Effects of Some Baking Ingredients on Physical and Structural Properties of Wheat Flour Extrudates[1]

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ABSTRACT

The effects of six baking ingredients (sucrose, nonfat dry milk, whole egg powder, shortening powder, glyceryl monostearate [GMS], sodium bicarbonate) on expansion, bulk density, breaking strength, and cell structure of wheat flour extrudates were studied. A Wenger TX52 twin-screw extruder was used to prepare extrudate samples. A one-half fractional 2^6 factorial experimental design was used to determine the effects of each baking ingredient on wheat flour processed under fixed extrusion conditions. Feed moisture content was 31%, barrel temperature before the die was 130°C, and screw speed was 400 rpm. Extrudate expansion was characterized by sectional, longitudinal, and volumetric expansion indexes (SEI, LEI, and VEI, respectively). Cell structure was analyzed with a scanning electron microscope and by counting the number of cells per unit area. The SEI and LEI were significantly affected by both sucrose and GMS ($P < 0.01$). The interaction of shortening powder and GMS had significant effects on the LEI ($P < 0.01$), and a sucrose-egg interaction affected the SEI ($P < 0.05$). Bulk density was significantly affected by sucrose, shortening powder, and GMS ($P < 0.05$). Sucrose and shortening powder had significant effects on breaking strength and cell structure.

Extrusion cooking is a high-temperature, short-time method applied in many food production processes, such as starch depolymerization, manufacture of snack food and textured vegetable protein, and oil extraction from oilseeds (Hakulin et al 1983, Abbott 1987, Dziezak 1989). Some bakeries have also developed and marketed extruded bread, which is decidedly simpler than the conventional baking process in regard to investment and operations (Harper 1981). However, most products made by extrusion cooking are directly expanded snacks, not bread, because extrusion is not completely comparable to conventional baking.

In breadmaking, a dough undergoes several levels of stress during mixing and proofing that cause mild expansion during fermentation. The most fundamental differences between conventional baking and extrusion are the short times allowed for dough development in the extruder system and the shear-based cooking process.

The first application of extrusion cooking to continuous baking was in flat bread, which has become quite popular in Europe. Most published tests have used a laboratory-scale extruder. Wiedmann (1987) studied the influence of individual process and formulation variables on some important product characteristics and reported that water, fiber, milk product, and starch were important in determining extrudate density. Scale-up of the extrusion process, product development, and regulation and control of extrusion were also studied extensively (Meuser and Wiedmann 1989).

Another approach to extrusion cooking for flat bread has been adding extrudate powder to the bread formula to improve quality and to substitute for flour (Linko et al 1984, Sharma and Rasper 1988). Linko et al (1984) studied flat-bread production with extrusion-cooked sprouted wheat kernels. They concluded that flour with a high amylase content could be employed successfully in flat-bread production with continuous extrusion. Wiedmann and Strobel (1987) reported that the cost of producing flat bread with extrusion cooking decreased about 55% compared to producing it with conventional baking methods. Pregelatinized flour, prepared by extrusion cooking, was substituted for unprocessed wheat flour in breadmaking. Bread containing extruded wheat flour was softer and more elastic and remained fresh during extended storage (Mattson et al 1985, Seiler 1985).

The influences of some baking ingredients during extrusion have been studied by several researchers (Faubion and Hoseney 1982 b, Lai et al 1989, Moore et al 1990). Faubion and Hoseney (1982 a,b) determined the effects of moisture content, flour type, proteins, and lipid on the expansion of wheat flour extrudates. Faubion et al (1982) also studied the effects of different emulsifiers on the expansion of wheat starch extrudates. They reported that the expansion of extruded starch was reduced as the emulsifier level increased from 0.25 to 0.75%.

Meuser and Wiedmann (1989) observed that the addition of casein to wheat starch decreased the extrudate's bulk density because casein expanded more than wheat starch.

Moisture content of feed materials also affects extrudate characteristics. Moisture is added to feed materials in many ways, including water, steam, and ingredient blends, such as emulsions or syrups (Harper 1981). Faubion and Hoseney (1982a) reported that wheat starch expanded more than flour within the 17–24% moisture range. Meuser and Wiedmann (1989) studied the effect of initial moisture content of the formulation on flat-bread density and concluded that density increased sharply with water addition.

Fats or oils tend to weaken the doughs, reducing the strength of the extruded product and increasing its plasticity (Harper 1981). Faubion and Hoseney (1982b) established that adding lipids to wheat flour decreases extrudate expansion and changes texture and ultrastructure.

Reduced sugars cause browning. Moore et al (1990) proposed that sucrose increases extrudate density by decreasing the water activity in the cooked doughs inside the extruder. On the other hand, Meuser and Wiedmann (1989) believed that an increase in extrudate density results from liquification of the sugar in the mixture, via melting. Lai et al (1989) reported that the extrusion of wheat starch with sodium bicarbonate improved extrudate expansion but weakened textural strength and caused browning.

Fundamental studies of the effects on extrudates of common baking ingredients that affect the quality of flat breads or snacks are needed before development of an extrusion-cooked bread process. Therefore, the objective of this study was to determine the effects of some baking ingredients on the physical and structural properties of wheat flour extrudates.

MATERIALS AND METHODS

Materials

Hard red winter wheat flour was obtained from a pilot mill (Department of Grain Science and Industry, Kansas State University, Manhattan). Proximate analysis indicated that it contained 11.6% protein (N × 6.25), 0.55% ash, and 14.4% moisture content. Baking ingredients used in this study included: sucrose (Amstar Sugar Corporation, New York, NY); spray processed nonfat dry milk (NFDM) (American Ingredients, Kansas City, KS); dry whole egg powder (Universal Foods Corporation, Milwaukee, WI); dry shortening powder (Armour Food, Springfield, KY); glyceryl monostearate (GMS, Eastman Chemical Products, Kingsport, TN); sodium bicarbonate (Church & Dwight, Princeton, NJ); and salt.

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Extrusion Cooking and Sample Preparation

Wheat flour was blended with the other baking ingredients in a ribbon mixer for 15 min. A Wenger TX52 corotating twin-screw extruder (Wenger Mixers, Sabetha, KS) was used. The extrusion conditions (process variables) were selected based on preliminary experiments to determine optimum wheat flour expansion and extruder operating conditions. Two die holes, 4.02 mm diameter, were open. Water was injected into the preconditioner and the extruder barrel to adjust dough moisture content. Dough moisture contents were 31 ± 1.3%, depending on differences in the baking ingredients. The barrel temperature before the die was controlled at 130°C by circulating heated oil to the jacket. The wheat flour and baking ingredient mixture was fed at 1.5 kg/min, and the screw speed was 400 rpm.

The two-knife cutter speed was 15 rpm. Cut extrudate was dried to approximately 15% moisture content. After drying, the pieces were kept in a refrigerator at 2°C. Samples of the extrudates were redried using a forced-air dryer (Chicago Surgical and Electrical, Chicago, IL) at 50°C for 12 hr. Extrudate samples dried to 8% moisture content were analyzed for physical properties. For structural analysis, extrudate samples were rehydrated to 30% moisture content in a desiccator containing distilled water for 12 hr.

Expansion Indexes

Sectional, longitudinal, and volumetric expansion indexes (SEI, LEI, and VEI, respectively) were determined according to the method reported by Alvarez-Martinez et al (1988). Extrudate diameters were measured with a caliper; ten pieces were selected at random and one reading was taken per piece.

Bulk Density

Density was calculated by weighing the quantity required to fill a known volume. Fine glass beads were used as a replacement media to minimize the void volume. Bulk density was expressed as the mean of five readings.

Breaking Strength

Breaking strength was determined with an Instron model 1130 Universal Texture Analyzer (Instron Corp., Canton, MA). Measuring conditions included: 50-kg compression load cell capacity, 5 cm/min crosshead speed, and 10 cm/min chart speed. A movable blade probe with triangular cutout (32-mm base width; 29-mm height; and 61° shearing angle) was used. The spacing between the two cut supports was 2.5 mm.

Extrudate Structure Examination

Extrudate samples were prepared for the scanning electron microscope (SEM) study and for cell structure and shape analysis. Softened extrudate samples were cut using a sharp razor blade and dried at 50°C for 5 hr. Cut extrudate pieces (~1 cm) at 8% moisture content were mounted on SEM sample stubs. After coating with carbon and gold-palladium, samples were examined and photographed using an ETEC (Perkin-Elmer, Hayward, CA) autoscanning electron microscope operating at 10 kV acceleration.

In addition, extrudate cross sections were cut and their surfaces blackened with ink and photocopied on a copy machine. The number of air cells per unit area was calculated from enlarged photocopies.

Experimental Design and Statistical Analysis

Formulations were prepared according to a one-half fractional 2^6 factorial design (Cochran and Cox 1957) with sucrose, NFDM, whole egg powder, shortening powder, GMS, and sodium bicarbonate (SBC) as the baking ingredients. Concentrations were calculated on the basis of wheat flour weight (baker's percent). The concentrations were (low, high): sucrose (5, 10%), NFDM (2, 8%), whole egg powder (3, 9%), shortening powder (2.5, 5%), GMS (0.25, 1%), and SBC (0.1, 0.5%). Salt concentration was fixed at 1%. Thirty-two treatments were separated into four blocks because four days were required to extrude that many samples (Table I).

The dependent response variables were expansion indexes, bulk density, breaking strength, and cell numbers per unit area. Data generated from the experimental design were used to analyze the main effects of the baking ingredients, the two-way interactions between them using analysis of variance, and the mean response variables at low and high ingredient concentrations (SAS 1991).

RESULTS AND DISCUSSION

Effect of Baking Ingredients on Expansion Indexes

Mean values and mean square errors for expansion indexes are shown in Tables II and III, respectively. The effects of the baking ingredients on the expansion indexes are shown in Figure 1.

The SEI was significantly affected by sugar, shortening powder, and GMS ($P < 0.01$). A sucrose by shortening powder interaction had a significant effect on the SEI ($P < 0.05$).

The SEI decreased when sugar content increased from 5 to 10%, in agreement with Meuser and Wiedmann (1989). NFDM did not significantly affect the SEI under the experimental conditions used. Extrusion of casein and wheat flour was performed by Van de Voort et al (1984). They also reported that casein, at 10–30% of total solids, did not significantly influence extrudate expansion.

Dried whole egg powder at 3 or 9% did not influence the SEI. With an increase in shortening powder content from 2.5 to 5%, the SEI decreased from 10.25 to 7.14. On the other hand, Faubion and Hoseney (1982b), using a Soxhlet extractor with petroleum ether, found that free wheat flour lipid increased extrudate expansion. A mixture of corn gluten and defatted soy protein concentration was extruded by Bhattacharya and Hanna (1988), who reported that the expansion ratio increased with decreasing

TABLE I
Baking Ingredients (%) Added to Wheat Flour Extrudates

Treatment No.[a]	Sucrose	NFDM[b]	Egg	Shortening	GMS[c]	SBC[d]	Salt
101	5	2	3	2.5	1	0.5	1
102	10	8	3	5	1	0.1	1
103	5	2	9	5	1	0.5	1
104	10	8	9	5	0.25	0.1	1
105	10	8	3	2.5	0.25	0.1	1
106	10	8	9	2.5	1	0.1	1
107	5	2	3	5	0.25	0.5	1
108	5	2	9	2.5	0.25	0.5	1
209	10	8	3	2.5	1	0.5	1
210	10	8	3	5	0.25	0.5	1
211	5	2	3	2.5	0.25	0.1	1
212	5	2	9	5	0.25	0.1	1
213	10	8	9	2.5	0.25	0.5	1
214	5	2	3	5	1	0.1	1
215	5	2	9	2.5	0.25	0.1	1
216	10	8	9	5	1	0.5	1
317	5	8	9	5	1	0.1	1
318	5	8	3	5	0.25	0.1	1
319	10	2	3	2.5	0.25	0.5	1
320	5	8	9	2.5	0.25	0.1	1
321	5	8	3	2.5	1	0.1	1
322	10	2	9	2.5	1	0.5	1
323	10	2	3	5	1	0.5	1
324	10	2	9	5	0.25	0.5	1
425	10	2	3	5	0.25	0.1	1
426	5	8	3	5	1	0.5	1
427	10	2	3	2.5	1	0.1	1
428	5	8	9	5	0.25	0.5	1
429	10	2	9	5	1	0.1	1
430	5	8	3	2.5	0.25	0.5	1
431	5	8	9	2.5	1	0.5	1
432	10	2	9	2.5	0.25	0.1	1

[a]Treatments 101–108 produced on the 1st day (block 1); 209–216 2nd day (block 2); 317–324 3rd day (block 3); 425–432 4th day (block 4).
[b]Nonfat dry milk.
[c]Glyceryl monostearate.
[d]Sodium bicarbonate.

lipid content.

The SEI decreased from 10.52 to 6.87 as GMS content increased from 0.25 to 1%. Faubion et al (1982) had suggested that the effects of emulsifiers on extrudate properties were complex and varied with the type, material being extruded, and amount and hydrophilic-lipophilic balance of the emulsifier. The addition of GMS caused a significant reduction in extrudate expansion because of the formation of an amylose-GMS complex (Galloway et al 1989).

SBC did not significantly influence SEI when it was added at 0.1 or 0.5%. When SBC was added to wheat starch (Lai et al 1989) and corn starch (Chinnaswamy and Hanna 1988) before extrusion, the expansion ratio decreased with increasing concentration. Chinnaswamy and Hanna (1988) speculated that SBC degraded the starch molecules, and starch molecular degradation during extrusion is known to reduce expansion.

The LEI is defined as the ratio of the extrudate velocity after expansion to the velocity of dough inside the die (Alvarez-Martinez et al 1988). GMS was the significant factor that most affected LEI ($P < 0.01$). LEI increased significantly, as the GMS content increased from 0.25 to 1% ($P < 0.01$). On the other hand, none of the other ingredients significantly influenced LEI. The addition of GMS may influence dough flow properties because it forms complexes with amylose and also acts as a lubricant. The resulting changes in rheological properties may increase the

TABLE II
Mean Values for Extrudate Sample Expansion Indexes

Treatment No.	Expansion Index		
	Sectional	Longitudinal	Volumetric
101	10.39	2.30	23.93
102	3.28	1.13	3.69
103	3.47	1.65	5.71
104	9.88	1.30	12.96
105	11.44	1.00	16.01
106	8.19	1.73	14.19
107	10.01	1.68	16.78
108	11.90	1.64	19.47
209	7.31	2.18	15.91
210	9.63	1.37	13.23
211	13.48	1.34	18.05
212	10.71	1.78	19.03
213	11.00	1.34	14.78
214	6.21	1.66	10.34
215	8.92	1.63	14.58
216	5.56	1.45	8.05
317	6.31	1.78	11.25
318	11.79	1.68	19.79
319	5.14	1.33	6.86
320	11.87	1.16	13.72
321	11.46	1.98	22.67
322	7.76	1.53	11.84
323	3.89	1.87	7.28
324	10.73	1.40	15.05
425	3.43	1.34	4.59
426	5.58	1.80	10.02
427	7.73	2.20	17.00
428	10.25	1.26	12.88
429	3.45	1.48	5.11
430	14.60	1.40	20.44
431	10.35	1.94	20.08
432	12.42	1.19	14.72
Mean	8.69	1.59	13.75
SD	3.239	0.308	5.391

TABLE III
Mean Square Errors for Extrudate Sample Expansion Indexes

Source	SEI[a]	LEI[b]	VEI[c]
Sucrose	41.5616***[d]	0.1845	187.5500***
NFDM[e]	11.5156	0.0385	11.6765
Egg	1.7113	0.1785	5.4203
Shortening	77.4390***	0.0851	244.7025***
GMS[f]	106.6530***	1.0178***	42.1133
SBC[g]	0.2813	0.0570	0.6641
Block	0.6275	0.0011	2.1777
Sucrose × Egg	22.5792**	0.0048	43.7814
NFDM × Egg	3.6181	0.0063	6.5975
Sucrose × Shortening	1.7578	0.0657	1.0476
NFDM × Shortening	0.1128	0.0345	0.3549
Egg × Shortening	1.0082	0.0751	14.8649
Sucrose × GMS	0.9180	0.0003	1.3001
NFDM × GMS	1.2880	0.0063	0.0205
Egg × GMS	3.8365	0.0675	22.5960
Shortening × GMS	11.2101	0.4255**	148.8244
Egg × SBC	0.0741	0.0344	0.0000
Shortening × SBC	3.8642	0.0158	0.0005
GMS × SBC	0.0085	0.0259	0.3549

[a] Sectional expansion index.
[b] Longitudinal expansion index.
[c] Volumetric expansion index.
[d] ** = $P < 0.05$; *** = $P < 0.01$.
[e] Nonfat dry milk.
[f] Glyceryl monostearate.
[g] Sodium bicarbonate ($NaHCO_3$).

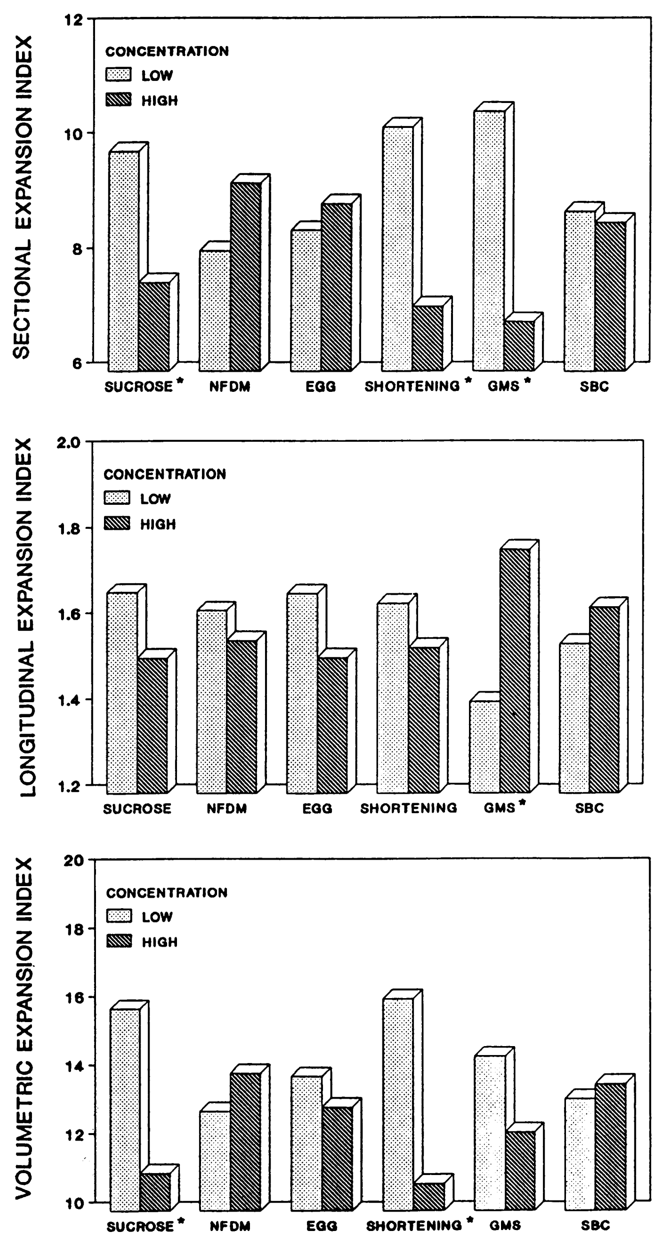

Fig. 1. Effects of baking ingredient concentrations on sectional, longitudinal, and volumetric expansion indexes. * = indicates significant differences ($P < 0.01$).

LEI, but molecular reformations, like those seen with vegetable protein, are not evident (Alvarez-Martinez et al 1988). Feed moisture contents can influence cereal extrudate LEI. Kim et al (1989) reported that flour extrudate LEI increased as the feed material moisture content increased from 15 to 22%.

TABLE IV
Mean Values for Bulk Density, Breaking Strength, and Cell Numbers

Treatment No.	Bulk Density	Breaking Strength	Cell Numbers[a]
101	0.262	4.69	8.37
102	0.767	15.93	48.20
103	0.710	6.96	59.28
104	0.346	10.73	24.01
105	0.379	4.58	12.43
106	0.340	4.96	16.40
107	0.312	5.78	11.84
108	0.285	6.20	6.64
209	0.359	4.66	23.78
210	0.344	8.89	18.05
211	0.263	6.40	9.96
212	0.328	6.09	17.70
213	0.307	7.30	15.08
214	0.473	11.68	24.17
215	0.297	6.81	23.03
216	0.515	12.01	21.34
317	0.444	5.23	20.05
318	0.311	3.89	11.40
319	0.289	5.91	49.22
320	0.308	7.43	15.98
321	0.261	3.34	14.48
322	0.382	6.08	21.39
323	0.487	4.68	54.86
324	0.317	6.85	14.74
425	0.315	5.95	50.64
426	0.434	3.00	35.42
427	0.342	4.39	27.61
428	0.313	6.21	16.96
429	0.662	10.44	45.77
430	0.263	4.13	10.83
431	0.285	3.86	15.27
432	0.293	7.99	10.82
Mean	0.375	6.66	23.62
SD	0.1295	2.863	14.898

[a]Cell numbers per area (cm^{-2}).

TABLE V
Mean Square Errors for Extrudate Bulk Density, Breaking Strength, and Cell Numbers

Source	Bulk Density	Breaking Strength	Cell Number[a]
Sucrose	0.0250**[b]	27.4726**	731.1488**
NFDM[c]	0.0000	0.0176	423.1141
Egg	0.0023	9.2988	139.4450
Shortening	0.1462***	39.5828**	1165.7206**
GMS[d]	0.1309***	0.6023**	831.5042**
SBC[e]	0.0022	10.8462	3.3930
Block	0.0093	12.7195	85.6258
Sucrose × Egg	0.0082	0.9419	837.2232**
NFDM × Egg	0.0196	0.0587	1.9013
Sucrose × Shortening	0.0000	17.4493	2.3220
NFDM × Shortening	0.0045	7.6734	80.5815
Egg × Shortening	0.0004	1.9061	0.2211
Sucrose × GMS	0.0072	0.9488	36.9800
NFDM × GMS	0.0045	0.6992	16.1312
Egg × GMS	0.0016	2.6970	45.3152
Shortening × GMS	0.0974***	22.2612**	483.4495
Egg × SBC	0.0065	3.2576	8.5491
Shortening × SBC	0.0008	4.8750	26.8644
GMS × SBC	0.0000	7.0782	27.3430

[a]Per unit area (cm^{-2}).
[b]* = $P < 0.01$; ** = $P < 0.01$.
[c]Nonfat dry milk.
[d]Glyceryl monostearate.
[e]Sodium bicarbonate.

The VEI is a function of the SEI and the LEI. Thus, the same factors affecting those two expansion indexes should also affect VEI. Sucrose and shortening powder significantly influenced VEI ($P < 0.01$ and $P < 0.01$, respectively). An increase in sucrose concentration from 5 to 10% reduced VEI from 16.17 to 11.33. An increase in shortening powder concentration (2.5 to 5%) also decreased VEI from 16.52 to 10.99. The shortening powder by GMS interaction was also significant ($P < 0.05$).

Effect of Baking Ingredients on Bulk Density

Tables IV and V contain mean values and mean square errors for bulk density. The effects of baking ingredients on bulk density, load, and number of cells per area are shown in Figure 2.

Sucrose, shortening powder, and GMS significantly influenced the bulk density ($P < 0.05$, $P < 0.01$, and $P < 0.01$, respectively). A shortening powder by GMS interaction was also significant ($P < 0.01$).

Extrudate bulk density increased with increasing sucrose, shortening powder, and GMS. Bulk density increased from 0.35 to 0.40 as sucrose concentration increased. When shortening powder and GMS were increased, the bulk density increased from

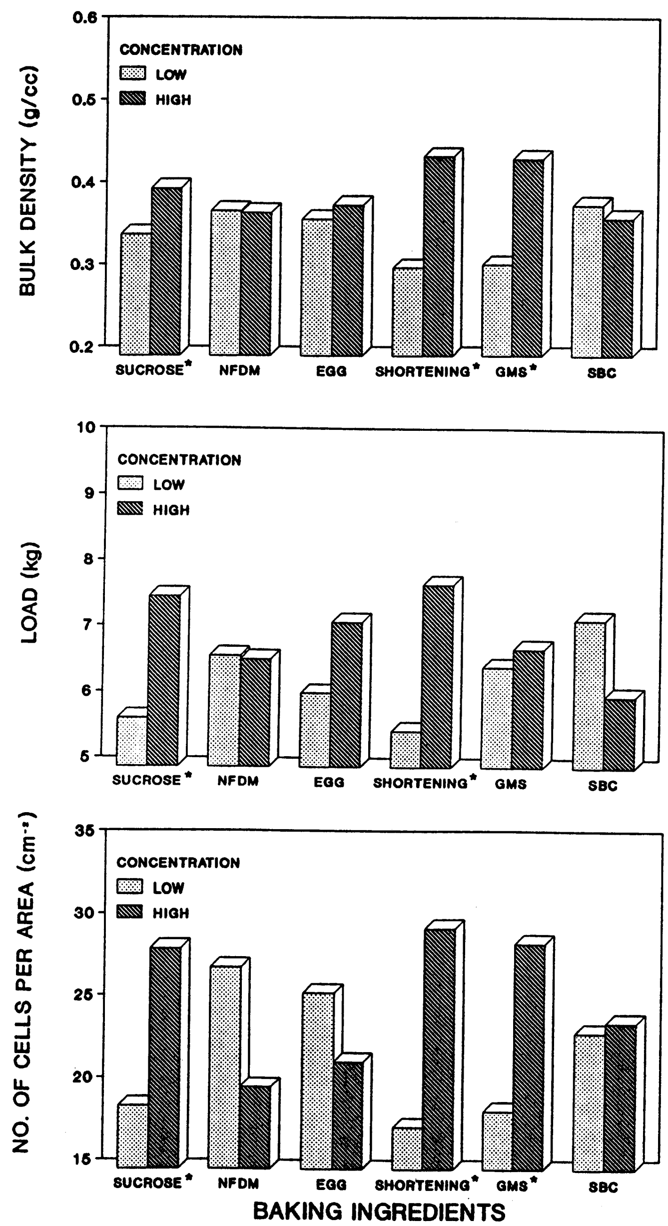

Fig. 2. Effects of baking ingredient concentrations on bulk density, breaking strength, and number of cells per unit area. * = indicates significant differences ($P < 0.05$).

0.30 to 0.44 and from 0.31 to 0.44, respectively. The increase in bulk density with sucrose may have resulted from its liquefaction, via melting, during extrusion cooking (Meuser and Wiedmann, 1989). Bulk density correlated negatively with SEI ($r = -0.75$, $P < 0.01$) and VEI ($r = -0.73$, $P < 0.01$) (Table VI).

Effect of Baking Ingredients on Breaking Strength

Mean values and mean square errors for extrudate breaking strengths are indicated in Tables IV and V. Sucrose and shortening powder significantly affected the breaking strength ($P < 0.1$ and $P < 0.05$, respectively). Shortening powder significantly interacted with GMS ($P < 0.1$). Strength increased from 5.73 to 7.58 kg as sucrose concentration increased from 5 to 10%. An increase in shortening powder concentration from 2.5 to 5% also increased breaking strength from 5.55 to 7.77. Although the differences were not statistically significant, an increase in SBC concentration from 0.1 to 0.5% reduced breaking strength from 7.24 to 6.07 kg. The other ingredients did not significantly influence breaking strength.

Bhattacharya and Hanna (1988) reported that the shear strength of corn gluten meal extrudate was influenced by moisture and lipid contents. Shear strength was highest at 1.8% lipid content but dropped off at 3.9 and 0.2%. They also suggested that protein and lipid interactions during extrusion were responsible for changing shear strength.

TABLE VI
Relationships Between Expansion Indexes, Bulk Density, Breaking Strength, and Cell Numbers

Characteristic	Expansion Indexes[a] SEI	LEI	VEI	Bulk Density ($g \cdot cm^{-3}$)	Breaking Strength (kg)	Cell Number[b]
SEI	1					
LEI	−0.08	1				
VEI	0.85**[c]	0.43*	1			
Bulk density	−0.75**	−0.13	−0.73**	1		
Breaking strength	−0.35	−0.54**	−0.55**	0.60**		
Cell Number	−0.88**	−0.14	−0.72**	0.68**	0.26	1

[a]Sectional, longitudinal, and volumatic expansion indexes (SEI, LEI, and VEI, respectively).
[b]Per unit area (cm^{-2}).
[c]* = $P < 0.05$, ** = $P < 0.01$.

Effect of Baking Ingredients on Extrudate Cell Structure

Cell structures were observed by SEM and photocopies of extrudate cross sections. The blackened cross-section surfaces allowed clear projection onto photocopies, from which cell size, shape, distribution, and cell-wall thickness were determined.

Figure 3 shows enlarged extrudate cross sections for the control and 32 treatments. These photocopies show the influence of wheat flour extrudates on structural characteristics such as number of cells per unit area, individual cell area, and cell-wall thickness.

The mean values and mean square errors for the number of cells per unit area are shown in Tables IV and V, respectively. Sucrose, shortening powder, and GMS significantly influenced the number of cells per unit area ($P < 0.1$, $P < 0.05$, and $P < 0.05$, respectively). A sucrose by egg powder interaction also had a significant effect ($P < 0.05$).

The number of cells per unit area increased from 18.8 to 28.4 cm^{-2}, as sucrose concentration increased from 5 to 10%. An increase in shortening powder from 0.25 to 1% increased the number of cells from 17.6 to 29.7 cm^{-2}. Increasing GMS concentrations from 2.5 to 5% increased the cell numbers from 18.5 to 28.7. The other ingredients did not significantly affect the number of cells per unit area. An increase in concentrations

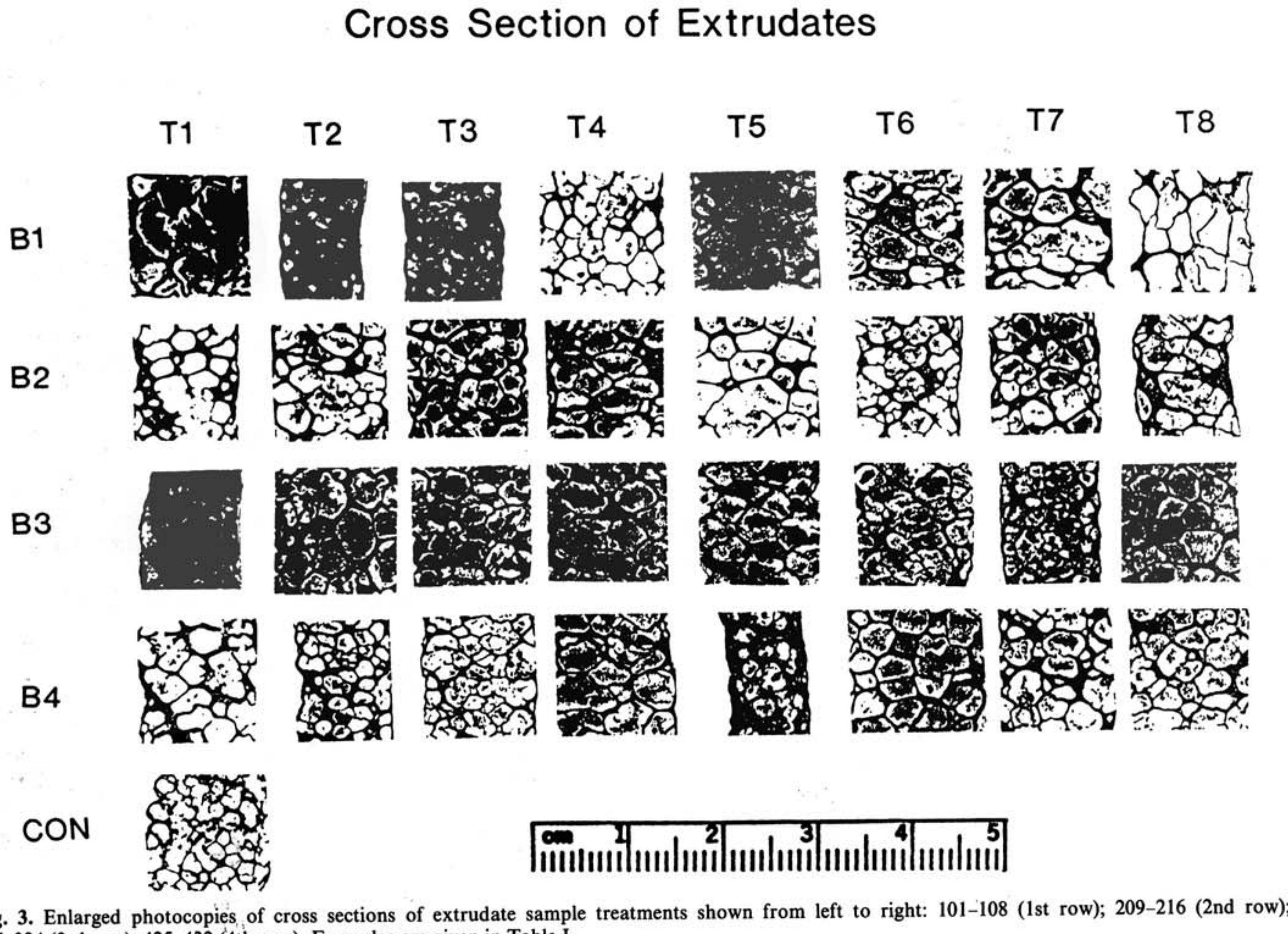

Fig. 3. Enlarged photocopies of cross sections of extrudate sample treatments shown from left to right: 101–108 (1st row); 209–216 (2nd row); 317–324 (3rd row); 425–432 (4th row). Formulas are given in Table I.

of these ingredients made the cells smaller. Cell numbers per unit area correlated negatively with SEI ($r = -0.88$, $P < 0.01$) and VEI ($r = -0.72$, $P < 0.01$) (Table VI).

The cross-sectional microstructure was also examined using SEM. The internal structure of the control wheat flour extrudate differed from those of extrudates containing baking ingredients (Figs. 4–6). The air cells of the control extrudate (Fig. 4a) are relatively small compared to those of a highly expanded extrudate, such as treatment 430 (Fig. 6f). In the control sample, tears in cell walls were common; both small and large cells are distributed throughout the sample (Fig. 4a).

The SEM of treatment 430, containing lower concentrations of sucrose (5%), shortening powder (2.5%), and GMS (0.25%), showed that large air cells with smooth surfaces and thin cell walls were evenly distributed (Fig. 6f). These ingredients most significantly affected expansion and cell porosity of wheat flour extrudates. In this sample, the cell walls were not disrupted.

In the less expanded treatment 102, higher concentrations of sucrose (10%), shortening powder (5%), and GMS (1%) produced smaller air cells with thick, dense cell walls (Fig. 4b). The cell structures of these samples were easily distinguishable from those of the control and highly expanded samples.

SEMs of extrudate samples containing higher concentrations of shortening powder and GMS (Fig. 5b, treatment 426; Fig. 6e, treatment 429) showed different cell size, cell-wall thickness, and distribution. The cells were small and had thick walls. When compared to SEMs of the control (Fig. 4a), the cell shapes tended to be circular. Cell size and cell-wall thickness depended on the concentration of the baking ingredients incorporated with wheat flour.

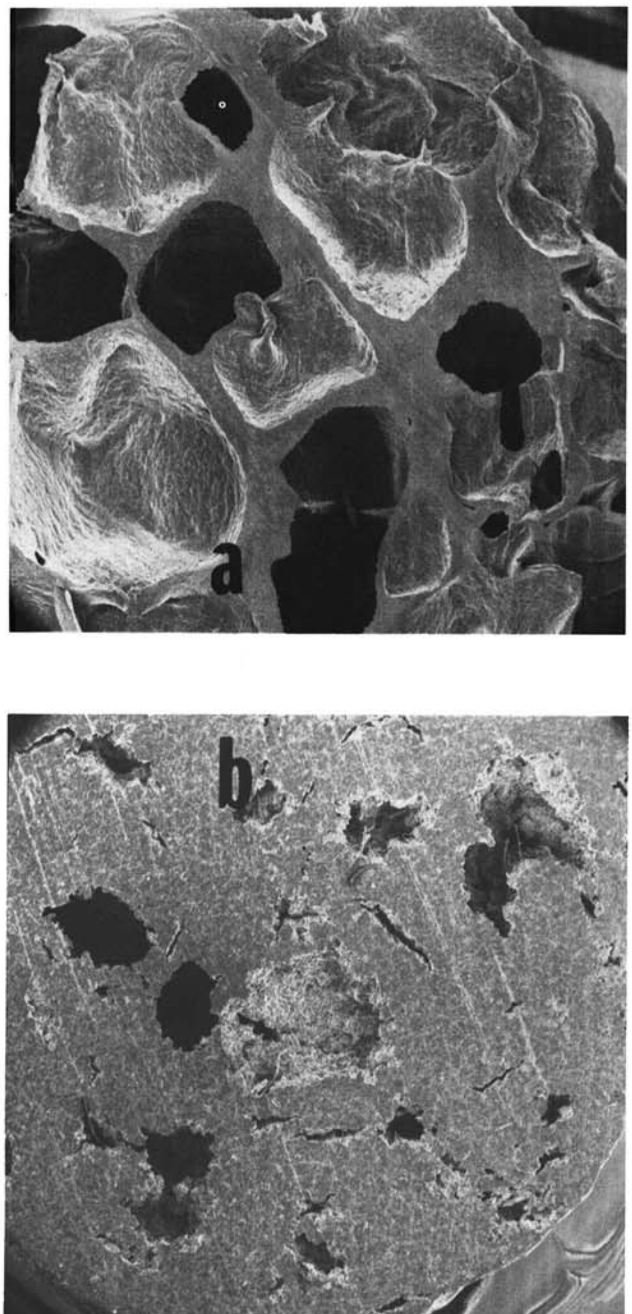

Fig. 4. Scanning electron photomicrographs for cross sections of control (**a**) and treatment 102 (**b**) wheat flour extrudate samples. (15×).

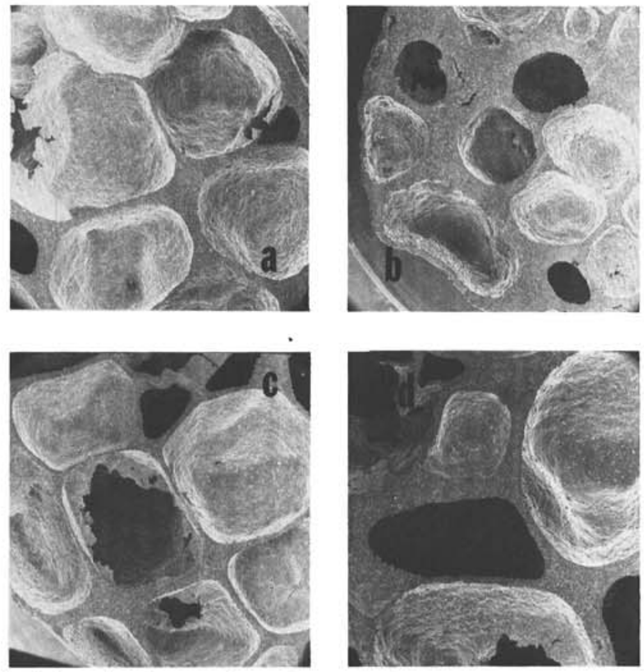

Fig. 5. Scanning electron photomicrographs for cross sections of treatment 425 (**a**), 426 (**b**), 427 (**c**), and 428 (**d**) wheat flour extrudate samples. (15×).

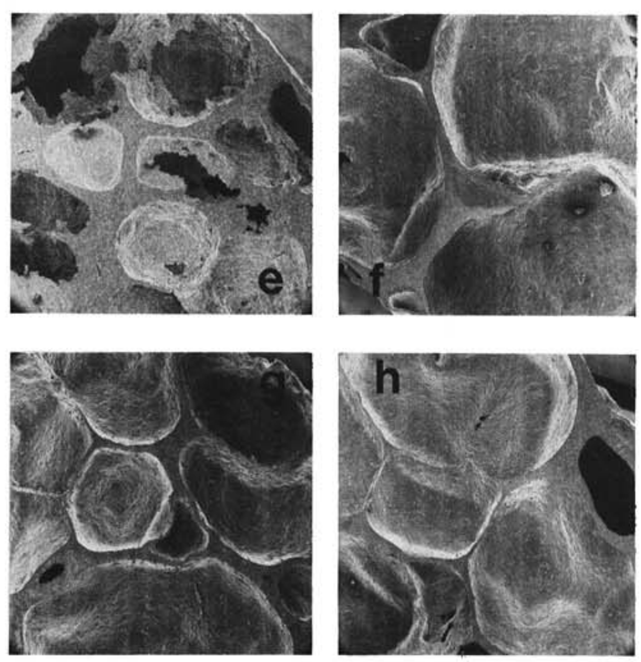

Fig. 6. Scanning electron photomicrographs for cross sections of treatment 429 (**e**), 430 (**f**), 431 (**g**), and 432 (**h**) wheat flour extrudate samples. (15×).

CONCLUSIONS

Our results show that sucrose, shortening powder, and GMS concentrations significantly influence the expansion indexes, bulk density, breaking strength, and number of cells per unit area of wheat flour extrudates. On the other hand, within the observed concentration ranges, NFDM, egg powder, and SBC had no significant effects on extrudate properties. Therefore, the physical and structural properties of wheat flour extrudates can be controlled by changing the concentrations of sucrose, shortening powder, and emulsifier.

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