MECHANICAL PROPERTIES OF FOODS

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Keywords: Density, porosity, shrinkage, surface area, sphericity, and roundness.

Contents

Summary

The mechanical properties of food mainly result from its structure, physical state, and rheology. These properties are needed for process design, estimating other properties, characterizing foods, and quality determination. This article describes a few classes of mechanical properties, such as mass-volume-area related properties (density, shrinkage, and porosity), and morphological properties (surface area, roundness, and sphericity). Each section contains definitions of terminology, measurement techniques, prediction models, and their applications to future needs.

1. Introduction

Density is defined as mass per unit volume, and is used in process calculations and characterizations of food products. Different forms of density are defined in the literature: true, material, particle, apparent, and bulk. The measurement of volume is needed to estimate the above densities. A material's volume can be measured by buoyant force, liquid, gas or solid displacement, gas adsorption, or estimated from the material's geometric dimensions. Shrinkage is the change of volume or geometric dimensions. Two types of shrinkage are usually observed in the case of food materials: isotropic and anisotropic. Isotropic shrinkage is described as the uniform shrinkage in all geometric dimensions of the materials, whereas non-uniform shrinkage develops in different geometric dimensions. Porosity indicates the volume fraction of void or air space inside a material.

Different types of porosity are also defined in the literature: open pore, closed pore, apparent, bulk, and total porosities. Porosity can be measured by direct and microscopic methods or can be estimated from density data. Porosity in foods is mainly predicted from empirical correlations, which are valid for individual foods and processing conditions used to develop the correlations. The ideal gas equation is common for estimating the density of gases and vapors at low pressures. As the pressure is increased, Van der Waal's equation of state is very good, except in the region of temperature and pressure near the critical point of the gas. Most of the density, shrinkage, and porosity prediction models for liquid and solid foods are empirical in nature. Fundamental models exist that are based on the conservation of mass and volume, as well as a number of terms that account for interaction of the components and formation or collapse of air or void phase during processing.

Two types of surface areas are used in process calculations and product

characterization: outer or boundary surface of a particle or object, and total surface area of a porous object. It is very common to estimate the surface area from its geometric dimensions in the case of a Euclidian geometric object. Many natural patterns are either irregular or fragmented, to such an extreme degree that Euclidian or classical geometry is of no help in describing their form. In this case, the shape has no characteristic length and is defined as a non-Euclidian geometric shape. Fractal analysis is used to characterize and estimate the surface areas of these shapes. Morphological properties, such as roundness and sphericity are also used to characterize the food's shape. Sphericity indicates how the shape of an object deviates from a sphere. In the literature, sphericity is defined from the volume, surface area, or geometric dimensions of an object. Sphericity and shape factors are also needed in heat and mass transfer calculations.

2. Classification of Mechanical Properties

Proper classification and terminology are essential for avoiding confusion or imprecision. Classification aids in recording available data, setting up a global database, and developing generic predictive relationships and rules. A good classification can facilitate sound interdisciplinary approaches to the understanding of food properties and the measurement and use of food properties data, leading to better process design and food product characterization. Mechanical properties are mainly a result of the food's structure, physical state, and rheology; they are a sub-class of physical and physico-chemical properties. Rahman and McCarthy (1999) provided a complete classification of food properties. They have classified mechanical properties into five groups: acoustic properties, mass-volume-area-related properties, morphometric properties, rheological properties, and surface properties.

3. Density

3.1. Terminology

Mass is defined as the amount of matter in a body. The international prototype kilogram is a simple cylinder of platinum-irradium alloy with the height equal to diameter. It is important to distinguish between mass and weight. Weight is defined as the force acting on an object as a result of gravity. Consequently, the weight of an object changes as the gravitational force changes, whereas the mass remains constant. Density is one of the most important mechanical properties and thus is widely used in process calculations and product characterization. It is defined as mass per unit volume:

$$Density = \frac{Mass}{Volume} \tag{1}$$

SI unit of density is kg m^{-3}. Rahman (1995) clearly explained the different forms of density used in process calculations and in characterizing food products. These definitions are given as follows:

- **True Density**

This is the density of a pure substance or a composite material calculated from its components' densities considering conservation of mass and volume (ρ_T).

- **Material Density**

This is the density measured when a material has been thoroughly broken into pieces small enough to guarantee that no closed pores remain (ρ_m).

- **Particle Density**

This is the density of a particle that includes the volume of all closed pores, but not the externally connected pores (ρ_p). In this case, the particle is not modified structurally as in material density.

- **Apparent Density**

This is the density of a substance including all pores remaining in the material (ρ_a).

- **Bulk Density**

This is the density of a material when packed or stacked in bulk (ρ_B). The bulk density of the packed materials depends on the geometry, size, and surface properties of individual particles.

3.2. Measurement Techniques

3.2.1. Apparent Density

Measurement of Dimensions

The apparent density of regular geometries can be determined from the volume calculated from the characteristic dimensions and mass. This method is not suitable for soft or irregular shape materials where it is difficult to measure the characteristic dimensions. There is not much information about the density measurement of frozen foods available in the literature. A thick-walled metal cylinder is usually used to measure the density of the frozen sugar solution. The density determination consists of finding the mass of frozen sample with a known volume. The unfrozen sample is placed in the cylindrical container and then frozen at desired temperature. The excess frozen sample can be removed with a sharp knife. Then the cylinder and frozen sample should be weighed immediately. Knowing the mass of the sample and the volume of the cylinder, density can be estimated. The metal container can be wrapped with insulating material, such as electrical tape, to reduce the heat gain during weighing. This method is only suitable for liquid and soft materials when no void exists in the packaging.

Buoyant Force Determination

In this procedure, buoyant force can be determined from sample weight in air and

liquid. The apparent density can be calculated from the next equation:

$$\rho_a = \rho_l \left(\frac{m}{G} \right) \tag{2}$$

where m and G are the mass of the sample in air and buoyant force (kg), and l is the density of liquid (kg/m3). The methods used in weighing samples are shown in Figure 1, for a top loading balance and an analytical balance. Two errors usually occur with this method, and hence precautions should be taken during measurement:

1) Errors due to mass transfer from the sample to liquid - the exchange of solid, liquid, or gas from the sample to liquid may causes errors. This is usually avoided by enclosing the sample in cellophane or polythene, or coating it with a thin layer of polyurethane varnish or wax. Plastic film coated samples of fresh and dried fruits and uncoated samples showed that there was no significant moisture take-up when the uncoated samples were used. This was due to the very small experimental time required for measurement. However, coating is the best possible option for accuracy, and care must be taken to prepare the coating.

2) Errors due to partial floating - this may be due to the partial floating of the sample. In this case, liquid with lower density than the sample can be used. A simple technique has been suggested that applies to large objects (e.g., fruits and vegetables), using a top loading balance (Figure 1). The fruit is first weighed on the scale in air and then forced into the water by means of a sinker rod. The second readings are from the scale with the fruit submerged minus the mass of the container and the mass of the displaced water (i.e., buoyant force). Again, if the solid is lighter than the liquid, another solid can be attached, heavier than liquid, to the object as a sinker. Then the density can be calculated as follows:

$$\rho_a = \rho_l \left(\frac{m_{sample}}{G_{both} - G_{\text{sin ker}}} \right) \tag{3}$$

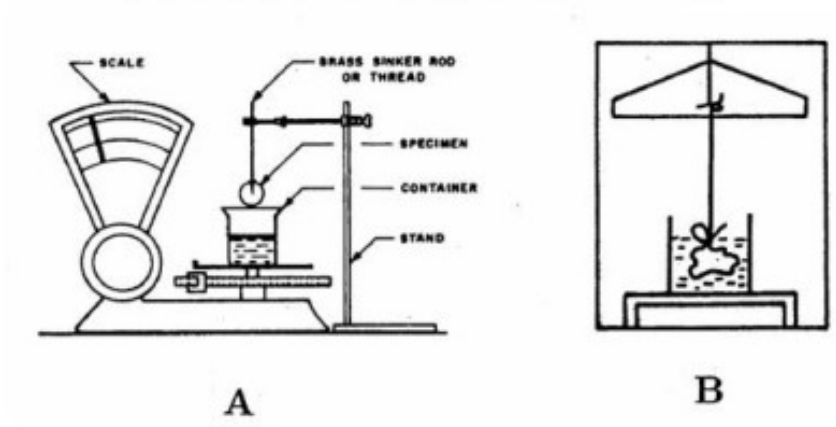

Figure 1. Buoyant force measurement. A) Top loading balance for lighter sample than liquid, B) Analytical balance for heavier sample than liquid.

[Mohsenin N.N. (1986). *Physical Properties of Plant and Animal Materials*. New York: Taylor and Francis].

It has also been suggested that a solution of 3cc of wetting agent in 500cc of distilled water can reduce errors due to surface tension and submergence in water. The buoyant force determination technique has also been used to measure the apparent density of frozen apple using water at 2 to 3^{o}C and apple frozen at -20 to -35^{o}C with a sinker. There is a real need to develop accurate and easy measurement techniques for frozen samples at sub-zero temperatures.

Volume Displacement Method

Liquid Displacement Method:

Volume of a sample can be measured by direct measurement of the volume of the liquid displaced. The difference of the initial volume of liquid in a measuring cylinder and the volume of the liquid with immersed material (coated) is the volume of the material. A non-wetting fluid such as mercury is used for displacement. The use of a specific gravity bottle and toluene has been in practice for many years. A small-necked specific gravity bottle is not suitable for large objects, thus a special design is required. The volume of a specific gravity bottle can be measured using distilled water. Toluene has many advantages when used as reference liquid: 1) little tendency to soak into the sample, 2) smooth flow over the surface due to surface tension, 3) low solvent action on constituents, especially fats and oils, 4) fairly high boiling point, 5) stable specific gravity and viscosity when exposed to the atmosphere, and 6) low specific gravity. Toluene is carcinogenic, thus adequate precautions need to be taken. It is recommended that the experiment be performed inside a fume chamber.

An alternative to the specific gravity bottle has been used for frozen samples. The alternative procedures were as follows: eight cylindrical glass bottles of diameter 2 cm with small necks filled to three-fourth (20 gm) with the sample and the rest with toluene were frozen at -40^{o}C. After freezing, the bottles were immediately placed inside glass wool insulation columns of inner and outer diameters 2 and 7 cm, respectively. The temperature was then recorded from one bottle by placing a thermocouple inside the center of the bottle. At different temperatures, the bottles were removed one at a time from the glass wool insulation, and toluene was added to completely fill the bottle. The bottle was closed immediately and the mass determined. From the mass and volume of the sample, which was estimated by subtracting the volume of toluene from the volume of the bottle, the density was calculated. The volume of toluene was estimated from the mass and density at the respective temperatures. This method gave reproducibility within 1 percent.

Commercial mercury porosimetry is available to measure the volume of porous and nonporous solids. The principle of mercury intrusion porosimetry is based on the fact that mercury ordinarily behaves as a non-wetting liquid (i.e., the contact angle of mercury is larger than 90^{o}C). Because it is non-wetting, mercury will not flow into the openings of porous solid bodies, unless it is forced to do so by a pressure gradient. The mercury injection method of measuring effective porosity is based on the fact that, due

to the surface tension and non-wetting properties of mercury, a porous sample can be immersed in mercury without entry of mercury into the sample at atmospheric pressure. Thus, the apparent volume of the sample can be determined by displacement of mercury from a sample chamber of known volume.

Gas Pycnometer Method:

There are different commercial gas pycnometers available for volume measurement. The gases used can be air, nitrogen, and helium. A method has been suggested to measure the volume by using high-pressure air (Figure 2). Material is placed in tank 2 and air is supplied to tank 1 when valve 2 is closed. When suitable manometer displacement is achieved, valve 1 is closed and equilibrium pressure P_1 is read. Now valve 3 is closed and valve 2 is opened and pressure P_3 is read. In this condition, with valves 1 and 3 closed, the volume of sample in tank 2 is measured as V_x. Then the volume of the sample in tank 2 is estimated based on the ideal gas law:

$$V_x = V_1 + \left(\frac{P_3 - P_1}{P_3}\right)V_1 \tag{4}$$

where V_1 is the empty volume of tanks 1 or 2. Commercially automatic helium gas pycnometers are available to measure the volume of the sample. Figure 3 shows the operating principle of the Horiba helium pycnometer VM-100. If a sample of volume V_x is placed in a sample cell with volume V_{xc}, and pressure P_1 is applied to the sample cell, and the valve is then opened and gas passed through an expansion cell with volume V_{ec}, the pressure will decrease to P_2 due to expansion of the gas. Volume V_x of the sample may be obtained from the known volumes V_{xc} and V_{ec} and the ratio of pressures P_1 and P_2 using the following formula:

$$V_x = V_{xc} + \left(\frac{1}{1-(P_1/P_2)}\right)V_{ec} \tag{5}$$

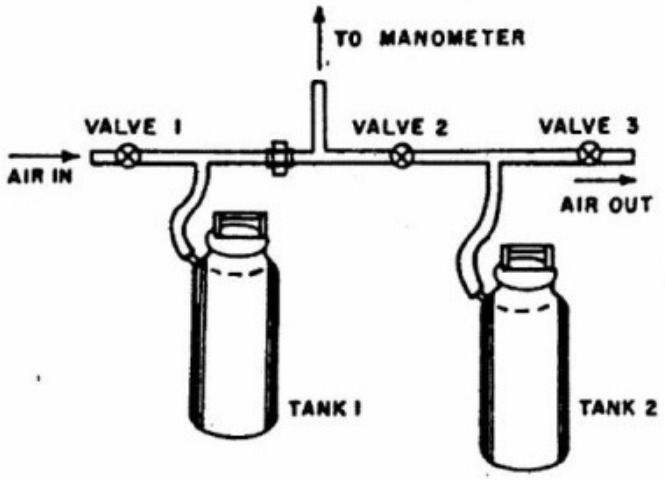

Figure 2. Air compression pycnometer.
[From: Mohsenin N.N. (1986). *Physical Properties of Plant and Animal Materials*. New York: Taylor and Francis].

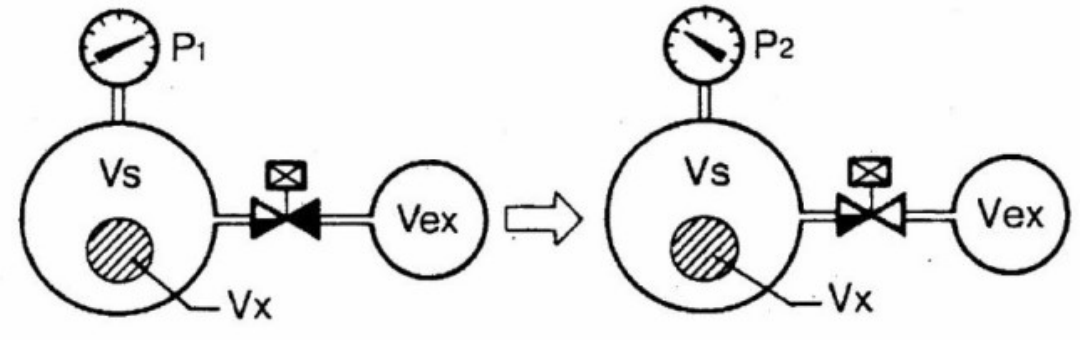

Figure 3. Operating principle of Horiba helium pycnometer VM-100.

The above equation is derived based on the ideal gas law. In order to measure the apparent density, the sample needs to be coated with wax before being placed inside the pressure chamber.

Solid Displacement Method:

The apparent volume of an irregular solid can be measured by the solid displacement or glass beads displacement method. The glass beads method has an advantage over sand, due to its uniform size and shape, thus producing reproducible results.

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Bibliography

Choi Y. and Okos M.R. (1985). Effects of temperature and composition on the thermal properties of foods. *Food Engineering and Process Applications, Vol. 1. Transport Phenomena* (eds. M. Le Maguer and P. Jelen). London: Elsevier Applied Science. [An interesting article presenting the generic density prediction models and correlations for density of food components as a function of temperature].

Hussain M. A., Rahman M. S., Ng C. W. (2002). Prediction of pores formation (porosity) in foods during drying: generic models by the use of hybrid neural network. *Journal of Food Engineering*. **51**, 239-248. [An interesting article on the generic empirical porosity prediction model of food during drying].

Lewis M.J. (1987). *Physical Properties of Foods and Food Processing Systems*. Ellis Horwood, England and VCH Verlagsgesellschaft, FRG. [This book describes the measurement, data, and prediction models of density and porosity].

Lowell S. and Shields J. E. (1984). *Powder Surface Area and Porosity*. 2nd edition. London: Chapman and Hall. [This book describes the details of mercury porosimetry and gas adsorption methods for studying pores].

Lozano J.E., Rotstein E., and Urbicain M.J. (1983). Shrinkage, porosity and bulk density of foodstuffs at

changing moisture contents. *J. Food Sci*. **48**, 1497. [An interesting article on data and models for density, shrinkage and porosity]

Mandelbrot B.B. (1977). *Fractals form, chance, and dimension*. San Francisco: W. H. Freeman and Company. [This book presents the concept of fractal analysis].

Mohsenin N.N. (1986). *Physical Properties of Plant and Animal Materials*. New York: Taylor and Francis. [This book presents details on density, porosity, surface area, sphericity, and roundness].

Rahman M.S. (1995). *Food Properties Handbook*. Boca Raton, FL: CRC Press. [This book is an excellent review on density, shrinkage, porosity, and surface area, including measurement, data, and prediction models].

Rahman M.S. (1997). Physical meaning and interpretation of fractal dimensions of fine particles measured by different methods. *J. Food Eng*. **32**, 447-456. [An interesting article presenting a critical evaluation of different methods of fractal analysis].

Rahman M.S. and McCarthy O.J. (1999). A classification of food properties. *Int. J. Food Proper*. **2(2)**, 93-100. [An interesting article on the complete classification of food properties].

Rahman M. S. (2001). Toward prediction of porosity in foods during drying: a brief review. *Drying Technology*. **19(1)**, 1-13. [An interesting review and hypothesis of the mechanisms of pore formation in foods during processing].

Rahman, M. S., Al-zakwani, I., and Guizani, N (2005). Pore formation in apple during air-drying as a function of temperature: porosity and pore-size distribution. *Journal of the Science of Food and Agriculture*. **85**: 979-989. [A paper presenting complete methods of characterizing pore-size by mercury porosimetry].

Sanz P.D., Domonguez M., and Mascheroni R.H. (1989). Equations for the prediction of thermophysical properties of meat products. *Latin Am. Appl. Res*. **19**, 155. [An interesting article presenting generic correlations for prediction of density in meat].

Suzuki K., Kubota K., Hasegawa T., and Hosoka H. (1976). Shrinkage in dehydration of root vegetables. *J. Food Sci*. **41**, 1189. [An interesting article presenting the shrinkage model during drying].

Takayasu H. (1990). *Fractals in the Physical Science*. Manchester: Manchester University Press. [This book presents a complete discussion of fractal analysis].

Toledo R.T. (1993). *Fundamentals of Food Process Engineering*, Second Edition. New York: Chapman & Hall. [This book presents the basics of food process engineering and the density prediction model].

Biographical Sketch

M. Shafiur Rahman is an Associate Professor at Sultan Qaboos University, in the Department of Food Science and Nutrition. Dr. Rahman has more than 20 years of experience in developing innovative research and technology programs for the food processing industry and teaching at the university level. He is the author or co-author of over 200 technical articles including journal articles, conference papers, reports, and books, and author of the internationally acclaimed Food Properties Handbook published by CRC Press, Boca Raton, Florida. He is also Editor of the Handbook of Food Preservation published by Marcel Dekker, New York. Dr. Rahman initiated the International Journal of Food Properties (Marcel Dekker, Inc.) and served as the founding Editor for more than nine years. In 1999, he was invited to serve as a member of the Food Engineering Series Editorial Board of Aspen Publishers, Maryland. Dr. Rahman was also invited to serve as Associated Editor for the Sultan Qaboos University journal, Agricultural Sciences. In 1998, Dr. Rahman was invited to serve as Food Science Adviser for the International Foundation for Science (IFS) in Sweden. His major research areas are food properties and food process engineering.