High-Temperature Short-Time Extrusion Cooking of Wheat Starch and Flour. I. Effect of Moisture and Flour Type on Extrudate Properties[1]

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ABSTRACT

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The role of wheat flour components in the extrusion cooking of wheat starch and flour was assessed. Feed materials varying in water content and flour type were extruded and the products analyzed for texture, expansion, and ultrastructure. Increased initial moisture content decreased the expansion and weakened the texture of both starch and flour. Starch showed the greatest sensitivity to differences in moisture content. Analysis by scanning electron microscopic showed that extruded starch and extruded flour had complex but identifiably different ultrastructures. The most obvious difference noted was the presence in extruded flour of roughened cell walls with frequent failures. Hard (11% protein) and soft (9% protein) wheat-flour extrudates were similar in expansion and ultrastructure, whereas the extrudate of a high-protein (15%) flour differed in all three characteristics. Supplementing low-protein flours with their own or with high-protein gluten showed that differences among flours were due primarily to gluten quantity rather than to source.

The production of cereal-based snack foods has grown rapidly in the last 15 years, partly because of the availability of technologies capable of economically producing a wide range of products. An excellent example of the phenomenon is the use of high-temperature, short-time (HTST) extrusion cooking. A versatile technology with its origins in the plastics industry, HTST extrusion cooking is used to produce products as diverse as pet foods (Smith 1975), infant formula bases (Anderson et al 1971), and expanded snack foods (Williams 1977) at production rates measured in thousands of pounds per hour. By its nature, it is a continuous rather than a batch process, and the extruder products are sterile and, because of complete starch gelatinization, very digestible (Seib 1976).

Despite the importance and popularity of extrusion cooking, literature on it is sparse and consists mainly of nontechnical articles describing a particular machine but lacking experimental data; and attempts to duplicate, by extrusion cooking, the properties of a traditionally produced food (Anderson et al 1971; Conway 1971a, 1971b; Maga and Lorenz 1978).

Few studies have considered how the components of a material to be extruded affect the properties of the extrudate. That situation is particularly noticeable in the study of starch- or flour-based snack foods. Wheat starch and flour differ in the character of the products they produce when extruded under identical conditions.[4] Under machine conditions optimal for expansion, flour may be incapable of achieving more than 80% of the expansion of 100% starch extrudate.[4] Systematic insights into the causes of such differences and into the functions of flour components in producing them are lacking.

Further, if textural and ultrastructural information on extruded flour or starch-protein blends exists, it has not been published. Such information, together with values for product expansion, would help in explaining how the biochemical components of a flour affect the texture and ultrastructure of its extruded product.

We investigated the changes in texture, structure, and expansion of extruded products as affected by the moisture content and types of wheat flour. For this work, we considered wheat flour to be a four-component system of starch, protein, lipid, and water. The starting point for the studies is the work of Stearns,[5] who identified the extruder-operating conditions optimal for expanding wheat starch. By keeping those parameters constant and varying the composition of the material being extruded, we examined effects attributable to each component.

MATERIALS AND METHODS

Starch

Prime wheat starch was obtained from Midwest Solvents Co. Inc., Atchison, KS.

Flours

Hard winter wheat flour with a protein content of 11.2% (N × 5.7) and ash of 0.38% was obtained from the Department of Grain Science and Industry, Kansas State University, and designated *medium-protein flour*. A commercially milled hard wheat flour (protein, 15.3%; ash, 0.52%) was obtained from Ross Industries Inc., Wichita, KS, and designated *high-protein flour*. Soft wheat cake flour (unchlorinated) with a protein content of 9.0% was the gift of Ronald Spies, Department of Grain Science and Industry, Kansas State University.

Moisture

The moisture content of materials to be extruded were determined according to the AACC method (1976).

Tempering

The final moisture content of materials to be extruded was adjusted by the method of Stearns.[5] Flour or starch was placed in a rotating drum, and tempering water was added as a fine mist from a sprayer designed to apply stain to thin-layer chromatography (TLC) plates. Tempered materials were placed in plastic bags and held overnight before extrusion to allow moisture distribution to equilibrate.

Gluten Isolation

Flour (200 g) was added with stirring to 600 ml of distilled water. After 5 min of stirring, the suspension was centrifuged 20 min at 1,000 × g. Starch was washed from the gluten-starch pellet by gentle kneading under a stream of water until the remaining gluten was a smooth, consistent mass (approximately 20 min). The resulting gluten ball was freeze-dried and ground in a Stein Mill to pass a 350-μ screen.

Reconstitution

Artificially compounded flours were created by combining, on a 14% moisture basis, wheat flour and gluten in amounts sufficient to produce the desired final concentrations. Blending was accomplished by shaking continuously for a minimum of 10 min.

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[4]M. A. Williams and S. Baer. 1965. Introduction to grain expansion. Presentation to the American Society of Agricultural Engineers. December, 1965.
[5]M. Stearns, 1974. Extrusion Cooking of Wheat Starch. Unpublished Master's thesis. Kansas State University, Manhattan.

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Extrusion

For all experiments, we used a laboratory-scale, single-screw extruder model 2403 manufactured by C. W. Brabender Co., South Hackensack, NJ.

Extruder specifications, operating procedures, and sample collection were as specified by Stearns[5] and Cabrera.[6] Initial start-up conditions were: water-cooled feeder block, air-cooled zone one, 100° C zone two, and 135° C zone three. Screw speed was 100 rpm. The machine was started with wheat flour at 25% moisture. After equilibrium, the zone three temperature was adjusted to the operating temperature desired and then the sample fed. The other zone temperatures were held constant. Final extruder operating parameters were those identified by Stearns[5] as being optimal for the expansion of starch (zone three temperature, 175° C; screw speed, 100 rpm).

Extrudate Analysis

The expansion of the extrudate at the die cap was determined by measuring the extrudate diameter with calipers. Duplicate measurements were made on 10 randomly chosen pieces of extrudate from each experiment.

Texture Analysis

Extrudate textural characteristics were measured with an Instron model 1130 Universal Texture Analyzer after the samples were dried to constant moisture (±0.5%). Two types of measurements were made on each sample: load required to shear through, and load required to break. For the former, a Warner-Bratzler shear apparatus was used to shear across the extruded rod at right angles to its long axis. For the latter, a sample was supported at both ends of a 9.25-cm free span and broken in the middle by a round, vertically driven anvil 1.0 cm in diameter. The amount of force, in kilograms, required to shear or break the rod was obtained from the strip chart tracings of force vs time for each sample.[7]

[6] J. Cabrera. 1978. Extrusion Cooking of Wheat Starch: Effects of pH and Emulsifers. Unpublished Master's thesis. Kansas State University, Manhattan.

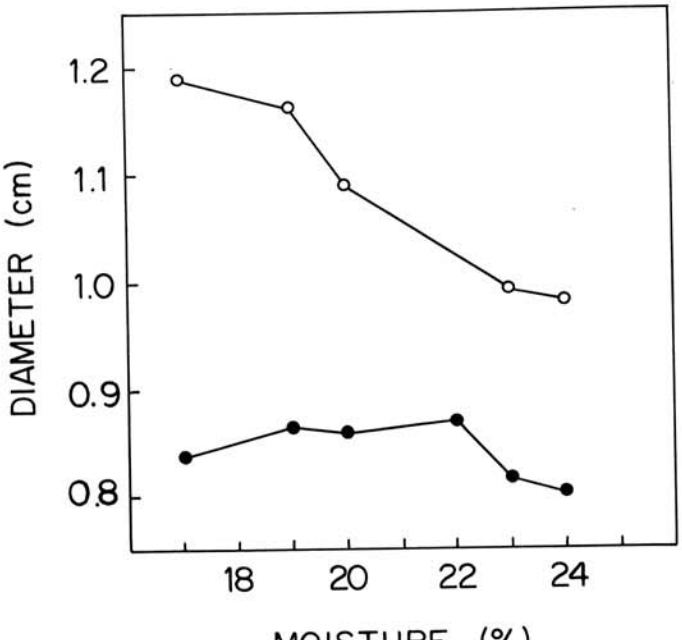

Fig. 1. Diameter of starch and flour extrudates vs initial moisture content of the feed material. o = Starch, • = flour.

TABLE I
Amperages Required to Extrude Starch and Flour

Moisture (%)	Starch (amps)	Flour (amps)
11	9.2	4.9
19	6.4	4.5
22	5.6	4.5
23	5.0	4.3

Scanning Electron Microscopy

Short (less than 2 cm) pieces of extruded sample were mounted on SEM sample stubs with cut surface exposed. After they were coated with carbon and gold-palladium, the samples were viewed and photographed on an ETEC Autoscan scanning electron microscope operating at an accelerating voltage of 10 kV.

Standard Deviations

The standard deviation for each of the extrudate properties measured was calculated as described by Steel and Torrie (1960): extrudate diameter, 0.12 cm; extrudate shear strength, 0.19 kg; and extrudate breaking strength, 0.06 kg.

RESULTS AND DISCUSSION

Wheat Starch and Flour at Various Moisture Contents

The relationship between the expansion of extruded wheat starch and flour and the initial moisture content of the feed material is depicted in Fig. 1. Upper and lower limits of moisture were by the ability of the extruder to operate reliably. Above 24% moisture, caking occurred in the feeder; below 17%, power requirements exceeded the operating limits of the machine.

Flour and starch responded differently to increased initial moisture. At all moisture levels, starch expanded more than did flour. As moisture content was increased from 17 to 24%, expansion of extruded starch decreased by 18% in diameter. With the machine conditions used, differences between starch and flour were greatest at low moisture contents. In contrast to starch, wheat flour exhibited no significant change in expansion as a function of moisture content.

Stearns[5] observed a similar relationship between starch expansion and moisture content and attributed it to the inability of thin-walled cells to maintain their integrity as they were expanded by large amounts of steam flashing off during extrusion. The net effect would be a partial collapse before setting of the structure, which would result in reduced expansion. Though this mechanism may, in fact, be involved in affecting the expansion of flour, it

[7] S. Bedolla. 1980. Effect of genotype on cooking and texture of corn for tortilla production. Unpublished Master's thesis. Texas A&M University, College Station.

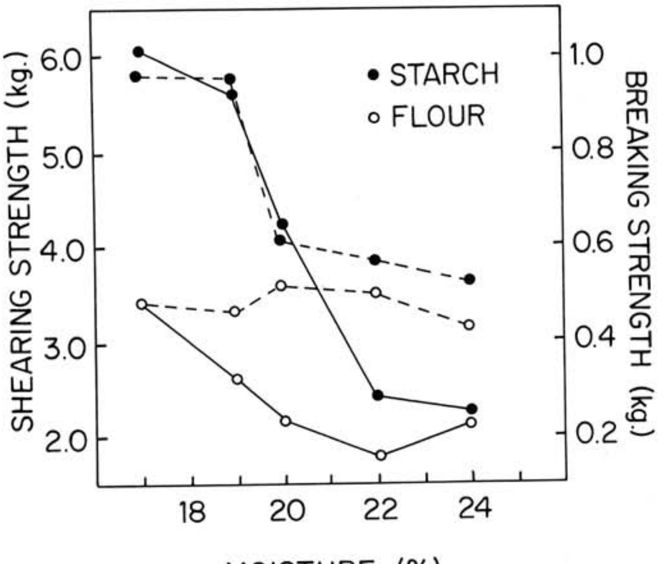

Fig. 2. Shearing and breaking strengths of starch and flour vs initial moisture content of the feed material. — = Shearing, --- = breaking.

clearly is not the only factor. The consistent inability of flour to expand as much as starch, regardless of moisture level, and the relatively small response to moisture suggest that one or more of the nonstarch components of flour are important in inhibiting expansion. Similar conclusions were reached by Conway and Anderson (1973).

Another difference between starch and flour was suggested by the relationship between moisture content and the power required to extrude (Table I). For starch, power consumption increased with decreased moisture, often causing machine failure at the 17% level. Flour required less power to extrude than did starch, and power consumption changed little over the range of moistures tested. Cabrera's study[6] of the extrusion of starch plus emulsifiers suggests that endogenous lipids may be responsible for the difference in power consumption between flour and starch. Cabrera's theory is that lipids allow slippage between the extruder barrel surface and the molten starch melt. Although that is plausible, the interaction of flour lipids with starch, protein, or the extruder barrel under the extreme heat and pressure of extrusion is not known. Extensive studies of the changes occurring in starch during extrusion have been reported by Mercier and Feillet (1975), Mercier et al (1979), and Linko et al (1981).

Subjecting extruded starch and flour to shearing and breaking forces gave the results shown in Fig 2. Extrusion at increased moisture levels appears to be detrimental to the ability of the extrudate to resist shearing and breaking forces. When tested with the Warner-Bratzler cell (shearing strength), both materials required a smaller load to shear through the extruded rod as moisture content increased. Starch consistently required a larger shearing load than did flour and showed a much larger decrease in shearing strength over the moisture range tested.

Loads required to break the extrudate (Fig. 2) were always less than those required to shear it. As with shearing strength, starch breaking strength decreased as initial moisture content increased. Although always less than starch values, flour breaking strengths changed little with increased moisture.

When viewed with the scanning electron microscope, extruded wheat starch and flour differed in their internal structures. At all moisture levels, starch extruded as a lattice-filled rod (Fig. 3). Samples extruded at 17 and 19% moisture were indistinguishable in their internal structures. They were characterized by large air cells evenly distributed throughout the rod (Fig. 3A). The cells appeared to be complete, with few holes or tears in their walls. Most cells at the rod periphery (Fig. 3B) were small with thick cell walls. Cell-wall surfaces were uniformly smooth or slightly wrinkled (Fig. 3D), suggesting that plasticity remained in the extrudate after the point of maximum expansion. If that were so, rippling might be the result of a small amount of flow or collapse before cells set to form a rigid structure.

Starch samples of high moisture content produced extrudates of small diameters and slightly different internal structures. Cell size was not uniform throughout the extruded rod. Although Fig. 3C shows a collection of smaller cells in the left center of the rod separating regions of much larger cells, the location of large and small cells was random. Cell-wall surfaces were smooth or rippled, and the larger cells often had holes or tears in the walls (Fig. 3D). That indicated failure of the wall before setting. As moisture content increased, more small cells and cells with failed walls were found.

The internal structure of wheat-flour extrudates differed from those of wheat starch. The distinguishing characteristic of extruded flour was the rough appearance of its cell walls. In all flour samples investigated, holes or tears in cell walls were common (Fig. 4A). Such wall failure occurred in both large and small cells and appeared evenly distributed throughout the sample. Figure 4A shows wall failure in the form of a hole at the base of a large air cell.

The feature that most clearly differentiated extruded flour from starch was rough or abraded rather than smooth or rippled cell walls. The cell wall did not appear to expand uniformly, and the wall itself was not homogeneous but was made up of several components. That characteristic appearance ranged from the broken or stretched surface shown in Fig. 4B to the fibrillar structure seen at the surfaces of Fig. 4C. At high moisture (24%), cell walls appeared fragmented and nonhomogeneous (Fig. 4D), with remnants of starch granules embedded in the wall.

Flour extruded at 17 and 20% moisture gave structures similar to each other in cell size and distribution; large and small cells were interspersed. Increased moisture content gave more small than large cells. Cell walls of flour extrudates (Fig. 5A) appeared thicker than did those of extruded starch. However, interpretation of wall thickness is complicated by the inability to control the angle at which walls are broken for viewing.

At the highest moisture levels tested (24%), extruded flour often gave areas of large, open cells in the center of the rod (Fig. 5B) rather than a lattice-filled structure. The amount of the extrudate

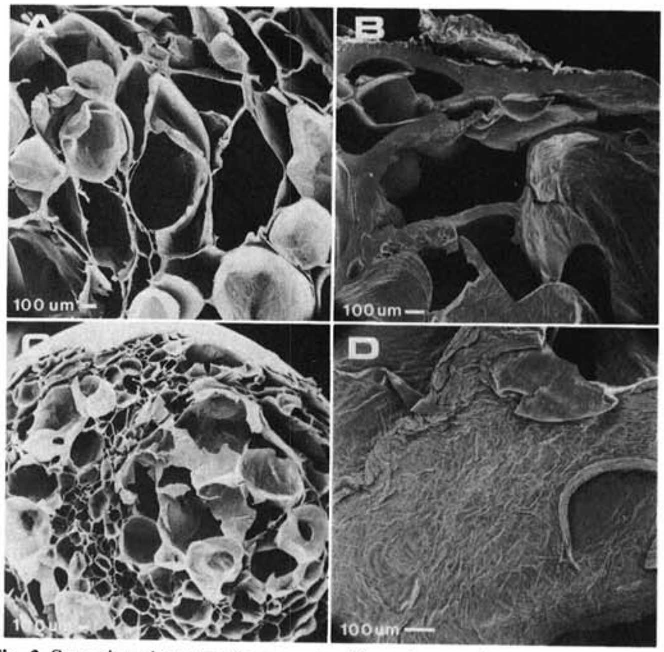

Fig. 3. Scanning electron micrographs of starch extrudates. **A**, 17% initial moisture; **B**, 19% initial moisture; **C**, 22% initial moisture; **D**, 19% initial moisture.

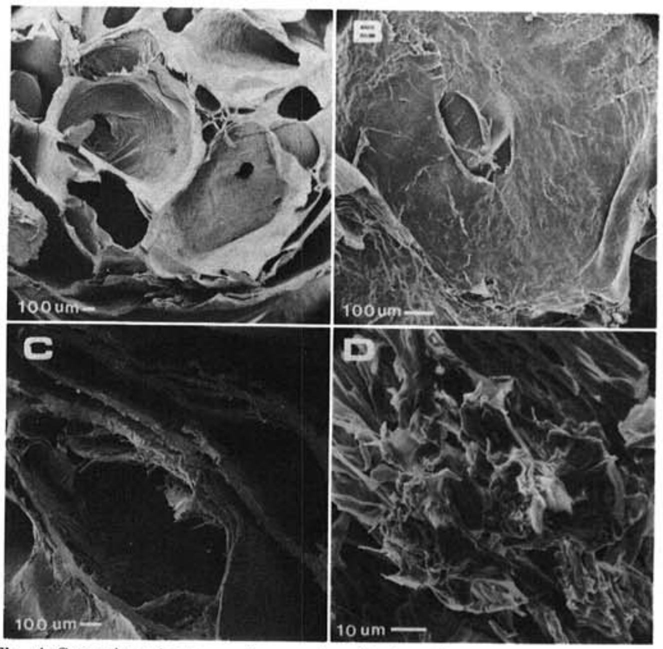

Fig. 4. Scanning electron micrographs of wheat-flour extrudates. **A**, soft wheat flour; **B, C, D**, medium-protein hard wheat flour. Initial moisture content was 19% for all extrudates.

cross-sectional area made up of the large cells varied widely; Fig. 5B represents an extreme instance. The material surrounding the large cells commonly consist of what appeared to be numerous layers that had collapsed on themselves and fused at random points along their lengths.

Effects Caused by Flour Type

The observable differences between extruded starch and extruded hard wheat flour prompted us to question: whether all types of flour would perform similarly if extruded under identical conditions, or whether extrudate characteristics would be influenced by flour type. Three flours milled from wheats representing a range of types were extruded at 19% moisture: unchlorinated soft wheat flour (9% protein), medium-protein hard wheat flour (11.2% protein), and a high-protein hard wheat flour (15.3% protein).

Expansion of the soft wheat flour was equivalent to that of the medium-protein hard wheat, despite the 2% difference in protein content (Table II). Attempts to extrude high-protein flour were only partially successful. Surging occurred, with the result that extrudate expansion was not uniform. The portions of the extrudate that expanded gave diameters exceeding those of medium-protein flour by 17%, whereas those that did not expand gave diameters that were 10% less than those of the medium-protein flour.

Power requirements to extrude the three flours are presented in Table II. Hard and soft wheat flours required the same amperage for extrusion. Because of surging, power consumption for high-protein flour varied; however, the average amperage was more than twice that for the other flours.

Visual and microscopic examination of the extruded products showed soft wheat and medium-protein hard wheat extrudates to be indistinguishable based on the distribution, size, or shape of their constituent cells (Fig. 4). Both had the characteristic internal structure previously described for the medium-protein hard wheat extrudate. In the areas that expanded, high-protein flour resembled its low-protein counterpart (Fig. 6). Large and small cells were again interspersed (Fig. 6A). Cell walls of high-protein flour were rough (Fig. 6B), often resembling a fully mixed dough that was stretched until it failed.

Shearing strength for soft and hard wheat extrudates were similar (Table III). Breaking strength for the extruded low-protein sample was nearly 10% greater than that of extruded soft wheat. Given their similarities in expansion and ultrastructure, the reason for that difference was not apparent.

Extruded high-protein flour was weaker in both shearing and breaking strengths than were the other flour types (Table III). Shearing strength was only half that of other samples. Apparently, the disruption of cell wall structure characteristically seen in high-protein samples (Fig. 6B) caused a weaker texture. That is interesting in that the decrease in textural strength occurred without equivalent loss of expansion.

The fact that high-protein flour differed from soft wheat and medium-protein hard wheat flours in the characteristics of the extrudate prompted us to determine whether the observed effects were due solely to protein quantity. Gluten was isolated from both soft and medium-protein hard wheat flours and added to soft wheat flour in amounts sufficient to bring its final protein content to 15%. When these gluten-supplemented flours were tempered to 19% moisture and extruded, their expansion and power requirements (Table II) were similar to those of the high-protein flour.

The ultrastructures of the supplemented flour were indistinguishable from the high-protein flour counterpart. As might be predicted from the similarities in their expansion and structures, soft wheat flour supplemented with gluten from either flour gave shearing and breaking strength values close to those of the native 15% protein flour (Table III). Textural values of extrudates from the supplemented flours were less than those for either medium-protein hard or soft wheat extrudates.

Taken together, the data suggested that starch and flour produce different extrudates. Further, the responses of these materials to extrusion at increased moisture contents was not the same, and the observed responses could not be attributed simply to the overexpansion and subsequent collapse of gas cells.

The data also suggested that flour type or, more precisely, gluten type is not an important factor in determining the extrusion characteristics of flour. That protein quantity is more important was particularly evident in our ability to mimic the extrusion behavior of high-protein flour by supplementing low-protein soft wheat flour with its own gluten or gluten from a hard wheat.

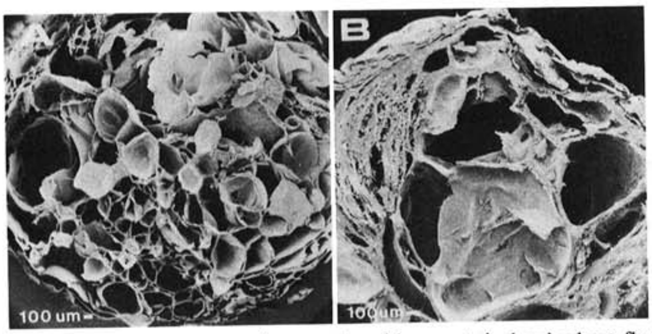

Fig. 5. Scanning electron micrographs of low-protein hard wheat flour extrudates. **A**, 19% moisture content; **B**, 24% moisture content.

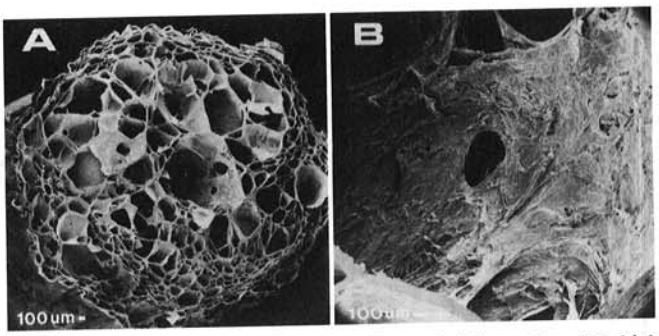

Fig. 6. Scanning electron micrographs of extruded flour. **A** and **B**, high-protein, hard wheat flour.

TABLE II
Extrusion Characteristics of Different Flour Types

Flour	Diameter (cm)	Power Consumption
Medium-protein	0.844	4.5
Soft wheat	0.851	4.5
High-protein	0.878[a]	9-14
Soft wheat[c]	0.889[b]	9-14
Soft wheat[d]	0.883	9-14

[a]Average of 0.987 expanded and 0.769 collapsed.
[b]Average of 0.995 expanded and 0.783 collapsed.
[c]Soft wheat flour plus medium-protein flour gluten to a final protein level of 16%.
[d]Soft wheat flour plus cake flour gluten to a final protein level of 16%.

TABLE III
Effect of Flour Type on Textural Measurements

Flour	Shearing Strength (kg)	Breaking Strength (kg)
Medium protein	2.56 (± 0.14)	0.460 (± 0.031)
Soft wheat	2.52 (± 0.14)	0.419 (± 0.033)
High protein	1.55 (± 0.39)	0.404 (± 0.081)
Soft wheat[a]	1.57 (± 0.40)	0.409 (± 0.072)
Soft wheat[b]	1.55 (± 0.39)	0.401 (± 0.077)

[a]Soft wheat flour plus medium-protein flour gluten to a final protein level of 16%.
[b]Soft wheat flour gluten replaced medium-protein flour gluten.

Considering the extreme conditions existing during the extrusion process, that conclusion is not surprising. High temperatures, pressures, and shear undoubtedly denatured the protein present regardless of flour type. Denaturation likely would obscure any functional differences between glutens.

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