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Extrudate Cell Structure-Texture Relationships

A.H. BARRETT and M. PELEG

ABSTRACT

Corn-based extrudates that ranged widely in mean cell size and density were produced by varying extrusion moisture and RPM and also by the addition of rice flour, citric acid, tricalcium phosphate, sodium bicarbonate, and gluten. Cell sizes were measured using an Olympus image analysis system and mechanical properties, including breaking stress and plateau stress values achieved during compression, were measured using an Instron. Breaking and plateau stresses were negatively dependent on mean cell size and positively dependent on density in pure corn samples but the form of the relationship was altered by the presence of additives in the extrudates.

Key Words: corn, extrudates, cell structure, texture, gluten, rice flour

INTRODUCTION

HIGH TEMPERATURE-short time extrusion of grains is commonly used in the food industry to produce expanded snack items. The popularity of such products is at least partly a result of their crunchy texture, which arises from the honeycomb structure imparted to the material during extrusion. These items are generally quite low in density, extremely porous, and distinctly cellular. Their complex failure patterns arise from these structural characteristics, since numerous individual cell walls undergo buckling or fracturing during deformation (or chewing). Models for the compression behavior of cellular solids in general have been proposed by Gibson and Ashby (1988) and include: a linear elastic region in which force rises proportionally with deformation, a plateau region during which force remains at a fairly constant level due to the buckling or breakage of cell walls; and a densification region in which force rises rapidly due to compaction of the structure. Plastic and elastic porous materials have smooth compression curves conforming to this overall "shape"; brittle porous structures have a characteristic jaggedness superimposed upon these curves that results from the abrupt fracturing of cell walls. Barrett et al. (1992) analyzed compression curves for corn extrudates and determined that the deformation behavior shifted from plastic to brittle, in conformance to the Gibson-Ashby models, as the storage humidity level was decreased.

The extrusion process and the resultant extruded products have been extensively analyzed, and many researchers have published results describing the effects of different process parameters and formulations on both the physical properties and texture of expanded extrudates. A frequently cited effect is the increase in extrudate density due to increased moisture content (Fletcher et al., 1985; Barrett and Ross, 1990) or reduced shaft speed (Fletcher et al., 1985).

Similarly, many different ingredients have been found to influence the physical and textural properties of extrudates, and the following are relevant to additives we used. Lai et al. (1989) observed that sodium bicarbonate, which releases CO_2 gas, increased the number of cells and decreased cell size in wheat starch extrudates. Faubion and Hoseney (1982b) reported that gluten decreased the radial expansion and breaking

Author Barrett is with the U.S. Army Natick RD&E Center, Food Engineering Directorate, Natick, MA 01760-5018. Author Peleg is with the Food Science Dept., Univ. of Massachusetts, FoodScience Dept. Amherst, MA 01003.

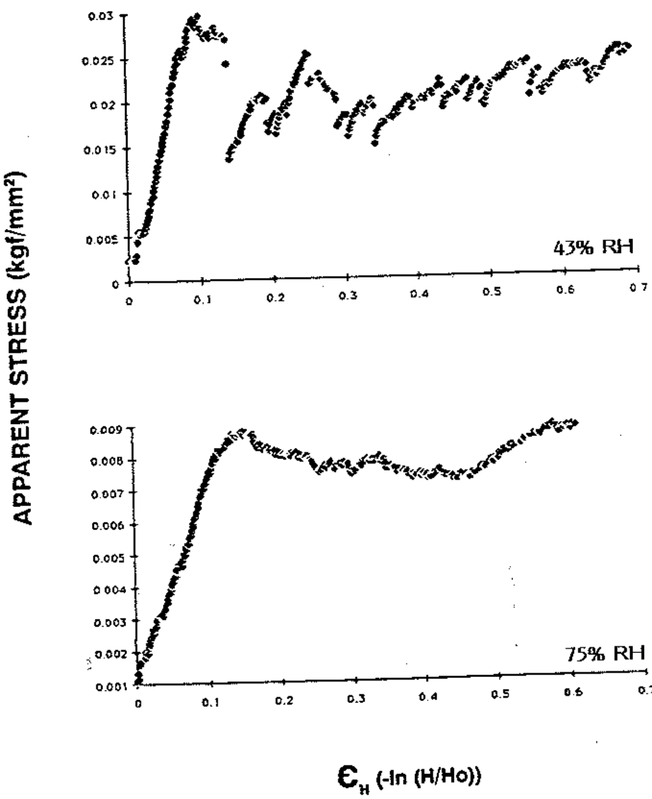

Fig. 1—Typical stress-strain curves of puffed corn meal extrudates.

Table 1—Physical properties of corn extrudates as a function of extrusion variables

Extrusion moisture (%)	rpm	Extrudate density (g/cm³)	Transverse mean cell size (mm²)	Longitudinal mean cell size (mm²)
20.0	400	0.121	8.6	11.0
20.0	300	0.149	6.6	8.2
17.5	400	0.091	12.8	13.8
17.5	300	0.102	12.4	12.2
15.0	400	0.065	13.9	12.1
15.0	300	0.078	12.3	11.7

force of wheat starch extrudates. Acidification of doughs was found to increase depolymerization of starch during extrusion (Kim and Hamdy, 1987) and was described as a potential means of altering texture and physical properties by Harper (1981). Tricalcium phosphate is not commonly employed in extrusion formulation but is used as an inert flow agent for dry powders (Peleg and Hollenbach, 1984) and potentially provides a cell nucleation site during expansion.

Methods of evaluating extrudates have included cell size analysis using image processing (Barrett and Ross, 1990; Barrett and Peleg, 1992; Moore et al., 1990) and textural analysis using Instron compression tests (Launey and Lisch, 1985), bending tests (Faubion and Hoseney, 1982a; Lai et al., 1989) and shear tests (Chinnaswamy and Hanna, 1988). Little work

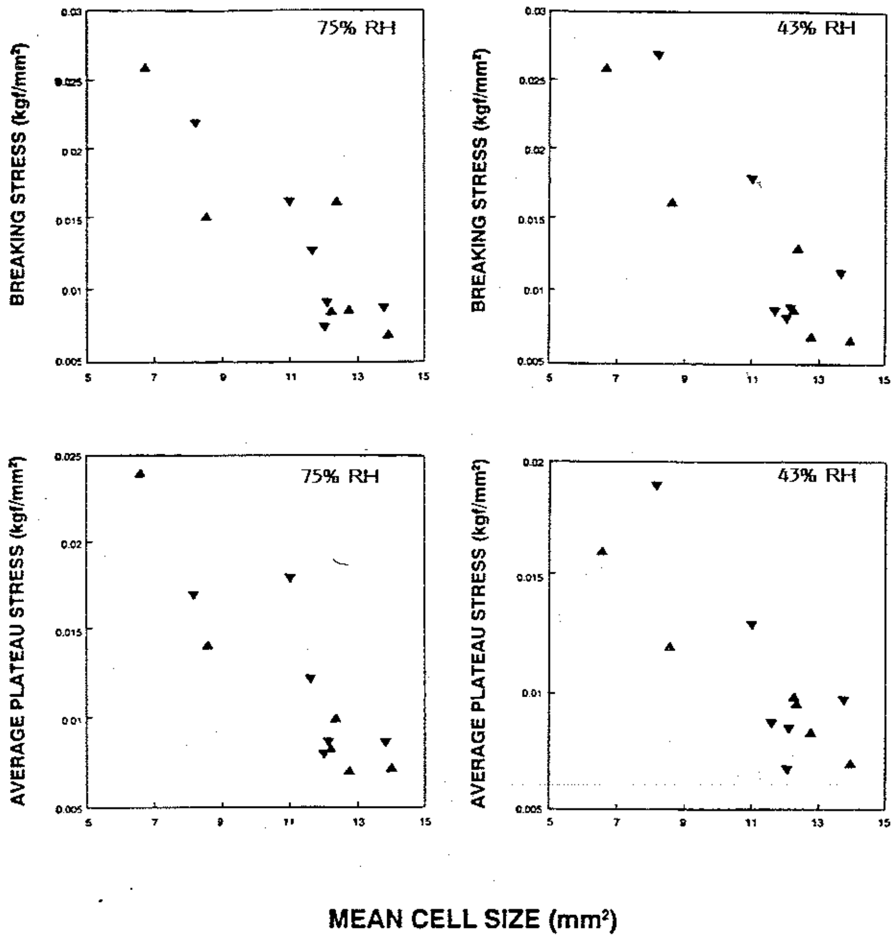

Fig. 2—Breaking and average plateau stress vs extrudate mean cell size. (a), (b) breaking stress; (c), (d) average plateau stress. ▲ transverse samples; ▼ longitudinal samples.

investigating the relationships between the structure and mechanical properties of expanded starch-based extrudates has been reported. However, correlations between cell structure and strength parameters could potentially be valuable product development tools that allow prediction of certain textural characteristics based upon measured physical properties of the materials. The objective of our work was to establish relationships between structual characteristics of extrudates, such as mean cell size and density, and strength parameters, such as breaking and plateau stresses developed during compression. Specifically, a range of samples having widely different structures were produced for these experiments by altering the processing conditions or incorporating additives. Moisture and screw speed were selected as variables because of obvious effects on melt viscosity and shear conditions in the extruder and also their reported effects on product properties. The additives were selected because of potential effects on cell nucleation and growth (in the case of sodium bicarbonate and tricalcium phosphate) or potential alteration of the starch network (hydrolysis in the case of citric acid; protein interaction in the case of gluten).

Analyses were conducted in directions both parallel and perpendicular to the direction of extrusion in order to determine any effect of anisotropy in the structures. Furthermore, mechanical tests were carried out on samples that had been equilibrated at 2 different humidity levels in order to assess the effects of water activity on observed structure-strength relationships. These two levels, 43% and 75% RH, in each case yielded samples having compression curves that indicated brittle and plastic collapse, respectively (Barrett et al., 1992).

MATERIALS & METHODS

A RANGE of corn meal based extrudates (raw material from Lincoln Grain Co.) that had widely varying structures were prepared using different extruder conditions and also different additives. Samples were produced on a Werner & Pfliederer ZSK-30 twin screw extruder using a 20:1 L/D ratio and a 4mm diameter die. Fixed parameters for the pure corn extrudates were a 27 kg/hr solids feed rate and a barrel temperature profile of 38-38-116-116-138-138°C. Process variables were feed moisture content, 15%, 17.5%, and 20%, and shaft rpm, 300 and 400 rpm at each moisture content. In separate experiments, the following additives were incorporated into corn extrudates produced using the low moisture (15%), high shear (400 rpm) processing conditins: tricalcium phosphate at 0.75 and 1.5%, citric acid at 0.80 and 1.6%, 50% rice flour plus gluten at 10% and 20%, 50% rice flour plus sodium bicarbonate at 0.50 and 1.0%. The samples containing rice flour were also produced at a lower solids feed rate of 19 kg/hr.

Image analysis of extrudates

An Olympus Company Cue 2 image analysis system was used to measure the mean area size of cells in cut sections of the extrudates. Transverse and longitudinal sections were sliced from the extruded products and prepared and analyzed according to the procedure described by Barrett and Ross (1990). Sections of each sample (2 to 4) in each orientation were evaluated and the data combined so that there were ≈ 50 to 100 cells in the distributions. Data were imported into a Minitab statistical program which computed the average cell size values for each sample.

Instron compression tests of extrudates

Each sample was cut into ≈ 1cm cubes. Care was taken to align cut faces so that edges were either perpendicular or parallel to the axis of the extrudate sample (direction of extrusion). Transverse and longitudinal faces were distinguished by marking the extrudates with ink dots. The cut samples were then equilibrated at 22°C for 72 hr in desiccators over saturated solutions of potassium carbonate (R.H. 43%) and sodium chloride (R.H. 75%). The samples were compressed to 50% of original height at a crosshead speed of 0.1667 mm/sec on an Instron UTM model interfaced with a Macintosh II computer. Voltage

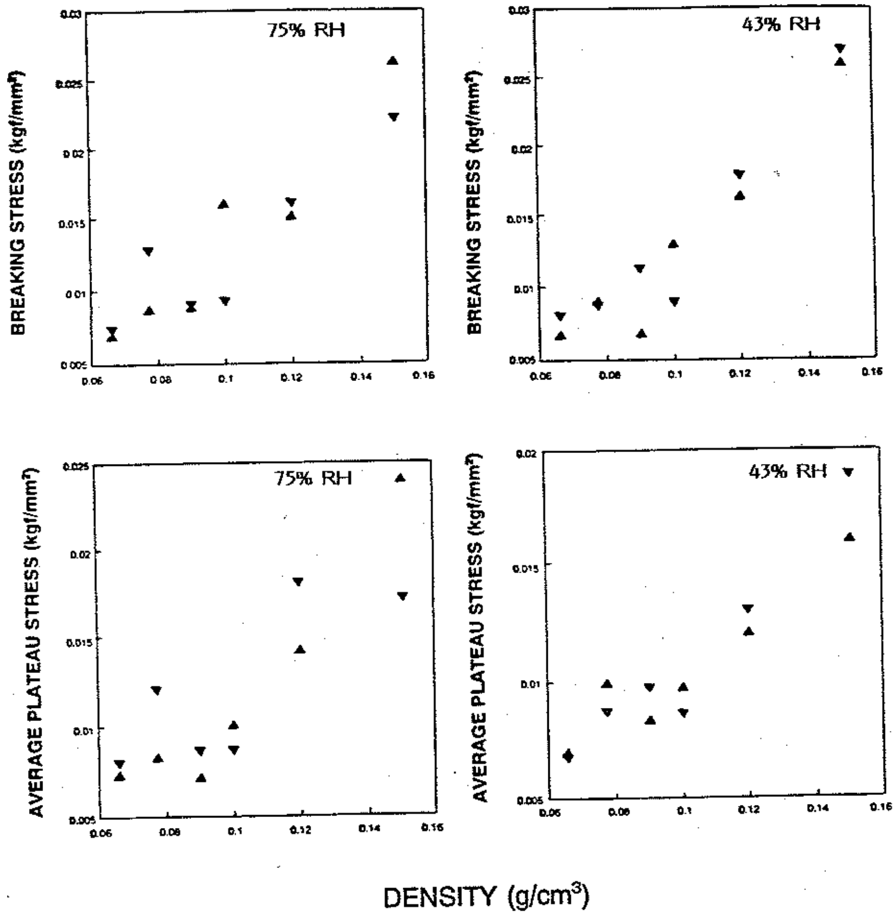

Fig. 3—Breaking and average plateau stress vs extrudate density. (a), (b) breaking stress; (c), (d) average plateau stress. ▲ transverse samples; ▼ longitudinal samples.

vs time output was converted into digitized stress (kgf/mm^2) vs Hencky strain ($e_H = -\ln(H/H_o)$ (where H and H_o are the sample height and original sample height, respectively) relationships at a sampling rate of 10 points/sec. Breaking stress was defined as either the first point at which stress fell appreciably (by at least 0.002 kgf/mm^2) or, in the case of the more plastic, high humidity samples, the stress level at which the slope of the stress-strain function decreased by at least 20 degrees. Average plateau stress was calculated directly by averaging the stress values between points 100 and 200 in the compression curve. Longitudinally and transversely oriented samples of each extrudate were compressed with either four or five replicates, and the average breaking stress and plateau stress for each extrudate calculated.

Density measurement

The bulk densities of extrudates were measured by weighing 10 cm long cylindrical sections and determining their diameter by caliper measurement (avg of three diameter measurements for each specimen). Bulk density determinations (4) of each extrudate lot were averaged.

RESULTS AND DISCUSSION

STRESS LEVELS rose linearly with strain and then abruptly formed a plateau region. Typical stress-strain curves for corn extrudates equilibrated under 75% RH and 43% RH were recorded (Fig. 1). Curves for the lower humidity samples were generally less smooth in the plateau region than were those for the high humidity samples.

The extrusion parameters produced extrudates with widely varying densities and average cell sizes (Table 1). In general, density increased and cell size decreased with increased moisture or decreased screw speed. The samples produced with higher moisture contents were slightly anisotropic. That is, they displayed larger cells when analyzed in the longitudinal as opposed to the transverse direction. This tendency was not apparent in the more expanded products produced at lower moisture contents. Strong dependencies between mean cell size and breaking or plateau stress were evident in the corn extrudates. Both breaking and plateau stress decreased (Fig. 2) as mean cell size increased, indicating a general weakening of structures with greater expansion of cells. This trend was evident in samples equilibrated at either humidity level. While humidity affected the overall shape of the compression curves, it did not, at these levels, markedly affect strength. Breaking and plateau stresses also correlated positively with bulk density, (Fig. 3). In addition, data for samples evaluated in transverse and longitudinal directions are distinguished by different symbols in these figures: clearly, relationships between strength parameters and either cell size or density were consistent in both orientations.

If either changes in density or cell size are considered independently some predictions can be made about effects on mechanical properties. Obviously, an increase in bulk density given a constant cell size would imply thickening of an invariant number of cell wall components, resulting in greater strength and in larger forces required to compress the material. The effects of a decrease in cell size given a constant density, which produces a more finely divided structure, are more difficult to predict. Individual cell walls are thinner, but there are many more of them to support the structure and the length of the wall struts is shorter. Moments of inertia, and hence resistance to buckling, in individual members are positively related to thickness and negatively related to length (Shigley, 1977). However, in the case of the corn extrudates, an increase in density was also coupled with decreased cell size, indicating that the structure was "filled in" and generally less porous (with thicker cell walls) as cell size decreased. Thus, the increased strength of the extrudates with smaller cells and more dense structures was not surprising. It is of course also possible

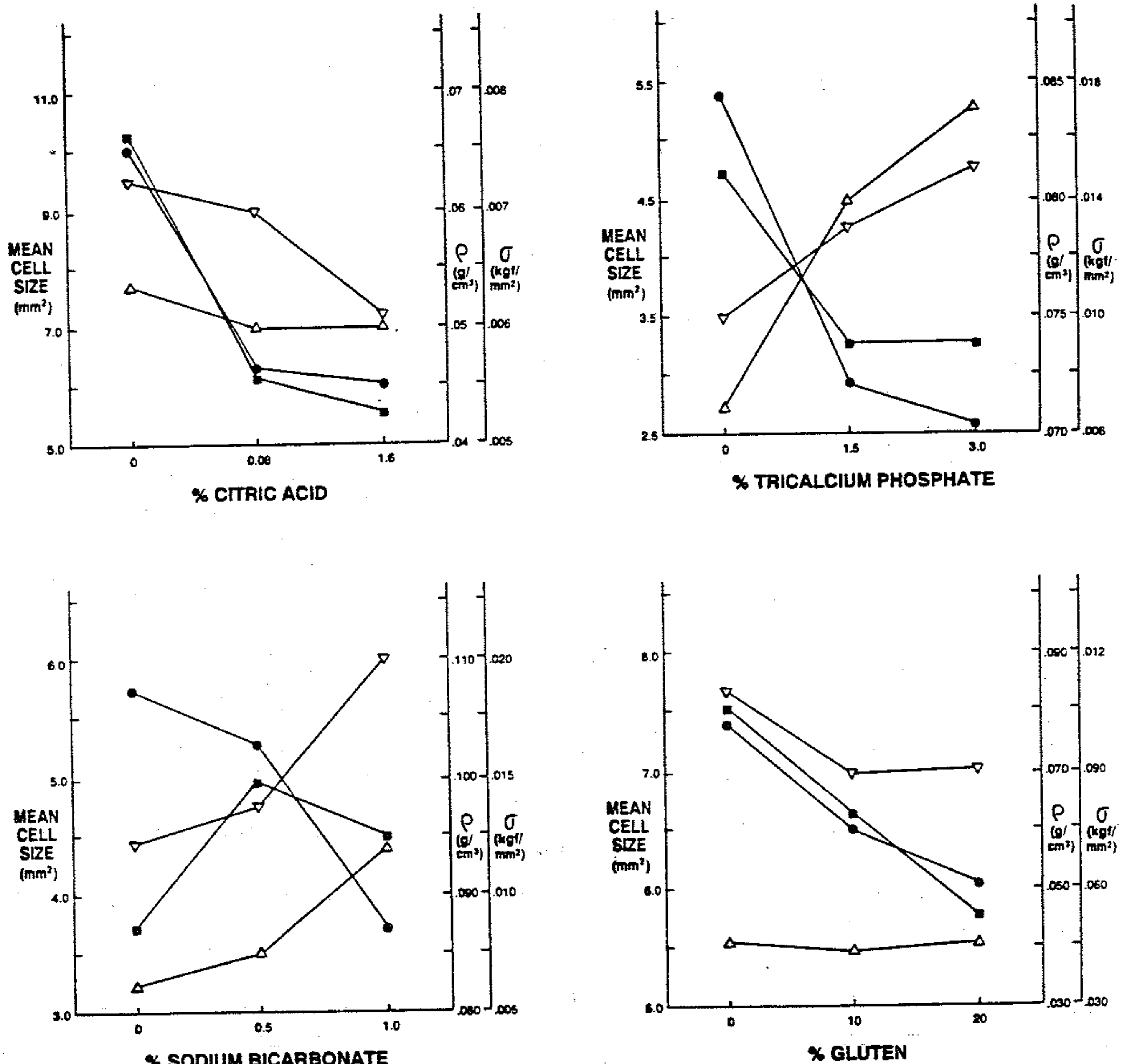

Fig. 4—Mean cell size (●), density (ρ, ■) and average plateau stress (σ; △ 43% RH, ▽ 75% RH) vs additive concentration.

that the samples were somewhat chemically and microstructurally different since different moisture levels or shaft speeds can effect different degrees of starch dextrinization (Gomez and Aguilera, 1984; Wen et al., 1990). For example, the extrudates produced at lower moisture levels, which had the lowest bulk densities, could have had inherently weaker cell walls because of a reduction in average molecular weight of the starch. Nevertheless, for the pure corn extrudates, breaking and plateau stresses correlated strongly with both density and average cell size in relationships that are potential guidelines of extrudate strength.

The other samples, which contained citric acid, tricalcium phosphate, sodium bicarbonate and gluten, did not show the same relationship between cell size and density. This illustrated that the effects of composition can in some instances supercede those of physical structure. Plots of bulk density, average cell size, and plateau stress vs additive concentration were compared for transverse sections equilibrated at 43 and 75% RH (Fig. 4). Each additive except sodium bicarbonate simultaneously reduced both density and average cell size. Sodium bicarbonate also reduced cell size but very slightly increased density. However, the resulting effects on strength were extremely variable. For example, while tricalcium phosphate and citric acid had similar effects on the density and average cell size of corn extrudates, they had markedly different effects on plateau stress. Tricalcium phosphate greatly increased plateau stress whereas citric acid had relatively little effect on that parameter and reduced it slightly. It is likely that the citric acid at least somewhat hydrolyzed the starch in the extrudates. A decrease in molecular weight may have reduced the inherent strength of the cell wall material and cancelled any strengthening effect of decreased cell size. Tricalcium phosphate probably acted as a bubble-nucleating agent, thus producing a very fine cellular structure that had a high resistance to compression.

Sodium bicarbonate and gluten in the corn-rice extrudates, at the concentrations used, also produced opposite textural effects. Sodium bicarbonate, which decreased mean cell size and slightly increased density (effects that were qualitatively similar to those of increased moisture in the corn extrudates) markedly increased plateau stress. Conversely, gluten had a negligible effect on plateau stress (reducing it slightly only at the high humidity level) even at high percentages. Once again, the differences in strength caused by these compounds were probably attributable to differences in chemistry or microstructure of the cell wall material. Faubion and Hoseney (1982b) reported extreme roughness and "shredding" in cell walls of wheat starch extrudates due to gluten addition, and a similar disruptive result may have occurred in this instance. The low level of sodium bicarbonate used, while markedly increasing the number of cells, probably had relatively less effect on cell wall properties. However, that additive may have slightly increased the pH of the extrudate (as was reported by Lai et al., 1989) and the product was slightly browned, indicating some degree of caramelization. Plateau stresses in the corn-rice extrudates were apparently more affected by equilibration humidity than were those in pure corn samples. Those values in the corn-rice products were much higher at 75% than at 43% relative humidity.

CONCLUSIONS

PLATEAU STRESS increased greatly with reduced cell size in two extrudates that contained additives. In the other two instances structures were weakened slightly, despite smaller cells. Samples that increased in strength showed either a modest reduction (<10%) or a slight increase in density, whereas samples that were slightly weakened had much more pronounced reductions in density (>30%). While no two samples were constituently identical, since either the ingredients or level of ingredients varied, cell size may be a dominant factor in extrudate strength that is lessened only by extreme changes in density or chemical composition.

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*DIFFERENTIATION OF INSOLUBLE FIBERS. . .*From page 1247

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*SPORE POPULATION DYNAMICS. . .*From page 1252

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