The Basics of Solid Foods Rheology

Micha Peleg Department of Food Engineering, University of Massachusetts, Amherst, Massachusetts

I. INTRODUCTION

The characteristics of perceived "texture" are determined by different physical and physicochemical properties of the food and by the unique and complex features of the human sensory systems. It can be argued, however, that the stimulus in texture perception is predominantly mechanical in nature. Consequently, most, if not all, of the instrumental methods of texture evaluation can also be classified as mechanical tests. To be able to establish the relationship between texture as perceived and the properties of the food, or to interpret the results of instrumental evaluation methods, it is essential to understand the mechanics, or rheology, of food deformation. This, of course, does not entail that rheology is the sole key to understanding texture, and there is ample evidence that geometrical, chemical, thermal, acoustic, and psychological factors can also play a major role in sensory textural assessment. But, even if we only attempt to deal with the rheological aspects of food texture evaluation, enormous difficulties immediately

arise. The reason is not so much the mathematical complexity of the pertinent mechanical theories. It is mainly because in comparison with engineering materials for which these theories were originally developed, most foods and biological materials are at the same time highly anisotropic, nonuniform, and, in many cases, chemically active and physically unstable. Anisotropy (as in meat fibers, for example) results in different mechanical properties in different directions, and physicochemical instability produces strong time-dependent properties. The fundamental principles of rheological evaluation of foods, however, are basically the same as those that are applicable to engineering materials, especially polymers. There are, however, differences in the interpretation of the test results. This is because any meaningful interpretation must take into account the specific structural features and the mechanical and biological history of the particular food material in question.

This chapter will only survey the mechanical terminology and describe the main rheological methods of solid foods characterization. It should be stated that the methods to be discussed are only those that are also used in mechanics and material science research, for which the theoretical rheological background is well developed. The discussion will focus, however, not on the quantitative aspects of the tests, but mainly on the physical significance of the results in the context of solid foods and their unique structures. Intentionally, the use of mathematical expressions in this chapter has been avoided as much as possible. The interested reader, however, will be able to find ample material on rheological models and the mathematical aspects of rheological data processing methods in the selected references that are cited in the text and in the general literature of rheology, mechanics, and material science.

II. STRESSES, STRAINS, AND RATES

A. Forces and Stresses

1. *Normal Forces and Stresses*

Normal forces are perpendicular to the surface on which they act and they can be either tensile or compressive (Figure 1a). Normal stress is expressed as units of force per unit area and, again, it can be either compressive or tensile. A normal stress can be presented as *engineering stress*, which is calculated by dividing the magnitude of the applied force by the initial area of the specimen. It can also be presented as what is called *true stress*, which is calculated by dividing the force by the

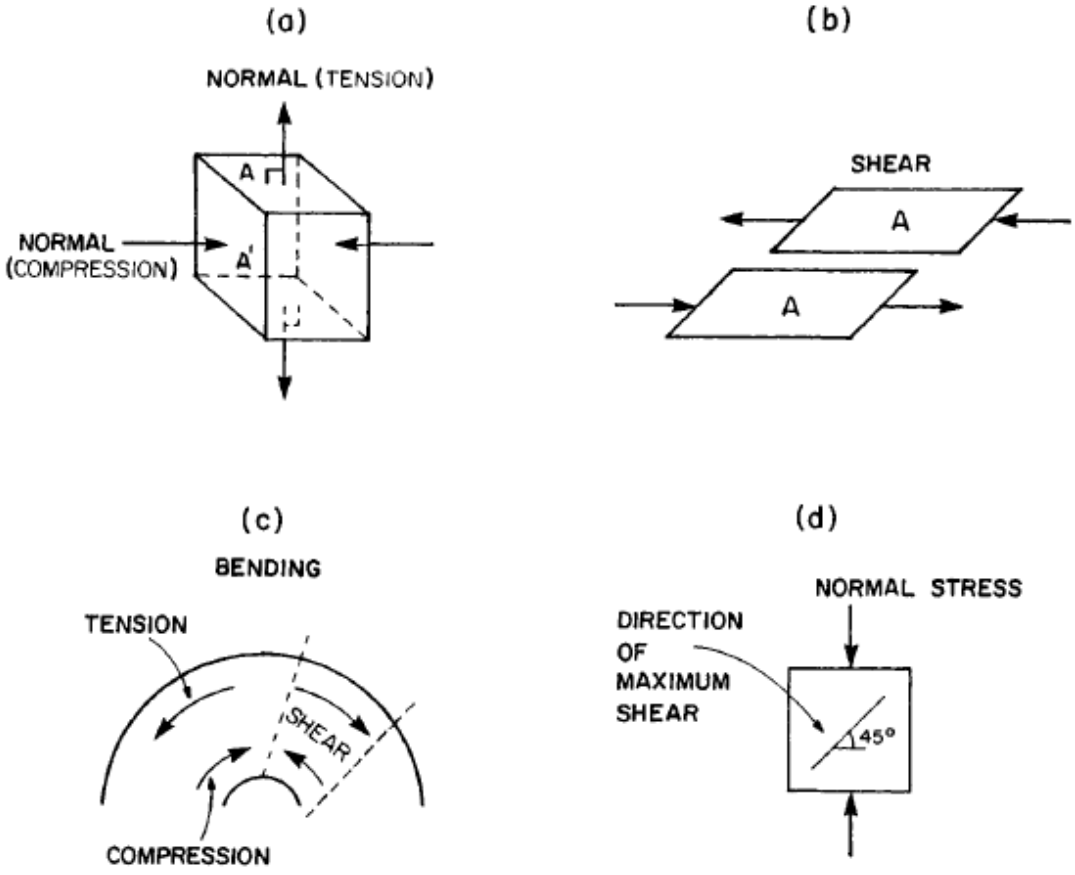


Figure 1 Normal and shear forces and stresses.

actual cross-sectional area of the *deformed specimen*. Thus, the apparent or engineering stress (σ_E) is given as (Figure 2):

$$\sigma_E = \frac{F(t)}{A_0} \tag{1}$$

and the true stress (σ_T) that varies with time as;

$$\sigma_T = \frac{F(t)}{A(t)} \tag{2}$$

where $F(t)$ is the force, and A_0 and $A(t)$ are the initial and momentary cross-sectional areas.

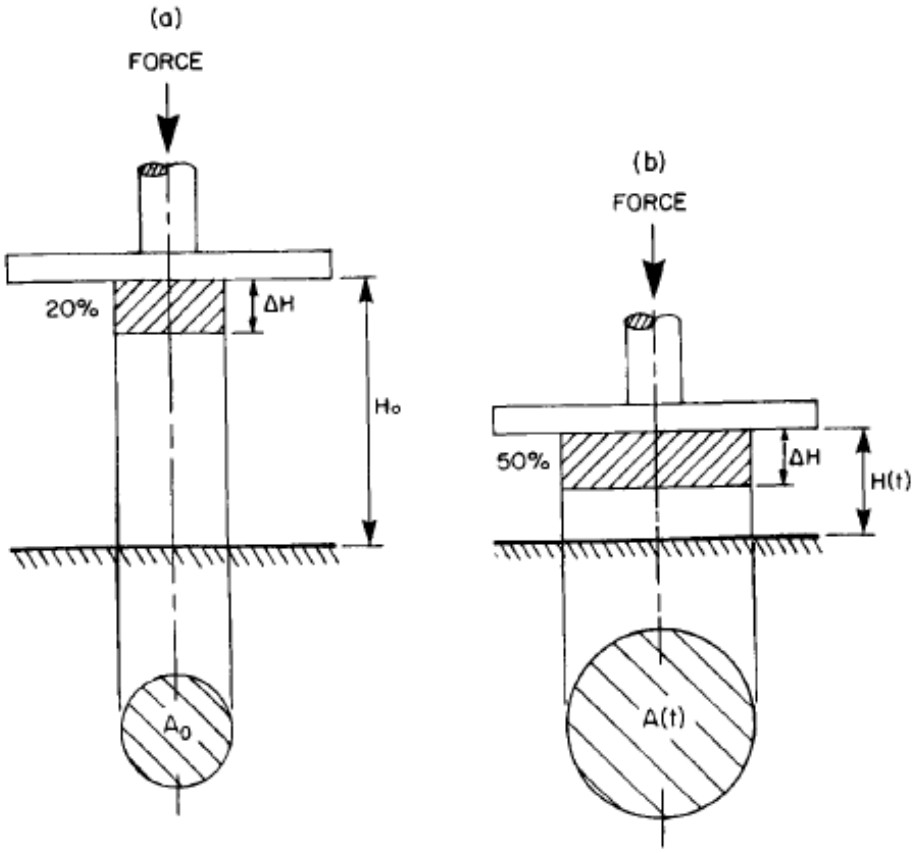


Figure 2 Changes in the specimen dimensions as a result of large deformation. (H_0 and A_0 are the original length and diameter, respectively; $H(t)$ and $A(t)$ are the dimensions after time t). Note that the same absolute deformation (ΔH) can be "felt" by the specimen as a different strain.

2. *Shear Forces and Stresses*

Shear forces are parallel to the surface on which they act (Figure 1b). The shear stress is expressed in the same units as a normal stress (i.e., force per unit area), but the area to be used for its calculation is parallel to its direction.

3. *Combined and Local Stresses*

In most real bodies, the application of external force will result in different kinds of internal stresses. An illustrative example is bending (Figure 1c), where compressive tensile and shear stresses develop. Even

in simpler configurations (e.g., the one shown in Figure 1d), shear stresses develop as a result of applying normal stresses and vice versa (1).

It is also clear that a stress as previously described only refers to an ideal averaged force intensity. For many practical purposes, these ways of stress calculation are satisfactory and provide an effective and convenient tool for analyzing the performance of mechanical systems. It is also recognized, however, that in the loading of a real body, especially with structural irregularities, the actual internal stress distribution can be far from uniform (Figure 3) and, in certain cases, can lead to *stress concentration* where the intensity by far exceeds the average stress.

B. Deformations and Strains

1. *Normal Deformation and Strain*

Normal deformation (ΔH) is the absolute elongation or length decrease in the direction of the applied force (Figure 2). The apparent or engineering strain (ϵ_E) is the ratio between the deformation and the initial length of the specimen (H_0):

$$\epsilon_E = \frac{\Delta H}{H_0} \tag{3}$$

Sometimes the engineering strain is given in percent, or percent deformation that is expressed by:

$$\epsilon_E = \frac{\Delta H}{H_0} \times 100 \tag{4}$$

For small deformations (i.e., where the length of the specimen can be assumed to be practically unchanged), the engineering strain can also be considered as a true strain. This is not so where the deformation is large, as is clearly evident from Figure 2. For large, absolute deformations, there are several strain definitions (2,3). It appears that for most food applications, the natural or true strain as defined by Hencky is the most appropriate.

According to this definition, the true strain (ϵ_T) for compression is given by the logarithmic dimensionless expression:

$$\epsilon_T = \ln\left(\frac{H_0}{H_0 - \Delta H}\right) \tag{5}$$

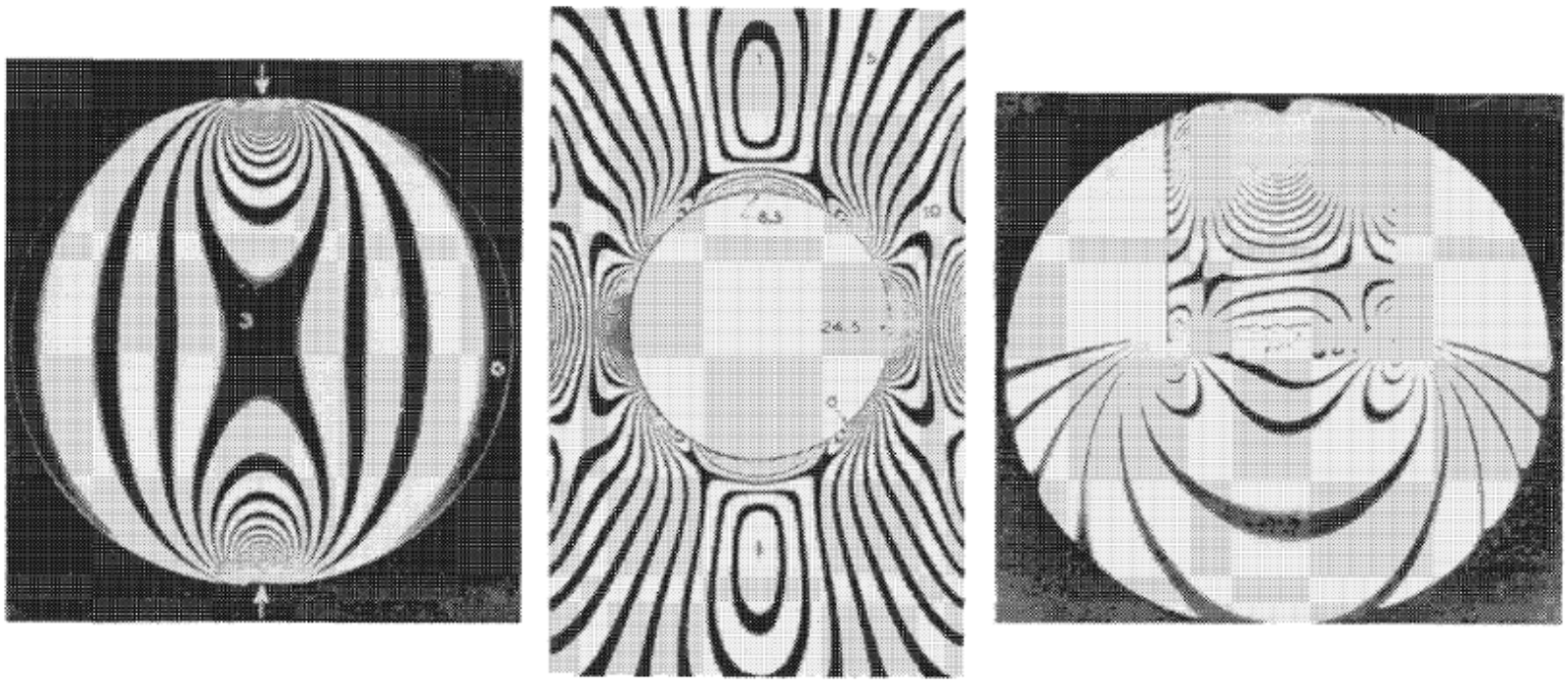


Figure 3 Internal stress distributions as revealed by photoelasticity. *Left*: A disk compressed between two parallel plates. *Middle*: The stresses around a hole. *Right*: The contact region of two flat bodies compressed one against the other. [From M. M. Frocht, *Photoelasticity*, Vols. 1 and 2, John Wiley & Sons, Inc., New York. (1946). Reproduced with permission, courtesy of John Wiley & Sons, Inc.]

(The reader will notice that while the engineering strain has a range between 0 and 1.0 (or 100%), the true strain has a range between zero and infinity).

2. *Shear Deformation and Strain*

The absolute shear deformation is demonstrated in Figure 4. For small deformations, the shear strain (dimensionless) (γ) is given by:

$$\gamma = \frac{\Delta X}{Y_0} \tag{6}$$

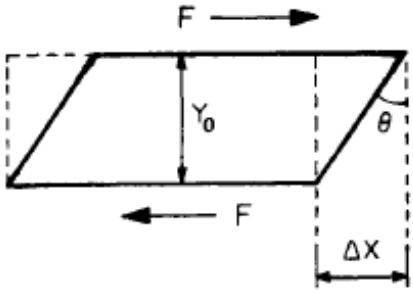
where ΔX is the deformation, and Y_0 is the specimen's thickness.

C. Loading Rates

Because most solid food materials are viscoelastic in nature (see below), the rate at which they are loaded or deformed may significantly affect their mechanical response. Usually, especially in deformation testing, the magnitude of the rate is selected so as to simulate practical situations. Its regime or mode, however, is usually established by instrumental design considerations. The most commonly referred to rates are the following.

1. *Constant Deformation (or Displacement) Rate*

Most Universal testing machines that are used in food testing operate at one or more constant speeds. This produces constant deformation rates (i.e., the distance traveled by the crosshead is the same for any given lapse of time irrespective of the specimen's initial and actual dimensions). If the deformation is small and the changes in the specimen's



length are negligible, the constant deformation rate can be used in the approximation of a constant strain rate ($\dot{\epsilon}$) or:

$$\dot{\epsilon} \cong \frac{V}{H_0} \tag{7}$$

where V is the machine's crosshead speed (e.g., $cm \cdot min^{-1}$) and H_0 is the initial length of the specimen (e.g., cm).

This is no longer true when the deformation becomes large. In compression, the strain rate actually "felt" by the specimen progressively increases with the advance of the deformation (Figure 5). This is because the same absolute displacement becomes larger relative to the decreasing length of the deformed specimen. In this case, the true strain rate ($\dot{\epsilon}_T$) is defined by:

$$\dot{\epsilon} = \frac{V}{H_0 - Vt} \tag{8}$$

and it approaches an infinite value as the specimen length is reduced to zero. The situation is, of course, the opposite in tension where, because of the length increase, the true strain rate progressively decreases.

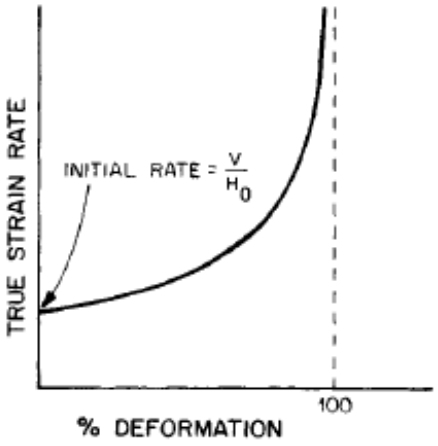


Figure 5 Schematic view of the relationship between the true strain rate and the deformation in a uniaxial compression test performed at a constant deformation rate. V is the constant deformation or displacement rate; H_0 is the specimen's initial length. (See also Figure 2.)

2. *Constant Force Increase Rate*

True constant force increase rate (i.e., force increasing linearly with time) is difficult to produce by ordinary table-size machines whose moving crosshead is driven by a screw or screws. It can be easily produced by hydraulic machines, but these are usually designed for higher load ranges than those relevant to food testing.

3. *Step Deformation* or *Loading*

For ideal creep and relaxation tests (see below), it is essential to load the specimen instantaneously. Because a true step deformation in the mathematical sense is not physically possible, the specimen is loaded either at the fastest deformation or force rate available or, in some cases, by simply dropping a load on the specimen. Theoretically, however, there is a fundamental difference between the ideal and "practical" step loading, the implications of which ought to be considered when the results are interpreted (see below).

4. *Sinusoidal Deformation*

This type of deformation is imposed on a specimen during dynamic testing (see below). The maximum absolute deformation and the actual amplitude are usually very small in comparison with the deformations applied in uniaxial loading tests. The frequency (ω) can be either low or high. Mathematically, the strain in such tests is given by:

$$\epsilon = A \sin \omega t \tag{9}$$

where A is the amplitude, so that the momentary strain rate ($\dot{\epsilon}$) is:

$$\dot{\epsilon} = A\,\omega \cos \omega t \tag{10}$$

III. RHEOLOGICAL BEHAVIOR OF SOLID FOODS

A. Uniaxial Deformation and Stress-Strain Relationships

1. *Compressive and Tensile Tests*

In most uniaxial compressive tests, a food specimen, usually a cylinder or cube, is deformed at a constant deformation rate, as shown schematically in Figure 2. The force that develops is recorded continuously, and the typical relationship between force and time (or absolute deformation) has the shape shown in Figure 6a. Since the

concave upward shape is partly a result of the increasing cross-sectional area and the nonlinearity of the strain, such "raw curves" convey little information regarding the rheological character of the food in question (4). If, however, the curves are converted into "true" stress-strain relationships (using Equations 2 and 5, for example), much more rheological information can be retrieved from the same set of experimental data (5–8).

The kind of additional information is demonstrated schematically in Figure 6b. The concave upward curve in true coordinates indicates a predominantly compressible material (e.g., bread, sponges). A concave downward curve is an indication of a predominantly yielding material that undergoes considerable structural disintegration as a result of straining. A linear or an approximately linear relationship has two possible interpretations. The first is that the material is predominantly elastic or rubbery (9). The second is that structural destruction and yielding is compensated by the compaction of the collapsed structure remnants. It is, of course, also possible that each of the described effects become dominant at a different strain, thus producing a relationship that has alternating concave and convex regions (5). In tension, the situation is reversed with respect to the slope of the force-deformation

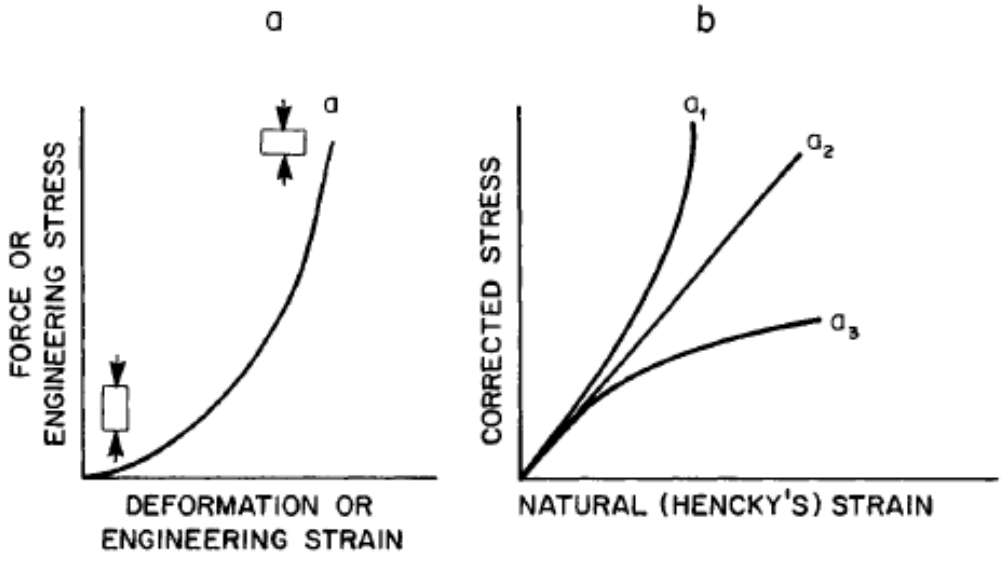


Figure 6 Engineering (*left*) and true (*right*) stress-strain relationships. Note that the rheological character of the material (e.g., compressible [σ_1], rubbery [σ_2], or yielding [σ_3]) is only evident when the data are replotted in corrected coordinates.

curve, primarily because the cross-sectional area decreases with the deformation. In true coordinates, the interpretation is similar, with the distinction that strain hardening replaces compressibility or compaction as a means of strength augmentation.

2. *The Deformability Modulus*

A convenient parameter to quantify the stiffness of a material is the slope of the true stress-strain relationship. If the material is elastic and the strains (deformations) are small, both the true and apparent curves are, for all practical purposes, straight lines. In such cases, the determination of Young's modulus as the slope of the stress-strain relationship (stress units) is straightforward, and its meaning as a mechanical measure of stiffness is unambiguous. For most food materials, in contrast, the stress-strain relationship is frequently curved, and is also a function of factors such as specimen size and deformation rate (see below). Under such circumstances, it is preferable to consider the stress-to-strain ratio as a "modulus of deformability" (10) and to treat its magnitude not as an absolute material property, but as a relative (and to some extent an arbitrarily determined) parameter whose usefulness may be limited to the particular conditions under which it has been determined.

3. *Compression-Decompression Tests*

If an ideal elastic body is subjected to a compression-decompression cycle (Figure 7a), it will always return to its original shape, and all the energy invested in the deformation process will be recovered. In most nonideal elastic materials (e.g., rubber), some energy is always lost mainly due to internal friction. The body, nevertheless, will return to its original shape and will exhibit the same or almost the same properties on being subjected to a subsequent deformation cycle. The energy that dissipates in the process, usually in the form of heat, is represented by the area of the hysteresis loop of the force-deformation curve (Figure 7b).

Most solid food materials are neither ideal elastic nor rubbery. Part of the deformation will, therefore, remain permanent after decompression (plastic deformation). In such materials, a considerable portion of the energy invested in the specimen deformation is irrecoverable due to both internal friction and irreversible structural modifications (Figure 7c). The ratio between the recoverable and the total deformation was suggested as a "degree of elasticity" (11) and, similarly, the ratio between recoverable and irrecoverable work can also be a characteristic of the material (6). It ought to be remembered, however, that the magnitude

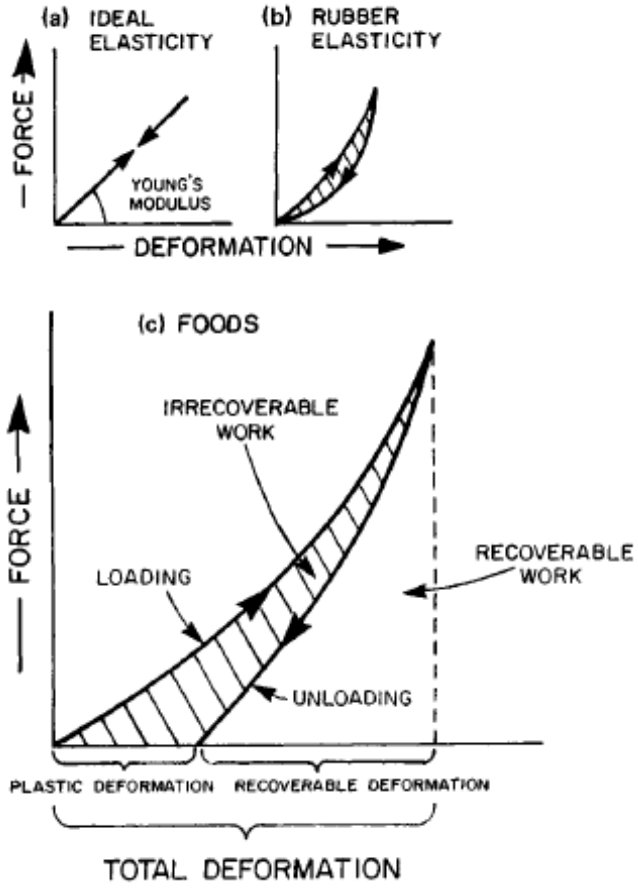


Figure 7 Different types of compression-decompression force-deformation curves.

of these parameters may strongly depend on the final strain level as well as on other factors (notably the specimen dimensions and the deformation rate) (12). In such cases, the *dependency* of these parameters on the test conditions (e.g., strain, specimen diameter) themselves can be considered as a rheological fingerprint of the material and be interpreted in terms such as continuous structural disintegration, build-up of hydrostatic pressure, etc.

4. *Effect of the Deformation Rate*

Most if not all solid foods are known to be viscoelastic materials. "Viscoelastic" in our context means that their mechanical behavior is neither purely elastic nor purely viscous, but something in between that shares the properties of both. One of the prominent characteristics of viscoelastic materials is that the stress they develop is not only a function

of the strain, but also of the rate at which it is applied. Generally, the faster the rate, the higher the stress (Figure 8). There is, however, a theoretical limit to the rate effect. At high rates, the actual level of which is primarily determined by the material's relaxation time (see below), the response of a viscoelastic body will converge to what is equivalent to the behavior of an elastic body (e.g., Ref. 13).

The exact nature of the rate dependency is a characteristic of the material. The more solid or elastic it is, the less is the rate effect. Thus, rigid food materials such as unripe fruits and vegetables are less rate-sensitive than are soft foods like some cheeses.

A point that ought to be remembered when the rate effect is evaluated is that a constant deformation rate is not the same as a constant strain rate. Thus, the distinction between true solid and liquid on the basis of the shape of the stress-strain relationship is not as straightforward as in the case of a constant strain rate deformation history (Figure 9), and it cannot be deduced, in any degree of certainty, on the basis of the data contained in a single curve (4).

5. *Effect of the Specimen Dimensions*

Theoretically, in a perfect test of an ideal material, the stress-strain relationship in uniaxial deformation ought to be independent of the specimen dimensions by definition. In practice, especially in compressive tests of relatively flat specimens (i.e., height-to-width or

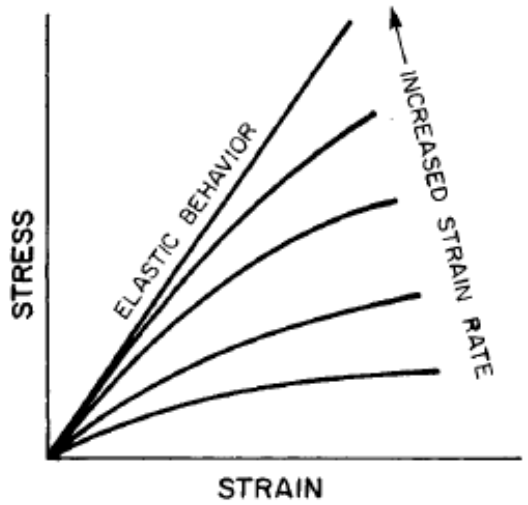


Figure 8 The theoretical effect of the strain rate on the stress-strain relationship of a linear viscoelastic material.

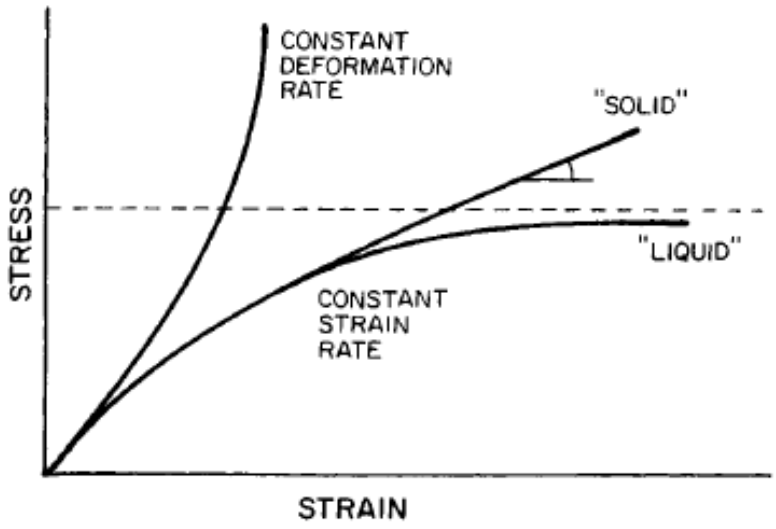


Figure 9 Schematic illustration of the difference between the compressive stress-strain relationships of a specimen deformed at a constant strain rate and a constant deformation rate.

height-to-diameter ratio of about unity or less), this is not always so, mainly for the following reasons:

1. Frictional forces along the contact surfaces can become significant and, consequently, the specimen will exhibit considerably higher apparent strength and probably a different deformability pattern (see Ref. 14 for an example). The effect is exploited in certain engineering applications of rubber as a cushioning material for machines and buildings. Quantitative evaluation of the height-to-area ratio effect on the apparent strength increase of constrained rubbery materials has been provided by Lindley (15).

2. Many food materials, notably plant and animal tissues, are fluid-containing structures. In many cases, the stress level in a deformed specimen taken from such materials is largely a result of hydrostatic pressure build-up. The pressure dissipation rate depends on the total resistance to the fluid outflow toward and through the specimen walls. This resistance is primarily determined by the density, porosity, and microstructure of the compressed solid matrix and the total length of the fluid path (Figure 10). It is, therefore, not surprising that, in such materials, a specimen with a larger diameter exhibits a higher apparent strength (i.e., higher stresses) compared with a "thinner" specimen at the same strain.

Other deformation mechanisms are, of course, also possible and are known to exist. Account of the specific mechanism is particularly important in the analysis of oriented structures or where the structural

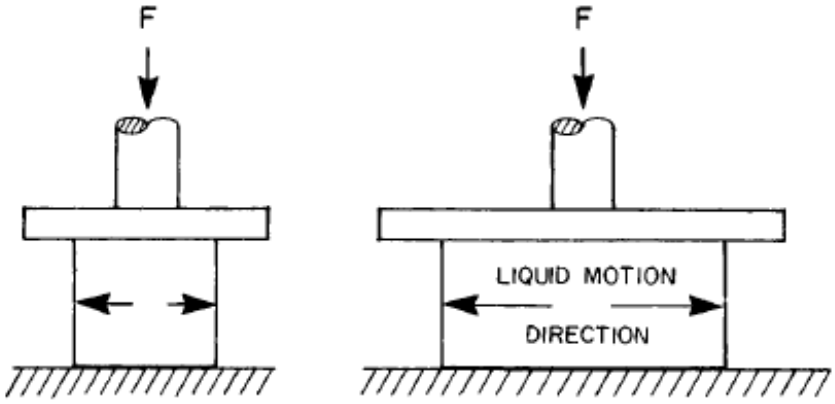


Figure 10 Schematic presentation of the resistance to internal flow in specimens having different diameters.

elements are of a size comparable with that of the specimen itself (e.g., fibrous and flaky materials).

Theoretically, the specimen's dimensional effects are also linked to that of the deformation rate's effects. This is because at the same constant deformation rate, a shorter specimen is deformed at a higher true strain rate (Figure 2). The absolute magnitude of the effect, because of its dependency both on experimental conditions (e.g., friction) and inherent structural properties, can vary considerably and, therefore, it is not surprising that there are conflicting reports as to whether the effect is indeed significant. Diehl et al. (16), for example, found no such effects in fruits, while Peleg et al. (17) did. It ought to be mentioned that when the effect is significant, the dependency itself can be considered as a textural property of the given food material.

B. Triaxial Deformation

In this kind of analysis, the specimen is subjected to hydrostatic pressure, applied through incompressible fluid, and the volume change is monitored (Figure 11). The source of rheological data in this case is the relationship between the dimensionless *volumetric strain* (defined as the fraction or percentage of the volume change) and the applied pressure (stress units). The ratio between stress and the volumetric strain is called the *bulk modulus* (1). As in the case of the deformability modulus, in uniaxial loading, the bulk modulus may have time and rate dependencies. Descriptions of the instrumentation for such tests as well as rheological analysis of the results obtained with foods can be found in various publications (11, 18, 19). Because of the stress geometry, the rheological information obtained in such tests is not the

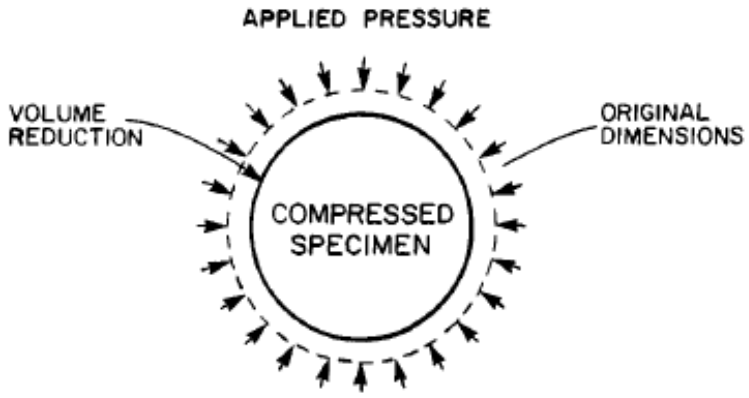


Figure 11 Triaxial or hydrostatic loading.

same as that derived from uniaxial or shear analyses. The bulk modulus, however, is related to the deformability and shear moduli (see below) as well as to the *poisson ratio*. The latter (Figure 12) is defined as the ratio between the lateral and axial strains in uniaxial deformation. Its numerical value can, theoretically, be between zero (totally compressible material) and 0.5 (incompressible material). The relationship between these four parameters in elastic materials is well defined in terms of simple algebraic expressions (1). This is not necessarily the case in many solid foods because of the large deviations from elasticity and the anisotropic structural features.

C. Torsional Tests

The application of torsion produces all three kinds of stresses (i.e., shear, compressive, and tensile stresses). For geometrical and technical reasons, a torsion is a convenient method to measure shear stresses directly for the calculation of shear moduli (i.e., the ratio between shear stress and strain). The pertinent data are derived from the torque, angle of twist, and the specimen dimensions. For many engineering applications (e.g., the strength of shafts), knowing the behavior of materials in torsion is particularly important. In solid foods testing, however, torsion has almost exclusively been used to obtain an independent measure of the shear or tensile strength so that they could be compared with values obtained from other tests. For recently published studies on the behavior of solid foods in torsion, see Refs. 16, 19, and 20.

D. Stress Relaxation

1. *The Test*

Ideally, a stress relaxation test is performed by a step deformation of the specimen (in tension, compression, or any test configuration),

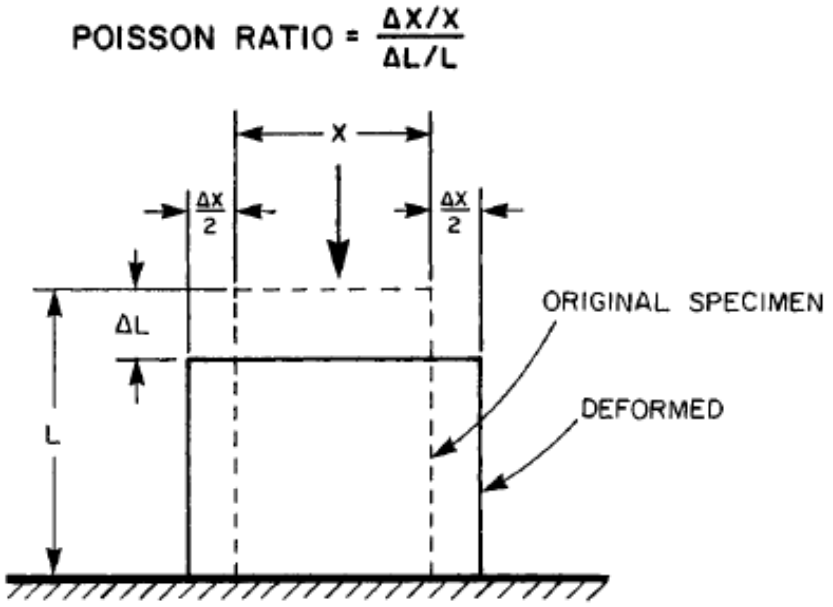


Figure 12 The definition of Poisson's ratio.

followed by recording of the force decay in time while the deformation remains fixed. In reality, step deformation is, of course, impossible and, therefore, some time must elapse before the specimen reaches the preset deformation (Figure 13). The "raw" relaxation curve (Figure 13) is in the form of force versus time relationship. It is usually presented, however, in the normalized form of stress or modulus decay curves. (The latter is calculated by dividing the momentary magnitude of the decaying force by the specimen area and by the strain that corresponds to the fixed deformation.) The test can also be repeated with different settings of the deformation (or strains) level, and by changing the deformation rate at which the preset deformation is reached.

Because maintaining a fixed deformation is the essence of the analysis, Universal testing machines, whose crosshead is driven by a screw or screws, are particularly suitable for such tests.

2. *The Phenomenon of Stress Relaxation*

An ideal elastic body does not relax at all (Figure 13), and all the energy invested in its deformation becomes *stored energy* that will be released on the return of the body to its initial undeformed state. (This behavior can be exemplified by a spring.) In contrast, an ideal viscous body cannot maintain any stress in the absence of motion, and it will relax instantaneously. This characteristic can actually be felt when a simple liquid (e.g., water) is stirred. The resistance, or force, will disappear immediately after the motion is stopped irrespectively of position.

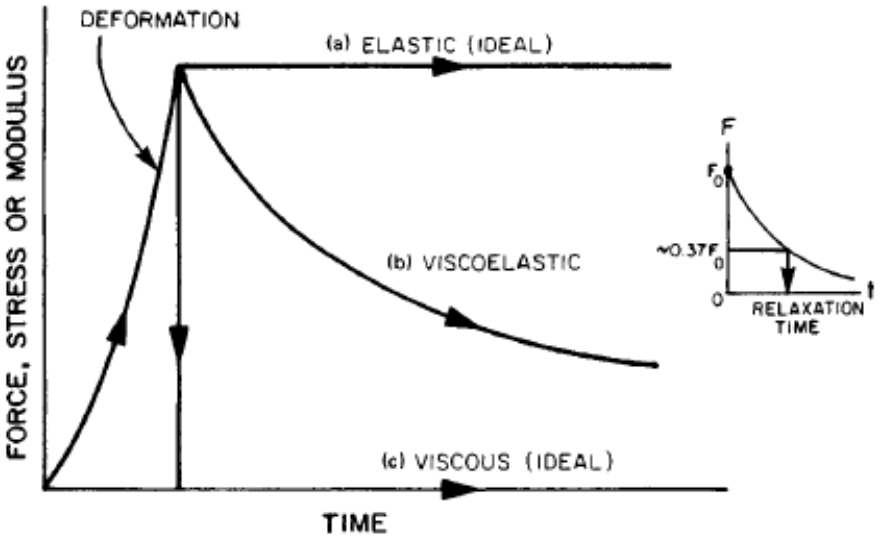


Figure 13 The relaxation test. (Note that ideally, the deformation stage is to be reduced to a step deformation.)

In viscoelastic materials, as previously mentioned, the behavior is intermediate. This is expressed by the fact that the force does relax, but at a definite, not necessarily constant, rate. The observed mechanical relaxation phenomenon is a result of molecular and structural reorientation. In many heterogeneous and cellular food materials, it can be a consequence of liquid flow as well. In certain compressed gels (e.g., agar), it appears that progressive rupture can also be a mechanism through which internal pressure is relieved (21). Regardless of the particular mechanism by which the stress relaxes, it can be assumed that the stress at any given strain (or the force at any given deformation) has either one or two types of components.

The first is in the form of an elastic stress that is proportional to the strain only. The second is in the form of a rate-dependent stress. If this is so, then after a sufficiently long time, all the stress of the second type will dissipate, and the remaining stress will be that of the first type only. It now becomes obvious that a stress-strain curve can be "opened up" by a relaxation test (Figure 14) and that the *degree of solidity*, at least in principle, can be determined from the stress that remains unrelaxed after a sufficiently long time. Thus, in an ideal elastic solid, 100% of the stress remains unrelaxed, while in liquids, all the stress relaxes. (This can also serve as a demonstration that elasticity, viscoelasticity, and viscosity form a continuous rheological domain and that the differences between the rheological behavior of materials are really in degree and not in kind.)

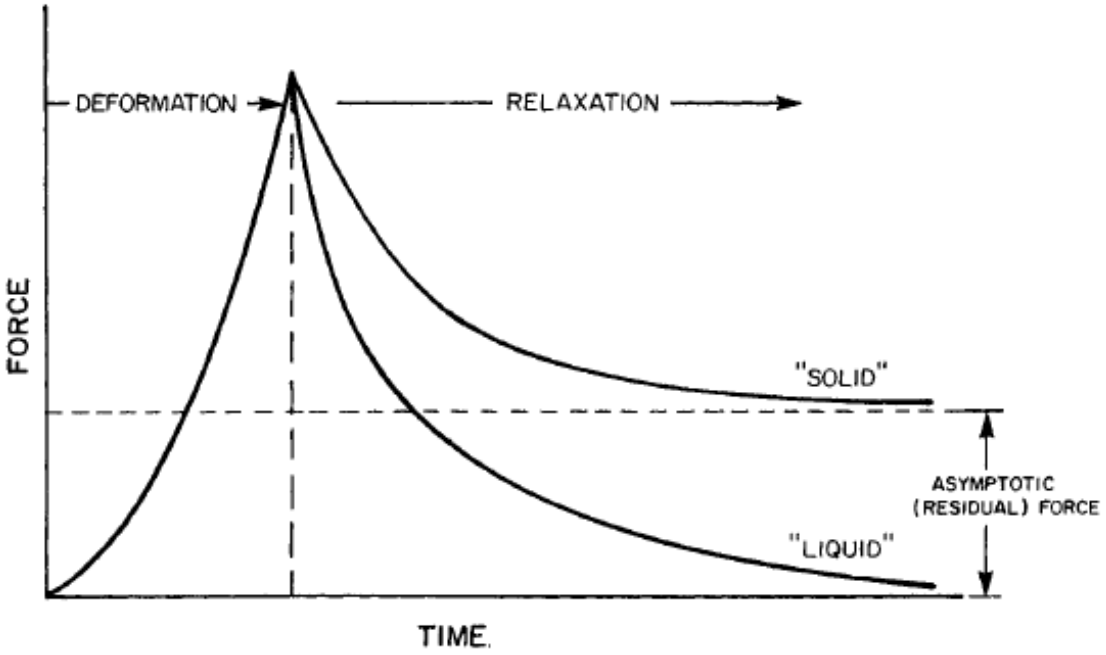


Figure 14 The difference between viscoelastic solid and liquid as can theoretically be revealed from a relaxation test. (Note, however, that the level of the asymptotic force and, consequently, that of the residual modulus can be a function of the strain and the specimen's mechanical history.)

The main problem in establishing quantitatively the degree of solidity of most foods in the described manner is that after a "sufficiently long time," the latter will decay as a result of microbial and or enzymatic activity or at least will exchange significant amount of moisture with the environment at a rate depending on the atmosphere's humidity. In both cases, therefore, the measured force after long time will have little relevance to the original rheological properties of the food in question. The problem can be "bypassed" to a certain extent by establishing an arbitrary time for the test duration (e.g., 10 minutes or less) and referring to the results obtained in this fashion as a solidity measure on a short-time scale. Some of the rheological implications of this and other options in food's analysis by relaxation tests, and a mathematical procedure by which the element of arbitrariness can be minimized, have recently been discussed elsewhere (21).

3. *The Relaxation Time*

The time at which the stress (or force) reaches 1/e (e is the basis of the natural logarithm), or about 37% of the initial level, can be called the

relaxation time. This parameter is a crude measure of the stress decay rate and can serve for comparison between different materials. A plot of the relaxation data as a semi-logarithmic relationship between stress and time will show that the relationship is not linear. Therefore, the single relaxation time as previously defined may not be the best representative of the decay pattern. (It also cannot indicate the degree of solidity in any unambiguous manner.) A more accurate way to describe the relaxation curve is in terms of a "relaxation time spectrum," which may be either discrete or continuous. (Mathematical and graphical methods for determining the "spectrum" can be found in many basic rheological textbooks [10, 22]. Today, however, a curve can easily be fitted to almost any desired model by using a computer nonlinear regression statistical package.) It was also demonstrated that for most foods, the whole shape of the relaxation curve can be described in terms of a two-parameter equation, thus avoiding the mathematical complexity that is associated with equations that account for more than one relaxation time (23, 24).

4. *Artifacts and Nonlinear Effects*

If the deformation of the specimen is done at a low rate, the recorded relaxation curve, at least initially, will be lower than that expected theoretically for step deformation. How much lower will be determined by both the material's rheological properties and the deformation rate. For this reason, the initial part of the relaxation curve (the one determined by the shorter relaxation times of the spectrum) may be an inaccurate account of the material's true behavior. If the test is performed at high deformation rates, but with machines having a slow recorder, then the initial force reading may be very inaccurate because of instrumental artifacts as well (25).

Another, more fundamental aspect of stress relaxation is that most food materials, especially under large deformation, exhibit nonlinear viscoelasticity. What it means to our discussion is that both the degree of solidity and the characteristic shape of the relaxation curve may significantly vary with the strain level (Figure 15). Thus, any rheological constants or parameters derived from relaxation data may have little significance unless they are presented as a function of the strain (e.g., Refs. 5 and 7).

E. Creep

1. *The Test*

Ideally, a creep test is performed by step-loading the specimen (in tension, compression, or other test configuration), then maintaining the

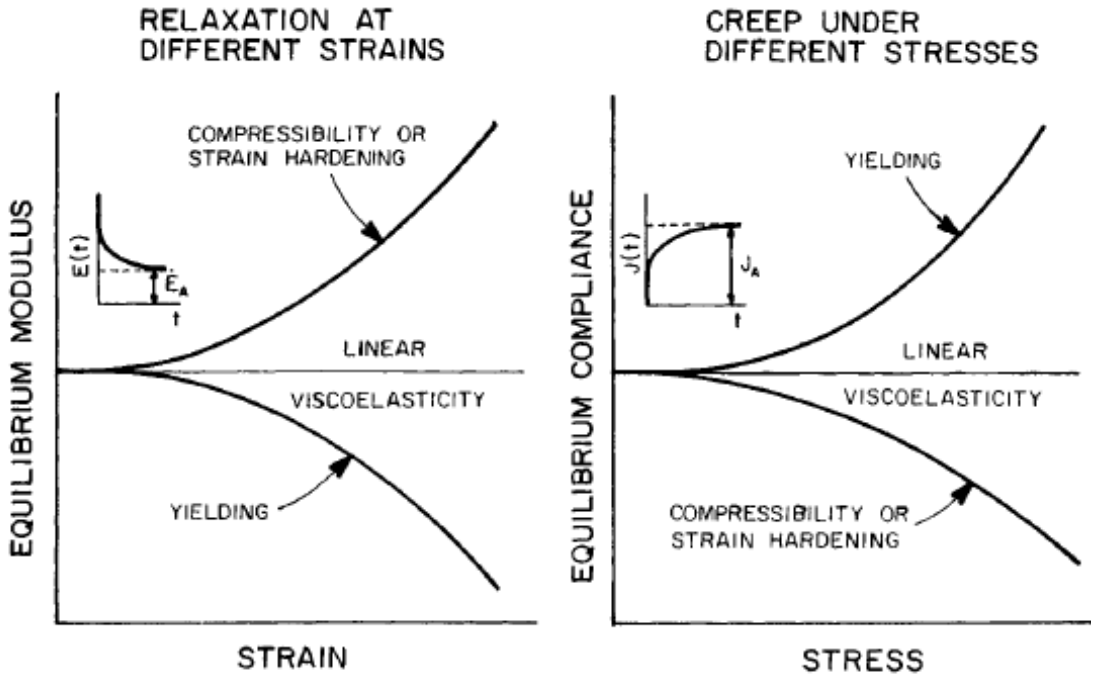


Figure 15 Residual "equilibrium" modulus after relaxation, and creep as a function of the strain and stress. (Note that alternating dominancy of yielding and strain hardening are also possible.)

stress constant, and recording the strain (or deformation) change with time (Figure 16). Although step-loading can be approximated by simply dropping the weight on the specimen, maintaining a constant stress is much more difficult. The reason is that with time, the cross-sectional area of the specimen progressively changes. Thus, in tension, maintaining a constant load (weight) means progressively *increasing stress* as a result of the decreasing cross-sectional area, while in compression, due to the cross-sectional area expansion, the effective stress continuously *decreases*. There are technical means to compensate for these effects, but these have rarely been used in solid foods testing. If the loads are small or the dimensional changes negligible, then the correction is, of course, unnecessary.

In many cases (Figure 16), the creep test is complemented by a *recovery* test (i.e., the load is removed and the specimen restoration is recorded). As mentioned, the creep test is usually performed under dead weights that are resting or hanging on the specimen directly (in compression or tension, respectively) or through an array of pulleys to produce torsion. The deformation is usually monitored by a linear variable displacement transducer (LVDT) connected to a power source

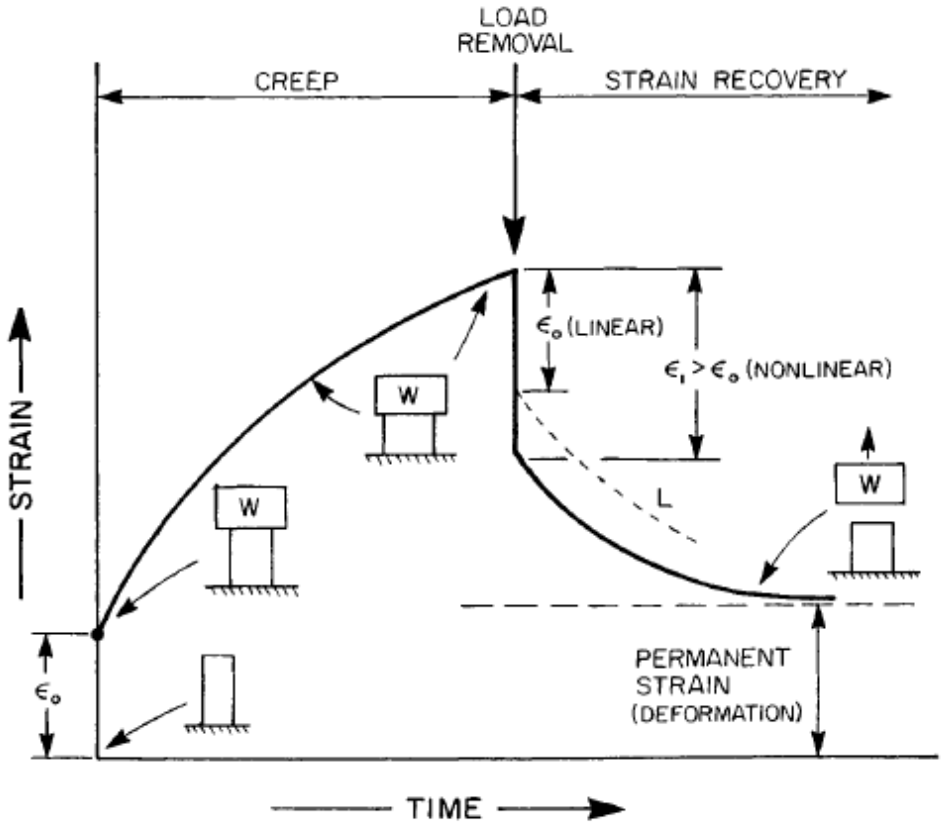


Figure 16 The different parts of a typical creep and creep recovery curve. (ϵ_0 is the instantaneous strain). Note that the permanent strain is usually independent of the instantaneous strain.

and a recorder. (Detailed descriptions of experimental creep systems can be found in Refs. 9 and 26.)

2. *The Results*

Typical experimental creep curves have one of the shapes shown in Figure 17. As already mentioned, the raw data are in the form of a recorded deformation versus time relationship. They are usually converted to and presented as strain versus time or strain per unit stress versus time relationship. The second parameter (i.e., strain per unit stress) is called *compliance*, and its units are those of a stress reciprocal. Unless changes in the specimen dimensions are taken into account in the calculation of the compliance magnitude, the typical shapes are maintained irrespective of whether the creep parameter is deformation, strain, or compliance.

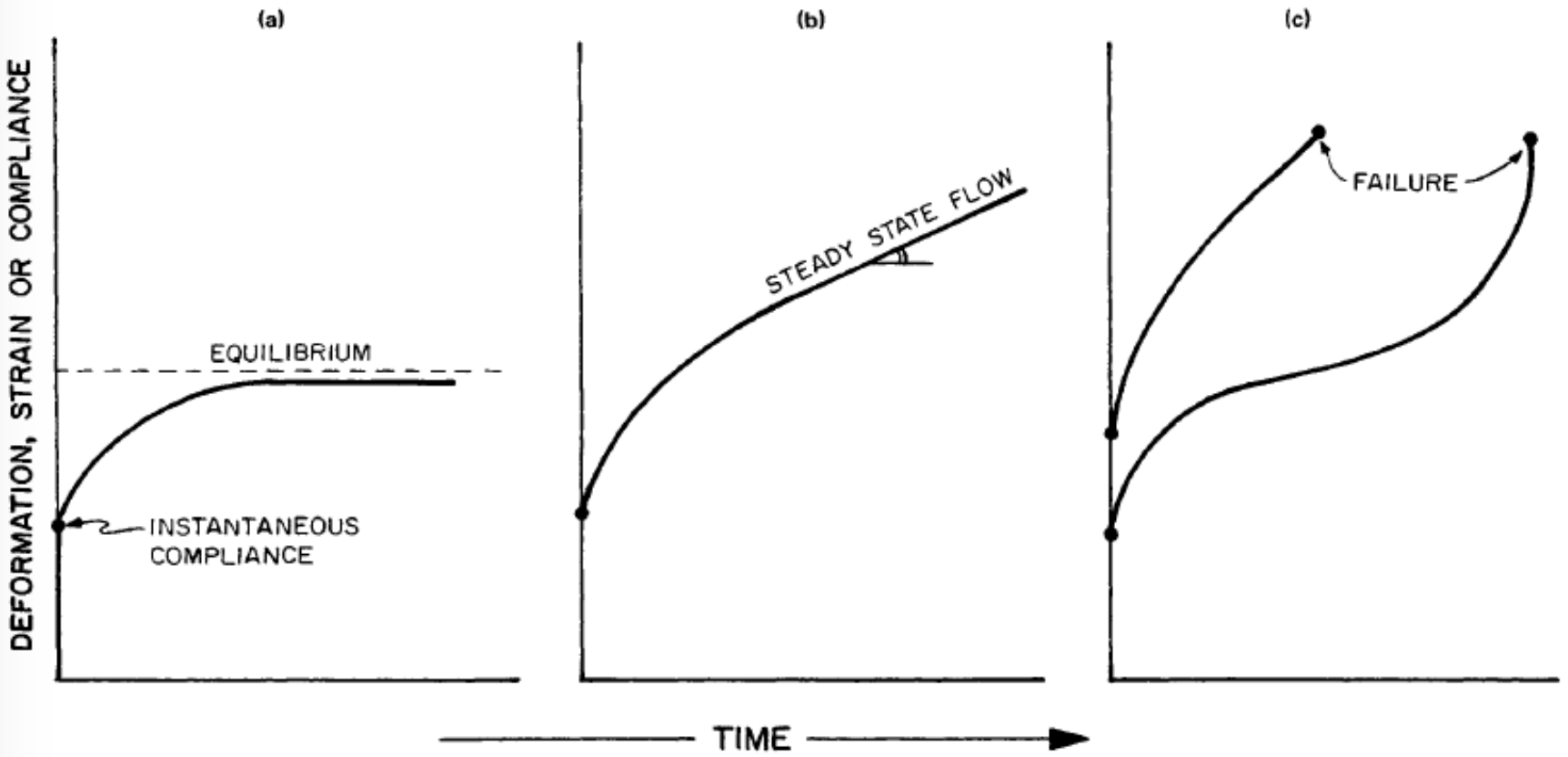


Figure 17 Typical shapes of creep curves. *a*: Ideal solid material. *b*: Ideal liquid material. *c*: Delayed failure in creep.

In almost every creep test, there is an instant (or almost instant) deformation (or compliance) followed by deformation at a progressively diminishing rate. (This, of course, is provided that the magnitude of the stress is not big enough to break the specimen when loading or shortly afterward.) In some cases, particularly in compressive tests, the deformation reaches an equilibrium state (i.e., the deformation becomes constant or practically constant) (Figure 17a). This feature is an indication that the material is solid in nature. The magnitude of this equilibrium strain or compliance, however, is influenced by the change in the cross-sectional area of the loaded specimen (Figure 18). Consequently, a material that shows high compliance in tension is in reality more rigid than the creep compliance indicates. In compression, for similar reasons, the situation is reversed (i.e., the material is actually less rigid than the creep compliance indicates).

Ideally, in the case of "liquids," the specimen continues to flow indefinitely and eventually reaches a steady rate of deformation instead of an equilibrium deformation (Figure 17b). It should be mentioned, however, that if the load is big enough, a true solid in tension can exhibit a similar creep behavior. The reason in such cases, however, is that the shrinking cross-sectional area results in a progressive increase in the stress that the specimen actually "feels." The third type of creep curve (Figure 17c) is observed when the load is high enough to cause a delayed failure. This is an inevitable outcome of a creep test of liquids, and the occurrence of failure in such materials in tension is only a matter of time. In true solids, failure, as already mentioned, may not occur at all (within any reasonable test duration) under small loads, but will occur in one or both fashions shown in Figure 17c if the load is increased.

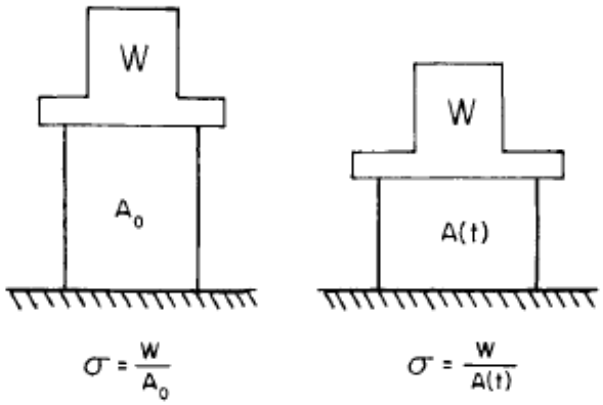


Figure 18 Demonstration of the cross-sectional area expansion in compressive creep under a constant load (W).

There are various mathematical models to describe the individual creep curves (e.g., Refs. 1, 10, 18, 23, 26–28). As in the case of relaxation, one ought to remember that foods are nonlinear viscoelastic materials. Therefore, the magnitude of the characteristic constant of such models is expected to be a function of the magnitude of the imposed load, and in many cases, of the specimen dimensions as well.

F. Dynamic Tests

In dynamic tests, the specimen, which can be the intact unit (e.g., a whole fruit), is subjected to sinusoidal deformation. The amplitude and frequency of the imposed deformation are usually the controllable experimental variables. Because the stress and strain are not in phase in viscoelastic materials (Figure 19), the phase lag can provide an indication of the rheological characteristics of the tested material. Ideally, an elastic solid will have no lag between stress and strain, while the phase angle for a Newtonian fluid is 90°. There are various methods to calculate the elastic or storage and the complex or loss moduli from the results of such tests. These moduli roughly represent the overall contributions of the "elastic" and "viscous" components of the viscoelastic material. The frequency dependency of these moduli can be treated as a rheological fingerprint of the tested specimen.

The modulus at the resonance frequency can also provide rheological information related to the rigidity of materials. It was actually used to monitor the textural properties of ripening bananas, apples, and potatoes. The deformations in dynamic tests are generally very small and, therefore, the method offers a way to test food materials nondestructively. Comprehensive reviews of the theoretical aspects of these tests and their practical applications to food materials have been published by Finney (29), and more recently by Rao (30).

IV. STRENGTH AND FAILURE

A. Failure Conditions and Propagation

Strength of materials, in the terminology used in mechanics, is the resistance to break. It is usually expressed in stress units, and its magnitude is determined by the stress at the point of failure. Because there are three basic kinds of stresses (i.e., compressive, tensile, and shear), any given material can have three types of strength corresponding to its resistance to break in tension, compression, or shear. The

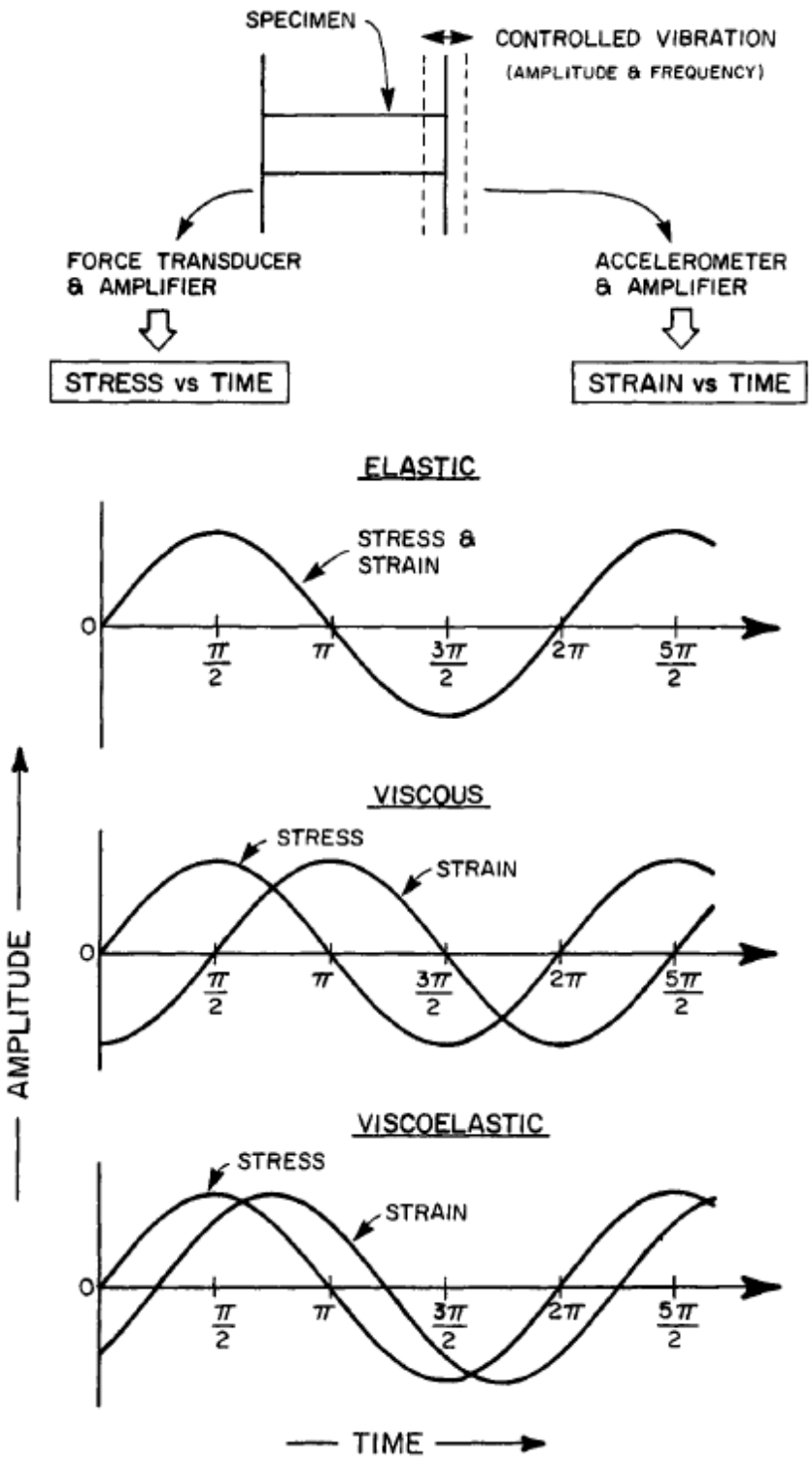


Figure 19 Stresses and strains in dynamic tests of elastic, viscoelastic, and viscous bodies.

absolute and relative magnitude of each type of strength depends on the structural and compositional features of the material. It is not uncommon to find materials that offer high resistance to one kind of stress but not to another. (An illustrative example is concrete. It can withstand large compressive stresses, but fails rather readily in tension and, therefore, needs reinforcement.)

In actual testing or deformation of a specimen, as previously shown, stresses of different kinds can be developed along planes with different directions. A notable example is the development of shear stresses as a result of uniaxial deformation (Figure 1d). If these stresses exceed the *shear strength*, the material can fail in shear, despite the fact that it is only compressed. This kind of failure can be observed in compressed hot dogs (31) or unripe fruit flesh (17). It ought to be remembered, however, that in these cases, the shear stresses that are of relevance to failure are those developed in the *compressed* specimen that underwent considerable deformation. For this reason, the observed failure plane is not at 45° to the specimen axis, as would be expected from theories developed for brittle materials.

In uniaxial compression, especially if there is appreciable friction at the areas in contact with the machine, the specimen tends to bulge or assume a barrel shape. In such cases (e.g., in certain cheeses), failure may be caused, at least in part, as a result of excessive *tensile* stresses at the specimen bulge region. Although not clearly identified in foods, one cannot exclude the possibility that failure is caused when a critical level of strain rather than stress is exceeded. This kind of criterion may be associated with the failure of brittle and/or glassy foods.

As mentioned earlier, stresses are not evenly distributed within the specimen, either because of geometrical factors and/or as a result of structural nonuniformity. Consequently, there are almost always regions or sites in the specimen where local conditions or stress concentrations can bring about local yielding and initiate motion. Typical sites are a structural fault, an existing crack or hole, a dislocation within a crystal or a weak boundary region between crystals or other structural components. The crack or cracks that are initiated in this manner usually propagate and can promote the yielding of other weak sites. This is evident by the appearance of visible cracks and eventually by the disintegration or rupture of the specimen as a whole. There are various general and specific theories that deal with the mechanics of fracture, but most were developed for materials whose structure or microstructure is better defined. The conditions in which various food materials fail in different kinds of loading have also been studied, although not as extensively as metals and polymers. Recent review

and discussion of most of these works can be found elsewhere (20, 32). Additional material on the failure conditions of fruits in creep can be found in Refs. 33 and 34.

B. Failure Patterns

Since many foods can be considered as multicomponent "structures" rather than homogeneous materials, the failure propagation pattern can vary to a great extent (Figure 20). The classical failure in shear, characterized by instantaneous propagation and a single inclined failure plane (see Figure 20a), can be found mainly in relatively homogeneous food materials such as unripe fruits flesh, tubers, and meat emulsion products (notably frankfurters, bologna, sausage). In other cases of relatively uniform materials (e.g., certain cheeses, gels, cooked egg albumin), the failure is characterized by a multitude of failure planes. If the material contains distinctly visible structural components such as flakes or fibers, the specimen will usually disintegrate, at least initially, in a manner that will leave such components intact. Noticeable examples are meats, fish flesh, and fibrous fruits such as

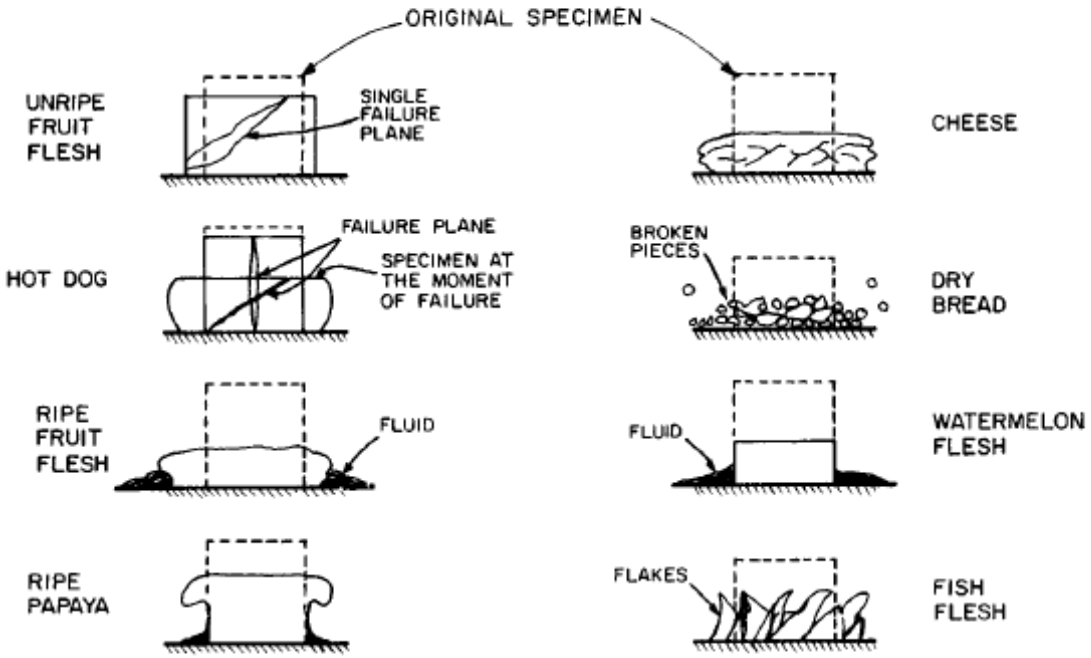


Figure 20 Schematic view of different kinds of compressive failure patterns in solid foods. (Note that in many cases, the dimensions of the specimen at failure are considerably different from those of the original.)

pineapple. Where a material is very brittle and hard (e.g., dry bread, biscuit), particles and aggregates can be "shot" out of the specimen at considerable velocities and the specimen remnants and aggregates will be of various sizes (Figure 20).

In the case of other materials, very specific patterns may emerge. Extreme examples are the "mushroom" type flow of ripe papaya and the folding-in of watermelon (17). In these cases, as well as in many plant and animal tissue materials, failure is also accompanied by a considerable amount of liquid release. There are also foods that deform or flow continuously without exhibiting any clearly identifiable state of an abrupt failure in a large range of deformation levels (e.g., process cheeses, marshmallow).

In all the preceding cases, the failure pattern, as well as the stress and strain conditions at which it occurs (or does not occur), are textural characteristics of the material and are a direct reflection of its structural features and its deformation mechanism. Since the deformation until failure is an inherent part of the failure phenomenon, test conditions (e.g., specimen dimensions and loading rate), may become influential factors, especially on the failure stress and, to a lesser extent, on the strain. The failure pattern, however, although typical to each material in a particular test, can be totally different under a different type of test. Thus, process cheeses, for example, which can sustain considerable deformation in compression (especially in flat specimens), will fail after fairly small deformation in tension. Similarly, if the geometry of the test is not well defined, as in various empirical instruments, the failure pattern actually exhibited by the material can be of a totally different character than that expected from the more controlled rheological tests.

It should also be added that failure is usually recognized as an instant phenomenon so that its occurrence can be identified by a point on the stress-strain relationship. There are, however, various indications that in many food materials, the observed gross failure is actually a culmination of a continuous yielding process. The nature of this process and its intensity can also be regarded as a textural characteristic. To reveal the extent of yielding at the prefailure deformation stage, however, requires additional rheological tests such as relaxation to be performed at a number of prefailure strains (35, 36).

ACKNOWLEDGMENTS

The author expresses his thanks to the Massachusetts Agricultural Experiment Station at Amherst for support of the work; to Mr. Richard J. Grant

for his graphical assistance; and to Mrs. Roberta Zidik for typing and editing the manuscript.

The author also expresses his thanks to John Wiley & Sons, Inc., New York, for permission to reproduce Figure 3.

REFERENCES

1. J. Marin, *Mechanical Behavior of Engineering Materials*, Prentice-Hall, Englewood Cliffs, New Jersey. (1962).
2. M. G. Sharma, Theories of phenomenological viscoelasticity underlying mechanical testing. *Testing of Polymers*, Vol. 1. (J. V. Schmitz, ed.), Interscience Publishers, New York, p. 196. (1965).
3. E. B. Bagley, Large deformations in testing and processing of food materials, *Physical Properties of Foods* (M. Peleg and E. B. Bagley, eds.), AVI Publishing Co., Inc., Westport, Connecticut, p. 331. (1983).
4. M. Peleg, Operational conditions and the stress-strain relationship of solid foods — theoretical evaluation, *J. Texture Stud.*, *8*: 283. (1977).
5. J. F. Calzada and M. Peleg, Mechanical interpretation of compressive stress-strain relationships of solid foods, *J. Food Sci.*, *43*: 1087. (1978).
6. A. Torres, H. G. Schwatzberg, M. Peleg, and R. Rufner, Textural properties of amylose sponges, *J. Food Sci.*, *43*: 1006. (1978).
7. J. R. Rosenau, J. F. Calzada, and M. Peleg. Some rheological characteristics of cheese-like products prepared by direct acidification. *J. Food Sci.*, *43*: 948. (1978).
8. E. A. Johnson, R. A. Segars, J. G. Kapsalis, M. D. Normand, and M. Peleg. Evaluation of the deformability modulus of fresh and cooked fish flesh. *J. Food Sci.*, *45*: 1318. (1980).
9. R. A. Segars, E. A. Johnson, J. G. Kapsalis, and M. Peleg, Some tensile characteristics of fresh fish flesh. *J. Texture Stud.*, *12*: 375. (1981).
10. N. N. Mohsenin and J. P. Mittal, Use of rheological terms and correlation of compatible measurements in food texture research. *J. Texture Stud.*, *8*: 365. (1977).
11. N. N. Mohsenin, *Physical Properties of Plant and Animal Materials*, Gordon and Breach Science Publishers, New York.
12. Y. C. Lee, J. R. Rosenau, and M. Peleg, Rheological characterization of tofu, *J. Texture Stud.*, *14*: 143. (1983).
13. M. Peleg and M. D. Normand, A computer assisted analysis of some theoretical rate effects in mastication and in deformation testing of foods, *J. Food Sci.*, *47*: 1572.
14. J. Culioli and P. Sherman, Evaluation of Gouda cheese firmness by compression tests, *J. Texture Stud.*, *7*: 353. (1976).
15. P. B. Lindley, *Engineering design with natural rubber*, The Malaysian Rubber Producers Association, Hartford, England.
16. K. C. Diehl, D. D. Hamann, and J. K. Whitefield, Structural failure in selected raw fruits and vegetables, *J. Texture Stud.*, *10*: 371. (1979).

17. M. Peleg, L. Gomez Brito, and Y. Malevski, Compressive failure patterns of some juicy fruits, *J. Food Sci., 41*: 1320. (1976).
18. C. T. Morrow and N. N. Mohsenin, Consideration of selected agricultural products as viscoelastic materials, *J. Food Sci., 31*: 686. (1966).
19. M. G. Sharma and S. S. Rafie, Rheological constitutive relations for the apple cortex, *J. Rheol., 27*: 637. (1983).
20. D. D. Hamann, Structural failure in solid foods, *Physical Properties of Foods.* (M. Peleg and E. B. Bagley, eds.), AVI Publishing Co., Westport, Connecticut, pp. 351–383. (1983).
21. M. Peleg and N. Pollak, The problem of equilibrium conditions in stress relaxation analyses of solid foods, *J. Texture Stud., 13*: 1. (1982).
22. T. Alfrey, *Mechanical Behavior of High Polymers,* Interscience Publishers, Inc., New York. (1948).
23. M. Peleg, Linearization of relaxation and creep curves of solid biological materials, *J. Rheol., 24*: 451. (1980).
24. M. Peleg and M. D. Normand, Comparison of two methods for stress relaxation data presentation of solid foods, *Rheol. Acta. 22*: 108. (1983).
25. P. W. Voisey and M. Kloek, Instron recorder pen response, *J. Texture Stud., 6*: 379. (1975).
26. M. O. Gross, V. N. M. Rao, and C. J. B. Smit, Rheological characterization of low methoxyl pectin gel by normal creep and relaxation, *J. Texture Stud., 11*: 271. (1980).
27. P. Sherman, *Industrial Rheology,* Academic Press, New York.
28. S. Purkayastha, M. Peleg, and M. D. Normand, Presentation of the creep curve of solid biological materials by a simplified mathematical version of the generalized Kelvin-Voigt model, *Rheol. Acta., 23*: 556. (1984).
29. E. E. Finney, Jr., Vibration techniques for testing fruit firmness, *J. Texture Stud., 2*: 263. (1972).
30. V. N. M. Rao, Dynamic force-deformation properties of foods, *Food Technol., 38*: 103.
31. P. W. Voisey, C. J. Randall, and E. Larmond, Selection of an objective test of wiener texture by sensory analysis, *J. Can. Inst. Food Sci. Technol., 8*: 23. (1975).
32. N. M. Mohsenin, Characterization and failure in solid foods with particular reference to fruits and vegetables, *J. Texture Stud., 8*: 169. (1977).
33. J. K. Wang and H. S. Chang, Mechanical properties of papaya and their dependence on maturity, *Trans. ASAE, 13*: 369.
34. Y. Chuma, T. Shiga, and M. Iwamoto, Mechanical properties of Satsuma oranges related to the design of a container for bulk transportation, *J. Texture Stud., 9*: 461. (1978).
35. N. Pollak and M. Peleg, Early indication of failure at large compressive deformation, *J. Food Sci., 45*: 825. (1980).
36. J. W. Finkowski and M. Peleg, Some rheological characteristics of soy extrudates in tension, *J. Food Sci., 46*: 207. (1981).