Engineering Properties of Agricultural Materials

Introduction

Engineering properties are the properties which are useful and necessary in the design and operation of equipment employed in the field of agricultural processing. They are also useful for design and development of other farm machinery. As mentioned earlier unit operations such as cleaning, grading, drying, dehydration, storage, milling, handling and transportation, thermal processing of foods are among the important operations in agricultural processing. In these operations while handling of grains and other commodities the properties which play and important role are physical, mechanical, frictional, rheological, aero and hydrodynamic, electrical and optical properties of the bio materials. Basic information on these properties are of great importance and help for the engineers, food scientists and processors towards efficient process and equipment development. An attempt has been made to describe some of the engineering properties usually encountered in post production handling of agricultural crops.

Physical properties

The physical properties such as size, shape, surface area, volume, density, porosity, colour and appearance are important in designing particular equipment or determining the behaviour of the product for its handling.

Various types of cleaning grading and separation equipment are designed on the basis of physical properties of seeds such as size, shape, specific gravity, surface roughness, colour etc. For designing an air screen grain cleaner, the shape and size of the grain determine the shape and size of screen openings, angle of inclination and vibration amplitude and frequency of screens. The density of the grains decides the size of screening surface. The frontal area and related diameters and density are essential for determination of terminal velocity of the grain. Terminal velocity is necessary to decide about the winnowing velocity of air blast for separation of lighter materials in air screen grain cleaners.

The shape of product is an important parameter which affects conveying characteristics of solid materials by air or water. The shape is also considered in calculation of various cooling and heating loads of food materials.

The frontal area and the related diameters are essential for determination of terminal velocity Reynold’s number and drag coefficient. The density and specific gravity are needed for calculating the thermal diffusivity in heart transfer operations, in determining Reynold’s number, in pneumatic and hydraulic handling of the agricultural materials.

The surface characteristics, colour and appearance are exploited for selective separation and storage of fruits and vegetables.

Some of the important physical properties are described below.

Shape and size

The following parameters may be measured for describing the shape and size of the granular agricultural materials.

(i)Roundness: It is a measure of the sharpness of the solid material. The most widely accepted methods for determining the roundness of irregular particle are given below.

$$\text{Roundness} = \frac{\text{Largest projected area of the particle when it is in natural rest position, } A_p}{\text{Area of smallest circumscribing circle, } A_c}$$

$$\text{`Roundness ratio} = \frac{\text{Radius of curvature, } r\text{, of the sharpest corner}}{\text{Mean radius of the particle, } R}$$

(ii)Sphericity : Sphericity may be defined as the ratio of the diameter of a sphere of the same volume as that of the particle and the diameter of the smallest circumscribing sphere or generally the largest diameter of the particle. This parameter shows the shape character of the particle relative to the sphere having same volume. If D_e is the diameter of a sphere having same volume as that of the particle and D_c is the diameter of the smallest circumscribing sphere, then the sphericity can be expressed as under.

$$\text{Sphericity} = \frac{D_e}{D_c}$$

The spericity can also be defined as:

$$\text{Sphericity} = \frac{D_i}{D_c}$$

where , D_i = diameter of the largest inscribing circle.

D_c = diameter of the smallest circumscribing circle

Density and specific gravity

The density of any material may be expressed as below,

$$\text{Density} = \frac{\text{Weight of the material, kg}}{\text{Volume of the material, } m^3}$$

The density and specific gravity values of grains and other commodities and silos, separation of desirable materials from impurities, cleaning and grading, evaluation of the grain maturity, texture and softness of fruits, quality evaluation of the products etc.

Some of the agricultural products having irregular shaped material is generally determined by displacement method which has been described here.

Determination of the volume by Platform scale: The platform scale is a simple technique which is commonly used for determination of volume of large materials like fruits and vegetables. The weight of material is determined by weighing on the scale in air, thereafter, the material is forced into the water with the help of a rod. The later reading of the scale while the material is submerged minus the weight of container and water is the actual weight of the displaced water. The volume density and specific gravity of the material are estimated by following formulae.

$$\text{Volume}, m^3 = \frac{\text{Weight of displace water, kg}}{\text{Weight density of water, kg/m}^3}$$

$$\text{Weight density, kg/m}^3 = \frac{\text{Weight of material in air, kg}}{\text{Volume of the material, m}^3}$$

$$\text{Specific gravity} = \frac{\text{Weight in air x specific gravity of water}}{\text{Weight of displaced water}}$$

Determination of Specific gravity by Pycnometer Method: The specific gravity bottle or pycnometer and toluene ($C_6H_5CH_3$) are used for determination of specific gravity of granular agricultural materials. The following procedure is used for determination of the specific gravity.

(i) The weight of empty pycnometer and the weight of pycnometer filled with water at 20C are taken.

(ii) The specific gravity of toluene is determined as the ratio of the weight of toluene in the bottle and weight of distilled water in the bottle at same temperature.

$$\text{Specific gravity of toluene} = \frac{\text{Weight of toluene}}{\text{Weight of water}}$$

(iii) Ten gram sample of grain is placed in the pycnometer and filled with toluene to cover the sample.

(iv) The air is completely exhausted from the bottle by a vacuum pump.

(v) When there is no air bubble remains in the bottle, the bottle is filled with toluene and the temperature is allowed to reach 20°C.

(vi) The bottle is weighted and the specific gravity of grain is calculated by following expressions,

$$\text{Specific gravity of grain} = \frac{\text{Specific gravity of toluene x weight of grain}}{\text{Weight of the toluene displaced by the grain}}$$

$$= \frac{\text{Specific gravity of toluene x weight of grain}}{[(\text{weight of sample}) - (\text{weight of toluene + sample + bottle}) - (\text{weight of toluene + bottle})]}$$

Aero and Hydrodynamic properties

The aero and hydrodynamic properties such as terminal velocity of agricultural products are important and required for designing of air and water conveying systems and the separation equipment. The physical properties such as density, shape and size, drag coefficient etc., are required for calculating the terminal velocity of the material. For example, in pneumatic conveying and separation processes of the material is lifted only when the air velocity is greater than its terminal velocity.

Terminal velocity

The terminal velocity of a particle may be defined as equal to the air velocity at which a particle remains in suspended state in a vertical pipe.

Table 1 Air velocity requirement for air borne of some of the agricultural materials

Grain	Unit density, kg/m^3	Terminal velocity, m/s
Wheat	998-1238	9-11.5
Rye	1158-1218	8.5-10
Oats	738-968	8-9
Corn	1138-1198	34.9
Soybean	1029-1152	44.3

Table 2 Terminal velocity and drag coefficient for groundnut and soybean

Grain	Terminal velocity m/s		Drag Coefficient	
	Range	Mean	Range	Mean
Groundnut kernel (RS-1)	12.31-13.78	13.23	0.52-0.64	0.58
Soybean (Punjab-1)	12.30-13.92	13.40	0.38-0.62	0.47
Soybean (Lee)	13.30-14.55	14.17	0.33-0.51	0.41

Frictional properties

The frictional properties such as coefficient of friction and angle of repose are important in designing o storage bins, hoppers, chutes, pneumatic conveying system, screw conveyors, forage harvesters, threshers etc.

The rolling resistance or maximum angle of stability in rolling of round shape agricultural materials is useful in designing handling equipment e.g. conveying of fruits and vegetables by gravity flow.

In mechanical and pneumatic conveying systems, the material generally moves or slides in direct with the trough, casing and other components of the machine. Thus various parameters affect the power requirement to drive the machine. Among these parameters, the frictional losses are one of the factors which must be overcome by providing additional power to the machine. Hence, the knowledge of frictional properties of the agricultural materials is necessary; therefore, some of the important frictional properties of agricultural products have been described here.

Static friction: The friction may be defined as the frictional forces acting between surfaces of contact oat rest with respect to each other.

Kinetic friction: It may be defined as the friction forces existing between the surfaces in relative motion.

If F is the force of friction and W is the force normal to the surface of contact, then the coefficient of friction ‘f’ is given by the relationship

$$f = \frac{F}{W}$$

The coefficient of friction may also be given as the tangent of the angle of the inclined surface upon which the friction force tangential to the surface and the component of the weight normal to the surfaces are acting.

Angle of repose: The angle of repose is the angle between the base and the slope of the cone formed on a free vertical fall of the granular material to a horizontal plane. The size, shape, moisture content and orientation of the grains affect the angle of repose.

There are two angles of repose, (1) static angle of repose, and (2) dynamic angle of repose.

Static angle of repose: It is the angle of friction when u by granular material to just slide upon itself.

Dynamic angle of repose: It comes in picture when bulk of the grain is in motion like discharge of grain from bins and hoppers. The dynamic angle of repose is more important than static angle.

Measurement of angle of repose

Method I:A wooden frame full of grain sample is mounted on a tilting top drafting table. The table top is tilted till the grain starts moving over the inclined surface. The angle of inclination is measured which is angle of repose of the grain sample.

Method II: This apparatus consists of a circular platform immersed in a box filled wit grain and with a glass window in one side. The platform is supported by three adjustable screw legs and is surrounded by a metal funnel leading to a discharge hole. The grain is allowed to escape from the box, leaving a free-standing cone of grains on the platform. A traveling microscope is used to measure the heights. The angle of repose, Ø, is obtained from the geometry of the cone as given below.

$$Ø = tan^{-1} \frac{2(H_a - H_b)}{D_b}$$

Where H_a, H_b and D_b are the height of the cone, height of the platform and diameter of the platform respectively. The angle of repose for some of the grains is given in Table 3.

Table 3. Angle of repose of some grains

Grain	Angle of repose, degree
Wheat	23-28
Paddy	30-45
Maize	30-40
Barley	28-40
Millets	20-25
Rye	23-28

Effect of moisture content of the angle of repose: It has been found that the angle of repose increases with the increase of moisture content of material. This variation of angle of the repose with moisture content occurs because surface layer of moisture surrounding the particle holds the aggregate of grain together by the surface tension.

An empirical equation has been developed to correlate the angle of repose and moisture content for rice. The equation was tested with the experimental values which gave the correlation coefficient of 97%. The equation is a follows.

M

$$\tan Ø = an^2 + b\ \mathrm{q}\ \frac{\text{----}}{\text{Dau}}\ \mathrm{r} + cs + d$$

Where,

Ø = angle of repose

$$n = \text{shape factor} = \frac{\text{specific surface of solid}}{\text{specific surface of sphere}}$$

M = percent moisture content

Dau = averages screen particle diameter

s = specific gravity

a, b, c and d = constants

Angle of internal friction: The value of angle of internal friction is equal to the tangent of the coefficient of friction for the material.

The angle of internal friction is an important property which helps to estimate the lateralpressure in storage silos. Angle of internal friction values are also used in designing of storage bins and hopper for gravity discharge. The coefficient of friction between grains is required as a designparameter for design of shallow and deep bins.

Difference between angle of repose and angle of internal friction

The engineers generally assume that both the angle of repose and angle of internal friction are same. Some investigators have indicated that for sorghum, the angle of repose and angle of internal friction are different. If one is used in place of other to design any system, it will lead to error.

Some investigators also attempted to develop a relationship between angle of repose and angle of internal friction so that by the simple test of angle of repose, the angle of internal friction could be estimated. But the results revealed that the two angles run almost parallel to each other for various moisture content levels, thus no simple relationship existed by which angle of internal friction could be estimated from angle of repose within a reasonable accuracy.

The angle of repose is generally higher than angle of the internal friction for the grains of approximately the same moisture content and density.

Mechanical properties

Mechanical properties may be defined as those which affect the behaviour of the agricultural material under the applied force. The mechanical properties such as hardness, compressive strength, impact and shear resistance and the rheological properties affect the various operations of agricultural processing. Data on these properties are useful for application in designing equipment for milling, handling, storage, transportation, food processing etc.

The mechanical damage to grain and seed in threshing and handling operations causes reduction in germination power and viability of seeds, increases the chances of insect and pest infestation and also affect the quality of final product.

The hardness of the grain effects the milling characteristics and it is also useful to live stock feeders and plant breeders.

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The impact and shear resistance are important for size reduction of food grains. This information is useful in determination of the appropriate methods of crushing, breaking or grinding the grains. These properties also play important roles towards seed resistance to cracking under harvesting and threshing conditions.

Thermal properties

The thermal properties like specific heat, thermal conductivity, thermal diffusivity, enthalpy, surface heat transfer coefficient, emissivity etc. are important for the development of any thermal processing system. The thermal processing may include heating, cooling, freezing, drying etc. There are some other thermal properties like melting or freezing points, latent heats, heat of adsorption, heat of respiration, coefficient of thermal expansion etc., but these are not of much importance for the most heat transfer applications.

(i) Specific heat : The specific heat may be defined as the amount of heat in kilocalories that must be added to or removed from 1kg of a substance to change its temperature by 1°C. The specific heat of wet agricultural material is the sum of specific heats of bone dry material and its moisture content. If C_d and C_w are the specific heats of bone dry material and water respectively, and m is the moisture content of the material in percent wet basis, then the specific heat can be expressed as given below.

$$C = \left(\frac{m}{100}\right) C_w + \left(\frac{100-m}{100}\right) C_d \text{ kcal/ kg°C}$$

Note: The above relationship exists above 8% moisture content of the grain only.

The specific heat of bone dry grain varies from 0.35-0.45 k cal/kg°C.

The specific heat is measured by calorimeter, generally a simple thermos vacuum bottle. The differential scanning - calorimeter (DSC) is suitable for measuring the specific heat.

(ii) Thermal conductivity: The thermal conductivity may be defined as the rate of heat flow through unit thickness of material per unit area normal to the direction of heat flow and per unit time for unit temperature difference. It is a measure of ability of the material to conduct heat. The thermal conductivity can be expressed by the following equation.

$$Q = K A \Delta T$$

Where Q=amount of heat flow, kcal

A=area, m^2

ΔT=temperature difference in the direction of heat flow, °C

K=thermal conductivity, kcal/m.hr.°C

If, m is the moisture content of the grain, then the thermal conductivity of wheat can be expressed as follows,

$$K = 0.060 + 0.002\, m, \text{ kcal/m.hr.°C}$$

The above relationship exists for the wheat bulk with the moisture content range of 10-20% (db). The thermal conductivity of sorghum may be given as follows,

$$K = 0.564 + 0.0858\, w, \text{ W/m.°C}$$

where, w=fraction of moisture present in material.

The thermal conductivity of single grain ranges from 0.3-0.6 kcal/m.hr.°C and bulk grain varies from 0.10-0.15 kcal/m.hr.°C. The difference is due to the air spaces present in the bulk grain. The thermal conductivity of air is 0.02 kcal/m.hr.°C.

Determination of thermal conductivity of grains and food materials

The measurement of thermal conductivity of agricultural grains poses much problem because it depends on the structure and chemical composition of the grain. Thermal conductivity probe is used for measurement of thermal conductivity of most of the food materials. The probe consists of a hypodermic needle of 0.66 mmdiameter and connected to handle. A0.077 mm diameter constantan heater wire insulated with plastic spaghetti tubing is inside the needle. The wire is taken from the handle to the top and back. The purpose of using constant wire is to avoid the change in electrical resistance with temperature. The insulated chromel constantan thermocouples wire 0.051 mm in diameter is wrapped around the upper half of the probe handle and the needle tip. The line-heat source probe is inserted into the sample having uniform initial temperature. The probe is heated at a constant rate, and the temperature adjacent to line-heat source is monitored. After a brief transient period, the plot of natural logarithm of time us temperature is plotted, which has a slope equal to Q/4π K. The thermal conductivity of material can be estimated by the following equation.

$$K = Q \frac{\ln [(t_2-t_0)/t_1-t_0)]}{4\pi(T_2-T_1)}$$

Where, K=thermal conductivity of the sample, W/m °C

Q=Power generated by the probe heater, W/m

t_1 and t_2=time since probe is energized, S

t_0=time conductance factor, S

T_1 andT_2=temperature of probe thermocouple at time t_1 and t_2 respectively, °C

(iii) Enthalpy : Enthalpy is the total heat content or energy level of a material. The enthalpy data are required for frozen foods that freeze over a range of temperatures below 0 °C and for those substances that freeze in a narrow temperature limit, as the case of pure substance like water. The enthalpy of the material can be estimated by using following expression.

$$h_2-h_1=m\,C_p(T_2-T_1)+m\,X_wL$$

Where,h_2-h_1=enthalpy difference

m=mass of the product

C_p=Specific heat of the product

X_w=Water fraction

T_2-T_1=temperature difference

L=latent heat of fusion for water

(iv) Thermal diffusivity: The thermal diffusivity may be calculated by dividing the thermal conductivity with the product of specific heat and mass density. It may be expressed as,

$$\mu = \frac{K}{\rho C_p}$$

Where , μ =thermal diffusivity

K=thermal conductivity

ρ=mass density

C_p=specific heat

Thermal diffusivity is important in determination of heat transfer rates in solid food materials of any shape. Physically it shows the relationship between the ability of a material to conduct heat to its ability to store heat.

The common method of determination of thermal diffusivity is to calculate from experimentally measured values of thermal conductivity, specific heat and mass density. In most of the cases the specific heat can be estimated from the product composition, so only experimental measurements of thermal conductivity and mass density are required.

Rheological properties

The rheological properties may be defined as the science which deals with the deformation and flow of the material under action of the applied forces. Time is an important parameter during application of load to the body. Therefore, in rheology three important parameters such as force, deformation and time are used for expressing the mechanical behaviour of the material.

The knowledge of rheological properties is useful in designing mechanical handling systems of agricultural product where deformation and flow of the material occur. In liquid foods, the knowledge of rheological propertiesis essential for the proper design and operation of various machines and also for understanding the pertinent transport processes in the operations. Some of the foods like milk, syrups, filtereddilute juices and vegetable oils are Newtonian fluids. For such foods, the knowledge of viscosity function and its dependence upontemperature and concentration is sufficient for engineering design. Other examples of the rheological properties are textural attributes of foods like firmness, yielding quality, crispness and fibrousness.

The deformation can be divided into elastic deformation and flow. The flow may be further divided into plastic flow and viscous flow. Thus the three basic properties which describe the rheological behaviour of the material are elasticity, plasticity and viscosity. These properties are generally represented by three classical ideal bodies known as Hookean body, St. Venant body and Newtonian liquid. The behaviour of none of the real material is perfectly elastic o r perfectly plastic, therefore, these three ideal bodies are used to serve as standards of comparison for analyzing the behaviour of an real material.

Ideal elastic behaviour or Hookean body **:** The Hook's law states that stress is directly proportional to strain within the elastic limit. This behavour of the material is referred to as Hookean behaviour and it may hold true for small strains generally less than 0.1% in some of the solids. But in any real material, perfect elasticity may not be obtained. Also in elasticity, the complete recovery of strain takes place upon removal of stress.

The compression tests conducted on some of the products like fruits and vegetables, cereal grains etc. Show that Hookean elasticity does not exist in these biological materials even for very small strains. The curve shows te residual deformation upon unloading. Similar nature of curve is obtained for most of the food materials.

Ideal plastic behaviour or St. Venant body **:** The St. Venant body or pure plastic behaviour of the material can be represented by a mechanical model consists of a friction block. The model indicates that there is no movement between the block and surface over which it rests due to the static friction. If the pulling fore is slightly increased than the static friction, the block will start moving. The pulling force is required to overcome only the kinetic friction to maintain the movement. In the model the displacement gradient (cm/cm) is similar to the shearing strain in a pure plastic material. The flow of the material does not start until a limiting value of shearing stress also called'yield stress' is reached. The material cannot sustain greater than this strain and flow occurs indefinitely under this stress till the distortion is restricted by some other factor.

Pure viscous behaviour or Newtonian liquid: The pure viscous flow of a liquid is said to be the flow when slightest force can cause movement of liquid and when the rate of its flow is proportional to the force applied. The flow of the liquid continues infinitely until the force is removed, upon removal o force, like in the caseof plastic flow, it will not regain its original state. Such a material is called a Newtonian liquid. This type of liquid can be represented by a dashpot, which may be assumed as a piston, it starts moving in or out of the cylinder at a constant velocity; the rate generally depends upon the magnitude of the force applied. After removal of the force, the piston remains stationary and cannot return to its original position. A material having such a nature has a rheological constant called the coefficient of viscosity (η). The coefficient of iscosity may be referred as the ratio of shearing stress applied to the resulting shear rate $\{ \eta = \iota / r \}$.

The relationship between the shear rate and shear stress is a straight line passing through the origin. The slope of the line is viscosity. It indicates that although the yield value of an ideal liquid is Zero, the internal frictional resistance causesthe flow which is called viscosity.