deformations (displacements) are additive, as also shown in the figure (right). Thus, the force-displacement curve of an array is constructed by adding the displacements of the individual layers that correspond to any given force. Since with few exceptions, like the previously discussed marshmallows, the cross sectional area of compressed solid foams does not expand to any significant extent, adjustment for the area is not needed here. It will be a factor to be reckoned with if one or more of the layers are incompressible or approximately incompressible, see below. The principle of same force and added deformation, pertains not only to arrays of cellular layers, each having a distinct structure and mechanical properties, but also to a single solid foam whose properties change gradually from top to bottom.

For an array of the kind depicted in Fig. 9, the *stress* is assumed to be the same in all the layers, i.e., $\sigma = \sigma_A = \sigma_B = \sigma_C = \ldots$ while the total *strain*, $\varepsilon_{Total}(\sigma)$, is constructed by adding the deformations, i.e.,

$$\varepsilon_{Total}(\sigma) = \frac{1}{h_{0Total}} \cdot \left[ h_{0A}\varepsilon_A(\sigma) + h_{0B}\varepsilon_B(\sigma) + h_{0C}\,\varepsilon_C(\sigma) + .... \right] \qquad (8)$$

where $h_{0Total}$ is the initial (combined) height (or thickness) of the array, i.e., $h_{0Total} = h_{0A} + h_{0B} + h_{0C} + \ldots$, and $\varepsilon_A(\sigma)$, $\varepsilon_B(\sigma)$, $\varepsilon_C(\sigma)$, etc., are *the strains* of the individual layers, which progressively change with the increasing stress.

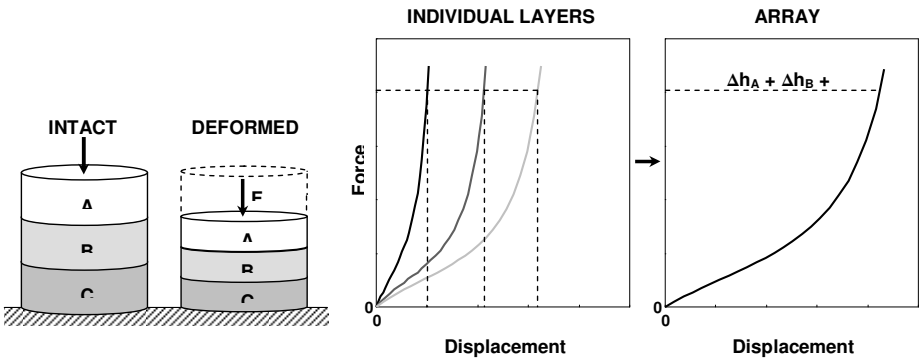


**Fig. 9.** Schematic view of the construction of the force-displacement curve of a layered array of cellular (spongy) solids. Notice that the force in the layers is the same and that the deformations are additive.

The validity of this model and its ability to predict the deformability of layered baked foods and polymeric solid foams arrays have been demonstrated by Swyngedau et al. (1991) and Swyngedau and Peleg (1992). When Hencky's strain is used to characterize the deformation, then (Peleg 1993):

$$\varepsilon_{HTotal}(\sigma) = \log_e h_{0total} - \log_e \{h_{0A} \exp[-\varepsilon_{HA}(\sigma)]\} + h_{0B} \exp[-\varepsilon_{HB}(\sigma)] + h_{0C} \exp[-\varepsilon_{HC}(\sigma)] + ...\} \tag{9}$$

If the stress-strain relationships of all the individual layers can be described by Eqs. 4 or 5, the layered array's total strain can be calculated analytically (Swyngedau et al. 1991). Since the strain of the first layer can be expressed algebraically, i.e.;

$$\varepsilon_A(\sigma) = \frac{C_2\left(\frac{\sigma}{C_1}\right)^{\frac{1}{n}}}{1+\left(\frac{\sigma}{C_1}\right)^{\frac{1}{n}}} \tag{10}$$

or

$$\varepsilon_A(\sigma) = C_1[1-\exp(-C_2\sigma)]^{\frac{1}{n}} \tag{11}$$

and so all the other layers, the terms $\varepsilon_A(\sigma)$, $\varepsilon_B(\sigma)$, $\varepsilon_C(\sigma)$ … are all fully defined and can be inserted into Eq. 8 or 9 with the corresponding layers' initial thickness ($h_{0A}$, $h_{0B}$, $h_{0C}$, etc.) These equations can then be used to construct the whole force-deformation or stress-strain relationships of the array. In cases where any or all the layers' deformabilities are characterized by Eqs. 2 or 3, the model can be solved numerically to produce the desired stress-strain relationships, again regardless of whether the layers have the same or different thickness.

### *Mixed Arrays*

The described principle of same force (stress) and added deformations (strains) equally applies to parallel layers of any kind, provided that their structure is isotropic. However, if any of the layers in the array is incompressible and softer than the rest, then it will expand laterally upon the force application. This is a familiar experience. When a sandwich or a layered cake is compressed, the filling sometimes leaks out from the sides, as shown in Fig. 10. For such a situation, Eqs. 8 or 9 will not be an appropriate model. However, because the cellular layers retain their cross-sectional area, and because the 'free' part of the expanded filling does not transmit any stress (theoretically), the stress-strain relationship of the array can still be calculated by accounting for the exuded material. The applicability of the method has been recently demonstrated by Barrett, Cardelo, Maguire, and Peleg (2005). They also showed that it can be used to monitor the moisture exchange between the filling and a model bread. In such a case, the *deviation from the model's predictions* would reveal that the mechanical properties of the layers have been altered. [The situation would be different, of course, if the liquid or semi-liquid filling is being absorbed into the neighboring cellular layers.]

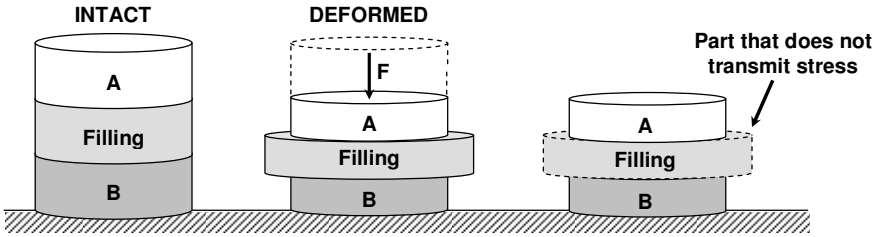


**Fig. 10.** Schematic view of the compressibility of a mixed layered array of cellular (spongy) and a soft incompressible component.

## 2.4 Tensile Properties of Cellular Solid Foods

Although never rigorously proven, the tensile or "tearing" strength of bread crumbs and most other soft cellular foods may be just as if not more relevant to their perceived texture than their compressibility. This is because the effort to tear the compacted structure is usually much bigger than that needed to cause the collapse of the open structure. [It does not mean that there is a universal relationship between the two and one ought to consider that the tearing, except for the initial bite into the food, might be of a compressed sponge already wetted by saliva.] But anyway, the main technical problem with testing food sponges in tension is the grip. Preparation of a suitable specimen seems to be a lesser problem because a bread crumb or similar solid foams can be carved with an electric knife or punched out. A proper grip can be achieved by attaching an adhesive tape to the slightly compressed specimen's ends (Nussinovitch, Roy, and Peleg 1990; Chen, Whitney, and Peleg 1994). When the tested specimen has a 'dog-bone' shape, failure is almost guaranteed to occur in the middle rather than in the grip regions (which would have invalidated the test) – see figure.

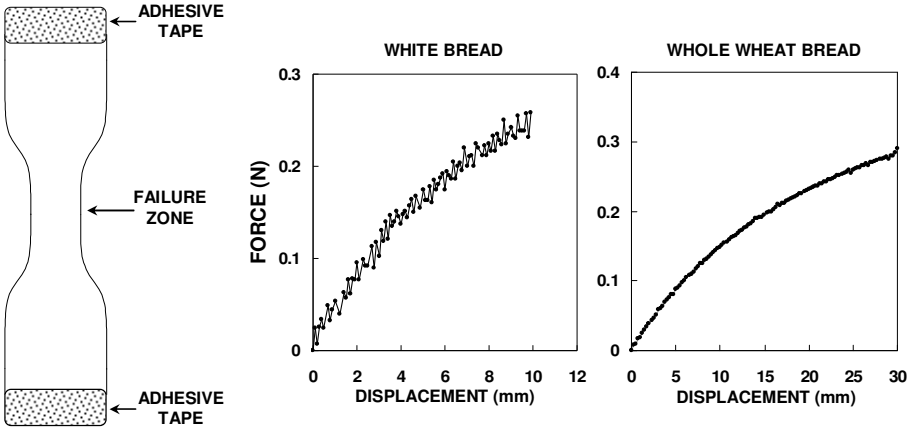


**Fig. 11**. Schematic view of a bread crumb specimen ready for tensile testing and typical tensile force-deformation curves. Notice that the serrated curve is a record of successive tearing of cell walls.

The typical shapes of the tensile force-displacement curves of breads are also shown in Fig. 11. They have a clear *downward concavity* caused by the simultaneous contraction of the cross-sectional area as the specimen stretches and by that the same absolute deformation produces a progressively *decreasing strain* as the specimen is elongated. Since all the tests reported by Nussinovitch et al. (1990) and Chen et al. (1994) were performed at low deformation rates, viscoelastic effects most probably had not played a significant role. The reader should notice the serrated appearance of the white bread's force-displacement curves. The force oscillations are records of local failure events that preceded the gross failure of the specimen. Results of various breads testing indicated that neither the bread crumb's original density, nor its pre-compression, had a dramatic effect on the measured tensile strength (the tensile stress at failure) or on the ultimate strains that the specimen could sustain (Nussinovitch et al. 1990). Moreover, the bread crumb's moisture loss during seven days of storage open to the air, also did not show a consistent dramatic effect on these two tensile parameters (Chen et al. 1994) as one would expect. The same can be said about the compression parameters, which too showed little correlation with the moisture loss, which was measurable, of course. These reported findings, if indeed representative of the three tested breads (white, Canadian and whole wheat), would suggest that the initial textural changes that accompany bread staling are quite subtle and hence cannot be always manifested in the described crude mechanical parameters. An alternative explanation is that the failure to find the expected trends was mainly due to the large scatter in the experimental results that masked the true trend, if it really existed.

# 3 Mechanical Characteristics of Brittle Cellular Foods

## 3.1 Interpretation of Jagged Compressive Force Displacement Curves

The most salient characteristic of brittle cellular foods, regardless of their composition and how they have been formed is that their force-displacement curves are irregular and irreproducible (Peleg 1997a). Examples are shown in Fig. 12. Brittleness is the property of certain solids to fail or shatter after very small deformation – glass is perhaps the most familiar brittle material. 'Brittleness' and 'strength' can be independent mechanical properties. A 'strong' material like a candy drop is brittle while a soft cheese is not. Yet, some cellular foods are both brittle and 'fragile', that is, they break or shatter after being subjected to a low stress. In the case of compressed cellular solid foods, brittleness causes fracture of cell wall material. Such a local fracture can propagate, triggering major failure, or remain a local event. The process can then repeat itself when more cell walls break down as the specimen is being further compressed. The successive failures of different magnitudes are manifested in corresponding force drops. The result is a force-displacement curve that has force oscillations of various amplitudes and frequencies. Cutting of a brittle food like a puffed snack, a cereal particle or instant coffee agglomerate can cause their disintegration. Therefore, it is better to test them intact. But since most such foods do not have parallel surfaces anywhere, meaningful calculation of stresses and strains is often impossible. The best one can do is to test specimens of more or less the same size and, if possible, in the same orientation. One can sometimes refer to the % deformation, calculated by dividing the absolute displacement by the specimen's initial height, as a 'pseudo strain'. But stresses are by far more difficult to calculate, even nominally, if the specimen's cross-sectional area is grossly non-uniform. The texture of brittle foods has been an active area of research and various methods to quantify their 'crunchiness' or 'crispiness' have been proposed, see Luyten, Plijter, and van Vliet (2004), Vincent, Saunders, Beyts (2002), Vincent (1998), Norton, Mitchell, and Blanshard (1998). For what follows, consider the compressive force-deformation curve as a 'mechanical signature'. Now compare this signature of a brittle foam with any of those of the soft cellular foods discussed in the previous sections of this chapter. The obvious difference between the two is their 'degree of jaggedness'. Quantifying a degree of jaggedness can be done in different ways (see Peleg 1997b and below). But before we address the various jaggedness measures, we should keep in mind that a jagged force-displacement curve has two elements:

a. A smooth "skeleton", which is a manifestation of the overall stiffness and toughness of the food in question. Obviously, there is a difference between a pretzel or crouton and a puffed cheese ball or a Cocoa Puff® breakfast cereal that has more to do with the effort to break them rather than with the brittleness that they all have, and
b. An irregular "noise" superimposed on the smooth "skeleton", whose amplitudes and frequencies are the record of the cascade of failure events that accompany the deformation.

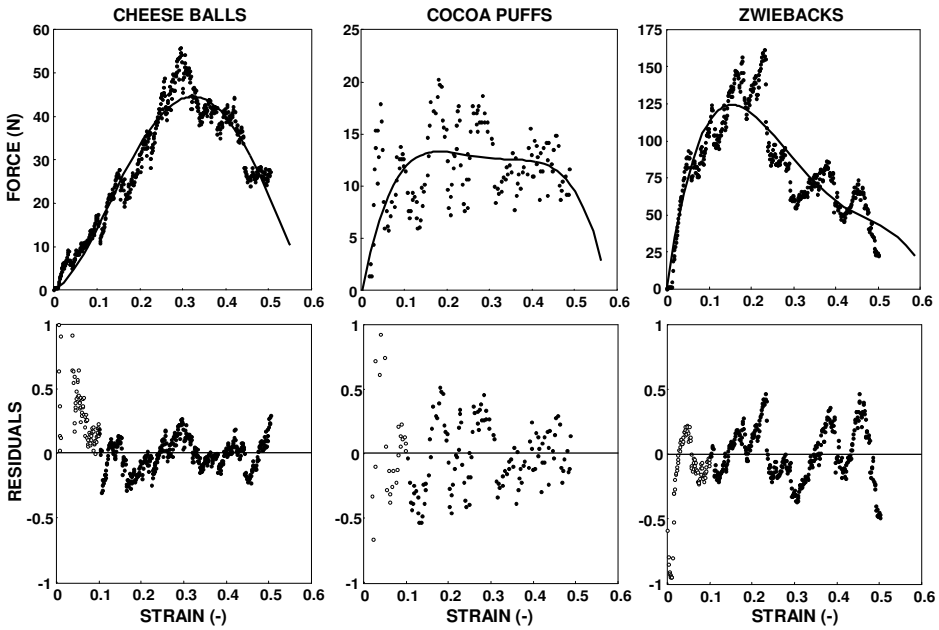


**Fig. 12.** Typical compressive force-displacement curves of three brittle cellular foods fitted ('smoothed') with a polynomial model. Bottom: the 'normalized signature' composed of the residuals around the 'smoothed' curve.

This is obviously an oversimplification of the deformation mechanism, which as already explained, involves failure initiation and propagation. Nevertheless, this approach facilitates the extraction of useful information from irregular and irreproducible force-displacement curves that would otherwise be viewed as meaningless.

## 3.2 Jaggedness Assessment

An irregular signature's jaggedness can be assessed by using the complete record for the analysis. Alternatively, the record can be fitted with a polynomial or another model, a process called 'smoothing', followed by the analysis of the oscillations around the smooth curve separately. If the original record is in the form of F(t) vs. t, and the fitted curve is F*(t) vs. t (see Fig. 12), the normalized residuals (dimensionless), y(t), will be calculated by:

$$y(t) = \frac{F(t) - F^*(t)}{F^*(t)} \tag{12}$$

Notice that y(t) oscillates around the zero line as shown in the figure. Also, since at the beginning of the "curve" the force oscillations can be very large relative to the absolute magnitude of either the measured or fitted force, the division of the absolute

residual F(t)-F*(t) by F*(t) can yield absurdly big numbers. Consequently this initial part of the normalized data, in our experience up to a displacement of about 10%, can be safely discarded. It is not representative of the textural properties and can be viewed as a mathematical artifact.

### *Statistical Measures of Jaggedness*

A jaggedness index $I_J$ can be formulated from the force oscillations' standard deviation, σ, not to be confused with the stress that has the same symbol, or the variance, $\sigma^2$. An example, see Tan, Gao, and Hsieh (1994), is:

$$I_J = 1 - \frac{1}{1+\sigma} \tag{13}$$

or

$$I_J = 1 - \frac{1}{1+\sigma^2} \tag{14}$$

When σ = 0 (smooth curve), $I_J = 0$ and when $\sigma \rightarrow \infty$, (extremely wide force fluctuations), $I_J \rightarrow 1$. This is a simple effective index. Its only drawback when applied to normalized records is its diminishing sensitivity as the standard deviation and variance become large.

A crude measure of jaggedness, promoted by the manufacturer of a popular mechanical testing instrument, is the force peaks counts. Probably, it is the simplest jaggedness measure, but it suffers from the uncertainty regarding what constitutes a true peak force - see section on the roles of sensitivity resolution - and it does not discriminate between small and large force oscillations.

### *The Power Spectrum*

An amplitude-time record can be converted into a power-frequency relationship by the Fourier Transform. This conversion can be done almost instantaneously with modern software which employs the Fast Fourier Transform (FFT) algorithm. A jagged force-time record will have a Fourier Transform "rich" in the high frequencies region. The curve's general shape will be primarily manifested in the low frequencies part, which can be filtered out. What remains provides a measure of the high frequencies contribution, which is prominent in jagged signatures but almost nonexistent in smooth ones. [Recall that the raw information that a standard testing machine generates is in the form of voltage-time data that are converted into force-displacement relationship by taking into account the sensor's calibration and the crosshead's velocity. Thus the reciprocals of the displacement are in fact representative of frequencies despite that their units are length$^{-1}$ and not time$^{-1}$.]

### *The Apparent Fractal Dimension*

A smooth curve has a Eucledian dimension of a line, i.e., D=1. But imagine an extremely jagged curve so convoluted and dense that it almost occupies the whole plane on which it is drawn. We can say that the dimension of such a curve approaches the Eucledian dimension of a plane, i.e., D→2. Curves having an intermediate degree of jaggedness will have non integer dimensions between 1.0 and 2.0. A curve or an object having a non integer dimension is known as 'fractal'. Examples of such curves, generated with two different algorithms are given in Fig. 13. The figure demonstrates that the fractal dimension, $D_F$, is unaffected by the general shape of the curves and therefore can serve as a universal measure of a line's jaggedness. [The same is true for a surface's roughness, in which case $D_F$ will be between 2.0 and 3.0.] However, for an object or signature to be truly fractal, i.e., to have a non-integer dimension, it has to be 'self-similar'. Self-similarity is manifested in that without the length scales being specified, the object's or curve's parts are indistinguishable from the whole (see figure).

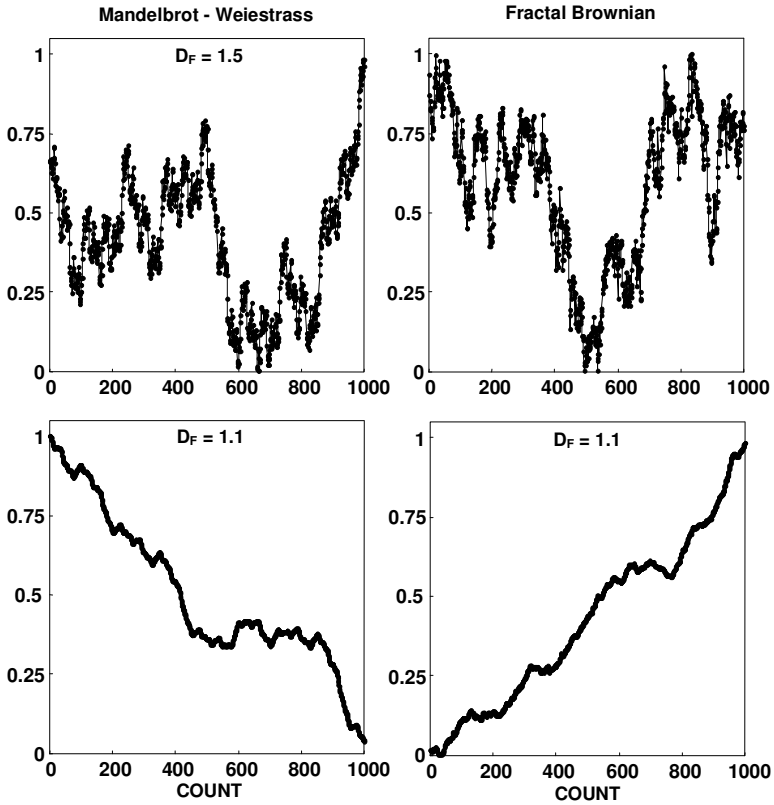


**Fig. 13**. Jagged fractal curves generated with Russ's program (Russ, 1994). Notice that the 'degree of jaggedness' is independent of the curve's general shape and the algorithm used for its generation.

In real physical objects, in contrast with purely mathematical creations, self-similarity can only exist over a limited range of length scales, but this is a technical rather than a conceptual limitation. A more serious difficulty arises in recorded mechanical or acoustic signatures, like the force-displacement or sound intensity-time relationships of brittle cellular foods, where the force or sound intensity is logged at fixed time intervals. Such signatures, like the contour of a rugged mountain's chain, cannot have self-similarity in the x-axis direction and are hence called 'self affine'. Nevertheless, in the case of mechanical signatures, the two most often used methods to determine a fractal dimension of a jagged line, the 'Richardson plot' and the Kolmogorov box-counting algorithm can be used to determine their apparent fractal dimension. Moreover, either method is based on converting the data into a plot, whose slope is used to calculate the dimension and whose linearity indicates that the algorithm is appropriate. In software like that offered by Russ (1994), this plot is produced automatically and is displayed together with the calculated dimension. When Russ's program is applied to the mechanical signatures of brittle cellular foods, other algorithms, more sensitive to the self-similarity requirement [like Minkowski's or Korcak's] almost invariably produce a curved plot instead of a linear one, indicating that the calculated dimension is wrong or suspect (Borges and Peleg 1996). But even if the method to calculate the apparent fractal dimension works, it will still be advisable to verify the magnitude of the resulting apparent dimension by comparing it to the dimension calculated by another algorithm. For example, subjecting the force-displacement experimental data to both the Richardson and Kolmogorov analyses, or to another jaggedness measure, like one derived from the records' Fourier Transform or the force oscillations statistical properties would strengthen any conclusion regarding the signature's degree of jaggedness.

### *The Role of the Sampling Rate and the Testing Machine's Resolution*

The term 'jaggedness' in the vernacular refers to a contour with sharp fluctuations. Yet the appearance of jaggedness can be attributed either to the fluctuations' amplitude, their frequency or both.Consequently, when the degree of jaggedness of a mechanical signature is expressed by a single number, *regardless of the index used*, its magnitude will depend simultaneously on the instrument's resolution and the chosen sampling rate. The former determines the smallest observable force oscillations and the latter, the highest frequency. Both, however, also depend on the testing machine's *time response*, which puts a physical limit to the signature's resolution. It can also affect the magnitude of the recorded forces, whose rise and fall is in most cases very steep. Therefore, although the machine's software may allow the user to set the sampling rate at will, the result might be a distorted record, if the machine's and electronic system's response times are not taken into account. There are theoretical ways to estimate "the true" fractal dimension of a signature from data sets obtained at finite resolutions. Their practicality in routine testing, however, is highly questionable (Damrau, Normand, and Peleg 1997; Peleg 1997). Thus when the jaggedness of different signatures is compared in terms of their apparent fractal dimension, effort should be made so that they are obtained at the same resolution and

sampling rate and that they have a similar number of points for the comparison to be meaningful. The same applies to any jaggedness measure.

### *Reproducibility*

The mechanical signatures of brittle cellular foods are not only jagged but also irreproducible, even when recorded under almost identical conditions. The irreproducibility is not an experimental artifact but *an inherent characteristic*, a manifestation of the haphazard nature of the failure mechanism. A minor crack or a particularly weak or thin cell wall can develop into a major structural failure expressed in a large force drop, but it does not have to. Consequently, and since the cellular structure is heterogeneous to start with, the actual failure pattern and the exact shape of the force-displacement curves are unpredictable *in principle*. However, if the tested specimens are of similar size, overall structure, composition and moisture contents, then their mechanical signature's *degree of jaggedness* can be remarkably reproducible. Although this is an empirical observation (see section on the effect of moisture) it is not totally unexpected. The *probability* that units having a similar structure and size will have a similar (but not identical) number of major and minor fracture events should be quite high. Thus, although each force-displacement relationship is unique, it still shares a certain general resemblance to other such relationships, even if not necessarily to all. And since the units of the same lot are expected to have a similar cell size and wall thickness distributions, the oscillations' frequencies and amplitudes are expected to have similar distributions too.

## 3.3 Stiffness and Toughness

'Stiffness' is the resistance of an object to deformation and is represented by a 'modulus' (see section on soft cellular materials). The modulus is defined as stress per unit strain (which is dimensionless) and hence has stress units. Although even in the uniaxial compression of a homogeneous cylindrical or rectangular specimen the stresses distribution is far from being uniform, one can still use the *'average stress'*, the measured force divided by the specimen's cross-sectional area, for the modulus calculation. 'Toughness', in material science, is defined as the work (mechanical energy) that ought to be invested in order to reach a given strain, usually determined at and specified for the failure strain. It is represented by the area under the force-displacement curve, or the stress-strain curve, in which case the units are of work per unit volume, as already mentioned. All the above hardly applies if the force-displacement curve at hand is spiky or extremely jagged as is almost always the case with brittle cellular foods. The cross-sectional area, the strain and consequently the 'slope' of the force-displacement curve are poorly defined, if at all, and so is the area under the curve. In such a case, the experimental or fitted force at a given deformation level, 15%, or 25% for example, can serve as a practical measure of the specimen's stiffness (e.g., Suwonsichon and Peleg 1997). Or alternatively, one can identify the heights of the increasingly larger peak forces, in which case a plot of their magnitude vs. the % displacement would usually be a straight line, whose slope will be a measure of the specimen's *minimal* stiffness (Peleg and Normand 1995) –

see Fig. 14. All the above measures of stiffness are fairly reproducible – see below – despite that the original data from which they are derived are not.

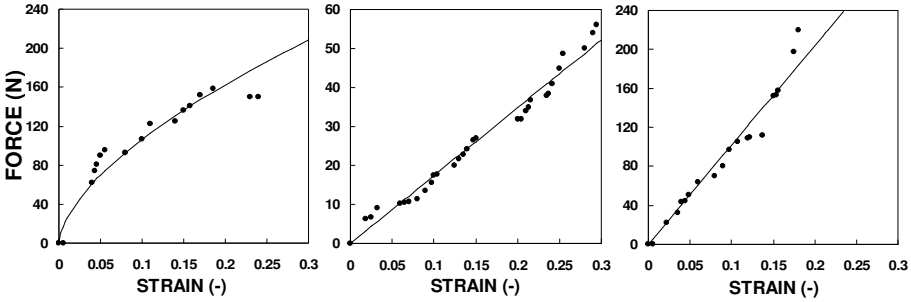


**Fig. 14**. Assessing the stiffness of brittle cellular foods by connecting the increasing force peaks in their jagged force-displacement curves. After Normand and Peleg (1995).

The area under the original or fitted force-displacement curve can be a measure of the specimen's toughness as already stated. However, since there is a multitude of "failures", (in contrast with a single failure of most polymers and engineering materials, the % deformation for the toughness determination must also be arbitrarily chosen. One can argue, though, that unless the force-displacement curves have very different shape, the stiffness and toughness of specimens of the same food will rise and fall more or less in unison. In such a case, an increase or decrease of the specimen's stiffness will also be indicative of similar changes in its toughness.

### *Directionality*

Puffed extrudates and other expanded foods can exhibit different mechanical properties if tested axially or transversally, i.e., in the extrusion's direction or perpendicular to it. An example is shown in Fig. 15. This is a manifestation of the oriented structure formed during the materials shear and expansion. Although the differences can be easily picked up by a testing machine, it is unclear whether they can also be perceived sensorily by humans.

### *Units Tested Individually and in Bulk*

Most cellular solid foods (breakfast cereals and agglomerated or freeze dried instant coffee included) come in units that are large enough to be tested individually with machines that have a good crosshead speed and positioning control. Thus, if tested slowly enough, a 'sufficiently detailed' force displacement curve can be obtained. Yet, in some cases it would be more convenient to test the particles in bulk, especially when the unit's size is extremely variable and so is their shape (see Nuebel and Peleg 1993 and González-Martínez, Corradini, and Peleg 2003, for example).

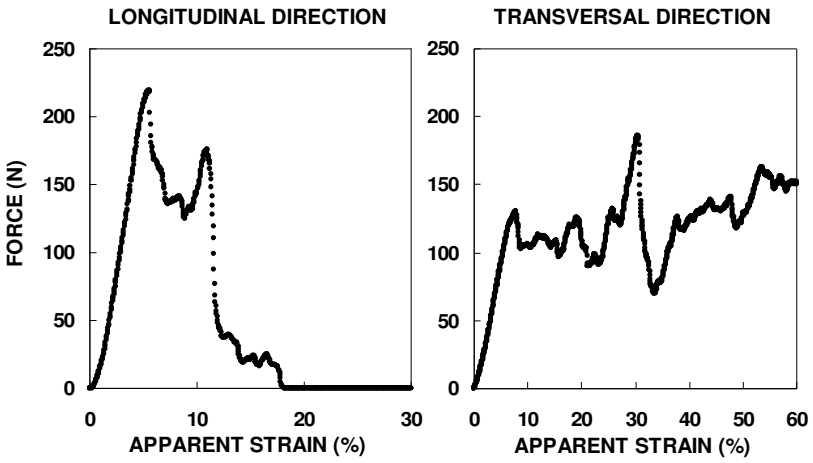


**Fig. 15**. The expression of anisotropy in puffed extruded cellular solids. Notice the qualitative as well as the quantitative difference in the force-displacement curves when determined in the longitudinal and transversal directions.

The relationship between the mechanical properties of individual cellular food particles and their assembly has been addressed in several publications from our laboratory (Nuebel and Peleg 1993; Nixon, Ulbricht, Nuebel,, Wollny, Normand, and Peleg 1994; Ulbricht, Normand, Peleg, and Horowitz 1994; Ulbricht, Normand, and Peleg 1995; Nixon and Peleg 1995; Suwonsichon and Peleg 1998; Gerhards, Ulbricht, and Peleg 1998). It has been demonstrated that, at least in the case of round puffed cereals particles, it is possible to reproduce the force-displacement curves of the individual particles from those of their assemblies.

When a single layer of such particles all having a similar size, a condition largely satisfied when it comes to commercial products, then the force of the assembly is simply the sum of the forces exerted by the individual particles. Consequently, the array's particles 'stiffness' can be assessed by dividing the measured force by the number of particles. The latter is proportional to the cross-sectional area of the container in which the particles are held. Hence when particulates are tested in a container, the total force is expected to be proportional to the container's diameter squared. The jaggedness of the force-displacement curve of brittle particles, when compressed as a layer or in bulk, is always considerably smaller than that of a single particle. The reason is that local peak forces would most likely be 'offset' by local minima and vice versa. The result would be a jagged record but with a *smaller* oscillations amplitude. If the "noise" in the force-displacement curve of the individual particles is or can be considered as random, the amplitude suppression would be proportional to the *square root* of the number of particles. Thus, one can estimate the force-displacement curve of an individual particle by dividing the layer's smoothed force readings by the number of particles and amplifying the "noise" around it by the square root of this number. As shown by Ulbricht et al. (1995), the principle can also be used to create "averaged" or "typical" signatures of puffed snacks and cereals, zwiebacks and the like, see Figs. 16 and 17.

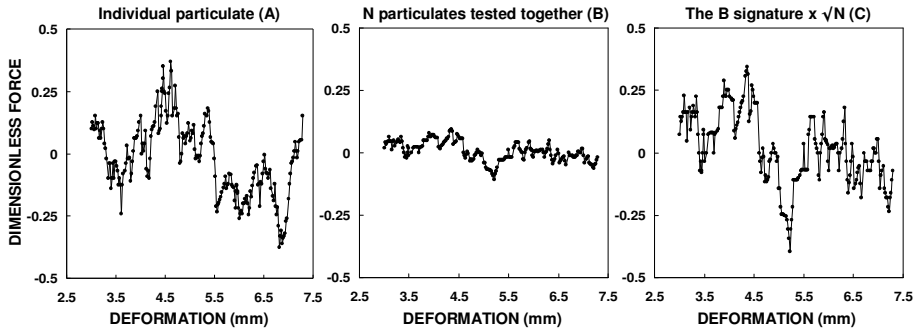


**Fig. 16**. Demonstration of the averaging effect when brittle particulates are tested together. Notice that signatures A and C have the same degree of jaggedness. After Ulbricht et al. (1995).

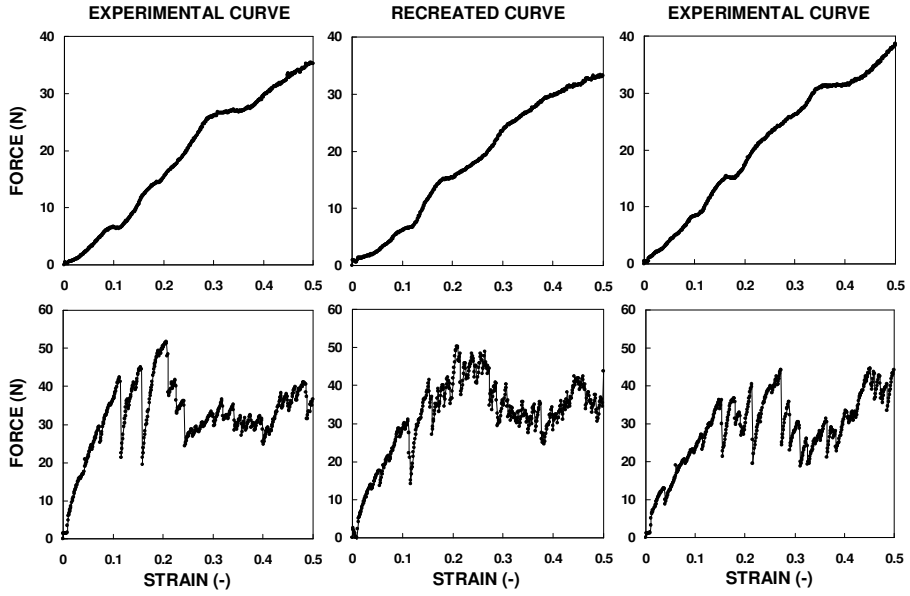


**Fig. 17.** Typical "smooth" (top) and jagged (bottom) force-displacement curves created by averaging the forces of five curves and adding their oscillations multiple by √5. Notice that the 'typical' (recreated) curve is indistinguishable from the experimental ones. From Ulbricht et al. (1995).

If the particulates are compressed as a bed of significant depth, then it is still possible to estimate the properties of a single particulate. This requires a series of tests performed on beds of different width and height, which makes it an unattractive option for most particulated cellular foods. However, particulates that always have non-uniform size and shape, like pork rind ("chicharrón") (González-Martínez et al.

2003), or corn flakes for that matter (Nixon and Peleg 1995), are a notable exception. It is therefore more convenient to test them as an assembly rather than individually.

## 4 Effect of Moisture

Moisture, absorbed or lost, invariably affects the mechanical properties of the cell walls material and consequently the texture of cellular solid foods. The plasticization or hardening of solid foods has been attributed to their 'glass transition' through lowering or elevating their "glass transition temperature", or "$T_g$". Hence, a food that is "glassy" at a given moisture content will become "rubbery" when it absorbs more moisture by being "above its $T_g$" at the same temperature. Similarly, a "rubbery" food will become "glassy", and therefore brittle, upon loosing moisture, which will move it to "below its $T_g$". The concept of a glass transition temperature, or "$T_g$", has been originally proposed in order to characterize the softening or hardening of non-crystalline materials like classic glasses (window glass, for example) and synthetic polymers in what is known to be a second order phase transition. In contrast with a 'first order transition', like melting or boiling, the changes take place, not at a point, but over a temperature range that can be shifted by changing the heating or cooling rate. Also, over the temperature range of the transition, the mechanical properties of the polymeric material need not change in unison. Consequently, different calorimetric and mechanical methods to determine the "glass transition temperature" or "$T_g$", yield values that can differ by *tens of degrees Celsius*, sometimes by over a hundred degrees, see Syler (1994) and Donth (2002). At ambient temperature, most solid food materials, cellular included, are in or very close to the transition region. Thus, if the concept that being above or below the "$T_g$" has a dramatic effect on a food's properties (especially mechanical) is accepted, then one could influence a food's physical stability by choosing the method to determine their "$T_g$"…

Moisture, no doubt, is an effective plasticizer. However, its exact effect on the mechanical properties of cellular solid foods, with a possible exception of the class of soluble low molecular materials (see below), cannot be predicted on the basis of their "$T_g$" even if there were an acceptable way to determine it. This is primarily because whenever the cell wall solid is mainly made of a high molecular weight polymer, such as starch and/or protein, moisture could affect its various mechanical properties differently and in a manner that must be determined experimentally.

### 4.1 Low Molecular Weight Matrices

Consider dry agglomerated or freeze dried coffee particles of approximately the same size. They have a considerable porosity and as shown in Fig. 18 (top) very jagged compressive force-displacement curves when dry. They are also rather stiff, as the level of the forces that they can sustain indicates, but they are still fragile and crumbly. Their crumbliness is primarily due to failure propagation in various directions. The process produces daughter particles of various sizes, which themselves can subsequently disintegrate and produce even smaller particles. It is

this failure at different levels that is responsible for the fractal appearance of the force-displacement curve, see figure.

Because of their moisture sorption pattern, instant coffees remain practically unchanged when their "water activity" is below about 0.5. At that point, they practically dissolve, in which case there is a *simultaneous* loss of brittleness and stiffness as shown in Fig. 18 (bottom).

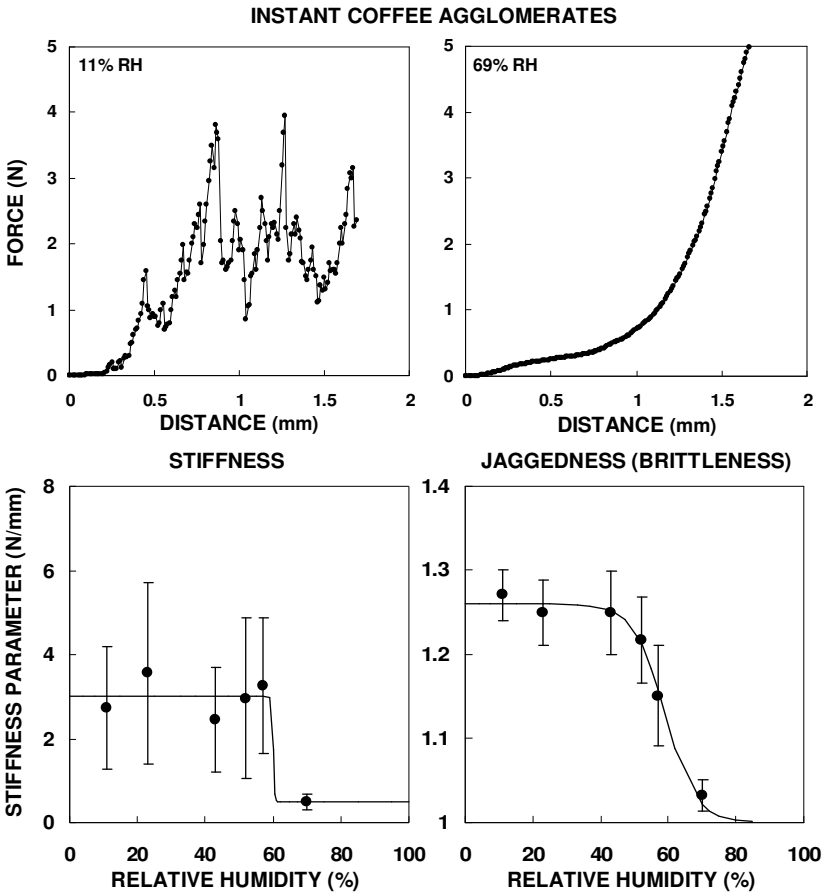


**Fig. 18**. Top: Typical force-displacement curves of agglomerated instant coffee when 'dry' and after moisture sorption. Bottom: The effect of water activity on the stiffness and brittleness of agglomerated instant coffee. Notice the sharp drop of both at about the same water activity. From Gerhard et al. (1998).

Such a dramatic change in both properties is clearly evident despite the large scatter in both the jaggedness and stiffness measures. Both indicate the occurrence of a 'sharp transition' at almost the same water activity. [The shown large scatter in the mechanical tests results was inevitable since the agglomerates were tested intact. Although they had been gently sieved to obtain a "uniform size", their shape was not

the same. Therefore, much of the scatter can be attributed to the variability in their morphology rather than to any substantial difference in their solid's mechanical properties.] A similar moisture effect can be expected in other particulates largely composed of soluble low molecular weight compounds. Examples are instant (agglomerated) milk and dry beverages. Their sugars are in a crystalline form and hence have a critical moisture above which they readily dissolve.

## 4.2 Cereals and snacks

The cell wall material of the puffed cereals and snacks is largely starch or protein although it can also contain a considerable amount of sugar or salt, as well as other materials usually at a much lower concentration. When the solid matrix is primarily a biopolymer (starch and/or protein), the effect of moisture on their properties can be somewhat different from that exerted on soluble solids of lower molecular weight. The main differences as has already been stated is that their plasticization, i.e., the transition from brittleness to ductility, takes place over a considerable range of moisture contents (or 'water activities', e.g., Attenburrow and Davies 1993; Roos 1995; Martínez-Navarrete, Moraga, Talens, and Chiralt 2004; Lewicki 2004; Aguilera 2006) as shown in Figs. 19-20. These figures demonstrate that regardless of whether the matrix is primarily starch-sugar (Cocoa Puffs®) or protein-salt (pork rinds), the transition has a considerable span. Thus the concept that the material just "crosses its $T_g$ line" is certainly inappropriate in this case. Any attempt to identify the beginning or middle of the drop as the cross over point will also be futile. It will tell nothing about the transition span, which can vary considerably among cereals and snacks. One must conclude, therefore, that any model of the brittleness loss in cereals and snacks must account for both the moisture or water activity level around which it occurs and the range over which the transition takes place. Or stated differently, the brittleness loss at the transition region must be characterized by at least two parameters, one to identify the transition's location and the other its steepness or broadness. [For more one this point see Peleg (1993), for example].

### *Moisture Toughening*

A peculiar phenomenon quite common in cellular foods can be called *'moisture toughening'* (Harris and Peleg 1996; Wollny and Peleg 1994). Water, as everyone knows and as already repeatedly stated, is a perfect plasticizer. Therefore, intuitively, one would expect that upon moisture sorption, the loss of brittleness (monitored in terms of the apparent fractal dimension, for example, or any other measure of jaggedness) will be accompanied by a corresponding loss of stiffness and toughness. After all, a completely plasticized or "soggy" food has hardly any stiffness or toughness at all. Yet, as shown in Figs. 19 and 22, this is not necessarily the case. At moderate levels of moisture absorption the particles' stiffness actually increases. Consequently, their toughness as represented by the area under the force-displacement curves – see Fig. 21 – also increases. This phenomenon has been observed in other brittle foods (e.g., Attenburrow, Goodband, Taylor, and Lillford

1989) and even in gluten films plasticized by water (Nicholls, Appelquist, Davies, Ingman, and Lillford 1995).

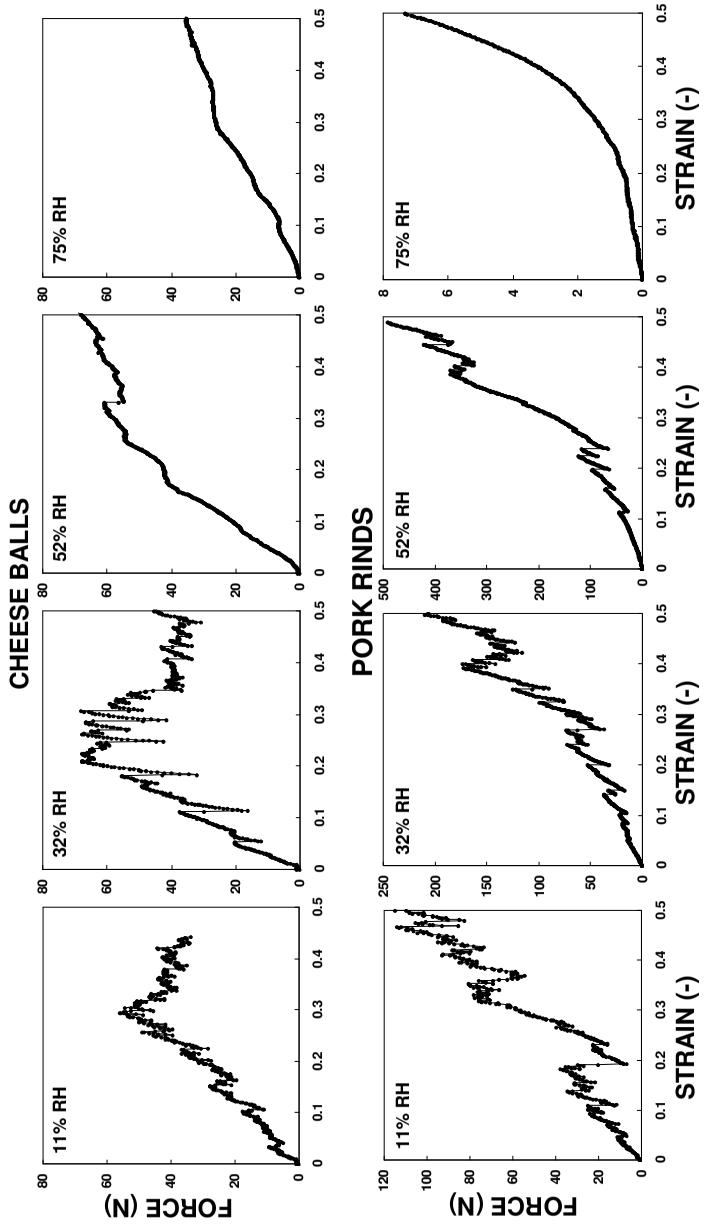


**Fig. 19.** The effect of moisture on the force-displacement curves of two puffed snacks. Notice the jaggedness loss in the wet particles force-displacement curves and that they can be higher than those of the dry ones.

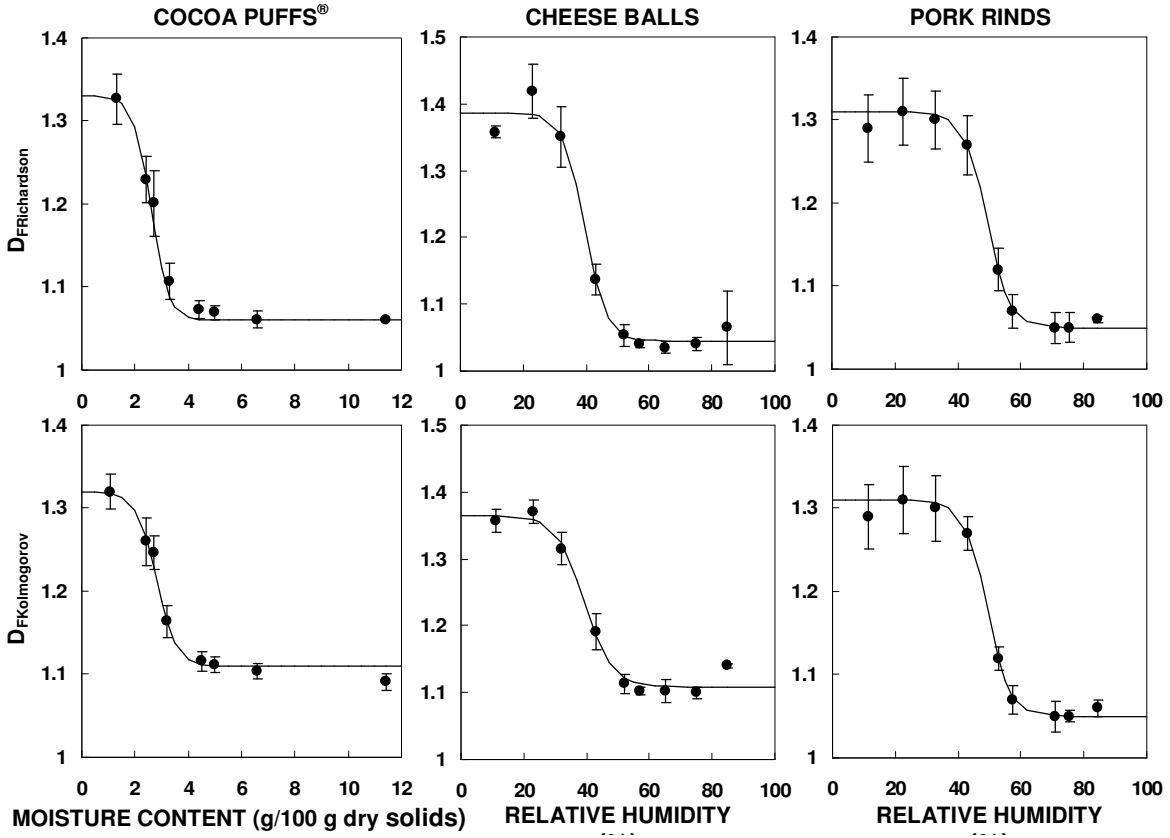


**Fig. 20.** The effect of moisture on the brittleness of three snacks. Notice the fit of the Fermi model and that the drop had a considerable span

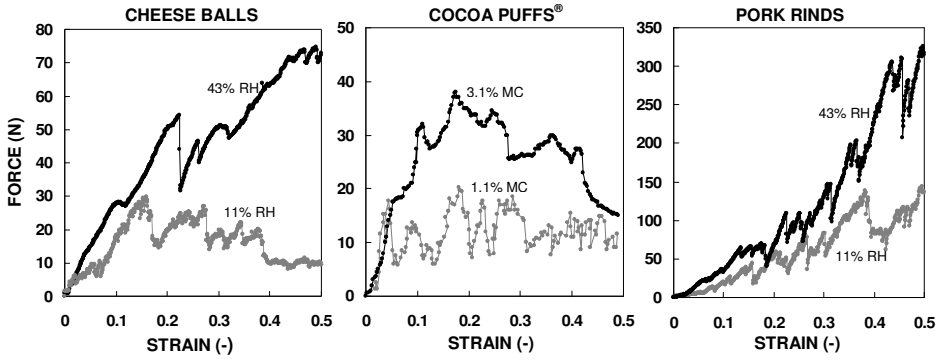


**Fig. 21.** 'Moisture toughening' in three snacks. Notice that the moderate moisture sorption can increase a snack's stiffness [and toughness (represented by the area under the force-displacement curve)] by inhibiting the ability of the fracture to propagate. From Suwonsichon and Peleg (1998) and González-Martínez et al. (2003).

This phenomenon has been observed in other brittle foods (e.g., Attenburrow, Goodband, Taylor, and Lillford 1989) and even in gluten films plasticized by water (Nicholls, Appelquist, Davies, Ingman, and Lillford 1995). Such observations can not be predicted from the standard glass transition theories, according to which plasticization by "crossing the Tg line" should be manifested in a total textural collapse of the specimen. The phenomenon of moisture toughening has a simple explanation. The *partial plasticization* of the solid matrix material, i.e., its loss of brittleness, inhibits the ability of failure to propagate (Suwonsichon and Peleg 1998; Aguilera 2006). Consequently, the cellular structure, by retaining some of its integrity, can continue to resist the imposed deformation, which is manifested in the continued force increase. But once the plasticization reaches a certain level, ductility sets in and the semi-liquid cell walls can no longer offer any a significant mechanical resistance. At this stage, the specimen's stiffness diminishes and it may disappear altogether when the solid is fully plasticized.

## *Sensory Perception*

The qualitative different effects of moisture absorption on the brittleness and stiffness of cereals and snacks may not be an academic matter. The difference can be perceived sensorily by humans as demonstrated in Fig. 23. This means that the brittleness loss (perceived as crunchiness/crispiness loss) and the stiffness and toughness rise (perceived as 'hardness' increase) can be sensed *simultaneously*, which might be of interest to those engaged in food products formulation. Since the sensation of crunchiness/crispiness is associated with acoustics, it can be added that the effect of moisture contents on the 'richness' of the acoustic signal follow a very similar pattern to that of the mechanical signatures jaggedness (Fig. 20) and of the sensory crunchiness/crispiness ratings (Fig. 23).

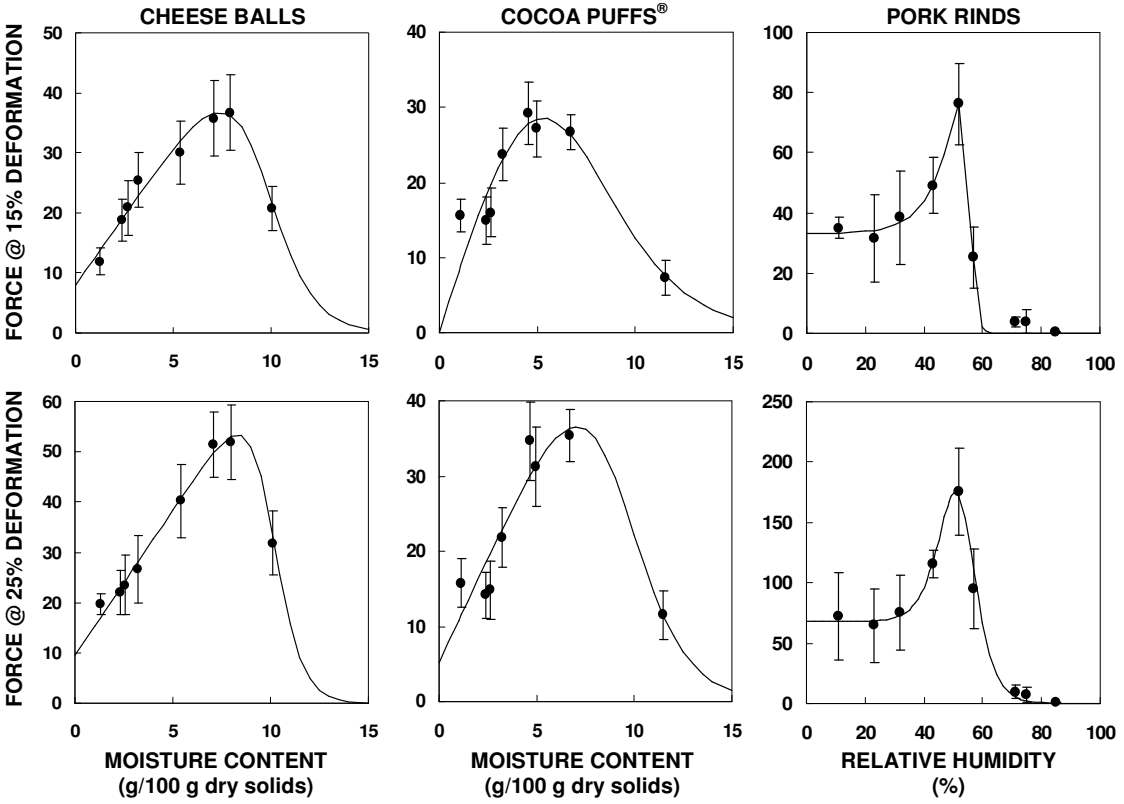


**Fig. 22.** The effect of moisture on the stiffness of three snacks. From Suwonsichon and Peleg (1998) and González-Martínez et al. (2003).

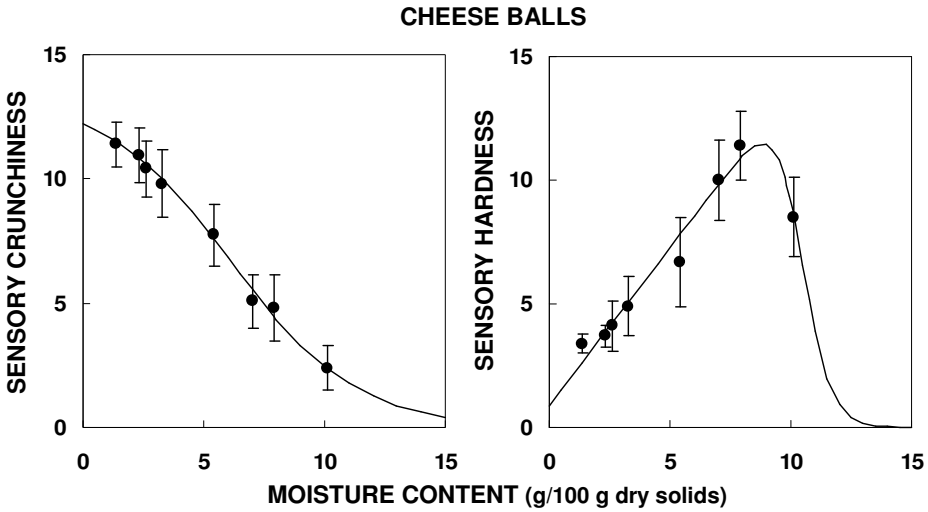


**Fig. 23**. The effect of moisture on the perceived 'crunchiness' and 'hardness' rating of a puffed snack. Notice that the loss of brittleness and 'moisture toughening' can be sensed simultaneously not only by machines (Figs. 19-22) but also by humans.

This suggests that the same failure/fracture events that are responsible for the irregular force oscillations are also responsible for the sound emissions. If the 'richness' of the mechanical and acoustic signatures is regulated by similar rules, i.e., those of several units compressed together are less jagged than that of one unit, then the perception of crunchiness or crispiness might be effected, to at least some extent, by the size and number of units consumed at the same time. However, a more systematic study will be required to establish that this indeed happens. The hypothesis that the jaggedness of the mechanical signature is associated with the sensory perception of crunchiness (or crispiness) has been demonstrated in the match of the apparent fractal dimension vs. moisture relationship and that between the corresponding perceived crunchiness ratings (Suwonsichon and Peleg 1998). However, the sensory scores indicated a significantly broader 'transition' than that found instrumentally. This was probability a reflection of the lesser sensitivity of humans when it comes to the edges of the brittleness range. The issue of sensitivity to textural attributes needs more in depth studies as has been pointed out elsewhere (Peleg 2006).

## 5 Concluding Remarks

The mechanics of a cellular solid is an excellent example of the role that *geometry* and *morphology* can play in the properties of materials. Buckling, for example, is a characteristic of all thin solid objects. Thus the mechanical properties of cellular foods can be affected to a large extent not only by their composition and thermal history but also by their matrix's structural features. Understanding and eventually control of the texture of cellular solid food products requires knowledge not only of

what affects the cell walls strength and flexibility but also of how the cells are organized in space. Ashby's theoretical studies of the mechanical behavior of cellular solids and that of his followers serve as most useful guidelines. But one should always keep in mind that cellular foods do not have cells of uniform size and geometry. Closed and open cells can coexist at different ratios and the former can sometimes burst open upon compression as has been demonstrated in breads. In the future, non destructive imaging methods to determine 3-D structures will probably provide information that will clarify the relationship between the cellular architecture, the cells properties and texture. In the past, many or perhaps most of the publications on cellular solids in the non-food literature were the result of an interest in their performance at relatively small deformations (strains). In contrast, during their mastication, foods are subjected to very large compressive strains and are then torn apart. Moreover, in engineering and biomechanics applications, the 'solid foam' is expected to be rather inert. Or, if it does interact with the environment, this would be a slow process that takes place on a time scale of months or years. In contrast, cellular foods interact with moisture very rapidly and the resulting changes can be quite unique, depending on the amount of water soluble components in their cell walls. A change in composition or a commercial food product's formulation is most likely to affect its cellular structure, especially if formed by extrusion or puffing. Thus, studying the effect of structure or composition in isolation may not be an easy task. However, there are ways to investigate their effects (See Chapter X). For example, freezing at different rates usually produces ice crystals of different sizes which upon dehydration can produce foams with almost identical composition but different cellular structure. Freeze dried model foams, based on food gums with and without additives can be used to study the effect of the cell wall material in foams that have a similar structure (see Nussinovitch, Corradini, Normand, and Peleg 2000; 2001 for an example). Whether this kind of study will generate wide interest, however, is highly in doubt.

The moisture and most probably temperature effects on cellular solid foods can have a large impact on several food producers, from the manufacturers of puffed cereals and snacks to the producers of instant coffee and agglomerated dry beverages. They also influence these products' fate once reaching the consumer. It appears though that the prevalent theories to explain the temperature or moisture effects on mechanical properties, originally developed for synthetic polymers and adapted for foods, notably those of 'glass transition', need a modification for successful application to cellular food products. Thus how to combine the roles of second order transitions and cellular solids mechanics might be an interesting area in food texture research. The results of such studies, no doubt, will have many practical implications in several food industries and probably in other industries as well.

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