FLOWABILITY OF FOOD POWDERS AND METHODS FOR ITS EVALUATION — A REVIEW

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INTRODUCTION

The term food powders represents a very wide range of powders that differ to a very great extent with regard to their chemical composition and physical characteristics (Table 1). Furthermore, the factors that effect the flowability of any given powder are numerous. They include surface properties, shape and size distribution on one hand and the geometry of the physical system on the other. It is obvious, therefore, that one general theory can hardly be applicable to all food powders and all possible conditions that may develop in practice. Furthermore, perhaps the only common feature of food powders is their tendency to develop physical and chemical changes with a strong dependency on the temperature — moisture history. As a result, a food powder should be looked upon as a dynamic system with properties that may progressively change with time.

Due to the complexity of the domain therefore, this work would only present the very general principles of powders flow and discuss their possible implication in major or common food processing and storage operations. The discussion would also be focused on those materials that are termed powders in everyday language (Table 1), and will exclude the group of granular materials (such as wheat or corn kernels). These materials have been extensively discussed by Mohsenin (1970), with a detailed reference to those pertinent aspects of powder technology. Because some of the testing procedures are based on similar principles however, effort has been made to avoid repetition as much as possible.

FLOW OF POWDERS

The mechanism involved in particulate solid flow has no similarity to liquid flow. The most remarkable practical differences are:

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Table 1. Characteristics of various food powders

Powder	Common Process of Production	Major Ingredient(s)	Commercial Moisture Content Level (%)[(a)]
Wheat flours	Milling	Starch, protein	12
Defatted soy flours	Residue of oil extraction process	Protein, carbohydrates	8
Mashed potato (flakes)	Drum drying	Starch	5
Whole milk	Spray drying	Lactose, fat, protein	2
Whole egg	Spray or freeze drying	Protein, lipids	4
Powdered onion	Grinding of dried flakes	Carbohydrates	4
Instant coffee	Spray or freeze drying (agglomeration)	Carmelized sugars, organic acids	2.6
Fruit juice drinks	Mixing	Carbohydrates (sugars) and citric acid	1
Sucrose	Crystallization and drying	Sucorse	0.5
Soup Mixes	Mixing	Salt, fat, carbohydrates	——
Ice cream & baking mixes	Mixing	Sugars, fat, carbohydrates	——

(a) Watt and Merrill (1963, 1975)

(a) In liquid flow the flow rate is proportional to the square root of the liquid head above the outlet. In powders the flow rate is independent, or almost independent, of the head provided the powder bed height is at least 2.5 times the outlet diameter, (Brown and Richards 1970).

(b) Particulate solid materials can support considerable shear stresses or form stable structures that will prevent flow despite the existing of "head".

Generally speaking, a flow of a powder is the relative movement of a bulk of particles among neighboring particles or along the container wall surface. The forces that are involved are gravitational forces, friction, cohesion (interparticle attraction) and adhesion (particle-wall attraction). The formation of a stable solid arch above the aperture is also possible. (Jenike 1967; Brown and Richards 1970).

Gravitation (pressure) is the natural driving force of unaided flow. It can also cause, however, a considerable compaction of the powder bed. Under such conditions the cohesive forces may be enhanced and the powder bed will develop "strength" with measurable mechanical properties such as tensile strength and compressive breaking strength. Flow in these terms is therefore a mechanical failure of the compacted powder bed. This led to the development of flow criteria based on solid failure theories. The most prominent theory of bulk solids flowability is the one suggested and elaborated by Jenike (1967). In food engineering textbooks, it is described by Mohsenin (1970) and by Leniger and Beverloo (1975).

Non-Cohesive Powders

Generally speaking, non-cohesive (or "free flowing") powders are those powders in which interparticle forces are negligible. It should be borne in mind though, that such forces can develop under special conditions such as moisture absorption (e.g., instant coffee), elevated temperature (e.g., fat or sugar containing powders) or static pressure (e.g., soup mixes, microcrystalline cellulose). As long as the powder is free flowing the major obstruction to flow is the internal friction. Or, in other words, the condition for flow to occur is:

$$\tau > \mu \sigma$$

where τ is the shear stress, μ the friction coefficient ($\mu = \mathrm{tg}\,\alpha$ where α the internal angle of friction) and σ is the normal stress. (See Fig. 1). Most food powders can be considered as non-cohesive only when they are dry and when their particle size is above the level of about 100 micron (White *et al.* 1967).

Cohesive Powders

As mentioned, cohesive powders are those in which interparticle forces do play a significant role in the powder bed mechanical behavior. These factors can reduce the flowability, stop it altogether or form stable bridging between particles (agglomeration). The latter phenomenon is usually referred to as a caking problem which can vary from the formation of soft lumps to the total solidification of the powder bed (Pietsch 1969). Most food powders, if unprotected, become cohesive rather easily especially due to moisture absorption.

The criteria for actual flow in any given physical system is less straightforward than in the case of non-cohesive powders. An analysis of such a system has to be more elaborated and to include both the powder properties and the geometry of the system (Jenike 1967).

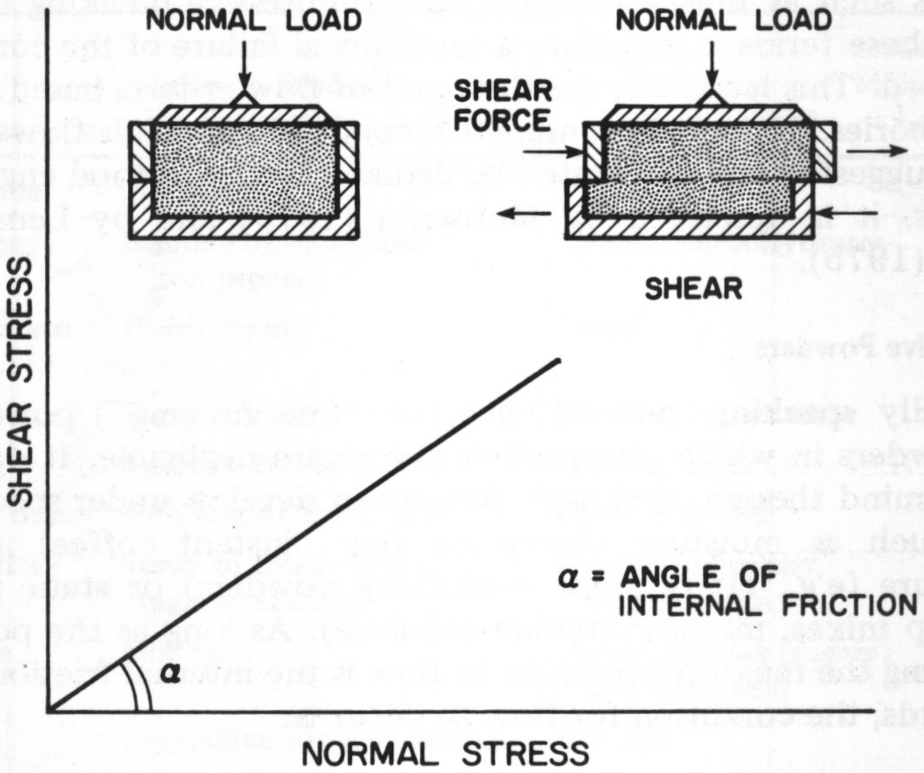

FIG. 1. THE YIELD CURVE OF NON-COHESIVE POWDER

THE NATURE OF INTERPARTICLE FORCES IN POWDER BEDS

The various kinds of mechanisms by which particles are attracted or interlocked have been classified and discussed in a classical work by Rumpf (1961) and recited by Pietsch (1969). The major mechanisms which are of concern in food powders are cited below.

Liquid Bridging

Liquid bridges can be formed when there is a liquid phase on the particle surface. This phase can be the result of:

(1) Moisture absorption (hygroscopic materials)
(2) Melting, (e.g., of fatty components)
(3) Chemical reactions that liberate liquid (e.g., browning)
(4) Excessive liquid ingredient (e.g., flavoring oils)
(5) Moisture liberation during the crystallization of amorphous sugars (Makower and Dye 1956; Berlin *et al.* 1968)
(6) Accidental wetting of the powder or the equipment.

The types of liquid bridges are shown in Fig. 2. Theoretical analysis of their contribution to mechanical strength of an agglomerate can be found in works by Rumpf (1961) and Derjagin (1961), Hotta *et al.* (1974), Schubert (1975) and Schubert *et al.* (1975).

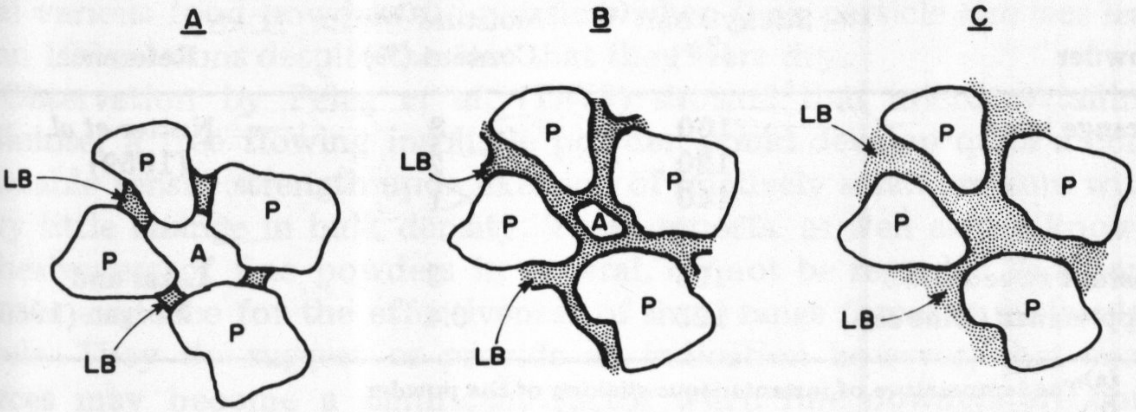

FIG. 2. SCHEMATIC REPRESENTATION OF DIFFERENT KINDS OF LIQUID BRIDGES ACCORDING TO RUMPF (1961)

P-particle LB-liquid bridge A-air. Note that any combination of the three types may also occur.

The composition of the liquid of the bridge may vary, especially in the case of food materials. This is due to the presence of numerous chemical components that have different solubilities, and different patterns by which temperature effects the latter.

The presence of the liquid bridges in itself is sometimes sufficient to obstruct flow (Peleg and Mannheim 1973) but does not necessarily result in lump formation (Makower and Dye 1959). If kept at a moderate level of moisture, for example, such a powder can maintain some degree of flowability despite the liquid bridges. If however, drying will occur after such a stage the bridges will solidify thus forming hard agglomerates or solidification of the whole bed. This process, very typical to soluble powders, (Pietsch 1969; Zimon 1969) has been termed "Humidity Caking" (Burak 1956). It has been recently discussed in connection with powdered onion (Peleg and Mannheim 1977).

Viscous liquid bridges may cause flow difficulties in fat-containing powders. The practice of cold mixing of such powders is partly due to this factor. If the temperature is elevated during processing or storage, part of the fat may melt forming liquid bridges of fatty composition. If the temperature drops later on, resolidification of the fat may occur resulting in a lumpy product. A similar problem is well recognized in the detergent industry which also uses ingredients having low melting points (Walter 1961).

A different kind of mechanism responsible for bridging is the thermoplastic characteristics of sugar-rich fruits or vegetable powders. When enough moisture is present thermoplastic properties develop at relatively low temperatures. Two examples are demonstrated:

Powder	Sticky Point[(a)] (°F)	Moisture[(b)] Content (%)	Reference
Orange juice	100	3	Notter *et al.* (1959)
	120	2	
	140	<1	
Instant sweetened applesauce (wine sap)	105	3	Lazar and Morgan (1966)
	125	0.4	

(a) The temperature of instantaneous sticking of the powder
(b) Approximated values

If after reaching the sticky point, the temperature decreases or the moisture is removed, the bridges will solidify to form hard solid bonds. Observation of this bond in polarized light reveals that they are not composed of crystals in contrast with similarly formed bonds of pure sugars (Peleg 1971).

It should also be mentioned that the formation of liquid bridges does not necessarily require the liquefaction of the whole particle mass. Local surface transformations are in most cases sufficient for bridging (Peleg and Mannheim 1973, 1977). This explains the frequent observation that caking does occur in apparently dry powders and where moisture changes are at practically undetectable levels (e.g., powdered sucrose).

Molecular Forces

Molecular attraction can be considered as a significant factor only at a short range. van der Waals forces for example have an effective range of up to about 100Å. Immobile absorbed liquid layers that can transform their excessive energy into particles attraction have similar effective range (Rumpf 1961). Possibilities of chemical interactions between the particle surfaces cannot be ruled out either. There is little information on the specific influence of such forces on the flowability of food powders. It is obvious though that their effect may become significant in very fine food powders or in compacted beds. In such cases the number of contact points between particles is considerably increased. Furthermore, because the finer the powder the larger its exposed surface area, the surface energy per unit weight (regardless of its physical-chemical character) also increases with the size reduction of the powder.

Indirect evidence of the contribution of such short-range forces in foods can be found in the work of White *et al.* (1967). They showed that various food powders did not flow when their particle size was less than 120 microns despite the fact that they were dry.

Observation by Peleg *et al.* (1973) showed that microcrystalline cellulose, a free flowing insoluble powder, could develop quite a considerable tensile strength upon exertion of relatively small pressure with very little change in bulk density. These reports, as well as the known cohesiveness of fine powders in general, cannot be regarded as a conclusive evidence for the effectiveness of short range forces at molecular levels. They do suggest or provide an indication however, that such forces may become a significant factor when fine powders are considered.

Mechanical Interlocking

Particles with irregular or fibrous shapes can be mechanically interlocked (Rumpf 1961; Mohsenin 1970). By the aid of vibration or pressure they may reach mutual orientations in which they are physically bound. The structures so formed can be mechanically stable and not always is it easy to bring the particles back to a flowing array. There is little or no evidence that such a mechanism becomes a dominant factor effecting the flowability of food powders. Under considerable pressure though a contribution by such type of mechanism cannot be ruled out.

FLOWABILITY RELATED PROPERTIES AND METHODS FOR THEIR DETERMINATION

Though the actual flowability of powder is determined by both the latter's physical properties and the geometry of the system (Jenike 1967) there are numerous experimental methods that can provide indication whether a given powder is free flowing or not. Some of these methods are discussed below.

Flow Tests

In such tests a powder is let to flow through laboratory bins or a conical funnel of different shapes. The flow can be spontaneous or aided by controlled vibrations.

In such tests, the flowability criterion is the mass flow rate. As previously mentioned, it is practically independent of the bed height if the latter is kept at a level more than 2.5 times the aperture diameter (Brown and Richards 1970). It is obvious that the method can only be applied to flowing powders. If a powder does not flow in the selected system the latter can be replaced. This, however, can be a burdensome procedure and with no guarantee that flow will eventually occur. When two or more powders do not flow under given conditions the method cannot provide clear indication on the degree of cohesiveness or suggest different conditions under which flow may perhaps be possible.

Numerous attempts have been made to correlate the mass flow rate with geometrical and physical parameters. Various such empirical equations have been cited in the literature and their application to food systems demonstrated. (Mohsenin 1970; Charm 1971; Sone 1972; Leniger and Beverloo 1975). The existence of a variety of non-coinciding equations suggests that more than a single mechanism are involved in the flow and therefore actual testing of systems is perhaps unavoidable.

From a dimensional point of view, isothermal flow through a funnel could be described as follows (White *et al.* 1969):

$$W = K\,\psi\,(\mu)\,\rho_p\,d_o^{2.5}\;g^{0.5}$$

where W is the mass flow rate K a constant, $\psi\,(\mu)$ a function of the friction coefficient ρ_p the particles density, d_o the cone apperture ($d_o \gg d_{\mathrm{particle}}$) and g the gravitational acceleration.

The limitation of this equation as well as most other empirical ones is that they cannot successfully predict conditions in which flow will stop altogether. If such equations are considered in a more restrictive way, however, they can provide useful guidelines for flow analysis, under limited conditions.

Angle of Repose

Perhaps the simplest test from a technical point of view is the measurement of the repose angle. In such a test the angle the powder forms with the horizon is determined. Regardless of the methods by which the cone (or other powder shape) is formed it can be assumed that the smaller the angle the more free flowing the powder is. As a thumb rule, powders with angle of repose of less than about 40 degress are free flowing. Powders exhibiting repose angle of 50 degrees and more are likely to cause flow problems. Because the formation of the cone involves both frictional forces, interparticle cohesive forces, and impact effects that may lead to segregation, the actual measurements depend on the experimental method procedure. It has been shown by Brown (1961) that results obtained by different techniques are significantly different and therefore incomparible.

In the case of cohesive powders irregular cones are sometimes formed and the measurement of the angle itself becomes difficult. Furthermore, powders may have different and non-uniform packing levels as well as moisture levels. Therefore, the relative contributions of the various physical factors that shape the heap may also vary with these parameters. This explains why moist powder exhibits higher repose angle (mainly due to cohesion) despite the fact that the angle of internal friction usually declines with the increase in moisture (Mohsenin 1970; Peleg and Mannheim 1973). General aspects of the repose angle have been discussed by Brown (1961), Gray (1968), Bruff and Jenike (1967, 1968), Brown and Richards (1970), and Carstensen and Chan (1976). Applications to food materials can be found in textbooks written by Mohsenin (1970). Sone (1972) and Heldman (1975).

The Principles of Cohesive Powders Characterization

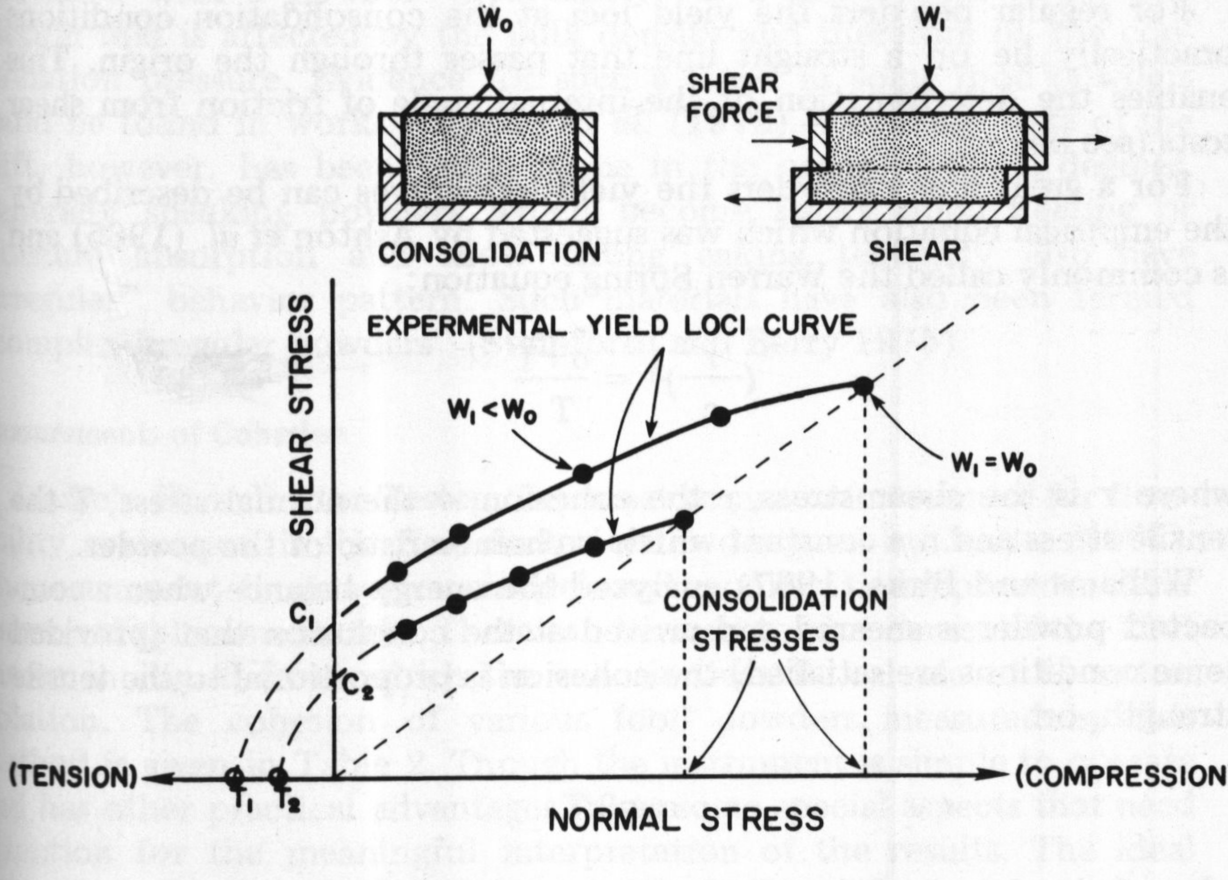

FIG. 3. THE YIELD CURVES OF COHESIVE POWDERS AT TWO CONSOLIDATION LEVELS
C_1 and C_2 — Cohesion, T_1 and T_2 — Tensile strength

A schematic view of the shear yield stress as a function of the normal stress at two consolidation levels is shown in Fig. 3. (The technical details regarding the determination of the curves are discussed later). The figure demonstrates that unlike the non-cohesive powders the cohesive powder is characterized by the following:

(a) There is a family of yield loci curves, i.e., at each consolidation level we get a different curve.

(b) The curves do not pass through the origin.

The latter indicates that at zero normal stress the compacted powder has non-zero shear strength. This parameter is referred to as "cohesion". The units of the cohesion are units of pressure and the magnitude depends not only on the powder properties but also on the consolidation conditions (C_1 and C_2 in Fig. 3).

Likewise, the yield loci curve intercepts with the normal stress axis indicate the "tensile strength" of the compact (T_1 and T_2 in Fig. 3). The values of the latter, however, cannot be calculated by mere extrapolation of the yield loci curve and various instrumental techniques have been developed for their determination.

For regular powders the yield loci at the consolidation conditions practically lie on a straight line that passes through the origin. This enables the determination of the internal angle of friction from shear tests (see below).

For a great many powders the yield loci curves can be described by the empirical equation which was suggested by Ashton *et al.* (1965) and is commonly called the Warren Spring equation:

$$\left(\frac{\tau}{c}\right)^n = \frac{\sigma+T}{T}$$

where τ is the shear stress, c the cohesion, σ the normal stress, T the tensile stress and n a constant which is characteristic of the powder.

Williams and Birks (1967) analyzed the energy balance when a compacted powder is sheared and arrived at the conclusion that (provided some conditions are satisfied) the cohesion is proportional to the tensile strength, or:

$$c = kT$$

where k is a constant that depends on the internal friction and the ratio between the normal and shear strains.

The practicality of their theory has been demonstrated by Farely and Valentine (1967, 1968) and Stainforth *et al.* (1970, 1971) who showed such a relationship in a variety of inorganic powders. Cheng *et al.* (1968) showed that the relationship had a strong dependency on particle size and the proportionality constant (k) in a range of up to about tenfold depending on the powder. Their measured values for soybean flour and egg powder were about $k = 1.5$.

Irregular Powders

In the Warren Spring equation the powder coefficient n is independent of the consolidation pressure and therefore is an intrinsic property of the tested powder. Obviously it will be affected by particle size, moisture, etc.

For some powders, however, it has been found that the assumption of a constant power coefficient n does not provide a satisfactory approximation. These powders have been termed "complex" (Kocova and Pilpel 1971, 1972) or "Irregular Powders" (Stainforth and Berry 1973). Analytical treatment of their flow behavior is significantly more difficult than that of the simple or regular powders. Another property associated with a powder "irregularity" is a static angle of internal friction that is affected by the bulk density and therefore by the consolidation pressure. Evidence for such a trend in some food powders could be found in works by Peleg *et al.* (1973). The magnitude of the shift, however, has been found to be in the order of single degrees. Generally speaking powders which become sticky upon heating or moisture absorption and show strong caking tendency also have "irregular" behavior pattern. Such materials have also been termed "complex irregular powders" (Stainforth and Berry 1975).

Measurements of Cohesion

Jenike's Flow Factor Tester. The most common instrument for flowability evaluation is the flow factor tester designed by Jenike (1967). The instrument (in its various models and modifications) provides shear force — displacement data. These can be used to plot curves of the kind shown in Fig. 3 from which the cohesion can be calculated by extrapolation. The cohesion of various food powders measured by this method is given in Table 2. Though the instrument is simple to operate and has other practical advantages it has some special aspects that need attention for the meaningful interpretation of the results. The ideal shear force-displacement curve is shown in Fig. 4A. Such surves are obtained for many dry food powders (e.g:, sucrose, onion) and identifying the yield force is simple and straight-forward. In special cases a more complicated curve shape may appear (Fig. 4B). In such a case the

Table 2. Cohesion of some food powders[(a)]

Powder	Moisture Content (%)	Cohesion[(b)] (g/cm^2)
Corn starch	<11	4–6
Corn starch	18.5	13
Gelatin	~10	1
Grapefruit juice	1.8	8
Grapefruit juice	2.6	10–11
Milk	1.0	7
Milk	4.4	10
Onion	< 3	< 7
Onion	3–6	8–15
Onion	> 6	Not measurable
Soy flour	~ 8	1

(a) Data from Peleg *et al.* (1973)

(b) Determined by Jenike Flow Factor Tester at consolidation load of 6.5 kg

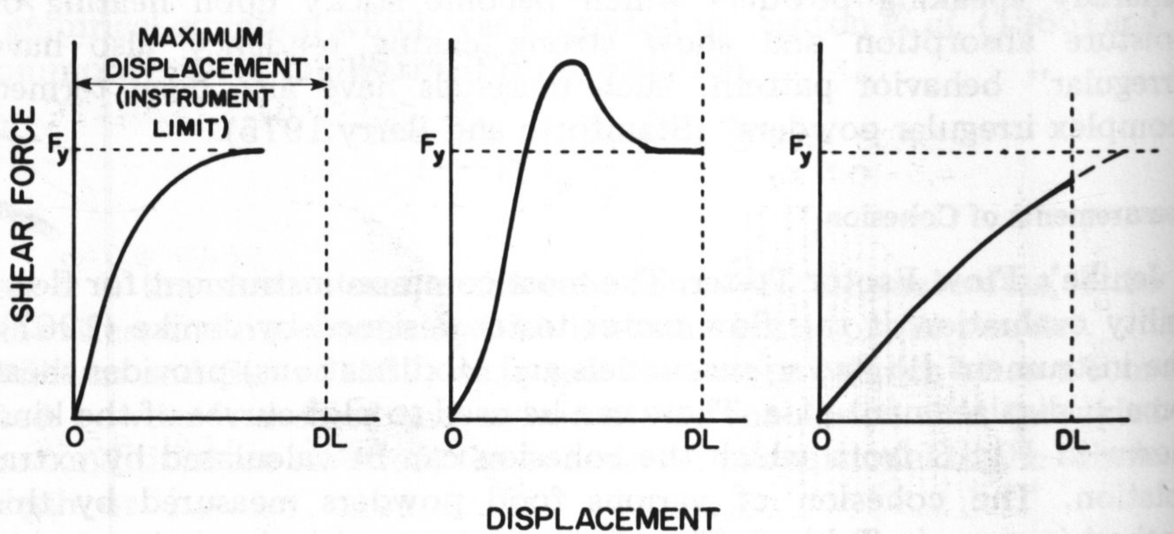

FIG. 4. TYPES OF SHEAR FORCE-DISPLACEMENT CURVES OBTAINED IN A LINEAR SHELL CELL

F_y — is the yield force. Type A curves are the basis for straightforward calculation of the flow function by Jenike's method. Types B and C require procedural or instrumental modifications — explanation in text.

experimental procedure ought to be modified. Such situations as well as other possibilities have been discussed by Williams and Birks (1965). A third shape Fig. 4C) is likely to appear in cohesive food powders (e.g., onion with more than 6% moisture, soup mix, citric acid). This kind of curve indicates that shear failure did not occur within the range of the instrument. Because the flow factor tester is based on linear motion, it has a physical limit to how much displacement is allowed.

If such a situation develops (i.e., the powder is extremely plastic and cohesive) and modification of the procedure is unlikely to improve the situation, yield data cannot be obtained. Under such circumstances, it should be mentioned, the meaning of the terms powder and flowability themselves may become questionable.

Another phenomenon that can be encountered in food powder testing is the "slip-stick effect." The latter is expressed by oscillations in the force-displacement curves (Fig. 5). The slip-stick effect is characteristic to pure starch and wheat flours. It has been suggested by Jenike (1970) that in such cases the pertinent force-displacement curve should be the one connecting the oscillation peaks as shown by the dashed curve in Fig. 5A. If such curves are the source of data to be used in design, addition of safety factors may be advisable. It is interesting to note that the admixture of calcium-stearate (a flow conditioner) introduces the slip-stick effect even if the host powder shows quite a normal shear behavior (e.g., sugars, Peleg 1971).

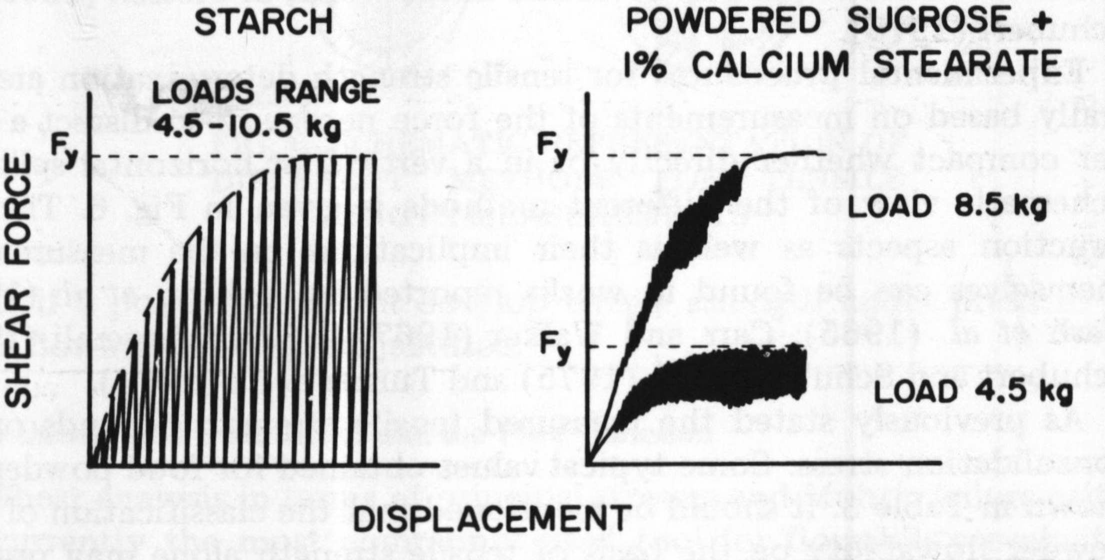

FIG. 5. SLIP-STICK EFFECT AS OBSERVED IN SOME FOOD POWDERS

Annular Cells

As mentioned the linear motion of the Jenike Flow Factor Tester or other instruments operated on same principles limits their applicability to relatively small displacements. In some cases (Fig. 4C is one example) this limitation has significant practical and theoretical implications. The latter is mainly due to the definition of the sheared area. These aspects have led to the development of annular cells in which the motion is angular. Calculation of the stresses under such conditions are less straightforward but the instruments provide at least some remedy to the deficiencies of linear instruments. Descriptions and discussions of such cells can be found in works by Carr and Walker (1967, 1968), Scarlett and Todd (1968), Kocova and Pilpel (1971) and Bagster *et al.* (1974).

Other Instruments

Though in principle similar various instrumental modification of linear and annular cell have been reported in the literature. Modifications on principle basis have also been suggested and an example is the simple shear apparatus discussed by Schwedes (1975).

Tensile Strength

The tensile strength of a powder provides a direct indication of the interparticle forces present and their magnitude. Theoretical relationships between the tensile strength and the various kinds of bonding mechanisms have been developed by Rumpf (1961). More recent information in this area can be found in the works of Pietsch (1969) and Schubert (1975).

Experimental procedures for tensile strength determination are generally based on measurements of the force necessary to dissect a powder compact whether directly or in a vertical or horizontal split cell. Schematic view of the different methods is given in Fig. 6. The construction aspects as well as their implications on the measurements themselves can be found in works reported by Ashton *et al.* (1964); Nash *et al.* (1965); Carr and Walker (1967, 1968); Schraemli (1967); Schubert and Schubert *et al.* (1975) and Turner *et al.* (1976).

As previously stated the measured tensile strength depends on the consolidation stress. Some typical values obtained for food powders are shown in Table 3. It should be mentioned that the classification of food powder flowability on the basis of tensile strength alone may result in erronous conclusion.

Examples are the microcellulose powder and the soup mix. Both are free flowing as long as they are not subjected to pressure and can be handled with relative ease in processing operation. (Precaution obviously ought to be taken to avoid pressure). The reversed conclusion, i.e.,

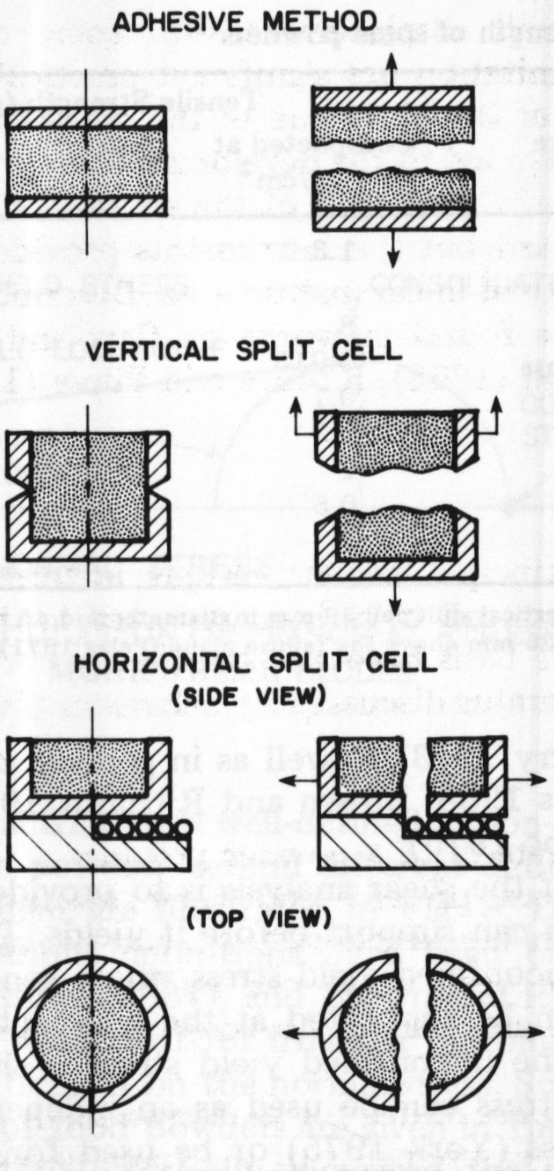

FIG. 6. SCHEMATIC REPRESENTATION OF DIFFERENT METHODS FOR TENSILE STRENGTH MEASUREMENTS

that if a powder does not develop tensile strength under pressure it is free flowing, is of course justified.

The Unconfined Yield Locus and the Flow Function

Shear analysis in terms of principal stresses and Mohr's failure criteria is currently the most commonly used tool for flowability evaluation. Practical theories and methods (like the prominent method of Jenike 1967) have been replacing the more empirical methods which are based on less fundamental characteristics of a powder system. The theoretical and practical aspects of the shear analysis have received very extensive attention in recent powder literature (Schwedes 1975; Molerus 1975;

Table 3. Tensile strength of some powders[(a)]

Powder	Moisture (%)	Tensile Strength (g/cm^2) Compacted at $0.1\ kg/cm^2$	Compacted at $0.4\ kg/cm^2$
Microcrystalline cellulose	—	1.3	4
Citric acid	—	8	11
Gelatin	~9	0.015	0.04
Onion	1.0	0.1	0.13
Onion	4.5	0.3	1.5
Soup mix	—	1	8
Sucrose	dry	0.5	1
Sucrose	0.2	3	4

(a) Data determined in a vertical split cell 39 mm in diameter and 45 mm in length. The consolidation pressure was applied 25 mm above the failure plane (Peleg 1971).

Stainforth and Berry 1973) as well as in general and food engineering textbooks (Williams 1968; Brown and Richards 1970; Mohsenin 1970; Leniger and Beverloo 1975).

The basic goal of the shear analysis is to provide information about the stress a powder can support before it yields. The most convenient parameter is the unconfined yield stress which generally represents the stress level that can be supported at the compact surface. Schematic representation of the unconfined yield stress is shown in Fig. 7. The unconfined yield stress can be used as an independent measure of a powder cohesiveness (York 1975) or be used for the construction of Jenik's flow function (1967). The latter is the relationship between the unconfined yield stress (or force) and the major consolidation stress (or force) as shown in Fig. 7, and it can provide data for quantitative flowability classification as well as for construction design of silos.

Analytical methods for the calculation of flow parameters based on shear analysis have been suggested by Stainforth *et al.* (1970, 1971), Stainforth and Berry (1975), Eelkman-Rooda (1975), and Eelkman-Rooda and Haaker (1977).

Such methods enable direct calculation of the parameters with the aid of computers rather than by the old (and cumbersome) graphical methods.

Because the yield loci curves of many food materials can well be approximated by a straight line (Sone 1972; Peleg and Mannheim 1973), the flow functions could be calculated by a simple and straightforward computer program (Peleg 1971).

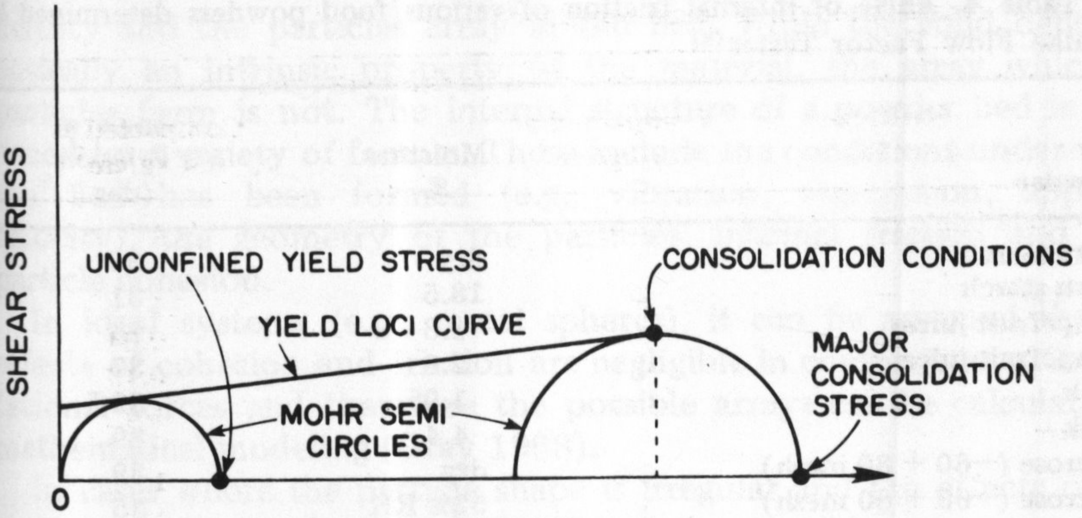

FIG. 7. CALCULATION OF PRINCIPAL STRESSES BY MOHR'S SEMICIRCLES

Angle of Internal Friction

The angle of internal friction is well-defined in non-cohesive powders (Fig. 1). For cohesive powders several different definitions have been suggested. Some of them are illustrated in Fig. 8. Discussions of the significance of the various definitions have been brought by Jenike (1967), Williams and Birks (1967), and Brown and Richards (1970). It should be mentioned again that for irregular or complex powders the angle of friction may depend on the normal stress. Some typical values of angles of frictions of food powders are given in Table 4. These show that moisture absorption drastically increased the cohesion and the tensile strength resulted in a significantly smaller angle of friction. This phenomenon can be explained by two mechanisms (Peleg 1971; Peleg and Mannheim 1973).

(a) The liquid layer that is formed on the particles surface acts as a lubricant.

(b) Solubility of parts of the particles surface smooth their shape thus eliminating rough points that promote friction.

It should also be mentioned that in cohesive food powders friction plays only a minor role in the obstruction to flow if compared to interparticle forces (Peleg *et al.* 1973).

Concentrated data on angles of frictions of food powders have been reported by Sone (1972) and Mohsenin (1970).

Bulk Density

The bulk density of a powder is primarily determined by the solid

Table 4. Angle of internal friction of various food powders determined by a Jenike Flow Factor Tester[(a)]

Powder	Moisture %	Angle of Friction (deg.)
Corn starch	dry	33
Corn starch	18.5	31
Grapefruit juice	1.8	38
Grapefruit juice	2.6	37
Milk	1.05	39.5
Milk	4.4	39
Sucrose (−60 + 80 mesh)	dry	39
Sucrose (−60 + 80 mesh)	52% RH	35
Analytical sand (−60 + 80 mesh)[(b)]	dry	40
Analytical sand (−60 + 80 mesh)[(b)]	1.1	36

[(a)] Determined at consolidation load of 6.5 kg (Peleg 1971)
[(b)] Part of data to support the suggestion of lubrication by liquid film. In the case of sand the water can only be present at the surface

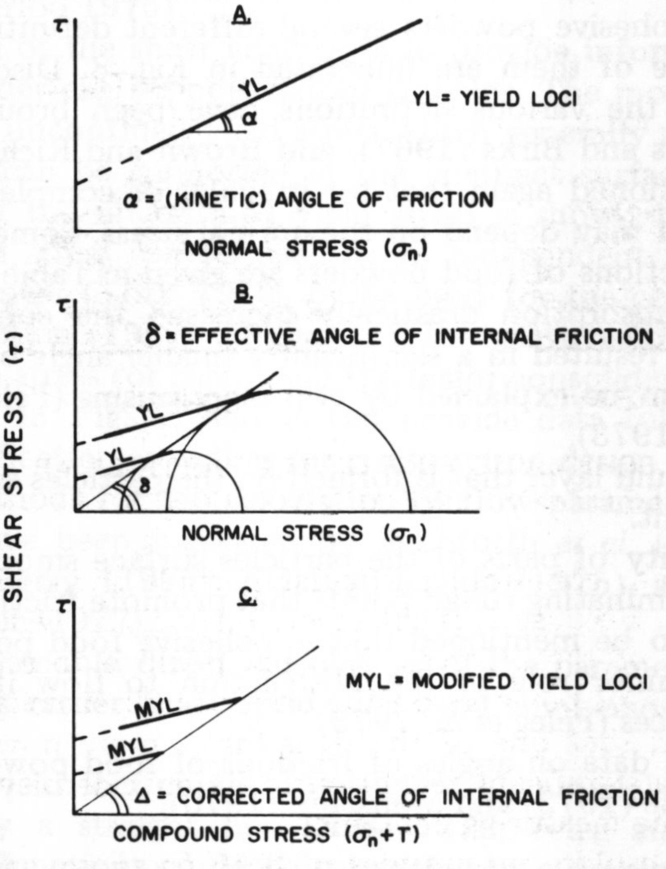

FIG. 8. VARIOUS WAYS OF REPRESENTING INTERNAL FRICTION IN POWDERS

(References and data: A. Sone 1973; B. Jenike 1967; Peleg *et al.* 1973; C. Williams and Birks 1967; Kocova and Pilpel 1973b).

density and the particles array in the bed. While the solid density is basically an intrinsic property of the material, the array which the particles form is not. The internal structure of a powder bed is influenced by a variety of factors. These include the conditions under which the bed has been formed (e.g., vibration, segregation, approach velocity), the geometry of the particles, internal friction and interparticle cohesion.

In ideal systems (e.g., metal spheres), it can be assumed that the effects of cohesion and friction are negligible in comparison with gravitational forces and therefore the possible arrays can be calculated by mathematical modeling (Gray 1968).

In cases where the particle shape is irregular and the effects of friction and cohesive forces are significant the possible arrays cannot be predicted from simplified models. Some trends, however, do exist and these have been used to evaluate or estimate the role of the internal forces. Generally speaking, a powder bed can have an open array of particles (loose packing) or a dense array (close packing). The existence or stability of the open arrays depend on the availability of mechanical forces that can support the open structure (Fig. 9). These forces may be due to friction, cohesion, particular particle shapes and any of their combinations. Because it is extremely difficult to evaluate the different contributions of these forces, it is not possible to estimate or predict the flowability of powders on the basis of bulk density alone. It can be said, however, that one of the signs that a given powder develops cohesiveness is a significant reduction in its bulk density, i.e. when freely poured into the measuring container.

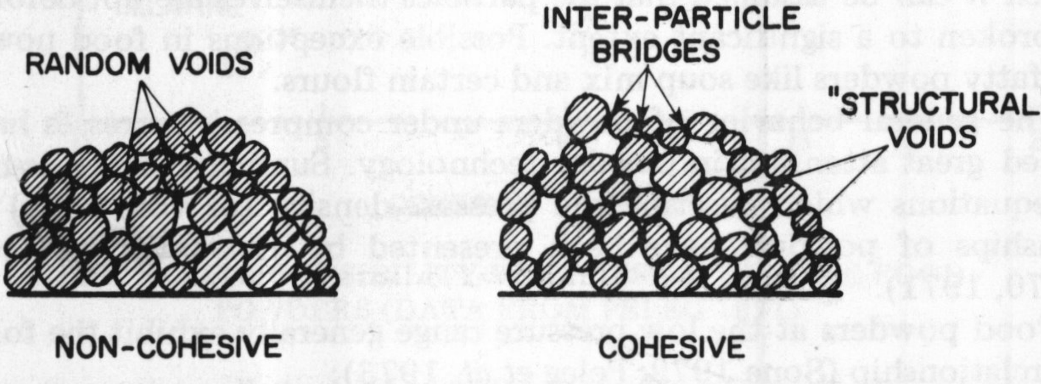

FIG. 9. SCHEMATIC VIEW OF THE PARTICLE ARRAY IN THE BEDS OF COHESIVE AND NON-COHESIVE POWDERS

Since the absolute magnitudes of both frictional and cohesive forces in the loose powder are relatively small, they can be overcome by relatively gentle means. These include vibrations or tapping and compression by application of low stresses.

Tapping

The amount of bulk density change due to tapping may be an index to the presence of attractive forces and friction. A considerable increase in bulk density due to tapping is usually interpreted as the existence of significant interparticle forces, mainly friction (Hausner 1967). The great advantage of such methods is the simplicity of the instrumentation (Sone 1972) and the test performance. It should be mentioned though that the experimental results may depend to a great extent on the test procedure (e.g. the number of taps) and such factors as particle size. Despite this limitation, however, the "Hausner Ratio," i.e. the ratio between tap and apparent bulk densities, has been found a useful criterion which well correlated with actual flowability and other physical characteristics of some powders (Grey and Bedow 1968, 1969).

Compressibility

As mentioned, the interparticle forces that enable open structure in the powder bed succumb under relatively low pressure. The term low pressure in this context refers to the range of up to about 1 kg/cm^2 in which it can be assumed that the particles themselves are not deformed or broken to a significant extent. Possible exceptions in food powders are fatty powders like soup mix and certain flours.

The general behavior of powders under compressive stresses has received great attention in powder technology. Summary and discussion of equations which describe the pressure-density (or void ratio) relationships of powders have been presented by Kawakita and Ludde (1970, 1971).

Food powders at the low pressure range generally exhibit the following relationship (Sone 1972; Peleg *et al.* 1973):

$$\mathrm{BD} = \mathrm{a} + \mathrm{b} \log \mathrm{P}$$

where BD is the bulk density, P the applied pressure, a and b constants. The constant b which in fact represents the compressibility of the powder has been found to correlate with the cohesion of a variety of food powders (Fig. 10) and therefore could be a simple parameter to indicate changes in flowability. (This was partially possible because the solid density of most food materials is around 1.6 g/cm^3).

Obviously, and as in the case of tapping, the experimental procedure is simple and does not require sophisticated or expensive instrumentation. There are, however, experimental factors that may effect the

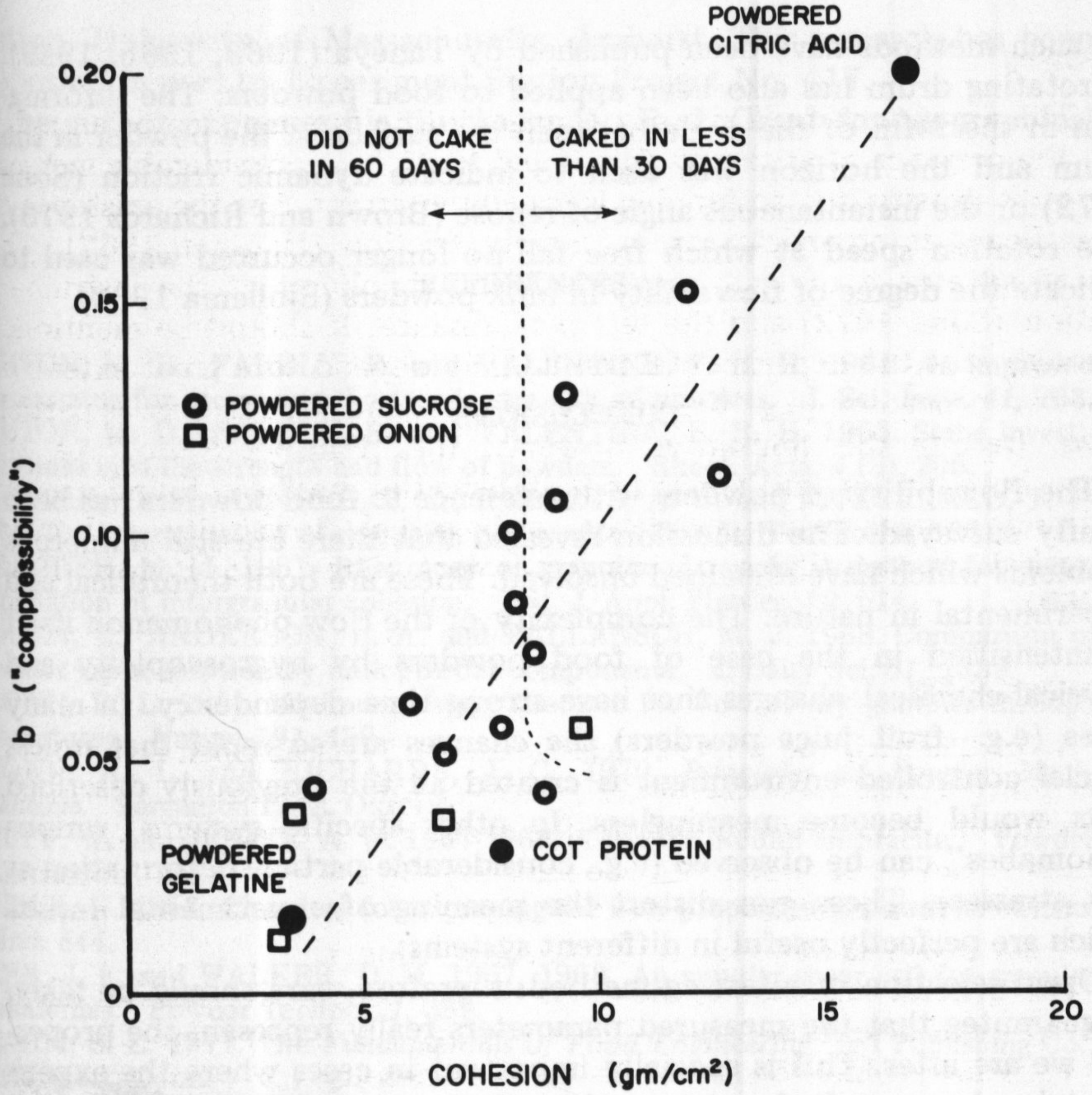

FIG. 10. COMPRESSIBILITY VS COHESION OF SOME FOOD POWDERS (DATA FROM PELEG 1971)

results (e.g., the cell dimensions, the compression time, the number of twists) and therefore the method can only provide a rough indication of flowability changes in powders.

Miscellaneous Methods

The methods that have been described are by no means the only methods to evaluate flowability. Among other techniques that have been applied to food powders is the "Rotational Viscometer". The instrument is similar in construction to viscometers used for liquids (Harwood and Pilpel 1968). The calculation of cohesion and friction, however, are done in a different way and from different testing procedures (Benarie 1961; Senna 1967). Data for food powders obtained by such methods have been published by Taneya (1963, 1965, 1969). A rotating drum has also been applied to food powders. The information in the form of the angle between the surface of the powder in the drum and the horizon was used to indicate dynamic friction (Sone 1972) or the instantaneous angle of repose (Brown and Richards 1970). The rotation speed at which free fall no longer occurred was used to indicate the degree of flowability in milk powders (Sjollema 1963).

CONCLUSIONS

The flowability of powders with reference to food powders has been briefly surveyed. The discussion revealed that there are still numerous problems which have remained unsolved. These are both theoretical and experimental in nature. The complexity of the flow phenomenon itself is intensified in the case of food powders by hygroscopicity and physical-chemical changes that have strong time dependency. In many cases (e.g. fruit juice powders) the changes are so rapid that unless special controlled environment is created all the previously described tests would become meaningless. In other specific systems, various "anomalies" can be observed (e.g., considerable particle deformation at low stresses). These can distort the meaning of experimental results which are perfectly useful in different systems.

Upon selection of a testing method, therefore, care should be taken to guarantee that the measured parameters really represent the properties we are after. This is specially important in cases where the experimental values result from a combined effect of unrelated properties (e.g., cohesion and internal friction). We should also bear in mind that actual flow depends on both the powder properties and the geometry and other physical characteristics of the system. Therefore, the term "flowability" itself has a relative meaning. In comparison to most other physical properties of foods, powder characteristics received only modest attention in the food literature. The increasing role of food powders in the food supply, both as an industrial raw material and as convenience or special finished food items would certainly change this situation. It is the belief of the author that food powder technology as active field of research would have to be developed to complement and elaborate our knowledge in this area of food engineering.

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