SOLID FOODS

Tabilo-Munizaga, Gipsy
Food Engineering Department, Universidad del Bío Bío, Chile

Barbosa-Cánovas, Gustavo V.
Department of Biological Systems Engineering, Washington State University, Pullman, USA

Fernández-Molina, Juan J.
Ezequiel Zamora University, Venezuela

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Contents

Summary

Since all materials have rheological properties, the focus of this work is to understand the rheology of solid foods as a critical point in optimizing product development, processing methodology and final product quality. Rheological solid behavior is presented in terms of fundamental tests (those conducted under conditions of static or quasi-static loading, and those conducted under dynamic conditions) and empirical or imitative tests. The behavior of solid foods is explained by evaluating the uniaxial compression test, stress relaxation, creep compliance and their dynamic properties. The basic concept of deformability modulus and failure is also developed.

1. Introduction

Most food products do not behave perfectly when acted upon by an outside force, whether solids or liquids. Nevertheless, one (or more) characteristic often predominates, which dictates the type of measurement likely to be made. It is helpful to maintain the distinction between solid and liquid materials. It is equally self-evident that not all food materials fall conveniently into these two classes. A considerable number exhibit both

solid and liquid characteristics at some stage, depending on the method of observation. One large group comprises the plastic materials, which appear solid in that they retain their form under their own weight, but can be readily deformed upon application of an outside agency, only to retain their new shape when that agency ceases to operate.
Ideal solids deform elastically. The energy required for this deformation is fully recovered when the stresses are removed. Real solids can also deform irreversibly under the influence of forces of sufficient magnitude – they creep, they flow. Classification of the rheological behavior of materials related to their response to applied stresses must be further extended by introducing the time-scale of any deformation process: It is written in the Bible that *"everything flows, if you wait long enough, even mountains…"*

Rheologically, the question as to whether a particular food is a solid or a liquid should be considered in terms of the non-dimensional Deborah number, D, as the ratio of the relaxation time of the sample divided by the time of observation. For all materials, a characteristic time factor λ can be determined, which is infinite in size for ideal elastic solids and almost zero for liquids such as water. On the other hand, deformation processes relate to characteristic time values "t". A high "Deborah number" (λ/t) defines a solid-like behavior and a low "Deborah number" defines a liquid-like behavior.

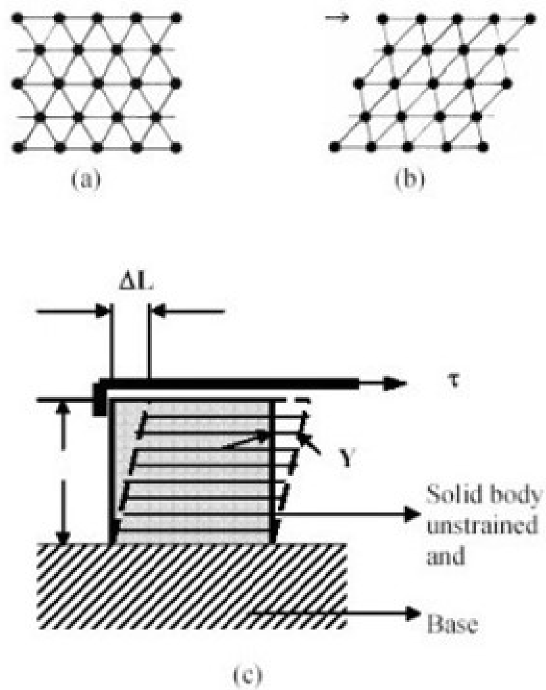

Figure 1. Representation of a solid structure a) at rest, b) sheared, c) deformation of a solid body. The arrow indicates the application direction of stress.
[From: Prentice J.H. (1984). *Measurements in the rheology of foodstuffs*. Elsevier Applied Science Publishers Ltd.]

The characteristic structure of a perfect solid is presented in Figure 1. Each structural element is acted upon by forces, due to the other structural elements surrounding it, and as a result, the whole will be in equilibrium with the elements a fixed distance apart. When an external force is applied to the block tangentially, to the upper plane surface, the equilibrium is disturbed and the array distorted as the elements move to the new equilibrium. Work is done as some of the bonds are stretched and some are compressed, which results in an increase in the potential energy stored in the system. Since the solid is supposed to be ideal, the elements are presumed to have no inertia, so that the new equilibrium positions will be taken up instantaneously. Thus, one characteristic of the ideal solid is defined - when an external force is applied, it is deformed immediately. The other characteristic is that this deformation is strictly proportional to the force applied. The behavior of a perfect solid in a single parameter, the constant of proportionality between the deformation and the force producing it, is known as the modulus of rigidity. The mathematical expression follows:

$$\tau = \eta \cdot \gamma \tag{1}$$

The fact that a fluid possesses no rigid structure distinguishes it from a solid. In this case, the net forces between the elements are usually many orders of magnitude less than the forces between the solid elements; the elements themselves are in a continuous state of thermal agitation or Brownian movement. There is no static equilibrium holding the elements in a fixed array.

2. Rheological Properties of Solid Foods

The study of the rheological properties of solid foods is of great importance in understanding their behavior. There are four reasons:

1. To allow insight into the structure of the material, because the physical manifestation of material is due to its chemical make-up. The relationship between cross-linkage of polymeric material and their elasticity is one example.
2. To improve quality control in the food industry.
3. To design machinery for handling solid foods.
4. To correlate consumer acceptance with some definite rheological property.

From a rheological viewpoint, when a force is applied to a material, two extremes of behavior may result: 1) pure elastic deformation of a solid and 2) pure viscous flow of a liquid. An ideal elastic element is one that instantaneously and finitely deforms upon application of force and instantaneously returns to its original form on release of force. Such material is called a Hookean solid and has a magnitude of deformation proportional to the magnitude of applied force. A Hookean solid is rheologically represented by a spring and has a rheological constant called the modulus or elastic modulus, which is defined as the ratio of the stress to the strain. Depending on the method of force application, three kinds of moduli can be computed for a Hookean solid. A material of this nature can be given a rheological constant, termed the elastic modulus.

The evaluation of rheological properties of solid foods is divided into two main classes:

- Fundamental Tests

These are tests that measure properties that are inherent to the material and do not depend on the geometry of the sample, the conditions of loading, or the apparatus (e.g., modulus of elasticity, Poisson's ratio, relaxation time, shear modulus, etc.).

- Empirical or Imitative Tests

These are tests used to determined properties such as puncture force, extrusion energy, etc., where the mass of the sample, the geometry, the speed of the test, etc., also determine the magnitude of the parameter estimated. The simplest test to study the behavior of solid foods is perhaps the uniaxial compression/tension test. In most uniaxial compressive tests, a food material with a convenient geometry (e.g., cylinder or cube) is deformed at a constant rate (Figure 2). The force developed is recorded continuously.

The resultant stress (σ) and strain (ε) is calculated as follows:

$$\sigma = \frac{F}{A} \tag{2}$$

and

$$\varepsilon = \frac{\Delta L}{L} \tag{3}$$

where F is the force, A is the cross-sectional area of the body, ΔL is the deformation, and L is the original length of the body.

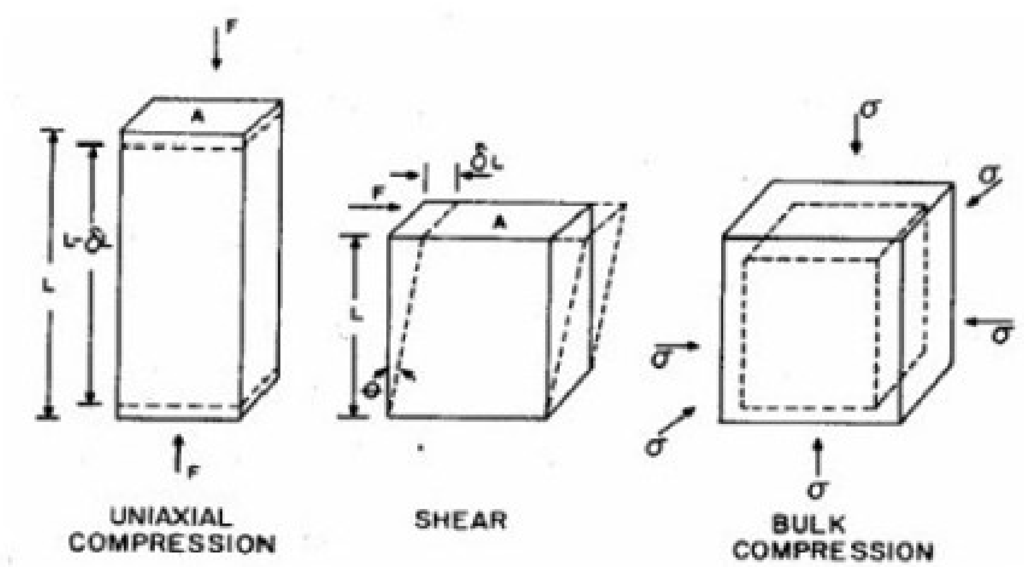

Figure 2. Uniaxial compression, shear and bulk (isotropic) compression of an elastic solid.

[From: Rao M.A. (1992.). Classification, description and measurement of viscoelastic properties of solid foods. In: *Viscoelastic properties of foods* (eds. M.A. Rao and J.F. Steffe). Elsevier Applied Science Publishers Ltd.]

3. The Deformability Modulus

A convenient parameter to quantify the stiffness of a material is the slope of the true stress-strain relationship The modulus computed by applying a force perpendicular to the area defined by the stress is called the modulus of elasticity or Young's modulus of Elasticity (E) and is expressed as:

$$E = \frac{\sigma}{\varepsilon} \tag{4}$$

and

$$\varepsilon = \delta L / L \tag{5}$$

where σ is the stress, ε is the strain, L is the original length, and δL is the change in length.

The modulus computed by applying a force parallel to the area defined by the stress, or a shearing force, is called the shear modulus or the modulus of rigidity (G). The modulus of rigidity is a measure of the materials resistance to change in shape. It is defined as the ratio of shear stress to shear strain and is expressed as:

$$G = \tau / \gamma \tag{6}$$

where G is the modulus of rigidity, τ is the shear stress, and γ is the shear strain.

If the force is applied from all directions (isotropically) and the change in volume is obtained, one can then compute the bulk modulus (K) as follows:

$$K = \sigma / \varepsilon \tag{7}$$

where σ is the isotropic stress and ε is the volumetric strain (change in volume/original volume).

Since the deformation is proportional to the applied force and unit area and length is considered in the calculations, the elastic moduli are fundamental material constants.

For most food material, the stress-strain relationship is frequently curved, and is also a function of factors such as specimen size and deformation rate (Figure 3). Under such circumstances, it is preferable to consider the stress-to-strain ratio as a modulus of deformability, and to treat its magnitude not as an absolute material property, but as a relative parameter whose usefulness is limited to the particular conditions under which it has been determined.

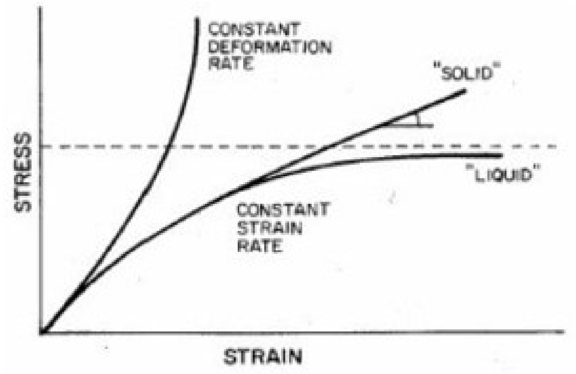

Figure 3. Difference between the compressive stress-strain relationships of a specimen deformed at a constant strain rate and a constant deformation rate.
[From: Peleg M. (1987). The basics of solid foods rheology. In *Food Texture* (ed. H. Moskowitz). New York: Marcel Dekker, Inc.]

If the deformations are large, Hencky strain (ε_h) should be used to calculate strain, and the area term needed in the stress calculation should be adjusted for the change in radius caused by compression.

$$\sigma = \frac{F}{\pi\left(R_0 + \delta R\right)^2} \quad (8)$$

A critical assumption is that the sample remains cylindrical in shape. For this reason lubricated contact surfaces are often recommended when testing materials such as food gels. Another important parameter considered in compression tests is the Poisson's ratio (ν), which can be defined from compression data (Figure 4).

$$\nu = \frac{lateral}{axial}\frac{strain}{strain} = \frac{\delta R / R_0}{\delta h / h_0} \quad (9)$$

where R_0 and R are the initial and final radii of the uncompressed and compressed shapes, respectively.

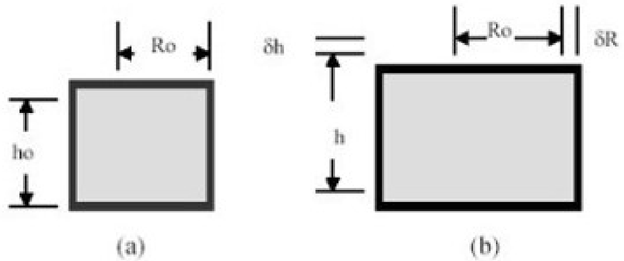

Figure 4. Uniaxial compression of a cylindrical sample (a) initial shape and (b) compressed shape.
[From: Steffe J.F. (1996). *Rheological Methods in Food Process Engineering*, Second Edition. East Lasting, Michigan: Freeman Press.]

Poisson's ratio may range from 0 to 0.5. ν and may vary from 0.0 for rigid-like materials containing large amounts of air to near 0.5 for liquid like materials. Values from 0.2 to 0.5 are common for biological materials, with 0.5 representing an uncompressible substance like potato flesh. Tissues with a high level of cellular gas, such as apple flesh, will exhibit values closer to 0.2. Metals usually have a Poisson ratio between 0.25 and 0.35.

Most solid food materials are not ideal elastics, or rubbery, therefore part of the deformation will remain permanent, contributing to a plastic deformation. In these types of materials, a considerable portion of the energy invested in the specimen deformation is irrecoverable due to both internal friction and irreversible structural modifications.

The ratio between recoverable and total deformation is suggested as the degree of elasticity, and the ratio between recoverable and irrecoverable work can also be used as a characteristic of the material.

4. Viscoelastic Properties of Solid Food

Classical theories describing mechanical behavior were developed based on the so-called ideal elastic (for solid) and ideal viscous (for liquids) materials (see *Viscoelasticity*). However, in reality, these theories are not easily extended to explaining the behavior of many real materials, much less in the case of food materials. However, by combining the elastic and viscous behavior, it is possible to explain some of the actual observed behavior of real materials.

This combined behavior of materials displaying both solid-like and liquid-like properties is generally called the viscoelastic behavior. One of the most important characteristics of viscoelastic behavior is the dependence of the material properties on time, in addition to temperature and moisture content. The response of solids can be explained by theories of elasticity and viscoelasticity.

In rheology, there are usually two basic quasi-static tests performed to explain the viscoelastic behavior of food materials and to gain insight into their mechanical behavior. They are known as stress relaxation and creep.

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Biographical Sketches

Gipsy Tabilo-Munizaga received her B.S. and M.S. in Food Engineering at the University of La Serena, Chile. She worked as an Assistant Professor of Food Engineering and Dean of the School of Food Engineering at University of Bío-Bío, Chillán, Chile (1993-1999). Next, she went to Washington State University (WSU) where received his Ph.D. in Engineering Science at Washington State University in the year 2002. Professor Tabilo-Munizaga was the Assistant Editor of two books in the Food Preservation Technology Series (CRC Press) and for the IFT Food Engineering Newsletter. Her research work is focused on the evaluation of physical properties of food treated by high hydrostatic pressure and on the rheological behavior of semisolid and solid foods. Tabilo-Munizaga is now Associate Professor and has published multiple research articles in the area of nonthermal processing of foods. Very recently she was awarded the Matsumae International Foundation Fellowship for postdoctoral studies in Japan (2005-2006) where she conducted extensive research on the processing of foods by High Hydrostatic Pressure technology.

Juan Fernández-Molina is Associate Professor of Food Process Engineering at Ezequiel Zamora University, San Carlos, Cojedes, Venezuela. Professor Fernández-Molina received his Ph.D. in

Engineering Science at Washington State University in the year 2000. His Doctoral dissertation was focused on the processing of milk with high intensity pulsed electric fields and other preservation technologies. Dr. Fernandez-Molina has published several papers in the area of non-thermal processing of foods. His research work is now focused on the evaluation of non-thermal processing of fruit beverages. Professor Fernández-Molina has also maintained an active research role in the processing of cereals and legumes by extrusion-cooking.

Gustavo V. Barbosa-Cánovas received his B.S. in Mechanical Engineering at the University of Uruguay and his M.S. and Ph.D. in Food Engineering at the University of Massachusetts-Amherst. He then worked as an Assistant Professor at the University of Puerto Rico from 1985-1990, during which he was granted two National Science Foundation (NSF) awards for research productivity. Following this, he went to Washington State University (WSU) where he is now Professor of Food Engineering and Director of the Center for Nonthermal Processing of Food (CNPF). Dr. Barbosa-Cánovas chaired the Organizing Committee for the 1997 and 1999 Conference of Food Engineering (CoFE). In addition, he is an Editor of the journal *Food Science and Technology International* published by SAGE, the journal *Innovative Food Science and Emerging Technologies* published by Elsevier Science, and the *Food Engineering* theme in the Encyclopedia of Life Support Systems (EOLSS) to be published by UNESCO. Dr. Barbosa-Cánovas is the Editor-in-Chief of the Food Engineering Book Series published by Kluwert Academic and Plenum Publishers (KAPP) as well as of the Food Preservation Technology Book Series published by CRC Press. He has chaired and organized several technical sessions at the American Institute of Chemical Engineers (AIChE) and Institute of Food Technologists (IFT) annual meetings, edited 12 books on Food Engineering topics, and authored, among others, *Dehydration of Foods* (Chapman and Hall), *Nonthermal Preservation of Foods* (Marcel Dekker), *Food Engineering Laboratory Manual* (Technomic), and *Engineering Properties of Biological Materials* (ASAE). Dr. Barbosa-Cánovas is also part of the editorial board for four technical journals, including the *Journal of Food Engineering*, *Journal of Food Process Engineering*, *Journal of Food Science and Technology (LWT)*, and the *International Journal of Physical Properties of Foods*. He is International Consultant for the United Nations' Food Agriculture Organization (FAO), Associate Researcher for the United Nations' PEDECIBA (a special program to develop basic sciences), and a consultant for several major food companies in the United States.