Factors Affecting the Bostwick Fluidity of Corn Flour/Water Systems[1]

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Cereal Chem. 65(6):497–500

ABSTRACT

Factors that affect the fluidity of corn flour/water dispersions were studied using volume fraction versus fluidity curves and packing fractions. Different corn flours had different volume fraction versus Bostwick fluidity curves and different packing fractions. The position of those curves and packing fractions along the volume fraction axis reflected the fluidity of the various corn flour/water dispersions. The major factors affecting that position were particle size, particle size distribution, and the amount of damaged starch in the flour.

The streams with the finest granulation obtained from a corn dry mill are termed corn flour (Brockington 1970, Wells 1979). For many years, corn flour was regarded as an unavoidable by-product of dry corn milling; recently, however, it has become a primary commodity. One reason for the increased use of corn flour in the food industry is its versatility. In addition to having an acceptable flavor, corn flour is economical and possesses a pleasing color. Corn flour is a standard ingredient in doughnuts, coatings, breadings, and batters. The presence of corn flour in a batter is thought to improve adhesion to fish that is frozen before frying (Roberts 1967).

The consistency or fluidity of a batter is critical for batter pickup by a product. The Brookfield rotary viscometer and the Bostwick consistometer are examples of instruments used to measure the consistency of corn flour batters.

The Brookfield rotary viscometer measures apparent relative viscosity as a function of torque on a spindle, which rotates at various speeds in the batter being evaluated (Mitchell and Peart 1968, Bourne 1982). Batters with very low or very high viscosities cannot be measured with this viscometer because of its limited range. Particle settling is another concern when the Brookfield rotary viscometer is used. Particles that settle to the bottom of the container may offer more resistance to the rotating cylinder, thereby increasing the apparent viscosity. Alternatively, particles may settle below the rotating cylinder and cause the remaining suspension to be more dilute, thus decreasing apparent viscosity.

The Bostwick consistometer measures the consistency or fluidity of flowable foods. The sample is held by a metal plate in a reservoir at one end of a horizontal metal trough. The plate is rapidly released and the sample flows under the force of gravity into the trough. Consistency or fluidity is measured as the distance the sample front travels in a given time (Elder and Smith 1969, Bourne 1982). While any of the commercially available viscometers could have been used for the present study, the Bostwick consistometer was selected because the measurements were reproducible (SD $\pm$ 0.4) and the data could be easily understood by those in the industry who are concerned with such measurements. Further, the effects of settling were minimized because of the concentrated slurry and the short time required.

The approach used to study the fluidity of corn flour/water systems was based on Einstein's work on the packing of rigid spheres in a colloidal dispersion. The application of this work has been described by Krieger (1983). A corn flour/water system is a dispersion that contains rigid particles, but most are not spheres. In our system, starch granules absorb water and the amount absorbed depends upon the condition of the granules (damaged granules absorb much more water than do native granules). In addition, we are concerned with a concentrated dispersion of corn flour in water. Even with those deviations from ideal, we felt that the discussion of Krieger (1983) provided a good starting place to understand the fluidity of corn flour/water systems.

The terms volume fraction and packing fraction are frequently used in describing the fluidity of dispersions. Volume fraction is the ratio of the volume of solid phase (corn flour) to the volume of the solvent (water). The packing fraction represents the highest concentration at which flow can occur without deformation of the particles themselves (Krieger 1983).

The methods currently used to measure consistency or fluidity of batters are adequate for end-use quality control purposes, however, the results do not give any insight as to what factors in corn flour contribute to the fluidity of the system. An understanding of these factors is important because different corn flours produce slurries having different fluidities when mixed with water at the same solids concentration. The objective of this study was to understand what factors in corn flour affect the fluidity of corn flour/water systems.

MATERIALS AND METHODS

Corn meal and corn flour were obtained from a commercial dry corn miller. Corn flour was defatted by Soxhlet extraction using petroleum ether as the solvent. The defatted corn flour was air-dried until no solvent odor was evident. Corn starch was obtained from the Kansas State University food service center, Manhattan, KS. To obtain damaged corn starch, samples were mechanically damaged by processing for two or four days in a ball mill (Process Equipment Division, U.S. Stoneware, Akron, OH).

Moisture and starch damage were determined according to AACC (1983) procedures.

Measurement of Fluidity

A Bostwick consistometer (CSC Scientific, Inc.) was used to determine the fluidity of slurries of corn flour and water. The ratio of corn flour to water varied for different slurries, depending upon corn flour moisture and the desired solids concentration of each slurry. Approximately 60–70 g of corn flour and 70–280 g of distilled water were mixed for 1 min in a small bowl with a Sunbeam hand-held five-speed kitchen mixer at low speed. The slurry was allowed to rest for 1 min, and then was mixed for an additional 1 min and poured into the reservoir of the consistometer. After 15 sec, the metal plate holding the sample in the reservoir was released, allowing the slurry to flow under the force of gravity into the horizontal metal trough of the consistometer. The distance (in centimeters) that the sample front traveled in 15 sec was recorded as the consistency or fluidity of the slurry.

Volume Fraction Versus Fluidity Curves

Corn flour/water slurries were made at several volume fractions of dry material for a single corn flour, and the fluidity of each slurry was determined with the consistometer. The fluidity values were plotted as a function of the volume fraction of dry material. Volume fractions were determined by dividing the volume of dry corn flour (weight of dry corn flour divided by the absolute density of corn flour, 1.32 [Anonymous 1976]) by the total of the dry flour volume and the volume of water in the slurry.

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Packing Fraction

Corn flour (12 g, dry weight basis) was placed in a tared centrifuge tube, and an excess of distilled water was added (approximately 40 g). The tube was agitated to mix the flour and water and then placed in a centrifuge (model CU-5000, Damon/International Equipment Company) and centrifuged for 20 min at 1,000 × g. After centrifugation, the supernatant was discarded. The centrifuge tube was inverted at a 15° angle, allowed to drain for 5 min, and then weighed. The amount of water retained by the corn flour was calculated by subtracting both the tube weight and the dry corn flour weight from the total wet weight. For this study the packing fraction was calculated by dividing the dry flour volume by the total of the dry flour volume and the volume of water retained.

Particle Size Distributions

Particle size distributions of corn flours were determined using an Alpine sieve system. A 25-g corn flour sample was sieved using a no. 60 sieve (250-μm opening), a no. 100 sieve (150-μm opening), a no. 140 sieve (106-μm opening), a no. 200 sieve (75-μm opening), and a no. 400 sieve (38-μm opening). The percent of corn flour that passed through each sieve was then calculated.

Corn Meal Fractionation

Corn meal was separated into fractions of different particle sizes by sieving with the Alpine sieve system. The fractions were: 1) through a no. 400 sieve, 2) over a no. 400 sieve and through a no. 100 sieve, and 3) over a no. 100 sieve and through a no. 60 sieve.

RESULTS AND DISCUSSION

Volume Fraction Versus Apparent Fluidity Curves and Packing Fractions of Corn Flours

By preparing corn flour/water systems at several different volume fractions and then using the consistometer to measure fluidity of each system, we established a volume fraction versus fluidity curve for each corn flour (Fig. 1). We also determined the packing fraction for each corn flour.

The slopes of the volume fraction versus fluidity curves for the various corn flour/water slurries were similar; however, the curves occurred at different points along the volume fraction axis (Fig. 1). The packing fractions for the different corn flours also varied.

Volume Fraction Versus Fluidity Curves and Packing Fractions of Damaged and Undamaged Corn Starch

Corn starch samples with varied degrees of starch damage were prepared by ball milling the starch for zero, two, or four days. The samples were slurried, and volume fraction versus fluidity curves were generated (Fig. 2). These curves were also distributed along the volume fraction axis and had similar slopes. The degree of starch damage (presuming more ball milling resulted in more starch damage) appeared to determine the volume fraction that produced a given fluidity. The slurry produced from the starch that had been ball milled the longest had a volume fraction versus fluidity curve at a low volume fraction of dry material. The slurry from the undamaged starch had a volume fraction versus fluidity curve at a high volume fraction of dry material. Therefore, at equal solids concentrations, a slurry made with damaged starch was more viscous than a slurry made with undamaged starch.

The packing fraction from the starch that had been ball milled the longest was lower (i.e., contained more water and less solids) than those of the starches ball milled for shorter times (Fig. 2). This was attributed to the increased water uptake by the damaged starch.

Relationship Between Packing Fraction and Volume Fraction at Zero Fluidity

We noted that the position of the volume fraction versus fluidity curve and the position of the packing fraction for a corn flour appeared to be related. However, the data showed large differences between the packing fraction and the volume fraction at zero fluidity for the different flours (zero fluidity as measured on the consistometer is maximum resistance to flow). For flours with volume fraction versus fluidity curves and packing fractions at higher volume fractions of dry material, the difference was smaller than for flours with volume fraction versus apparent relative viscosity curves and packing fractions at lower volume fractions of dry material (Fig. 1).

As reported by Gillespie (1982), a similar trend was evident in a summary of the data of Lewis and Nielson, who measured the relative viscosity of suspensions of aggregates of large spherical particles. The difference between the volume fraction at maximum relative viscosity (minimum fluidity) and the packing fraction was smallest for the smaller particle aggregates; the difference between the volume fraction at maximum relative viscosity (minimum fluidity) and the packing fraction became larger and larger as the size of the particle aggregates increased. As the size of the particle aggregates increased, the volume fraction at maximum relative viscosity (minimum fluidity) and the packing fraction shifted to a lower volume fraction of the solid phase.

We speculated that the difference between the volume fraction at zero fluidity and the packing fraction for our corn flour/water systems was largely related to particle shape. With spherical particles, the packing fraction and the volume fraction at zero fluidity should be the same. However, flour particles are not perfect spheres. It should be possible to pack more nonspherical particles into a given volume at rest than under shear (Gillespie 1982). Hence, the volume fraction as zero fluidity is approached would be less than the packing fraction.

Effect of Corn Flour Solubles on Volume Fraction Versus Fluidity Curves of Corn Flours

Corn flour was washed with water and the wash water (with

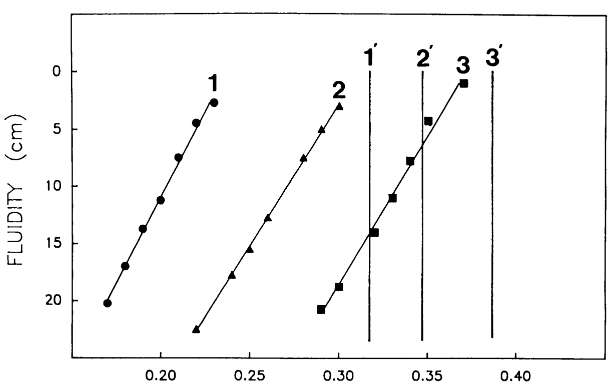

Fig. 1. Volume fraction versus fluidity curves and packing fractions for three corn flours. **1**, **2**, and **3** = Fluidity curves for samples 1, 2, and 3, respectively, and packing fractions for samples 1 (**1′**), 2 (**2′**), and 3 (**3′**).

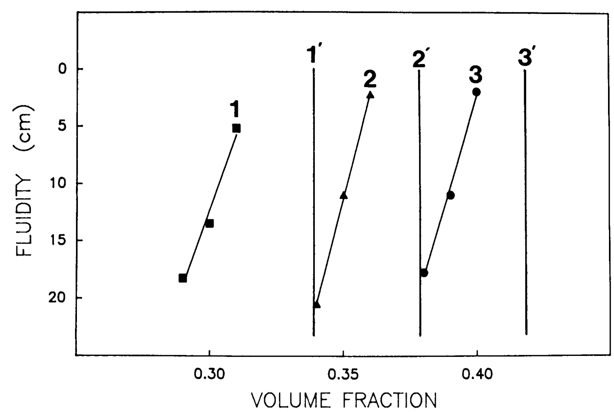

Fig. 2. Volume fraction versus fluidity curves and packing fractions for damaged and undamaged corn starch. Volume fraction versus fluidity curve for corn starch that had been ball milled for four days (**1**), two days (**2**), or zero days (**3**). Packing fraction for corn starch that had been ball milled for four days (**1′**), two days (**2′**), or zero days (**3′**).

soluble material) was removed. The washed corn flour was dried and then made into slurries with fresh water. Volume fraction versus fluidity curves showed that the washed corn flour slurries were more fluid than untreated corn flour slurries. However, the difference in the curves for washed (no solubles) and unwashed (solubles included) corn flours was not caused by soluble material, because the difference was the result of a shift in the packing fraction. Soluble material would not affect the packing fraction. Thus, the observed change in fluidity was probably caused by expansion of the flour during wetting. That resulted in the washed flour having a lower density, which caused a shift in the packing fraction.

Particle Size Analysis of Corn Flours

A particle size test (Alpine sieve system) showed that slurries made from flours with small average particle size (no. 3) had volume fraction versus fluidity curves at higher volume fractions of dry material, whereas slurries made from flours with large average particle size (no. 1) had volume fraction versus fluidity curves at lower volume fractions of dry material (Fig. 1). Therefore, it takes a smaller amount of a flour with large average particle size (assuming constant density of corn flour) than of a flour with small average particle size to produce a given fluidity.

The packing fractions of the flours with small average particle size were at higher volume fractions of dry material than the packing fractions of the flours with large average particle size. However, because the sieved fractions are distributions of particle sizes, it is not clear whether the observed differences are the result of average particle size or just changes in particle size distribution.

Effect of Defatted Flour on Volume Fraction Versus Fluidity Curves of Corn Flours

When they were compared, slurries made from defatted flours had volume fraction versus fluidity curves at lower volume fractions of dry material (e.g., more water and less solids) than slurries made from untreated corn flour. It follows that, at equal solids concentrations, a defatted flour slurry would be more viscous than a slurry made from an untreated flour. The shift (to the left) in fluidity curves for defatted flours indicated that defatting the flour increased its ability to absorb water.

Effect of Grinding on Volume Fraction Versus Fluidity Curves of Corn Flours

Our data indicated that grinding shifted the volume fraction versus fluidity curves to the right (i.e., increased fluidity) and that damaging starch or defatting the flour shifted the curves to the left (i.e., decreased fluidity). Corn flour millers often regrind corn flour to decrease the fluidity of flour/water mixtures. It would appear that additional milling of corn flour decreases fluidity by increasing starch damage. The effect of increased starch damage would then more than offset any other effects.

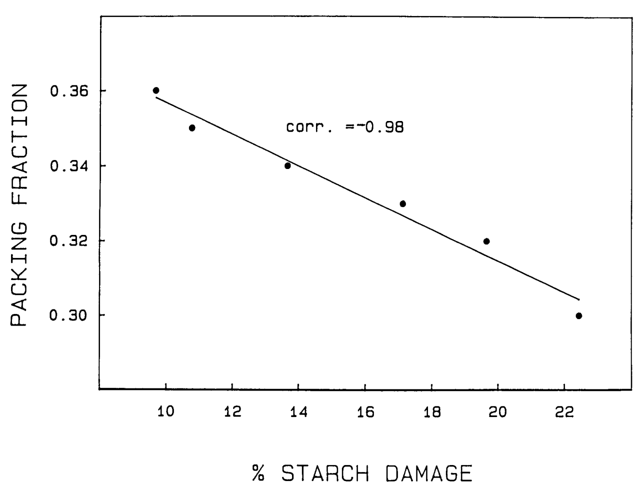

Fig. 3. Relationship between packing fraction and percent starch damage for corn flours ground with increasing severity.

To determine if the above scenario was correct, a series of corn flour samples was obtained that had been ground with increasing severity. Volume fraction versus fluidity curves and packing fractions were generated. Starch damage tests and sieve analyses were also run on the samples.

Effect of Grinding on Starch Damage

Starch damage values increased with increasing grinding severity for the corn flour samples.

Effect of Grinding on Volume Fraction Versus Fluidity Curves and Packing Fractions

Slurries made from corn flours that were severely ground had volume fraction versus fluidity curves at lower volume fractions of dry material; slurries made from corn flours that were less severely

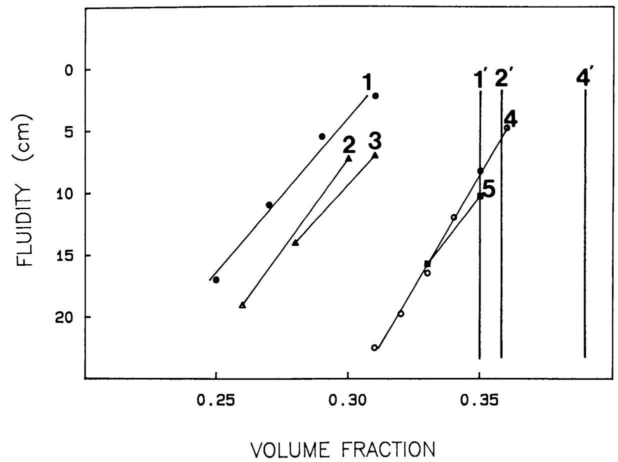

Fig. 4. Effect of fractionation of corn meal on volume fraction versus fluidity curves and packing fractions. Volume fraction versus fluidity curves of **(1)** fraction 1 (through no. 60 and over no. 100 sieve), **(2)** fraction 2 (through no. 100 and over no. 400 sieve), **(3)** fraction 3 (through a no. 400 sieve), **(4)** the starting material, and **(5)** the recombined sample. Packing fractions of **(1′)** fraction 1, **(2′)** fractions 2 and 3, and **(4′)** the starting material and the recombined sample.

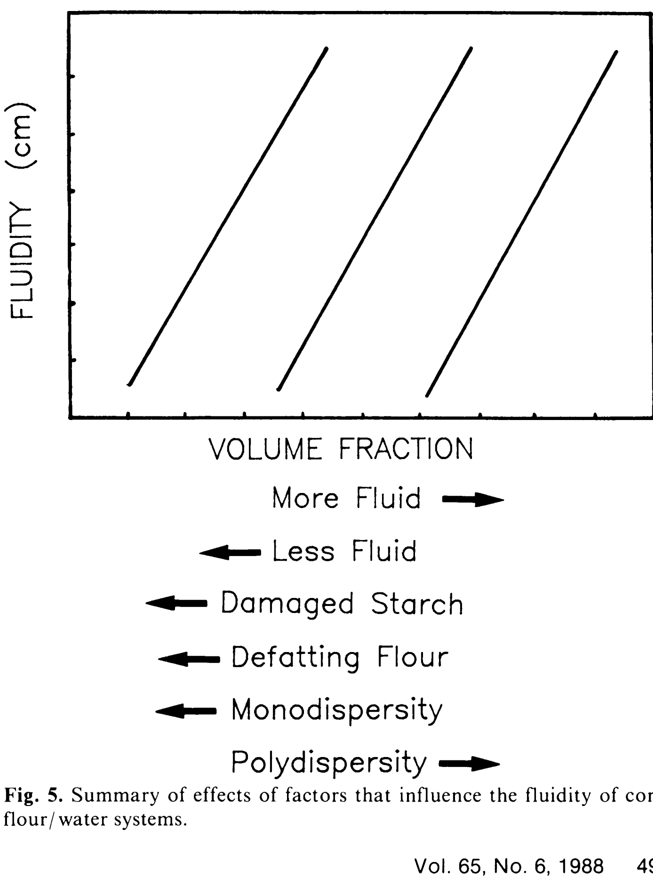

Fig. 5. Summary of effects of factors that influence the fluidity of corn flour/water systems.

ground had volume fraction versus fluidity curves at higher volume fractions of dry material. Likewise, increasing grinding severity shifted the packing fractions to lower volume fractions of dry material. This effect is consistent with results obtained by increasing levels of damaged starch. There was a high negative correlation (−0.98) between packing fraction and percent damaged starch (Fig. 3) for the flours ground with increasing severity.

Effect of Grinding on Particle Size Distribution

As grinding severity increased, average particle size decreased for the corn flour samples.

Corn Meal Fractionation

Volume fraction versus fluidity curves and packing fractions of sieved fractions of corn meal were compared to those of the recombined fractions and the starting material.

Volume fraction versus fluidity curves for the fractions were at lower volume fractions of dry material than those for the starting material (Fig. 4). This indicated that a slurry from any fraction alone was less fluid than a slurry of the starting material at equal solids concentration. Presumably, each fraction had a narrower particle size distribution (was more monodispersed) than the starting material. This is in agreement with others (Jeffrey and Acrivos 1976), who showed that slurries containing particles of uniform size (monodispersed) were more viscous (less fluid) than slurries containing particles of nonuniform size (polydispersed) at equal solids concentrations. The increase in fluidity in polydispersed systems has been attributed to an increase in free water as smaller particles occupy the voids between larger particles.

As average particle size decreased, the fluidity curves shifted to higher volume fractions of dry material (to the right). It appears that at equal solids concentrations, a decrease in average particle size increases fluidity; therefore, a greater concentration of dry material was necessary to obtain a constant fluidity. This was consistent with our previous data and with the results of others (Jinescu 1974), who reported that as particle size decreased, apparent relative viscosity decreased (fluidity increased) at equal solids concentration for particles in this size range. However, it must be kept in mind that particle shape and particle size distribution may also change as the average particle size changes.

The fluidity curve for the recombined sample was essentially the same as the fluidity curve of the original starting material. This lends support to the hypothesis that changes in average particle size or particle size distribution cause the fluidity curves of the fractions to shift when a sample is fractionated.

Summary

This study demonstrated that a corn flour/water system could be studied as a dispersion of rigid spheres. Different corn flours had different volume fraction versus fluidity curves and different packing fractions. The positions of these curves and packing fractions along the volume fraction axis reflected the fluidity of the various corn flour/water dispersions. Effects of factors that influence the position of the volume fraction versus fluidity curves of corn flour/water systems along the volume fraction axis are summarized in Figure 5.

ACKNOWLEDGMENTS

Grant-in-Aid of Research provided by Sigma-Xi, The Scientific Research Society.

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[Received November 16, 1987. Revision received July 17, 1988. Accepted July 18, 1988.]