Effect of Starch Gelatinization on Physical Properties of Extruded Wheat- and Corn-Based Products[1]

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ABSTRACT

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Wheat flour, wheat starch, corn meal, and corn starch were extruded in the form of a half-product using a pilot-plant model twin-screw extruder. Starch was gelatinized from 20 to 100%. The final cooked product (vegetable oil, 196°C) was tested for texture using the Kramer shear press on an Instron universal testing machine. As gelatinization increased, volume of the puffed product increased and bulk density decreased. A minimum bulk density was achieved at approximately 75% gelatinization for all products except corn meal, which had a minimum density at approximately 55% gelatinization. Peak force at failure had a parabolic response to gelatinization. The same force is required for failure at high and low extents of gelatinization, although textural and physical attributes differed substantially. Gelatinization was modeled by the ratio of total energy to peak force at failure (E_t/PkF) from the Instron data, which was influenced by the combination of bulk density and deformability.

Extrusion of flour- and starch-based products is widely used within the food industry to manufacture a variety of snack foods. Extrusion processing cooks and texturizes the starch-based material.

The main thrust of recent extrusion research has focused on the effect of extrusion variables on texture, microstructure, and gelatinization. Lawton et al (1972) investigated the chemical and physical changes that occurred in an extruded corn starch product due to extruder variables. These researchers found that moisture and barrel temperature had the greatest effects on gelatinization of corn starch. Gomez and Aguilera (1984) developed a physicochemical model for extrusion cooking of corn starch, noting that dextrinization predominates at moisture contents below 20%, whereas gelatinization predominates at moisture contents above 20%. These researchers also found that maximum gelatinization was observed at about 28–29% moisture. Chiang and Johnson (1977) studied the effects of extruder variables on gelatinization as well. They varied gelatinization by changing moisture content of the raw materials, temperature, screw speed, and die nozzle size. Increasing extrusion temperature enhanced starch gelatinization; increasing shear rate and die nozzle size decreased starch gelatinization. In a later study, Owusu-Ansah et al (1984) investigated the textural and microstructural changes in corn starch as a function of extrusion variables. Screw speed and feed moisture were significant variables influencing breaking strength, as measured by Warner-Bratzler shear. Porosities of the extrudates increased with decreased moisture, accompanied by an increase in expansion and a decrease in breaking strength. Percent gelatinization was not measured to determine its influence on breaking strength.

Comparisons of extents of gelatinization of starch in extruded products and their textural attributes have not been addressed. The objective of this study was to investigate the effects of gelatinization on mechanical textural properties in extruded wheat- and corn-based products.

MATERIALS AND METHODS

Extrusion

The materials were prepared by premoistening in a ribbon blender 18–24 hr before extrusion. The moisture contents were 28% (dry basis) for wheat flour and 35% (dry basis) for corn meal, corn starch, and wheat starch. The premoistened material was delivered into the extruder barrel through a K-Tron feeder (K-Tron, Pitman, NJ) calibrated for the desired feed rate. A Werner & Pfleiderer model ZSK 30 corotating twin-screw extruder (Werner & Pfleiderer, Ramsey, NJ) was used to extrude strips made from wheat flour (Cargill Inc., Minneapolis, MN), wheat starch (Manildra Milling Corp., Minneapolis, MN), corn meal (A. E. Staley Manufacturing Co., Decatur, IL), and corn starch (A. E. Staley Co.).

The product was manufactured in the form of a half-product (pellet). Such products are not completely processed during extrusion cooking. There is no expansion at the die, and the pellets are not intended for consumption until further processing by deep-fat frying. A rectangular die, 50.8 × 0.7614 mm, was used. The strips of extruded product were cut into approximately 5- to 8-cm-square pellets by hand or with a cutter. The pellets were dried for 12–24 hr at ambient conditions and placed in polypropylene zip-lock bags for storage.

A factorial arrangement, using barrel temperature, screw speed, and feed rate as variables, was developed to vary the extent of gelatinization during extrusion cooking. Barrel temperatures ranging from 60 to 120°C, screw speeds ranging from 50 to 175 rpm, and feed rates of 5, 10, and 15 kg/hr were used. The screw configuration was the same for all runs.

Enzymatic Analysis

Pellets were freeze-dried for enzymatic analysis. Samples of the dried pellets (10–20 g each) were ground in a Wiley mill (Arthur H. Thomas Co., Philadelphia, PA) to pass through a U.S. standard no. 60 screen (0.25 mm). Dry ice (5–10 g) was ground with each sample to minimize heat buildup. The milled sample was then ground by hand with a mortar and pestle to pass through a U.S. standard no. 170 sieve (0.09 mm). The portion not passing through the screen was reground. This step was repeated until six fractions were collected. This assured collection of a representative sample for enzymatic analysis. All samples were stored over anhydrous calcium sulfate before enzymatic analysis.

Percent gelatinization was determined for each sample using the β-amylase-pullulanase method developed by Kainuma et al (1981). Results were based on duplicate analyses.

Texture Analysis

The pellets were further processed by deep-fat frying (190–199°C) in vegetable oil for an average of 20 sec. Frying caused expansion or "puffing" of the pellets. After draining the free oil on absorbent toweling, the product was stored in desiccators over anhydrous calcium sulfate for a minimum of one week before analysis. Effects of varying moisture contents were eliminated by this procedure.

Texture was measured on an Instron universal testing machine (model 1122, Instron Corp., Canton, MA) equipped with the Kramer shear press (model CS-1, Food Technology Corp., Rockville, MD). A 2.00-g sample (±0.02 g) was placed flat and spread

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evenly over the bottom of the sample cup. A 500-kg compression load cell was used and the full-scale force was set at 50 kg for all compressions. The crosshead speed was 100 mm/min. The force-deformation curve was recorded at a chart speed of 1,000 mm/min. Maximum force at failure was recorded and the total energy (work) was measured as the area under the curve. Variation in shape and thickness of the samples prevented calculation of stress and strain at failure. Maximum force and the ratio of total energy to peak force were used as textural parameters for correlation of gelatinization to texture. Results were based on an average of quadruplicate analyses.

Bulk Density Determination

Bulk densities in kilograms per cubic meter were determined on the puffed product by rapeseed displacement (Binnington and Geddes 1938). Bulk density results were based on an average of six measurements.

Statistical Analysis

Linear regression was used to determine the line of best fit. Error bars for regression curves were based on the complete data set for the regression.

RESULTS AND DISCUSSION

Physical Properties of the Expanded Chips

The expanded chips showed an increase in volume as extent of gelatinization increased (Fig. 1). Chips with a low amount of gelatinization were thin after puffing. The highly gelatinized chips were larger in volume and less dense. Mercier (1977) reported similar findings for directly expanded and extruded potato starch. The products extruded at lower temperatures (lower gelatinization) were thin. Expansion was greatest at the highest extrusion temperatures (high gelatinization). This also confirms the results of Bhattacharya and Hanna (1987). They noted that, as temperature increased during extrusion of corn starch products, gelatinization was more complete, resulting in more expansion and reduced density. Although the product in this study is a half-product and not a directly expanded product like that in the work of Mercier and Bhattacharya and Hanna, the response of volume to gelatinization was the same. The extent of gelatinization versus bulk density relation was similar for each of the four materials in this study (Fig. 1). Once the bulk density of the product had dropped below 300 kg/m^3 (at approximately 55–70% gelatinization), it continued to decrease, but at a much slower rate. The minimum bulk density achieved for all products in this study was no lower than 160 kg/m^3. This was reached in all cases, except for corn starch, at approximately 75% gelatinization. As gelatinization increased above 75%, bulk density no longer decreased.

Instrumental Textural Analysis

Maximum shear press force at failure, obtained from the force-deformation curves, was plotted versus percent gelatinization. Figure 2 shows a parabolic trend for all four products. The same amount of force was required to cause failure in both the high- and low-gelatinized products. However, the physical and textural characteristics differed greatly from the high to low levels of gelatinization. The low-gelatinized, thin chips were brittle, and failure was accompanied by a snap. The highly gelatinized, highly expanded products were more friable, and failure was related best to a crumble during compression. This held true for all samples manufactured from the four different raw materials.

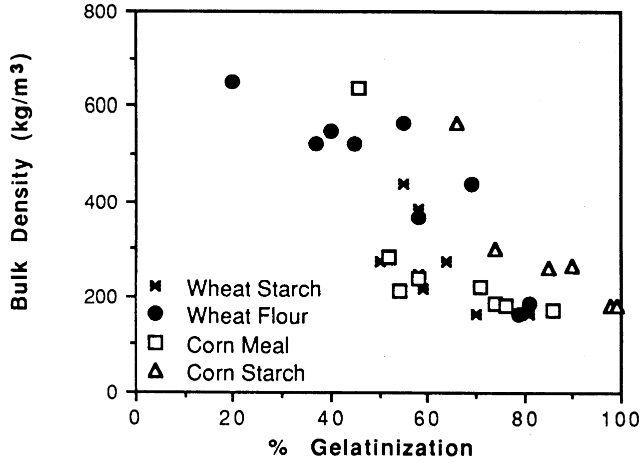

Fig. 1. Relationship of bulk density to percent gelatinization.

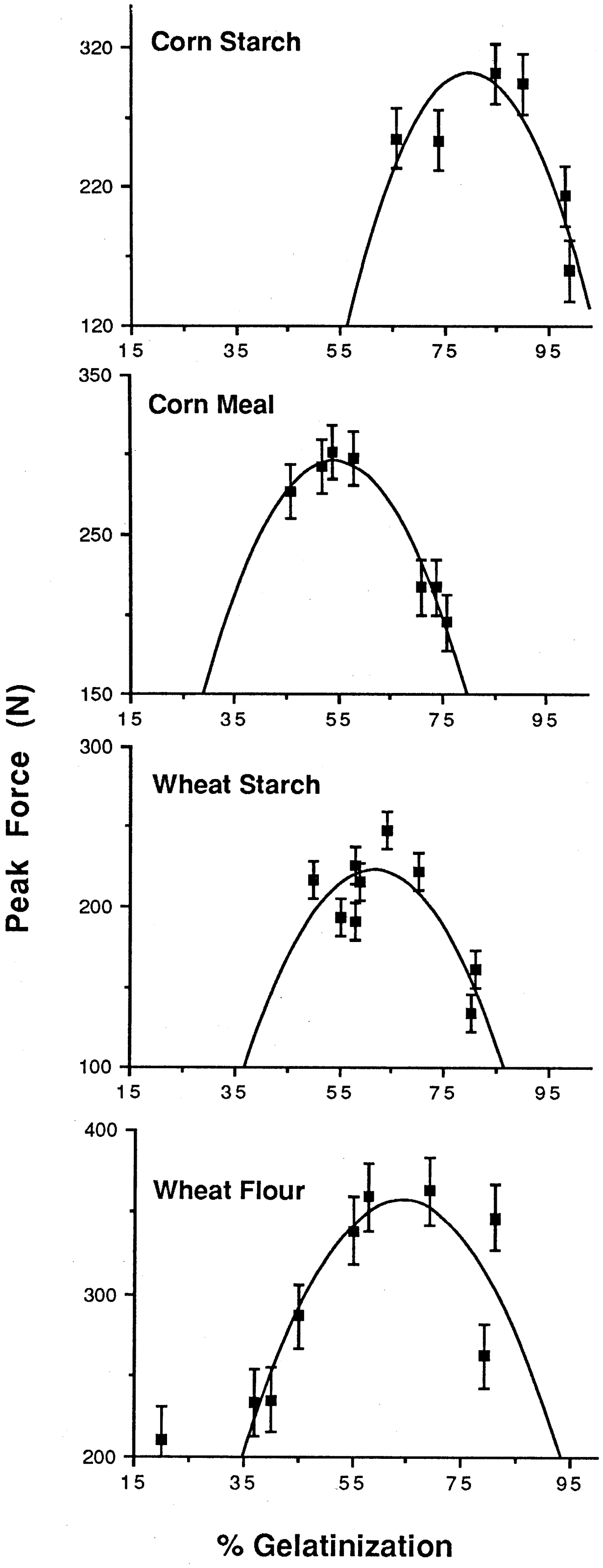

Fig. 2. Plots of peak force at failure versus percent gelatinization.

It is interesting to note that the point of transition (bulk density versus percent gelatinization slope change) for the lower values of bulk density data (Fig. 1) for each material approximately corresponded to the peak of the peak force graphs. The parabolic form observed for the peak failure force data can be explained by applying the information acquired from the bulk density data. It is noted in Figure 2 that as gelatinization increased, shear force increased. There was a point, however, where the force at failure began to decrease. This was near the point at which increased gelatinization started to have less influence on density.

Two theories can be constructed for these data. Although bulk density decreased slowly, it is possible that once it fell below 300 kg/m^3, structural wall dimensions and porosity still significantly changed as gelatinization increased. Because of these macrostructural changes, shear force at failure decreased with increasing gelatinization. The second explanation is based on the possibility that structural wall dimensions do not undergo significant changes as gelatinization increases; however, greater gelatinization reduced the strength of the material making up the structure. Although only small additional expansion occurred, there were other changes occurring within the material as gelatinization increased, causing the molecular structure to weaken.

Energy to failure (E_f) is the measurement of the area under the force-deformation curve to the point of failure (PkF) (maximum peak height). In samples where the force-deformation ratio is constant and failure occurs at a single point, as in high moisture starch and protein gels, the equation for energy to failure was

$$E_f = \text{PkF} \times \text{deformation (length of baseline to PkF)}/2$$

This suggested that E_f/PkF was, to a large extent, a measure of deformability of the product before rupture. The ratio of total energy to peak force at failure, E_t/PkF, used in this study was somewhat more complex since it included energy beyond the major rupture point. This was because failure did not occur at a single point but occurred continually throughout the compression-shear cycle. The measurement was largely dependent on the extent of expansion or bulk density, however, only up to a certain point (Fig. 3). Even after bulk density reached its limit, at approximately 170 kg/m^3, the E_t/PkF values continued to increase. This was observed in the change in slope in Figure 3. Some other structural attribute appeared to affect E_t/PkF values when bulk density reached its limit at the higher extents of gelatinization. Therefore, E_t/PkF was a measurement of a combination of primarily bulk density and possibly deformability.

The decrease in values of peak force (Fig. 2) and the increase in values of total energy to peak force (Fig. 3), even after bulk density no longer changes, may be due in part to degradation or dextrinization of amylose and amylopectin. Macromolecular degradation of starches has been reported to occur during extrusion conditions by Mercier (1977, potato starch), Gomez and Aguilera (1983, corn starch), Chiang and Johnson (1977, wheat flour), Chinnaswamy et al (1989, corn starch), and Colonna et al (1984, wheat starch).

E_t/PkF was plotted versus percent starch gelatinization for each material. The fit of the data for each individual product was tested statistically using the analysis of variance F test (Table I). A linear fit was found to be optimum in all cases.

The extent of gelatinization can be predicted using E_t/PkF. Responses of percent gelatinization to E_t/PkF are similar for wheat flour, wheat starch, and corn meal, as can be seen by superimposing the data for these products on the same graph (Fig. 4).

Table II shows that the products extruded in this study required different extrusion conditions to achieve the same level of gelatinization. The two examples in Table II show that the starch samples required much less heat and energy input to achieve the same extent of gelatinization as the corn meal and wheat flour samples. This is likely due to the lack of protein, lipids, bran, and other components in the starches that are found in the flour and meal. These components may act as a heat sink, absorbing the heat and energy that are required to gelatinize the starch. They also may limit the water available for gelatinization. Presumably, these components protect the starch and result in lower extents of gelatinization.

Research conducted on directly expanded products by Mercier and Feillet (1975), Mercier (1977), Bhattacharya and Hanna (1987), and Chinnaswamy and Hanna (1988) have concluded that starches of different amylose contents, within the same species as well as starches of various origins, respond differently under the same conditions of extrusion. Falcone and Phillips (1988) and Holay and Harper (1982) also noted that results from extrusion studies are machine-dependent and results between studies are difficult to compare. In the case of the half-product prepared in this study, using gelatinization and the texture measurement E_t/PkF, we may be able to overcome species- and extruder-

TABLE I
***F*-Test Values and Correlation Coefficients Indicating Dependence of Percent Gelatinization on E_t/PkF**[a]

Material	F Value[b]	R^2
Wheat flour	51.99	0.875
Wheat starch	32.17	0.753
Corn meal	33.42	0.708

[a] Ratio of total energy to peak force at failure.
[b] All F values were highly significant ($P < 0.01$).

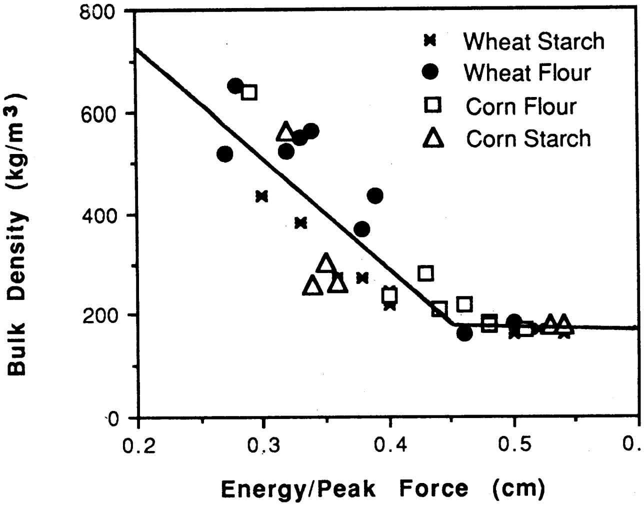

Fig. 3. Relationship of bulk density to the texture measurement ratio of total energy to peak force at failure.

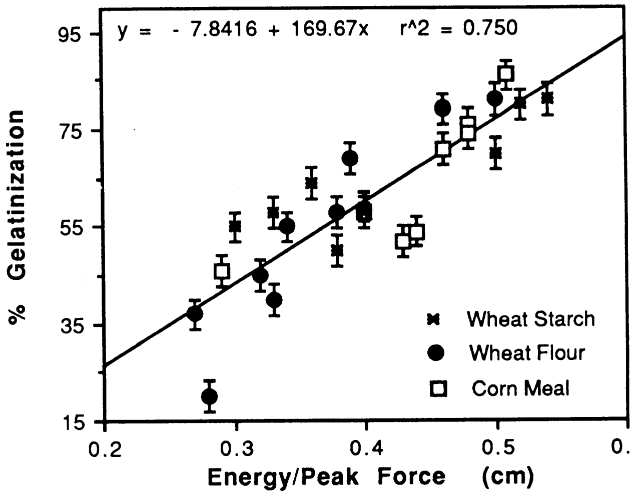

Fig. 4. Regression plots of percent gelatinization versus the ratio of total energy to peak force at failure.

TABLE II
Recorded Running Parameters and Extent of Gelatinization

Product	Temperature (°C) of Barrel Zones						Percent MC[b]	rpm	Feed[c] (kg/hr)	Percent Gelatinization[d]
	1	2	3[a]	4[a]	5	Die				
Wheat flour	51	62	68	NA[e]	65	95	28	175	15	55 ± 3
Wheat starch	26	29	44	36	26	56	35	126	3	55 ± 3
Corn meal	30	70	85	55	74	65	35	150	10	54 ± 1
Wheat flour	64	80	95	NA	67	110	28	200	15	86 ± 1
Corn meal	38	83	112	104	74	85	35	125	5	86 ± 1
Corn starch	32	31	52	48	58	68	35	109	2.5	85 ± 1

[a] Cook zones.
[b] Moisture content.
[c] Feed rate.
[d] Mean ± standard deviation.
[e] Not available.

dependent results. However, it must be recognized that these results compare only two starch types that are fairly similar in their amylose content and gelatinization temperatures. These findings need to be confirmed using different extruders as well as starches that have greater differences in their amylose contents.

CONCLUSIONS

Gelatinization can be modeled with E_t/PkF as measured by Kramer shear press. It is possible to use this textural result as an estimation of gelatinization. The shear force at failure data follows a parabolic curve when compared with percent gelatinization, showing that the force at failure value can be similar for high- and low-gelatinized products even though the textural and physical properties are very different.

Bulk density decreased as gelatinization of the starch increased. Minimum bulk density occurred between 55 and 75% gelatinization, depending on the raw material.

The ratio of E_f/PkF for foods where failure occurs at a single force value is related to the deformability of the product before rupture. However, in this study, the measurement E_t/PkF was incorporated as a measurement primarily of bulk density and possibly deformability at the higher levels of gelatinization. The concept of E_f/PkF being indicative of deformation to failure is lost when observing the progressive failure patterns noted with this material.

This study also suggests that the use of gelatinization, E_t/PkF, and bulk density measurements may be good standards of measurement for comparison of starches of different species and when comparing results from different extruders. It appears that, once gelatinization is achieved, the effects of product makeup are negligible when using gelatinization and texture measurements.

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