PHYSICAL PROPERTIES OF FOOD POWDERS

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Summary

Food powders are a diverse group of particulates. They vary considerably with respect to composition, microstructure, particle size and the physical properties that stem from them. Among these are cohesion, flowability, density, compressibility, mechanical strength, and segregation tendency. There are simple mechanical methods to determine such properties. However, most of these are 'response properties', that is, the outcome of their determination may strongly depend on the test conditions. Consequently, the relationship between the measured parameters and the test's mechanical history is of paramount importance. The same applies to interpreting the mechanical behavior of a powder's bulk in terms of events or properties at the particles level. Various methods to assess the bulk properties of food powders are surveyed in this entry. Most can be performed with inexpensive custom-made sensors, mounted on a Universal Testing Machine, sieve shaker or other standard laboratory equipment. The mathematical models used to describe their results, although simple, can still capture the powder's characteristics, and be used for their expression in quantitative terms.

1. Introduction

Food powders, as the name implies, are powders used as, or within, food products . Their chemical compositions vary considerably, as does their particle size, shape, color, hygroscopicity, mechanical strength, etc. The physical properties of powders, including those of food powders, are not independent. Thus, a modification of particle size distribution, for example, can result in simultaneous change in bulk density, flowability, and appearance. Moreover, the particle preparation method can have a profound effect on the powder’s physical properties, and the same applies to handling and storage conditions. The effect can be very dramatic, as in the case of caking, or subtler, as in mild segregation (see *Food Powder Processing*).

Powders belong to a continuous domain known as particulatedsolids, covering a size range from fine dust to rock assemblies. Thus, the distinction between fine powders, powders, and granular materials is to some extent based on arbitrary criteria, and a certain degree of overlap is unavoidable. In this paper, the term “powders”’ will refer to food particulates in the size range of roughly 50 to 1000 μm (e.g., flour, spices, sugar, soup mixes, and instant beverages). Some of the principles discussed may apply to granular foods, for example, grains and legumes, and in limited cases to larger particles, such as breakfast cereals or raisins and even dehydrated fruit.

One of the main manifestations of an object’s size is the ratio between the gravitational and surface forces acting on it. The smaller the particle, the more noticeable the latter becomes. The motion of most familiar objects (size ranges from centimeters to a few meters) is dominated by gravitation, and superficial forces are negligible. In the powder realm, interactions caused by surface forces cannot only be significant, but also dominant. A distinction should be made between cohesive and non-cohesive powders. The former is a powder in which interparticle attractive forces are clearly larger than the particle weight. In contrast, particle weight has a dominant effect on the bulk properties and flowability of non-cohesive powders, or granular materials. In most food powders, as will be shown, the relative dominance of these forces can shift, primarily, as a result of moisture sorption, loss or redistribution, and/or heating or cooling. The same is true for hydrostatic pressure, which may be produced in storage. By bringing the particles together and increasing the contact area between them, the effects of extant weak forces can be intensified considerably. Therefore, food powders should be considered as dynamic systems where the properties change significantly with time, especially when moisture exchange and temperature are uncontrolled.

2. Bulk Density and Compressibility

The bulk density of powders is determined by particle density, which in turn is determined by solid density and particle internal porosity, and also by spatial arrangement of the particles in the container. Powders have “loose bulk density”, that is, a measured density after a powder is freely poured into a container, and “compact density”, after it is allowed to compress by mechanical pressure, vibration, and/or impact(s) (see Figure 1).

A powder’s loose bulk density is one of its most important characteristics. It determines the choice of the container size and strength of the reconstituted food, if prepared from a given volume (e.g., tablespoon, cup, etc.). The compressibility of the powder determines the appearance of a container’s contents upon reaching the consumer, and may serve as an index of cohesion (see below). Bulk density control, therefore, is a prime objective of many food processes, especially spray drying and grinding.

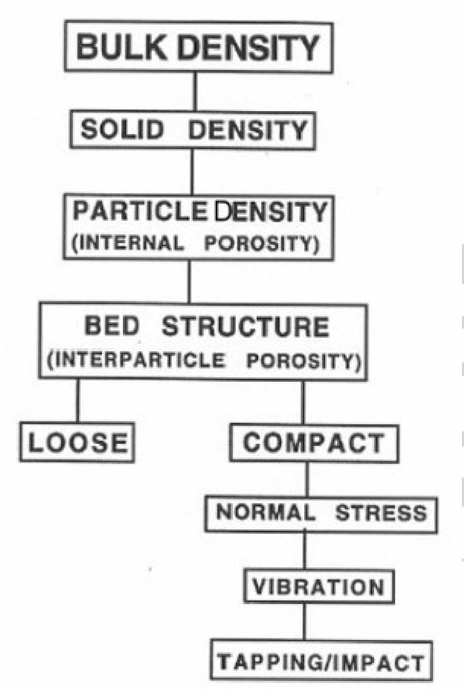

Figure 1. Types of bulk density associated with powders and what affects them.

2.1. Bulk Density Determination

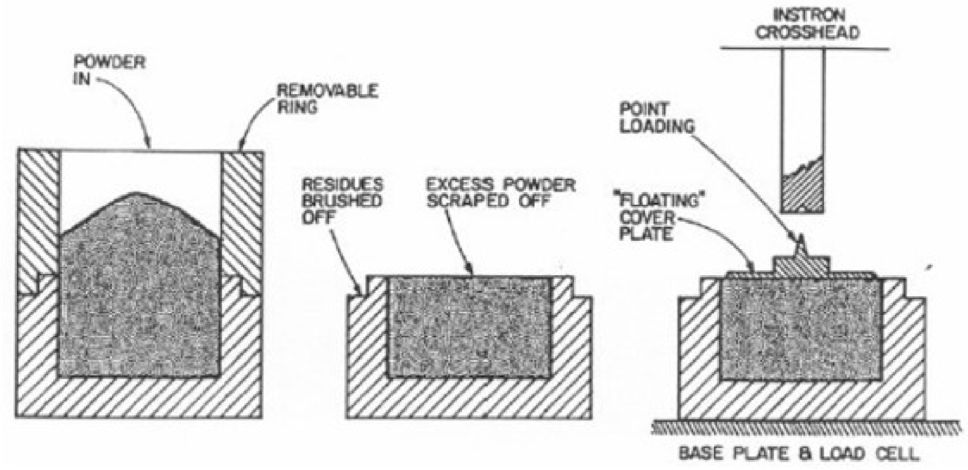

Figure 2. A cell for determining the bulk density and compressibility of food powders.

Loose bulk density can be determined by filling a graduated transparent container to a chosen volume, and determining the net weight of the powder. The difficulty with this method is that the powder height is not always easy to control. A more precise method is to use a split cell (Figure 2).

With this device, the excess powder is scraped off in order to obtain a standard volume. The method is of course only applicable to powders in which particle size is very small relative to the cell diameter. Both methods can be used to determine the compact density after vibration or impact(s). In the first case, the volume reduction is observed directly, while in the second, the density is measured after removing the upper ring.

2.2. Bulk Density and Cohesion

When poured into a container, the particles of a non-cohesive powder (i.e., a powder in which particle weight is more than the attractive interparticle forces) tend to occupy most of the available volume (Figure 3).

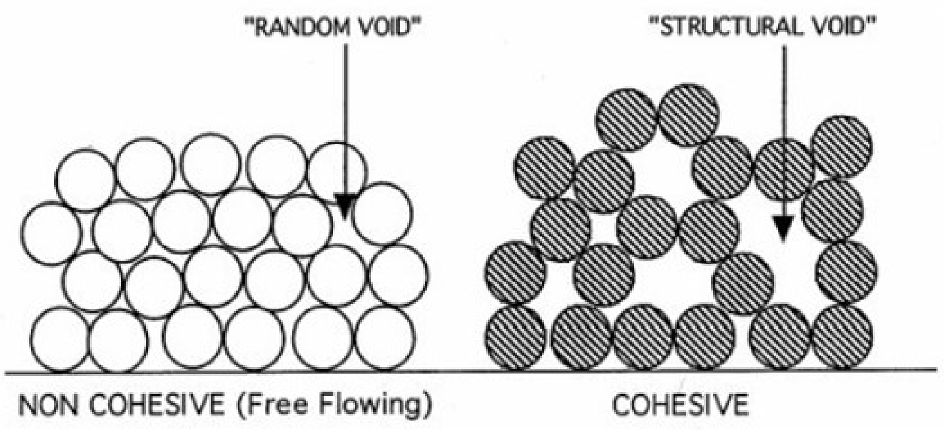

Figure 3. Schematic view of bed structure of non-cohesive and cohesive powders.

A few unoccupied spaces may remain because of the more or less random arrival pattern of the particles, but their total volume is usually small. Thus, in relative terms, the density of a non-cohesive powder is high, and can hardly be increased by compression.

In contrast, a cohesive powder, (i.e., a powder in which attractive interparticle forces outweigh its particle weight) tends to produce an open structure supported by the interparticle forces (Figure 3).

The result is therefore a relatively low bulk density. However, since the structures produced are not strong, they will readily collapse when subjected to low pressure. The bed of a cohesive powder therefore has relatively high compressibility, even if the particles themselves remain largely underformed by the applied pressure (see below).

2.3. Mechanical Compressibility

Under low compressive loads, which may exist during powder storage on the order of up to about 1 kgf.cm^{-2}, the relationship between bulk density and stress usually obeys the empirical logarithmic or semi-logarithmic relationship, for example,

$$\log\left[\rho(\sigma)/\rho_0\right] = b\log\left(\sigma/\sigma_0\right) \qquad (1)$$

where $\rho(\sigma)$ and ρ_0 are the compact and loose density, and σ and σ_0 the normal stress and atmosphere pressure, respectively. The constant, b, can be used as a measure of the powder's mechanical compressibility. Simultaneous decrease in a powder's loose bulk density and increase in compressibility can indicate it has become more cohesive (Figure 4) This index, however, becomes insensitive if the powder in its native state is cohesive enough to produce a structure that has the maximum openness possible.

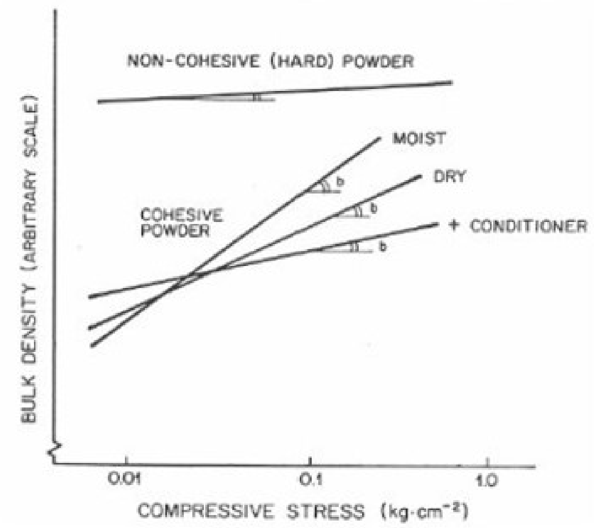

Figure 4. Schematic view of the bulk density vs. compressive normal stress relationships of non-cohesive and cohesive food powders.

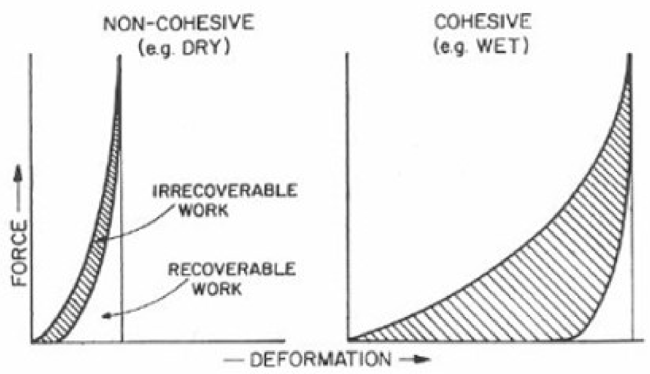

Figure 5. Schematic view of apparent stress-stress relationships of cohesive and non-cohesive powders.

Mechanical compressibility can be determined by compressing a specimen with a Universal Testing Machine and recording its apparent stress-strain relationship (from which log ρ *vs*. log σ can be calculated, if the initial powder mass and cell dimensions are known). A schematic view of the stress-strain relationship of a powder subjected to a compression-decompression cycle is shown in Figure 5.

The figure shows that the irrecoverable work invested in the compression of a cohesive powder is much larger than in non-cohesive powders. In fact, while the compact produced by compression of a cohesive powder is mechanically stable, the one produced from a non-cohesive powder readily disintegrates. Examination of the compact stability therefore provides a simple measure of powder cohesion, albeit imprecise and subjective. The relaxation curve of a cohesive powder's compact is usually steeper than that of a non-cohesive powder. Nevertheless, due to the noticeable differences in their compressibility interpretation of relaxation data, in terms of relative cohesiveness, it is not as straightforward as one would intuitively expect. All the above statements are only relevant to relatively shallow powder beds. Since powders can transmit stress to the walls, stress distribution within a compressed powder bed is far from uniform, which may result in uneven compaction.

Under high compressive stress on the order of tons per cm^2, deformability of the particle alone becomes a dominant factor. Such pressures are reached in processes aimed at producing tablets, and are beyond the scope of this entry. Suffice it to say, under extremely high pressure, the compact density begins to approach solid density. Under such conditions, Equation 1 (or similar expressions) is clearly inadequate, and models especially developed for the various deformation mechanisms should be used to describe the density-pressure relationship.

2.4. Compressibility under Vibration, Tapping, and Drop

Subjecting a powder to vibration tapping or impact usually results in its compaction (Figure 6); repeated impacts can also undo the compaction, at least temporarily.

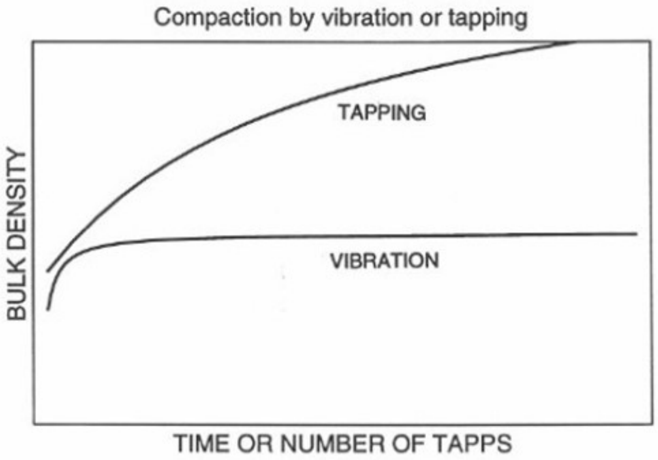

Figure 6. Compression of powders by vibration or tapping.

However, the compact density cannot increase indefinitely. It usually approaches an asymptotic value determined by the nature of the motion, i.e., the vibration's amplitude and frequency, impact intensity or drop height, etc. Generally, the compaction of a powder under vibration or set of impacts can be described by empirical relationships of the kind:

$$\rho(n) = \rho_0\left[1 + n/(k_1 + k_2 n)\right] \tag{2}$$

or

$$\rho(n) = \rho_0 + \left(\rho_{asymp} - \rho_0\right)\left[1 - \exp(-kn)\right] \tag{3}$$

where $\rho(n)$ is the compact density after n vibrations or impacts, ρ_0 the loose bulk density, ρ_{asymp} the asymptotic density, (i.e., when $n\to\infty$), and k's the constants. The reader will notice that for vibrations, time t can replace n as an independent variable in the above equations. Also, asymptotic density ρ_{asymp} can be calculated from Equation 2, (i.e., $\rho_{asymp} = \rho_0 + 1/k_2$). The ratio, ρ_{asymp}/ρ_0, is known as the Hausner ratio. It was originally used by Hausner to assess the internal friction and flowability of mineral powders. Many food powders are cohesive, and hence the internal friction plays only a minor role in their flowability, relative to that of cohesion (see below). Consequently, the Hausner ratio may not be a reliable flowability index for most food powders. Moreover, there is evidence that the compaction pattern of food powders, including the asymptotic density, can strongly depend on the vibrations/impacts regime. The Hausner ratio can therefore vary dramatically and the value should not be considered typical, let alone unique. The purpose of food powder compaction tests, therefore, is primarily to simulate density changes during handling and transportation, rather than to assess their flowability. There is also evidence that impact can cause breakage of brittle particles, as in instant coffee or milk agglomerates. In such cases, density changes can be attributed, at least partly, to progressive changes in particle size distribution and not only to their spatial rearrangement.

3. Angle of Repose

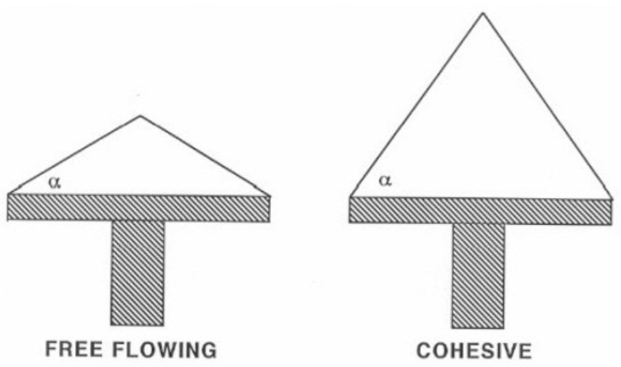

Figure 7. Schematic view of the angle of repose for non-cohesive and cohesive powders.

Free flowing and granular materials when poured through a funnel on a flat surface, produce a cone with a small angle on the order of 35° or less (Figure 7), known as the angle of repose.

Cohesive powders, in contrast, have a higher angle of repose (i.e., on the order of 55° or higher) in which case the powder cone can also have an irregular and distorted shape. The angle of repose should not be confused with the angle of internal friction (see below). In cohesive powders, the ability of the powder to maintain a steep, conical shape is primarily due to interparticle forces, and to a much lesser extent, friction. The angle of repose can be used as a crude measure of flowability. However, since the actual shape of the cone depends on the way in which it was formed, (e.g., fall height), it is not a consistent index. If determined under pertinent conditions, its magnitude can provide useful information in the design of conveyers used to remove bin discharge, and of other powder unloading devices. In instant dry beverages or soups, knowledge of the angle of repose, and of the powder's bulk density, are also needed to calculate the volume and weight of a powder heap when scooped with a spoon.

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Bibliography

Barbosa-Cánovas G. V., Malave J. and Peleg M. (l985). Segregation in food powders. *Biotechnol. Progress* **l**, l40-l46. [A source of references on mixing and segregation indices].

Barbosa-Cánovas G.V., Rufner R. and Peleg M. (1985). Microstructure of selected binary food powder mixtures. *J. Food. Sci*. **50**, 473-477 & 48. [Shows pictures of the different types of mixtures and provides a list of references on mixture classification].

Jenike A.W. (1964). Storage and flow of solids. Bull. No 123 of the Utah Engineering Experiment Station, University of Utah, Salt Lake City. [The basic theory of particulates flow from bins].

Moreyra R. and Peleg M. (1980). Compressive deformation patterns of selected food powders. *J. Food Sci*. **45**, 864-868. [Description of the application of a Universal Testing Machine to determination of the properties of powders].

Moreyra R. and Peleg M. (1981). Effect of equilibrium relative humidity on the bulk properties of selected food powders. *J. Food Sci*. **46**, 1918-1922. [Comparison of the density and compressibility of different types of food powders and how moisture affects them].

Peleg M. (l978). Flowability of food powders and methods for its evaluation. (A Review). *J. Food Proc. Eng*. **1**, 303-328. [A concise survey of the principles behind powders flowability evaluation].

Peleg M. (1983). Physical characteristics of food powders. In *Physical Properties of Foods* (eds. M. Peleg and E. B. Bagley), 293-324. Westport, CT: AVI Publishing Co. [A very brief review of what affects the properties of food powders].

Popplewell L. M. and Peleg M. (l989). An "Erosion Index" to characterize fines production in size reduction processes. *Powder Technol*. **58**, l45-l48. [A proposed index to quantify the relative contributions of shattering and erosion in the disintegration of particulates].

Popplewell L. M., Campanella O. H. and Peleg M. (l989). Simulation of bimodal size distributions in aggregation and disintegration processes. *Chemical Engineering Progress* **85**, 56-62. [One of the few publications in which the biomodal nature of the particle size distributions of particulates undergoing size enlargement or reduction is stressed].

Schubert H. (1987). Food particle technology, Part I: Properties of particles and particulated food systems. *J. Food Eng*. **6**, 1-32. [A most comprehensive and in depth review of the forces and other factors affecting the properties of foods and other particulates].

Biographical Sketch

Micha Peleg is Professor of Food Engineering at the University of Massachusetts, Amherst, MA, in the Department of Food Science (since 1990). He first obtained his B.Sc. (Chemical Engineering) at Technion, Israel Institute of Technology in 1963, his M.Sc. (Food Engineering and Biotechnology) at Technion, Israel Institute of Technology in 1967, and his D.Sc. (Food Engineering and Biotechnology) at Technion, Israel Institute of Technology in 1971. Dr. Peleg’s current research areas are mathematical and computer aided modeling and analysis of rheological behavior of solid foods, mechanical testing of food materials, viscosimetry, powders, particle size distributions, and microbial populations dynamics. He has editorial board membership at the following journals: Journal of Texture Studies (since 1982), Journal of Food Science (l985-l988, since 1999), Journal of Food Process Engineering (l987-l990), Food Science and Technology International (since 1996), Journal of Food Properties (since 1997), Food Engineering Series - Aspen Publishing (since 1998), and Journal of Food Protection (2001-2006). Publication Referee (partial list): Transactions of the American Society of Agricultural Engineers, Journal of Texture Studies, Journal of Food Science, Powder Technology, Journal of Food Process Engineering, Food Technology, Journal of Food Processing and Preservation, Biotechnology Progress, Journal of Rheology, Rheologica Acta, American Institute of Chemical Engineers Journal, Food Science and Technology (lwt), Journal of Food Engineering, Food Hydrocolloids, Critical Reviews Food Science & Nutrition, Food Microbiology, Food Research International, Food Science and Technology International, and Journal of Material Science. He has been a Research Proposals Referee (partial list) for National Science Foundation, Sea Grant, United States Department of Agriculture, Research Canada, International Science Foundation, and the national research councils of Argentina, Chile and Israel. He has published over 300 technical publications.