INTRODUCTION – PROPERTIES OF BIOLOGICAL MATERIALS

1. Definitions

1.1. Foods

A food is a substance taken into the body to sustain life and growth. Foods are biological materials of plant and animal origin obtained from species that have been either deliberately cultivated or husbanded by the methods of agricultural, horticulture and aquaculture, or gathered from the wild (e.g. by fishing).

It is convenient, to classify foods into two groups depending on the relative ease with which their properties can be controlled.

<u>Native Foods</u>

Native foods are those in which the original natural (biological) structure of the food remains, and is required to remain, essentially intact (e.g. fruits, meat cuts). With these foods the food engineer has to take what nature provides (in the form of fruits, vegetables, fishes, meat cuts, etc.) and can change of manipulate properties only by applying processes such as mild heating, mild cooling and sorting and grading which do not drastically alter the nature of the product. Usually there is almost no direct control over the compositions of these materials, although it is possible sometimes to control compositions and structures, and thus properties, by breeding practices, genetic agricultural/horticultural/aquacultural practices, selection of time of harvest/slaughter handling, processing and packaging practices.

Although very diverse in origin, shape and structure, every native food is composed of the same basic components, though in varying proportions. These are the major components *water, carbohydrates, protein and fats*, and the minor (although important) components *minerals, vitamins* and numerous other *chemical compounds*, some of them responsible for giving the food its characteristic color, taste and smell.

As water is a major component of most foods, many physical properties of foods are similar to those of water (or of ice at temperatures below freezing), or are strongly influenced by the food's water (or ice) content.

<u>Process and formulated foods</u>

Processed foods are foods in which the native plant of animal structure and organization are lost because of the application of relatively severe processing conditions. For example, white flour is made by grinding and fractionating (native) wheat grain. The resulting non-native, processed material (flour) is further dramatically altered by mixing it with water and yeast and fermenting and baking the resulting dough to make bread – a material totally unlike anything found naturally.

Formulated foods are foods made by combining together a number of processed and/or initially native foods. Examples are strawberry jam (made from strawberries, sugar and pectin) and sausage (made from different comminuted meat, salt and spices).

For processed and formulated foods, it is possible to control properties by manipulating processing conditions. In the case of formulated foods it is possible as well to change properties by changing the number, proportions and qualities of ingredients. This, here, there are more options available for controlling the characteristics of the in-process food and of the finished product, and for developing foods and novel compositions, structures and properties.

1.2 Packaging and packaging materials

Most food items purchased by the consumer are packaged in some way prior to being offered for sale. (Exceptions include some fresh vegetables, fruits, meat, fish and bakery products, but even they are usually placed in a package of some sort at the point of sale after the consumer has selected them).

<u>Packaging definition and functions</u>

Food packaging may be defined as the enclosing of the food product or food time in some form of wrap or container (pouch, bag, box, cup tray, can tube, bottle, etc.) design to perform one or more of the following functions.

- *Containment*. This is the most obvious and primary function, and one that facilitates handling, transport and storage of food items.
- *Protection* of the product from mechanical damage.
- *Preservation* of the product by stopping or inhibiting chemical, biological and microbiological changes.
- *Communication* (product identification, product information, bar codes).

<u>Packaging materials</u>

The container (the package) is made of suitable packaging material selected from among the following.

Polymeric materials
Paper and paper-based materials
Metals
Glass
Laminates (e.g. polymer/metal foil/paper).

<u>Levels of packaging</u>

These are the four levels of packaging:

- *Primary package*. This is the package that actually contains the food product.
- *Secondary package*. This gives immediate protection to the primary package. (Not all primary packages need a secondary package).
- *Distribution package*. This contains and holds together a number of secondary and/or primary packages for ease of handling.
- *Unit load*. This comprises number distributions packages held together as a single entity (e.g. a shipping container) for the purpose of bulk handling and storage, and long distance transport.

Packaging environments

Packaging has to perform its functions in three different environments (to which it may be exposed in some random sequence or simultaneously):

- The *physical environment*. The package must protect the product from mechanical shock, vibration, compression and crushing.
- The *ambient environment*. One of the main functions of a food packaging material is to provide an adequate barrier between the food product inside the package and the outside environment, and thus help to maintain the food's storage stability.

  The packaging material may be required to reduce the amount of light that reaches the product, prevent the entry of micro-organisms and other environmental contaminants, prevent of modify the transmission of water vapor, and oxygen and other gases, and to control the gain or loss of heat – as demanded by the particular food and its desired storage stability.
- The *human environment*. The package must be carefully designed to meet convenience and communication requirements.

A packaging material must be selected, and a package designed, so that for a particular food product-package combination, the package performs to the required degree in each of these three environments.

The primary packaging is usually of major importance in the ambient and human environments (and in the physical as well if there is no secondary packaging).

The secondary packaging, where it exists, and distribution packaging, tend to be of major importance in the physical environment.

There are exceptions. An example is a box of chocolates, where the primary packaging, the cardboard box, protects the product mainly from the physical environment, while the secondary packaging, the polymer film wrapped around the box, protects the product mainly from the ambient environment.

1.3 Physical properties

Physics may be defined as the study of the interaction of matter and energy.

A *property* of an object or material may be defined as an *attribute or characteristic* of that object or material. Thus a physical property of a food material or a packaging material may be defined as *an attribute of the material that gives a particular measure of the material's behavior* as **matter** or its behavior with respect to **energy**.

A physical property, to be of any use to the technologist, must be capable of being precisely defined in scientific terms. It will therefore, in general, have precise dimensions and thus units. Some physical properties however are dimensionless by virtue of their scientific definitions; refractive index, for example, is dimensionless, and therefore unitless, because it is defined as the ratio of the sines of two angles.

Physical properties are properties that are defined, measured and expressed in **physical** as opposed to chemical, biological or microbiological ways.

A selective list of physical properties is given in the next section.

A SELECTIVE LIST OF PHYSICAL PROPERTIES

Physical properties are conveniently divided info four main groups:

> **MECHANICAL PROPERTIES**
> **THERMAL PROPERTIES**
> **SORPTION AND DIFFUSION PROPERTIES**
> **ELECTROMAGNETIC PROPERTIES**

An individual property is listed in one of these main groups.

The detailed list that follows is a selective one: not all possible physical properties of matter included – only those of most relevance to the study of foods and packaging materials. Those included do, however, represent all properties of practical inters tot technologists and engineers working in the food industry.

Note, that there is no clear dividing line between physical properties and physico-chemical properties, not between physical properties and some biological properties.

Each property in the list is identified as being either *intrinsic* or *not-intrinsic*.

<u>Intrinsic properties (denoted by *I*)</u>

An intrinsic property is a property of the **material itself** (*i.e. of the material* ***substance***). It is independent of how much of the material is present and is independent of the form the material is in (e.g. one large piece or a collection of smaller pieces).

Intrinsic properties are dependent mainly on the chemical composition of the material. Some intrinsic properties are dependent also on the material structure.

Examples of intrinsic properties are true density (kg/m^3) and specific heat capacity $(\frac{J}{kg \cdot K})$

<u>Non-intrinsic properties (denoted by NI (a) or NI (b))</u>

A non-intrinsic property is one of two kinds:

NI (a): a property that depends on, or has to do with, the sizes and/or shapes of pieces of the material (e.g. *specific surface area*, m^2/kg or m^2/m^3), or interactions between pieces of the material (e.g. *angle of repose*, degrees).

NI (b): a property that depends either wholly or in part on the system in which the material finds itself (e.g. *heat transfer coefficient*, $\frac{W}{m^2 K}$).

Strictly, a *NI (b)* property is not a property of the material at all, but is an attribute of the system (in which the material is being handled or processed) dependent *likely* on some physical property or properties of the material.

<u>Selective list of physical properties</u>

MECHANICAL PROPERTIES

> *MORPHOMETRIC PROPERTIES (NI(a))*

Shape and size
Specific surface area
PARTICLE SIZE DISTRIBUTION (NI (a))
DENSITY
True Density (I)
Substance density (I)
Particle density (NI (a))
Apparent density (I)
Bulk density (NI (a))
Specific volume (I or NI (a))
Specific gravity (I or NI (a))
POROSITY
Apparent porosity (I)
Open pore porosity (I)
Bulk porosity (NI (a))
Total porosity (NI (a))
AERODYNAMIC AND HYDRODYNAMIC PROPERTIES (NI (b))
Terminal velocity
Drag coefficient
SURFACE PROPERTIES
Interfacial tension (NI (b))
Surface tension (NI (b))
ACOUSTIC PROPERTIES (I)
Velocity of sound
Sound absorption coefficient

FRICTIONAL PROPERTIES OF OBJECTS (NI)(b))
Coefficients of static and dynamic friction
FRICTIONAL PROPERTIES OF PARTICULATE MATERIALS AND POWDERS NI(a)
Angle of repose
Angle of internal friction
RHEOLOGICAL PROPERTIES (I)
Of solids
Of liquids
Of plastic material[(*)]
Of viscoelastic materials

THERMAL PROPERTIES
Enthalpy, specific heat, latent heat (I)
Initial and final freezing/thawing temperatures (I)
Initial and final melting/solidifying temperatures (I)
Initial and final boiling temperatures (I)
Thermal conductivity (I)
Thermal diffusivity (I)
Thermal expansion coefficients (I)
Linear
Cubic
Heat transfer coefficients (between fluids and solid surfaces) (NI (b))

Heat of respiration(I)
Heat of solution, dilution, hydration and reaction (I)

SORPTION AND DIFFUSION PROPERTIES
Solubility (NI(b))
Osmotic pressure (I)
Sorption properties (I)
Saturated vapor pressure
Water activity
Diffusion coefficient (NI(b))
Permeability (NI(b))
Mass transfer coefficient (NI)b))

ELECTROMAGNETIC PROPERTIES
Electrical properties (I)
Conductivity, resistivity, electrostatic properties
Permittivity
Dielectric loss factor
Dielectric loss tangent
Optical properties (I)
Refractive index
Optical rotation of plane of polarized light
Absortivity, reflectivity, transmittivity, emissivity with respect to UV, visible and IR radiation.

2. WHERE PHYSICAL PROPERTY DATA ARE USED

Five general areas can be identified, the first four relating to foods and the fifth relating to packaging:

- In the engineering design, installation, optimization and operation of food processes and food processing plant and equipment.
- In quality control and automatic process control.
- In the instrumental measurement of organoleptic (sensory) properties.
- In fundamental and applied research and in product development.
- In the selection of packaging materials, and in the design of packages, packaging machines and packaging operations.

There are now discussed in turn.

2.1 In the engineering design, installation, optimization and operation of food processes and food processing plant and equipment.

In the processing of a food consists of a sequence or series of processing steps. Each step can be classes as either *a unit operation* or a *unit process.* In both unit operations and unit processes the food material being processed is subjected to controlled physical conditions. However, the aim of a unit operation is to bring about merely a physical change as much, while the aim (or result) of a unit process is a change which is itself chemical, biochemical, and biological, microbiological or organoleptic (sensory) or some combination of these.

Heat transfer is a common processing step on which a heat exchanger or any sort of heating/coololing equipment is used to either raise or lower the temperature of the in-process material. If a change in temperature (i.e. a physical change) is all that happens, then the heat transfer step is called a unit operation. If the change in temperature causes one or more non-physical changes (of the types listed just above) to occur as well, then the heat transfer step is a unit process. Thus unit processes are simply unit operations in which significant non-physical change(s) as well as physical changes, take place.

Note that in a unit process the non-physical change may be desirable or undesirable. For example, in milk pasteurization, milk is heated (the physical change) to a temperature at which pathogenic micro-organisms are killed (the desired microbiological change), but some undesirable heat-induced chemical changes in the milk (affecting its nutritional or functional properties) can occur at the same time depending on pasteurization conditions.

<u>Examples of unit operations</u>

Grinding to make smaller (e.g. milling wheat to make flour.)
Agglomeration to make bigger (e.g. agglomerating milk powder into free-flowing, dust-free, readily wettable granules).
Fractionation to separate components (e.g. centrifugal separation of whole milk into skim milk and cream).
Mixing to blend components (e.g. ribbon blending of the dry components of a soup mix).
Emulsification (e.g. emulsifying vegetable oil into aqueous phase containing vinegar, sugar, etc to make salad cream).
Heating or *cooling* merely to raise or lower temperature (e.g. heating milk to optimum temperature (~50 degrees C) for centrifugal separation).
Filling or packing a food product into a package.

<u>Examples of unit processes</u>

In each of the following processes the action is physical but the (desired) result is non-physical.
Mixing skim milk with mineral acid (physical action) to precipitate the casein (chemical result).
Blanching vegetables (physical action) to destroy undesirable enzymes (biochemical result).
Chilling fresh fruits and vegetable (physical action) to slow down maturation and ripening (biological result).
High temperature treatment of food (physical action) to sterilize it (microbiological result).
Extrusion cooking of food mix (physical action involving heat, pressure and shear) to create a novel texture (organoleptic result).

Note that in a unit process the engineer has no **direct** control over whether or not desirable or non-desirable **non-physical** changes take place. All that can be directly controlled are the physical conditions, e.g. mixing rate, temperature, pressure, shear rate, etc. The non-physical change will occur, or will not occur, depending on whether or not the right combination of **physica**l conditions exists.

In both unit operations and unit processes the way in which a biological material will respond to its physical environment during processing (i.e. to processing conditions) will obviously depend on its **physical** properties – hence the importance of these properties in the process engineering context. Data on physical properties is essential for engineering design.

2.2 In quality management and automatic process control

Physical properties are important here either as attributes in their own right or as indicators of other more complex non-physical properties and qualities.

Quality management

Quality management in the food industry (and other industries) has to do with running processing and packaging operations and supporting activities in such a way as to efficiently produce products with the required attributes in the required quantities. Success in doing this depends on setting the right objectives (the *Quality Assurance* function) and then making sure that theses objectives are actually met (the *Quality Control* function).

Quality Assurance (QA) asks the question '*Are we doing the right things?*' QA sets specifications and standards for raw materials, intermediate products during manufacture and finished products, and also sets processing conditions.

Quality Control (QC) asks the question '*Are we doing things right?*' this is 'Are we successfully (or not) meeting the specifications and standards, and keeping the processing conditions, laid down by QA? To answer this question, the QC function must frequently monitor all materials and conditions in the manufacturing operation and, where necessary, require adjustments to be made to bring anything that is out of control (i.e. deviating from values laid down by QA) back into control.

Monitoring the attributes of in-process materials and finished products means taking samples at regular intervals, making appropriate measurements, recording the results and then deciding what action to take, if any.

The quantity measured is frequently a physical property; it is often simpler and quicker (and consequently cheaper) to measure a physical property related quantitatively to a perhaps complex non-physical property that must be controlled than it is to measure the non-physical property itself, for example:

- Measurements of the freezing point of milk to check whether or not the milk has been accidentally or deliberately diluted with water.
- Infra-red (IR) reflectance spectroscopy of a food a sample to measure its chemical composition. The measurement can be done in a fraction of the time required for the classical wet chemical compositional analyses.
- Measurement of refractive index is an extremely rapid and easy means of measuring the concentration of dissolved solids in products such as jams and condensed milk.

Monitoring process conditions means measuring temperatures, pressures, flow rates, etc, using portable or permanently installed instruments. Adjustments are then made to these conditions if they are not at the correct levels. Monitoring and adjustment can be done manually, but automatic process control is now common.

Automatic process control

The processing of biological materials is continually increasing in scale and complexity as a result of automation – which means the automatic control of processes by using microprocessors and computers. These monitor a process by receiving signals generated by automatic instrumental measurements of processing conditions or of attributes of the in-process food material

Measurements are made of sensors of various kinds of installed in the processing line. For example, the flow rate of a liquid being processed might be sensed by an in-line electromagnetic flow meter (the sensor) which continuously sends an electrical signal, proportional to the flow rate, to the controller (microprocessor or computer) (Fig 1).
The controller compares this signal with a reference electrical signal corresponding to the desired flow rate. Any discrepancy between these two signals causes the controller to send back a control signal to the speed adjustment on a pump (in this example) causing the pump to speed up or slow down to bring the actual flow rate back to the desired (set) value.

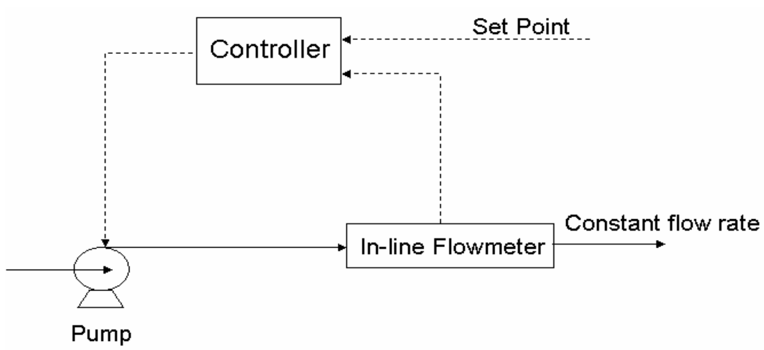

Figure 1. Automatic Control of flow rate.

The characteristics of the in-process material that are sensed can be general ones like flow rate, temperature and pressure or they can be, and often are, physical properties, e.g. refractive index (Fig.2).

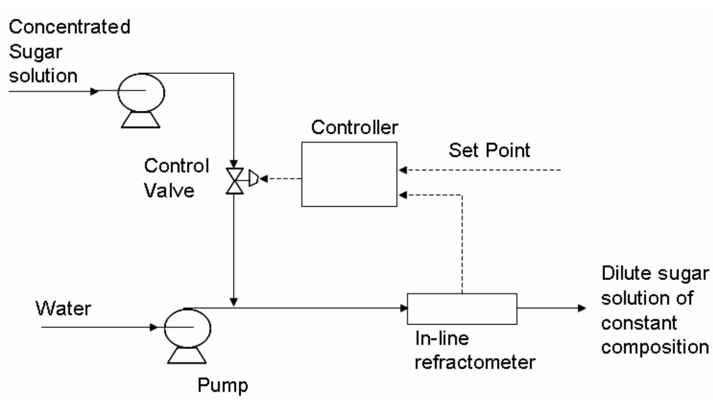

Figure 2. Automatic control of sugar solution composition.

In the example in Fig.2, any discrepancy between the measured refractive index and the desired refractive index (which is directly related to the desired dilute sugar solution composition) causes the control valve to be adjusted in such a way as to bring the flow rate of the concentrated solution to the correct value relative to the water flow rate.

In the instrumental measurement of organoleptic (sensory) properties

This area is, as one would expect, of great importance in the food industry. The organoleptic or sensory properties are: taste or flavor, smell or aroma, texture, color, appearance, and even sound (snap, crackle and pop!). The traditional method of measuring these properties is by using trained sensory panels. The running of sensory panels and the subsequent statistical analyses of their finding are, however, time-consuming and expensive, and the results obtained are subjective. These disadvantages can sometime be overcome by developing an empirical correlation between the sensory property of interest and a physical property; one then simply measures the physical property instrumentally to obtain an assessment of the sensory property. Such a physical property measurement is relatively fast, reproducible, objective and cheap.

The development of a suitable correlation is, however, more easily said than done; because of the high degree of sensitivity and discrimination of the human brain (the ultimate assessor of sensory properties) a correlation between a sensory property must be a very good one if the correlation is to be of any use. Good correlations are difficult to develop. For example, although food texture is mainly a physical characteristic of food (***it is strongly related to a food's rheological properties***) it is extremely difficult still to assess texture by instrumental means with the accuracy, consistency, sensitivity and discrimination of which the brain of even the most ordinary consumer is capable. It can however, be done adequately in some cases, for example:

- An instrument called the pea tenderometer measures the force required to compress and shear a sample of peas. This force correlates will with consumers' perceptions of pea tenderness/toughness.
- An instrumental penetration test to measure the mechanical strength of whey protein concentrate gels correlates well with Japanese consumers' assessments of the textures of fish and meat gels containing whey protein concentrates.

2.3 In fundamental and applied research and in product development

Here, measurements of changes in physical properties (measurements that often are relatively quick and easy to make) are used to probe to follow the courses and indirectly to measure complex chemical, biochemical, biological and microbiological changes in foods – changes that occur in controlled experiments, and during processing, storage and use. The study of such complex changes is vital to the task of elucidating the subtle and intricate natures of food materials. An example is the measurement of the change of time of the rigidity modulus (a viscoelastic property) of a whey protein solution as it turns into a gel whole being heated (Fig. 3).

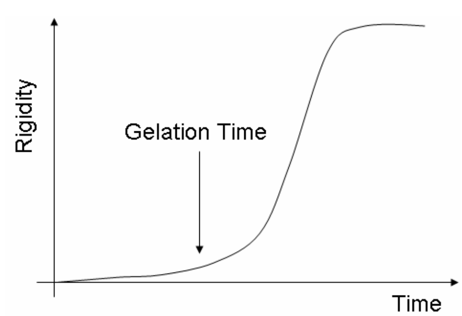

Figure 3. Plot of the Rigidity of a milk protein (whey) solution during heating at a constant temperature high enough (about 80C) to cause gelling.

Here, measurements of the rigidity using a rheometer are used to follow a complex physico-chemical process (heat-induced gelling of proteins). Such a measurement is straight forward and fast (given the availability of a suitable rheometer, which sometimes is a relatively expensive instrument). By investigating the effects of gelling behavior (change of rigidity with time) of variables such as temperature, pH, protein concentration and salt content (ionic strength) one can infer the molecular processes involved in the gelation phenomenon. Such information is extremely useful in developing applications for whey protein as food ingredients. Getting the same information by the methods of chemistry would be comparatively slow and tedious, if not impossible.

2.4 In the selection of packaging material, and in the design of packages, packaging machinery and packaging operations.

As already implied in Section 1.2, among the physical properties of primary packaging materials that are of major importance are those governing the ability of the material to transmit water vapors, gases, light and heat. In the case of secondary and distribution packaging materials, the physical properties governing the materials' abilities to resist mechanical damage are of major importance. The efficient and effective selection of packaging material, and the design of packages, would clearly be impossible without accurate and comprehensive date on these physical properties.

Packaging (the action of filling or packing a good into a package) is a physical operation (i.e. a unit operation). The design of packaging operations and of the packaging machinery used depends therefore on knowledge of the physical properties of packaging material, and also, of course, the foods being packed.

3. A Discussion of The Physical Properties Listed In Section 2, with further examples of applications

The emphasis in this section is on the physical properties of foods rather than of packaging material. Unless packaging materials are specifically mentioned it may be assumed that information given relates to foods.

3.1 Mechanical properties

Mechanical properties characterize a material as matter or a material's behavior when subjected to mechanical forces.

<u>Morphometric properties</u>

These can be thought of as the properties of the geometry (shape) and size of food objects large enough for these properties to be discerned by the naked eye.

Shape and size are important in, for example,

- the consumer acceptability of some products (e.g. fruits);
- the design of sorting and cleaning equipment;
- operations that depend of aero – hydrodynamic properties (see below);
- unsteady state heating and cooling;
- packaging

Specific surface area (surface area per unit weight or per unit volume) is important in, for example:

- processes involving mass transfer through surfaces, e.g. respiration of fruits, extraction of coffee beans, smoking of hams, salting of cheeses, gas and water vapor transfer into and out of packages.
- Determining the ratio of usable material to peel (unusable material) in fruits and vegetables. This is important economically; one ton of small potatoes, for example has a much greater total specific surface area (m^2/kg) than one ton of large potatoes, and therefore the wastage when they are peeled is much greater (for a given peel thickness).

Particle size distribution

The size of distribution of particles in a product in which the particles are too small to be seen by the naked eye (e.g. the particles of milk powder, and the oil droplet in an emulsion such as mayonnaise) is expresses as a plot or table of fraction or percentage (of the total number of particles) against particle diameter like the one illustrated below:

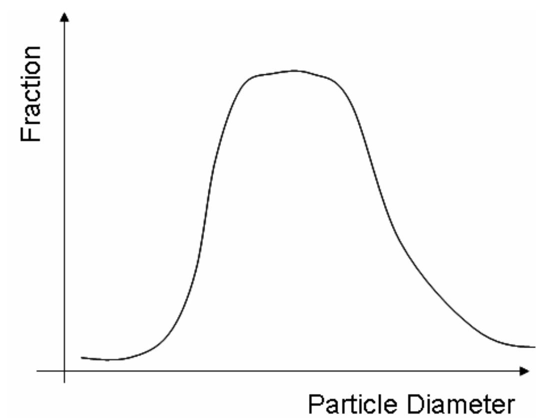

Figure 4. Particle size distribution of a given food or non-food system

Knowledge of particle size distributions is important in, for example,

- designing size separation equipment (e.g. the screens/sieves used in flour milling);
- operating extraction processes (e.g. an excessive fraction of small particles (fines) in ground roasted coffee can cause serious processing problems in instant coffee manufacturing by clogging extraction columns);
- the rheology (and thus the texture) of suspensions of solids in liquids; the sensory smoothness of products like sweetened condensed milk and apples sauce depend upon smoothness of products like sweetened condensed milk and apple sauce depend upon suspended particles (lactose crystals in the first, ruptured apple cells in the second) being smaller than the threshold size detectable by the tongue;
- product specifications (e.g. the specification for milk powder lays down permissible limits and ranged for particle size, because this affects properties such as dispersibility in water).

A similar property, the molecular weight distribution, is an important characteristic of polymers used as packaging materials.

Aero- and hydrodynamics properties

In the handling and processing of food materials, a flow of air or water is often used for transporting the material or for separating desirable from undesirable material. The properties involved are the drag coefficients and the terminal velocity. In pneumatic and hydraulic transport, the moving fluid (air or water) drags the object in the direction of flow because of the friction between the moving fluid and the object's surface. The drag coefficient is a dimensionless measure of the force required to transport the object at a given velocity. It depends, among other factors, on the object's shape and size. The terminal velocity of an object is the velocity the object will reach in free fall in a fluid when the net gravitational accelerating force is equal to the upwards drag force. When the terminal velocity has been reached, the particle motion will be downwards relative to the fluid if its density is greater than the fluid's, and upwards if its density is small that the fluid's. Knowledge of terminal velocities is used, for example, in designing separation equipment (Fig. 5).

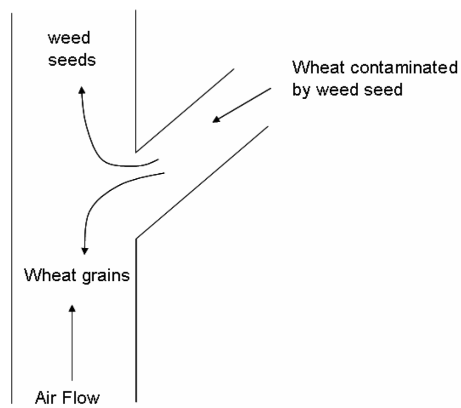

Figure 5. Aspiration of wheat with air to remove weed seeds

The air velocity in the aspirator in Fig. 5 (achieved with a fan) is adjusted so that it is lower than the terminal velocity of wheat in air (9 m/s) but higher than the terminal velocity of week seeds in air (e.g. 5m/s).

Surface properties

The interfacial tension between two phases, e.g. the oil phase and the aqueous phase in a food emulsion such as milk or salad cream, is a measure of the resistance of the interface to being enlarged, e.g. by homogenization – which therefore requires energy expenditure. Interfacial tension depends on the compositions of the two phases and on any substances adsorbed on the interface. When one phase is a liquid and the other phase is a gas, interfacial tension is called surface tension. Typical values of surface tension for liquids in air at 20 degrees C are as follows:

Water	:	72.7 mN/m
Ethyl alcohol	:	22.7 mN/m
Milk	:	50.0 mN/m
Cream	:	44.8 mN/m
Cotton seed oil	:	35.4 mN/m

Interfacial tension is primarily of importance is colloid chemistry, which is part of physical chemistry.

Acoustic properties

The use of ultrasound for characterizing food material is being used increasingly. One example is the measurement of the ice content of frozen meat by measuring the velocity of ultrasound in it. Yet another is the non-invasive measurement of fat thickness on carcasses, and, indeed, on live animals, with an instrument that measures how long it takes for an ultrasound pulse to travel through the fat layer, be reflected from the underlying muscle and return to a detector in the instrument. This kind of ultrasound imaging is, of course, widely used in medicine.

Measurement of the attenuation of sound (absorption of energy) can be used to measure food composition, and to follow **in real time** processes such as the ripening of an individual fruit or the rennet-induced coagulation of milk in cheese making.

Particle size distribution and particle concentration (e.g. the size distribution and concentration of oil droplets in a food emulsion) can be measured by measuring the attenuation of sound, and sound velocity, simultaneously.

Sound patterns recorded while a sample of food is being masticated can be related to the textural characteristics of the food. These in turn depend to an important extent on the food's rheological properties.

Frictional properties of objects

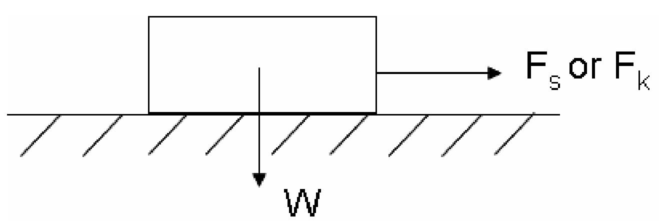

Figure 6. Forces involved in sliding friction

W = weight (N)
F_s = force required to initiate movement (N)
F_k = force required to maintain movement (N)

Coefficient of static friction = F_s/W (dimensionless) (1)

Coefficient of static friction = F_k/W (dimensionless) (2)

Examples: F_k for barley on steel = 0.38
F_k for wheat on aluminum = 0.42

Frictional properties are important in, for example,

- determining the power requirements of mechanical, pneumatic and hydraulic conveying equipment.

- Designing sifting, sorting, peeling, dehusking and packaging equipment, and other equipment where relative movement occurs between foods and surfaces with which they are in contact.

<u>Frictional properties of particulate materials and powders</u>

The angle of repose and the angle of internal friction are measures of the flowability of finely divided solid materials, for example grains, seeds, flours and powdered foods such as instant coffee, dried soup mixes and milk powders. The angle of repose is defined as in Fig. 7.

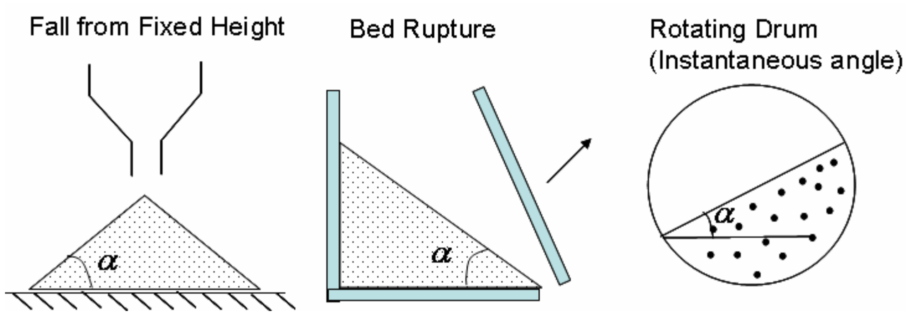

Figure 7. Definitions of static kinetic angles of repose

The angle of internal friction is an important property of **compressible** powders and one devise to measure in a more "fundamental way" is the use of the Jenicke cell illustrated in Figure 8.

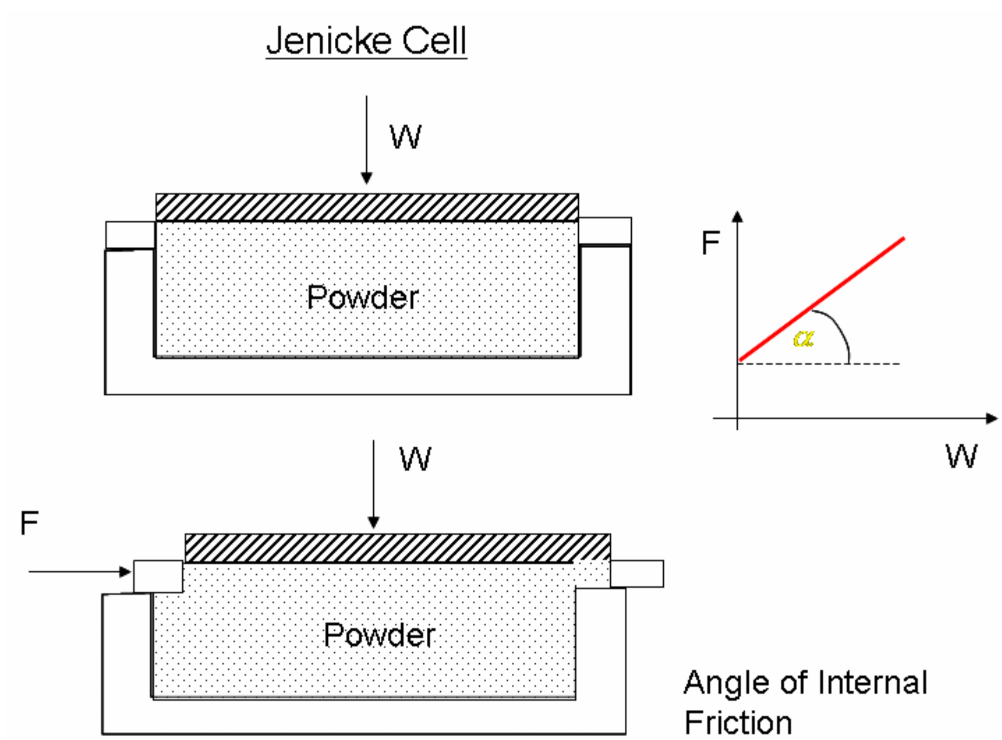

Figure 8. Schematic of the Jenicke Cell used to measure flowability of powders

These and other related properties are of great importance in the design of silos, bins and hoppers, which are major items of equipment in the storage handling, blending and packaging of granular and powdered food materials.

Rheological properties

Rheology is *the science of the deformation and flow of matter* in response to applied forces.

Knowledge of rheological properties is extremely important in:

- the engineering design of equipment of the handling, transporting, processing and packaging of pumpable foods;
- assessing the susceptibility of solid foods to mechanical damage, and minimizing that damage during handling;
- the objective assessments of the textures of liquid and solid foods;
- quality control and automatic process control, where the attribute of the food material that is measured is often a rheological property;
- fundamental research, where rheological measurements are often used to indirectly measure and observe complex changes in food materials (see Section 3.4);
- the selection, design and testing of packaging material and packages with respect to their ability to withstand and physical environment (as defined in Section 1.2).

Density and porosity

These properties are directly related and are extremely important.

Density - basic definition

$$Density = \frac{Mass}{Volume} \qquad (3)$$

Density has the dimensions [M/L] and the SI units kg/m^3.

Porosity – basic definition

Porous materials contain internal voids or gas spaces (i.e. pores). Breadcrumb and crispy snack foods are good examples. Porosity is defined as:

$$Porosity = \frac{Total\ volume\ of\ pores}{Total\ volume\ of\ sample} \qquad (4)$$

Because porosity is defined as a ratio of volume, porosity is a dimensionless variable, and therefore had no units. It is essentially a volume fraction.

Porosity and density, for a porous material, are obviously related. In equation (3), for a porous material, the mass will be the mass of the material **substance** (because the mass if gas in pores in negligibly small by comparison), but the volume of the material will include the pores. Obviously, porosity results in lower densities; e.g. the density of breadcrumb, for example, is much lower than the density of the baked dough comprising the **substance** of the breadcrumb.

Density and porosity take different forms, and it is extremely important to understand the definitions of these and how they are interrelated.

The different forms of density

1. True density, ρ_t

The true density, ρ_t, of a non-porous material is the density as calculated from the densities of the material's pure components:

$$\rho_t = \frac{1}{\sum_i \frac{x_i}{\rho_i}} \tag{5}$$

where:

ρ_t	=	True density (kg/m^3)
x_i	=	mass fraction of the i-th component
ρ_i	=	density of the i-th component (kg/m^3)

For a substance comprising three components, for example, the true density can be calculated as:

$$\rho_t = \frac{1}{\frac{x_1}{\rho_1} + \frac{x_2}{\rho_2} + \frac{x_3}{\rho_3}} \tag{6}$$

and $x_1 + x_2 + x_3 = 1$, because they are **fractions**.

In defining true density it is assumed that there are no chemical or physico-chemical interactions of any kind between the components that would change their densities (ρ_1, ρ_2, etc) from what they would be if each component was in the pure state.

2. Substance density, ρ_s

Substance density, ρ_s, is the density of a **non-porous** substance or material **as measured**. (The substance density of the substance of a **porous** material must be measured after the material has been broken into pieces small enough to guarantee that no pores remain).

$$\rho_s = \frac{1}{\sum_i \frac{x_i}{\rho_i}} + \Delta\rho \tag{7}$$

where ρ_s = substance density (kg/m^3)

$\Delta\rho$ = adjustment to calculated ρ_t (Eq.5) to allow for interaction between components (kg/m^3).

This definition of the density of a material substance allows for any interactions between components that change their densities from what they would be if each component was in the pure state. $\Delta\rho$ can only be found experimentally, and can be positive or negative. If there are no component interactions, $\Delta\rho = 0$ and $\rho_s = \rho_t$.

For engineering purposes can be assumed that, for foods, $\Delta\rho$ is zero, that $\rho_s = \rho_t$, and that ρ_s can therefore be calculated by Eq.5.

3. Particle density, ρ_{part}

Particle density in the density as measured of a piece of a porous material. The volume of the piece as measured includes all the closed (true) pores, but not pores that are connected to the outside (open pores) (Fig. 9); open pores may be regarded as irregularities in the surface enclosing the measured volume. The particle density is thus the mass of material substance divided by the particle volume, which includes only the closed pores.

$$\rho_{part} = \frac{mass\ of\ substance}{Actual\ volume\ of\ particle} \tag{9}$$

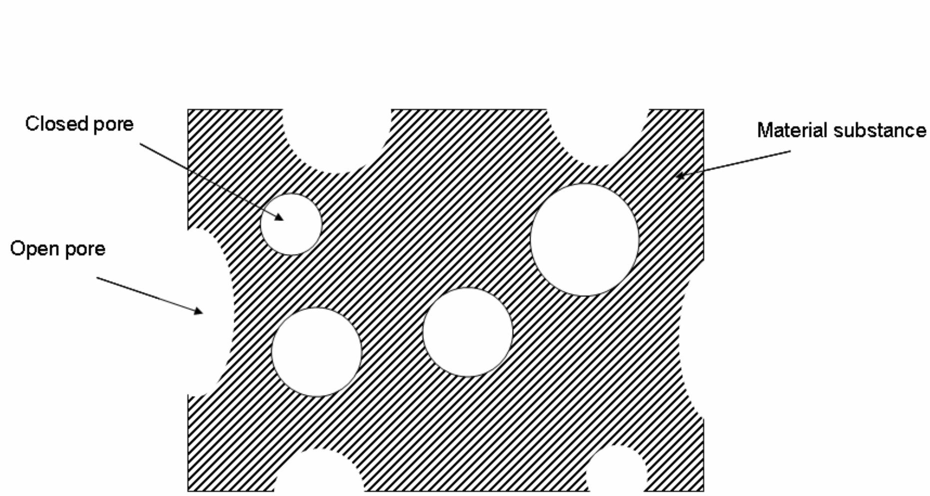

Figure 9. Cross-section through a cubic particle of a porous material, showing the actual surface boundary

The importance of particle density lies in the fact that later will be used to estimate open pore and bulk porosities of a porous material (see Eqs. 15 and 16). For a non-porous material, of course:

$$\rho_{part} = \rho_s \tag{10}$$

4. Apparent density, ρ_{app}

The apparent density, ρ_{app} of a porous material is calculated as the mass of the material divided by its apparent volume, i.e. the volume that includes both closed and open pores (Fig. 10).

$$\rho_{app} = \frac{mass\ of\ substance}{Apparent\ volume} \tag{11}$$

The surface boundary can be a regular shape (cube, parallelepiped, sphere, spheroid, ovoid, cone, etc.) or a completely random shape.

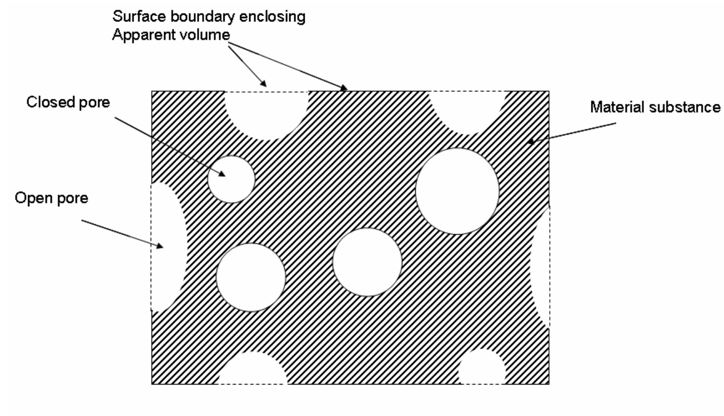

Figure 10. Cross-section of a cube a porous material showing the surface boundary enclosing the apparent volume.

Apparent density is important in the packaging of regularly shaped blocks of food, and in calculating the ***component volume fractions*** needed in equations for predicting the thermal conductivity and thermal diffusivity of porous foods. This is described in detail in the notes used to predict *thermophysical properties*. For the non-porous material, of course, $\rho_{app} = \rho_s$.

5. Bulk density, ρ_B

Bulk density is the effective density of a collection of particles of a material. It is defines as the mass of material divided by the volume (bulk volume) enclosing and containing the particles (Fig. 11).

$$\rho_{app} = \frac{mass\ of\ substance\, in\ particles}{Bulk\, volume} \tag{12}$$

Bulk density is important in the packaging of food particulates and powders, and in designing ventilation systems for removing moisture and heat produced by the respiration of, for example, wheat in a silo or apples in a carton. Bulk density is also important in predicting the effective thermal diffusivity of bulk particulate and powdered foods. This, again, is covered in more details under **thermophysical properties**.

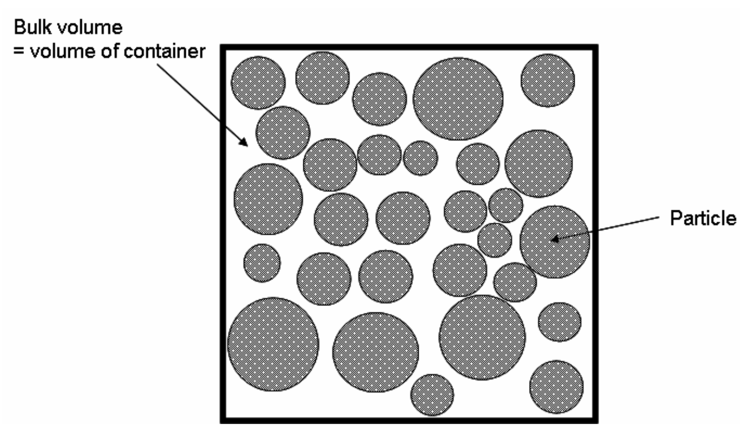

Figure 11. Cross-section through a container holding a collection of pieces of a material. The different forms of porosity

- **Apparent porosity**, ε_{app}

$$\varepsilon_{app} = \frac{Total\ volume\ of\ both\ open\ and\ closed\ pores}{Apparent\ volume} = 1 - \frac{\rho_{app}}{\rho_s} \tag{13}$$

See Fig. 10. Apparent porosity, like apparent density, to which it is related by Eq.13, is important in packaging and in the prediction of thermal conductivity and thermal diffusivity.

- **Open pore porosity,** ε_{op}

$$\varepsilon_{op} = \frac{Total\ volume\ of\ open\ pores}{Apparent\ volume} = 1 - \frac{\rho_{app}}{\rho_{part}} \tag{14}$$

Open pore porosity is an important property with respect to the dispersability of food powders (e.g. milk powder) in water.

- **Closed pore porosity,** ε_{cp}

$$\varepsilon_{cp} = \frac{Total\ volume\ of\ closed\ pores}{Total\ volume\ of\ material} = 1 - \frac{\rho_{part}}{\rho_s} \tag{15}$$

The equation relates the closed pore porosity of a particle (see Fig. 9) to particle density and substance density.

Bulk porosity, ε_B

For a porous material,

$$\varepsilon_B = \frac{Total\ volume\ of\ open\ pores\ plus\ total\ volume\ of\ interparticle\ space}{Bulk\ volume} = 1 - \frac{\rho_B}{\rho_{part}} \tag{16}$$

The open pores and the interparticle space together form one continuous space. For a non-porous material, $\rho_{part} = \rho_s$ (Eq.10), and:

$$\varepsilon_B = 1 - \frac{\rho_B}{\rho_s} \tag{17}$$

See Fig. 11. Bulk porosity, like bulk density, to which it is related by equation (16) or equation (17), is important in packaging and in ventilation systems.

- **Total porosity,** ε_{TP}

For both porous and non-porous materials,

$$\varepsilon_B = \frac{Total\ volume\ of\ interparticle\ space\ (both\ open\ and\ closed),\ if\ any}{Bulk\ volume} = 1 - \frac{\rho_B}{\rho_s} \tag{18}$$

For non-porous materials, from equations (16) and (17),

$$\varepsilon_{TP} = \varepsilon_B \tag{19}$$

Total porosity is important in calculating the capacities of storage vessels and packages, an in the prediction of thermal conductivity and thermal diffusivity.

NOTE

The equations for the different forms of density, and equations for the different forms of porosity, can all easily be derived from the first principles embodied in the basic definitions of density and porosity, and the assumption that gases and vapors in pores have no mass.

The density and porosity equations discussed above are summarized in Table 1. The prediction of food densities and component volume fractions will be covered under *thermophysical properties*. Some of these equations will be used again then.

Applications of density data

Some applications have already been mentioned above. Other important applications are as follows:

- Density (in the appropriate form) is essential for relating mass to volume, or volume to mass. The ability to do this is vital in numerous applications including the design of packages and of food storage, handling and transport facilities.
- Designing food sorting and cleaning equipment whose principles of operation depend on density differences. An example is the bring flotation separation of potatoes from stones; if the brine density is suitably set (by adjusting brine concentration) the potatoes will float and the stones will sink.
- Density can be an index of quality, e.g. the density of an alcoholic beverage us a measure of its alcohol content, and old-fashioned bushel weight of wheat is essentially a bulk density.
- Heat transfer: density is a thermophysical property (this is covered later in the paper), but not, of course, a thermal property.