

Effects of Calcium Hydroxide and Processing Conditions on Corn Meal Extrudates

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ABSTRACT

Cereal Chem. 75(6):796–801

The effects of added calcium hydroxide (0.0, 0.15, 0.25, and 0.35%) and processing conditions, feed moisture content (mc) (16, 18, and 20%) and barrel temperature (130 and 150°C) on characteristics of corn meal extrudates were studied. Extruder screw speed was maintained at 130 rpm. Corn meal was extruded with a single-screw extruder (Brabender model GNF 1014/2) with a screw compression ratio of 3:1. The highest values ($P < 0.05$) for radial expansion and the lowest values for density and breaking force of extrudates were found for the treatment with 0.00% calcium hydroxide extruded at 16% feed mc and 130°C barrel temperature. This treatment was statistically different from the other treatments. Best values for radial expansion of samples extruded with added calcium hydroxide were

for the samples with 0.15% calcium hydroxide at 18% feed mc and 130°C barrel temperature, followed by the sample with 0.35% calcium hydroxide at 16% feed mc and 130°C barrel temperature. Water absorption index and water solubility index were affected by calcium hydroxide and extrusion conditions evaluated. Extrudates had large numbers of flattened and sheared granules. Increases in calcium hydroxide increased extrudate yellowness. The combined action of calcium hydroxide and extrusion conditions completely modified the organized structure of the starch and suggest the formation of a starch-calcium complex (crystalline region). The texture of the extruded products was crispy after puffing.

High-temperature short-time extrusion of grains commonly is used in the food industry to produce extruded foods, such as ready-to-eat breakfast cereals and snacks. The acceptance of such foods is at least in part a consequence of their fragility and soft crunchy texture. Alkaline cooking of corn to produce dry masa flour, tortillas, and snack foods, such as corn and tortilla chips, is becoming more important as the popularity of Mexican food increases in the United States. Corn and tortilla chips represent 5% of the nearly \$42 billion U.S. snack food market, compared with 6.2% for potato chips (Pollak and White 1995). Corn tortillas are an important source of protein and carbohydrates and supply 37% of the calcium requirements for adults in many Latin American countries (Serna-Saldívar et al 1991). However, people consuming unlimited (no added calcium hydroxide), cooked corn grain (Colombia, Venezuela, and some countries in Africa) obtain less than 1% of their daily recommended requirements.

Calcium is recognized as an important component of the human body, constituting $\approx 2\%$ of total body weight; $\approx 99\%$ of the calcium is present in the human skeleton (Ranhotra 1986). The recommended dietary allowance of calcium for adults and pregnant or lactating women is 800 and 1,200 mg/day, respectively (U.S. Food and Nutrition Board 1974). Calcium deficiency causes osteoporosis, affecting ≈ 24 million Americans annually (NIH 1991). The lime used in preparing masa for tortilla, dry corn masa, and corn chip production controls microbial activity, provides a lighter, more wholesome flavor, and improves both the shelf-life and nutritional value of products. Also, calcium in corn tortillas has high bioavailability (Poneros and Erdman 1988, Serna-Saldívar et al 1991).

Many modern consumers have developed a taste for corn and corn-based snacks. These snacks can make a positive contribution

to the human diet by providing certain necessary nutrients and minerals. In addition, they provide good flavor, pleasing textural contrast to other dietary components, and “fun eating” when part of an overall balanced diet. The extrusion process and resultant products have been extensively analyzed, and much research has been published that describe the effects of different process parameters and formulations on both the physical properties and texture of expanded extrudates (Mercier and Feillet 1975, Mercier 1977, Faubion and Hosney 1982, Peri et al 1983, Launay and Lisch 1983, Gomez and Aguilera 1984, Fletcher et al 1985, Hsieh et al 1993, Chinnaswamy and Hanna 1988a). Similarly, many ingredients influence the physical and textural properties of extrudates (Harper 1981, Faubion and Hosney 1982, Kim and Hamdy 1987, Chinnaswamy and Hanna 1988c, Lai et al 1989). However, further studies are needed to evaluate use of snack foods as sources of essential nutrients. The purpose of our research was to determine the effects of added calcium hydroxide concentrations, feed moisture content (mc), and barrel temperature, on the properties of corn meal extrudates.

MATERIALS AND METHODS

Commercially available, degermed yellow corn meal (corn fuba) was obtained from the local market in Campinas, São Paulo, Brazil. Food-grade calcium hydroxide (reagent powder) was obtained from Merck (São Paulo, Brazil). The proximate composition of the corn meal was 10.7% moisture, 8.03% protein, 2.46% lipids, 0.46% ash, and 89.05% carbohydrates (by difference). The particle size distribution of the corn meal was 3.4% (mesh 35, 0.420 mm); 61.5% (mesh 60, 0.250 mm); 27.5% (mesh 80, 0.177 mm); 1.95% (mesh 100, 0.149 mm); and 5.7% (>100).

Extrusion Process

Extrusion experiments were performed with a laboratory extruder (Brabender model GNF 1014/2) with an extruder barrel 380 mm long and 19 mm in diameter. The barrel had three sections, with electric heaters controlled independently and a 3:1 screw compression ratio. A die with 20 die-nozzle orifices, 4 mm diameter each, was used. Compressed air was circulated around the barrel to maintain precise control of the barrel temperature and die assembly. Flour samples were force-fed. The feed rate was maintained at a constant 70 g/min (dry matter). Conditions were calcium hydroxide extruded at 0.0, 0.15, 0.25, and 0.35% w/w; feed mc of 16, 18, and 20%; and barrel temperature fixed in zones 1 and 2 at 80 and 100°C, respectively. Barrel temperature in zone 3 (die) varied from 130 to 150°C. Screw speed was maintained at a constant 130 rpm.

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Analytical Methods

Moisture content was determined using the Approved Methods (AACC 1995) procedure. Water absorption index (WAI) and water solubility index (WSI) were determined as described by Anderson et al (1969).

Radial Expansion and Density

Radial expansion was calculated for 10 samples by dividing the average cross-section area of the extrudate by the cross-section area of the extruder die-nozzle orifice. Density was calculated by weighing 10 extruded product pieces and measuring the length and average diameter and calculating as:

$$b = 4m/\pi d^2 h$$

where b = density (g/cm^3); m = mass of a sample (g); d = diameter of a sample (cm); and h = length of a sample (cm).

Color Measurements

The color of ground extrudates (passed through a U.S. standard sieve no. 10) was measured with a spectrophotometer (CM-2002, Minolta Camera Co., Ltd., Osaka, Japan) interfaced with a personal computer (Minolta software), and the values of L , a , and b were recorded, where L = lightness (100 = white, 0 = black); a = red (+100); $-a$ = green (-80); b = yellow (+70); and $-b$ = blue (-80). A 100-g sample was placed on a 16-cm-diameter and 1-cm-deep petri glass. The means from three replicates were reported.

Texture Analysis

A universal texture analyzer (model TA.XT2, Texture Technologies Corp., Scarsdale, NY) was used in the compression mode to record the force required to break the extruded product and register the area under the force-deformation curve ($N - m$). The extruded 5-cm-long sample was placed on the platform transversally over a metal sheet support (1 cm thick) and operated in the compression mode with a sharp testing blade (TA-90, 3 mm thick, 6.93 mm wide). The texturometer head moved the probe down at a rate of 2 mm/sec until it broke the extrudate.

X-ray Diffraction Analysis

X-ray powder diffraction was performed on dried samples according to the method of Rodriguez et al (1996). Extruded products were ground to a fine powder to pass through a screen with 150- μm openings. The samples in powder form were densely packed into an Al frame. The x-ray diffraction patterns of samples were recorded on a diffractometer (Siemens D500) operating at 35 kV and 15 mA with Cu K_{α} radiation wavelength $\lambda = 1.5406 \text{ \AA}$. Data were collected from 4 to 30° on a 2 θ scale with a step size of 0.05° and reported as interplanar d -spacing values (Å). Crystallinity (%) was calculated by normalizing the integrated diffracted intensity over the measured 2 θ range to the integrated noncoherent intensity. The noncoherent intensity was obtained by subtracting the sharp diffraction peaks from the total diffraction pattern, using software (Diffract/AT, Socabim V3.2, Siemens, Newton Square, PA). Two measurements were taken for each sample.

Microscopic Examinations

Extruded samples were analyzed with a universal microscope (Zeiss) with a polarized filter. Samples were mounted with double-stick tape on an aluminum stub and coated with 200 Å of gold palladium and viewed on a scanning electron microscope (JEOL JSM25) at an accelerating voltage of 12.5 kV.

Statistical Analysis

The following operating conditions were analyzed: 1) calcium hydroxide extruded at 0.0, 0.15, 0.25, and 0.35% w/w; 2) feed mc at 16, 18, and 20%; and 3) compression zones temperatures of 130 and 150°C varied in a 4 \times 3 \times 2 completely random design. Data were analyzed using the Statistical Analysis System (version 5,

SAS Institute, Cary, NC). Tukey analysis ($P < 0.05$) was applied for means with significant differences.

RESULTS AND DISCUSSION

Radial Expansion, Density, and Breaking Force

Table I shows radial expansion, density, and breaking force (area under the force-deformation curve) of the extruded products. The highest value ($P < 0.05$) for radial expansion and lowest value for density of extrudates were for the treatment with 0.00% calcium hydroxide extruded at 16% feed mc and 130°C barrel temperature. This treatment was statistically different from the other treatments. The best values for radial expansion of samples extruded with added calcium hydroxide were for those samples with 0.15% calcium hydroxide at 18% feed mc and 130°C barrel temperature, followed by the sample with 0.35% calcium hydroxide at 16% feed mc and 130°C barrel temperature. The lowest values of radial expansion were for extrudates with 0.35% calcium hydroxide at 20% feed mc and 150°C barrel temperature.

Expansion was significantly ($P < 0.05$) affected by addition of calcium hydroxide and processing extrusion conditions. Calcium hydroxide probably degraded the starch molecules and reduced expansion, as suggested by some researchers. Kervinen et al (1984) reported that both acid and alkali treatments during extrusion markedly decreased the average molecular weight of starch, which also decreased expansion. Chinnaswamy and Hanna (1988c) speculated that sodium bicarbonate degraded starch molecules, which reduced expansion. When sodium bicarbonate was added to wheat starch (Lai et al 1989) and corn starch (Chinnaswamy and Hanna 1988b) before extrusion, expansion decreased with increasing concentration. Samples extruded with 0.00% calcium hydroxide showed an increase in radial expansion as moisture content decreased, and values for samples extruded at 130°C were higher than those at 150°C barrel temperature. Samples extruded with added calcium hydroxide did not show the same trend, thus the decrease in radial expansion was dependent on calcium hydroxide concentration and

TABLE I
Effects of Calcium Hydroxide Concentration and Extrusion Conditions on Radial Expansion, Density, and Texture of Corn Meal Extrudates^a

Extrusion Conditions (Ca(OH) ₂ /°C/%) ^b	Radial Expansion	Density (g/cm ³)	Texture Area Under Curve
0/130/16	3.50a	0.10g	0.037h
0/130/18	2.87b	0.15f	0.038f-h
0/130/20	2.65e	0.18f	0.041cd
0.15/130/16	2.70d	0.16f	0.060b
0.15/130/18	2.87b	0.16f	0.037h
0.15/130/20	2.50g	0.28e	0.038f-h
0.25/130/16	2.15j	0.35d	0.040d-g
0.25/130/18	2.55f	0.28e	0.038f-h
0.25/130/20	2.43h	0.30e	0.039e-h
0.35/130/16	2.82c	0.16f	0.038f-h
0.35/130/18	2.72d	0.16f	0.062a
0.35/130/20	2.55f	0.28e	0.038f-h
0/150/16	2.80c	0.16f	0.038f-h
0/150/18	2.65e	0.18f	0.041cd
0/150/20	2.15j	0.35d	0.040d-g
0.15/150/16	2.05i	0.40bc	0.040d-g
0.15/150/18	2.50g	0.29e	0.038f-h
0.15/150/20	2.50g	0.36cd	0.040d-g
0.25/150/16	2.12jk	0.36cd	0.039e-h
0.25/150/18	1.92m	0.48a	0.042cd
0.25/150/20	2.05i	0.40bc	0.040d-f
0.35/150/16	2.25i	0.29e	0.040d-g
0.35/150/18	2.02l	0.41b	0.042cd
0.35/150/20	1.82n	0.48a	0.043c
LSD	0.03	0.03	0.002

^a Determined with a Minolta color meter. Each value is the mean of three observations. Means with the same letter within a column are not significantly different ($P < 0.05$).

^b Calcium hydroxide concentration/barrel temperature/feed moisture content.

extrusion variables. Chinnaswamy and Hanna (1988b) obtained maximum expansion of corn starch at 140°C in a single-screw extruder and suggested that at barrel temperatures >140°C, corn starch undergoes molecular degradation and expands less.

The expansion of starch (or cereals) depends mainly on its degree of gelatinization (Chinnaswamy and Bhattacharya 1983), which in turn is determined by temperature, shear rate, and moisture content of feed material (Chiang and Johnson 1977, Bhattacharya and Hanna 1987). Low moisture content of starch may restrict material flow inside the extruder barrel, increasing shear rate and residence time, which might increase the degree of starch gelatinization and, thus, expansion. Gujska and Khan (1991) suggested that the degree of expansion affects density, fragility, and softness of extruded products. Therefore, the degree of expansion is an important factor to monitor, especially if the extruded product is to be used as a snack. Lai and Sarkanen (1989) showed that in 0.01–0.1*N* sodium hydroxide solutions at 100°C, amylose was totally degraded. Kervinen et al (1984) found that phosphoric acid or sodium hydroxide, rather than thermostable enzymes, can be added during extrusion to hydrolyze starch.

Density

Density was associated directly with radial expansion of extruded products. In general, the lowest density was found in samples that had the highest radial expansion values, and the highest densities were found in samples that had the lowest radial expansion values. Expansion volume is the primary quality parameter associated with product density, crispness, water absorption, water solubility, and crunchiness (Vickers 1988).

Breaking Force

The results showed a trend toward increasing expansion, decreasing density, and decreasing breaking force (area under the force-deformation curve) with barrel temperatures from 150 to 130°C and feed moisture contents from 20 to 16%. Variations observed in the breaking force of extruded products indicated that calcium

hydroxide, feed moisture content, and barrel temperature are critical for this characteristic in corn flour extrusion. Breaking force is influenced by the expansion index and starch layer alignment for formation of the final structure. Hsieh et al (1990) reported similar results for extrusion of corn meal with added salt. Also, Hsieh et al (1990) cited that it seemed a thinner cell wall was formed in extrudates with greater radial expansion, resulting in a lower breaking force.

WAI, WSI, and Color

The WAI, WSI, and color of corn meal extrudates at barrel temperatures of 130 and 150°C are shown in Table II. Significant variations were observed in the WAI and WSI of extruded products as a result of the combined action of calcium hydroxide, feed moisture content, and barrel temperature. Raw corn meal had values of 2.55% WAI and 0.45% WSI. The highest values ($P < 0.05$) of WAI were for samples extruded with 0.00% calcium hydroxide at 20% feed mc and 150°C barrel temperature, followed by samples with 0.25% calcium hydroxide at 18% feed mc and 130°C barrel temperature. WAI values were similar at barrel temperatures of 130°C (5.5–7.4 g of water/g of dry sediment) and 150°C (5.6–7.7 g of water/g of dry sediment). Doublier et al (1986) reported a similar range of values (3.9–9.2 g of water/g of dry sediment) for extruded wheat starches processed in a twin-screw extruder. WSI values were similar at barrel temperatures of 130°C and 150°C (8.4–21.3 and 5.6–21.1% dry sample, respectively). Mercier and Feillet (1975) found similar values for WSI and WAI of extruded corn starch processed at barrel temperatures of 135 and 170°C.

Extrusion cooking is an industrial process that leads to the breakdown of starch granules. Such treatment produces significant ultrastructural changes, and cold-water absorption as well as cold-water solubility are increased (Doublier et al 1986). Kervinen et al (1984) found that an increase in phosphoric acid content generally decreased the WAI value and increased the WSI. Darnoko and Artz (1988) showed that the effect of pH on WSI was temperature dependent. The effects of extrusion on water solubility, water absorption, and viscosity of starch have been studied by several authors (Anderson

TABLE II
Effects of Calcium Hydroxide Concentration and Extrusion Conditions
on Water Absorption Index (WAI), Water Solubility Index (WSI), and Color of Corn Meal Extrudates^a

Extrusion Conditions (Ca(OH) ₂ /°C/%) ^b	WAI	WSI	Color		
			<i>L</i>	<i>a</i>	<i>b</i>
0/130/16	6.51hi	16.40b-d	71.69b-d	8.06c-e	16.77b
0/130/18	6.70ef	19.20a-c	76.20a-c	6.98h-j	15.89bc
0/130/20	7.00c	10.40g-j	73.61b-d	7.43f-h	15.69bc
0.15/130/16	6.60gh	12.40e-h	75.23bc	6.53j-l	12.38i
0.15/130/18	6.77e	12.80d-g	73.28b-d	6.96h-j	14.83c-e
0.15/130/20	6.60g	11.66f-i	76.04a-c	6.10lm	13.96e-h
0.25/130/16	5.50o	8.40i-k	70.63cd	7.88d-f	14.54d-f
0.25/130/18	7.40b	21.33a	73.36b-d	8.53bc	13.80e-h
0.25/130/20	6.51hi	13.20d-g	74.69bc	7.51e-h	14.26d-g
0.35/130/16	6.37j	15.60c-e	66.58d	10.24a	14.84c-e
0.35/130/18	6.70f	16.43b-d	70.68cd	8.83b	13.48f-i
0.35/130/20	6.93cd	18.80a-c	71.57b-d	8.56bc	13.33g-i
0/150/16	6.86d	14.07d-g	75.45a-c	7.71e-g	15.35cd
0/150/18	6.76ef	21.10a	76.08a-c	7.20h-g	14.80c-e
0/150/20	7.69a	19.63ab	77.58a-c	5.66m	12.47i
0.15/150/16	6.27k	12.80d-g	71.69b-d	8.08c-e	14.12e-h
0.15/150/18	6.01l	12.76d-g	72.85b-d	8.34b-d	14.22e-g
0.15/150/20	6.36j	11.80f-i	74.16bc	6.82ij	13.20g-i
0.25/150/16	6.48i	5.60k	78.28ab	6.71i-k	13.82e-h
0.25/150/18	6.20k	8.78h-k	77.24a-c	-0.94n	21.47a
0.25/150/20	5.89m	14.80d-f	78.65ab	6.19k-m	13.02hi
0.35/150/16	6.88d	5.60k	77.28a-c	-1.44n	20.35a
0.35/150/18	5.59n	7.20jk	76.94a-c	7.16h-g	14.11e-h
0.35/150/20	6.87d	5.60k	82.76a	7.06h-j	13.43f-i
LSD	0.08	3.66	7.50	0.58	1.12

^a Determined with a Minolta color meter. Each value is the mean of three observations. Means with the same letter within a column are not significantly different ($P < 0.05$).

^b Calcium hydroxide concentration/barrel temperature/feed moisture content.

et al 1969, Colonna and Mercier 1983, Colonna et al 1984, Gomez and Aguilera 1984) who reported that with a decrease in extrusion moisture and higher temperatures water solubility of extruded material was greater and viscosity lower than those of either the raw material or material extruded at higher moisture contents (lower temperatures). Darnoko and Artz (1988) reported that extrusion temperature and pH affected key parameters associated with hydrolysis of starch, such as WSI, WAI, apparent viscosity, and susceptibility of extruded starch to glucoamylase.

The three color parameters for extrudates were affected by calcium hydroxide content (0.00–0.35%). The highest value for lightness was for the sample extruded with 0.35% calcium hydroxide at 20% feed mc and 150°C barrel temperature, which did not differ significantly ($P < 0.05$) from the rest of the samples extruded at 150°C barrel temperature, except for all products extruded with 0.15% calcium hydroxide. Also, the samples extruded with 0.35% calcium hydroxide at 20% feed mc and 150°C barrel temperature did not differ significantly ($P < 0.05$) from samples extruded at 130°C barrel temperature with 0.15% calcium hydroxide and 20% feed mc or from the sample extruded with 0.00 calcium hydroxide and 18% feed mc. The values measured for extruded samples varied within a range of values from -0.94 to 10.24. Flour extruded with 0.35% calcium hydroxide at 16% feed mc and 130°C barrel temperature had the highest value for a ; the sample extruded with 0.35% calcium hydroxide at 16% feed mc and 150°C had the lowest value. The highest values for yellowness were for samples extruded

with 0.25 and 0.35% calcium hydroxide at 16 and 18% feed mc and 150°C barrel temperature, respectively. Evidently, calcium hydroxide reacted with different pigments in the corn meal and interfered with browning reactions, such as caramelization and Maillard reactions (Hsieh et al 1990).

Microscopic Examinations

Extruded corn meal samples had porous, open-celled structures, with the characteristic color and flavor of products processed with alkali. Figure 1A shows intact starch granules in raw corn flour. Figure 1B shows extruded starch granules that have lost their organized structure. Important granule damage occurred during extrusion—extrudates showed large numbers of flattened and sheared granules. Similar results were obtained using corn semolina (Mercier et al 1979), corn grits and starch (Gomez and Aguilera 1984, Richmond and Smith 1985), and potato starch (Senouci and Smith 1986).

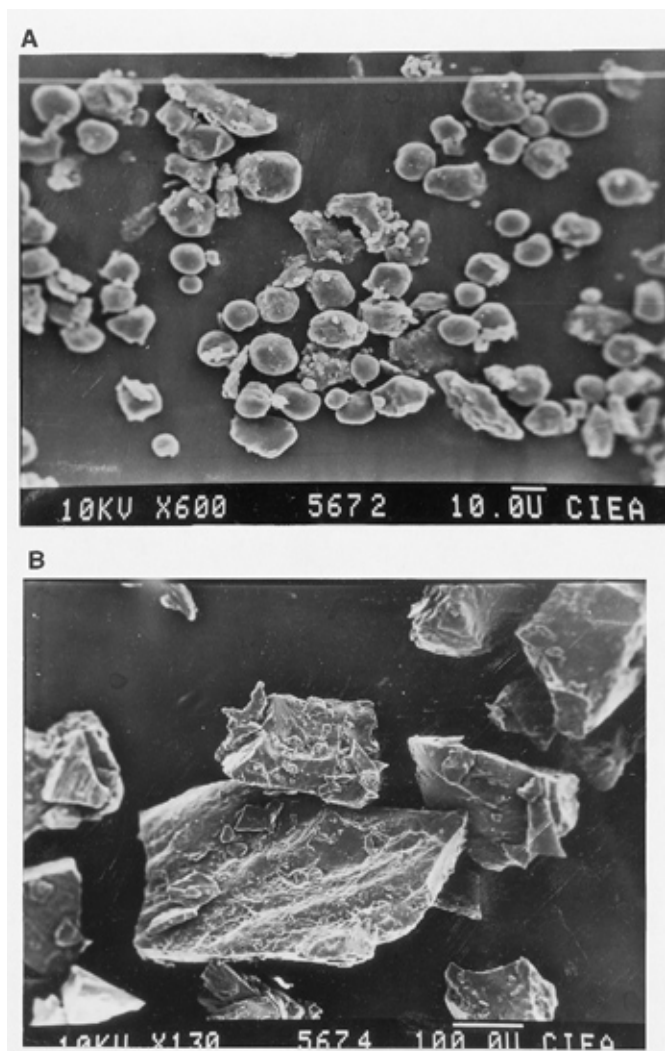


Fig. 1. Scanning electron micrographs of raw (A) and extruded (B) starch granules.

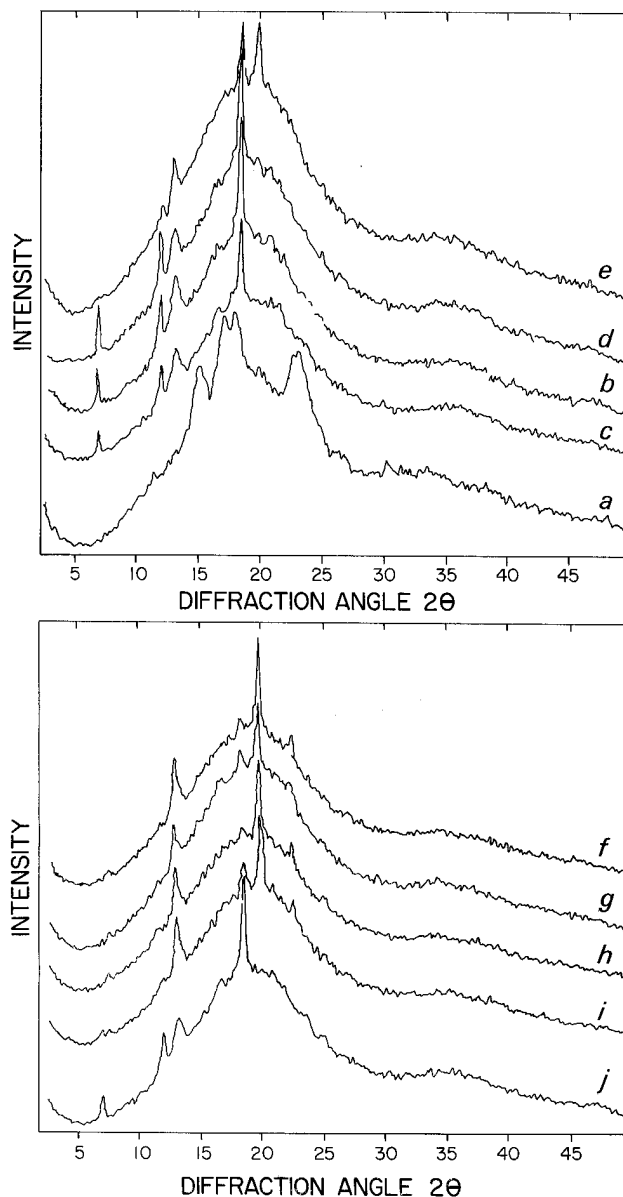


Fig. 2. Effects of calcium hydroxide concentration (%), feed moisture content (%), and barrel temperature (°C) on X-ray diffraction patterns of native and extruded corn meal: a, 9.11% crystallinity (control); b, 0.00%, 16%, 130°C, 5.6% crystallinity; c, 0.15%, 16%, 130°C, 7.2% crystallinity; d, 0.00%, 20%, 150°C, 5.0% crystallinity; e, 0.15%, 20%, 150°C, 6.8% crystallinity; f, 0.25%, 16%, 130°C, 5.4% crystallinity; g, 0.35%, 16%, 130°C, 4.9% crystallinity; h, 0.35%, 20%, 150°C, 5.1% crystallinity; i, 0.35%, 20%, 130°C, 4.9% crystallinity; j, 0.00%, 20%, 130°C, 6.4% crystallinity.

X-ray Diffraction

Loss of the organized crystalline structure of raw starch granules during extrusion cooking can be demonstrated by X-ray techniques. Charbonniere et al (1973) investigated the effect of extrusion on the crystallinity of waxy corn starch. They reported that extrusion cooking destroyed the crystalline structure partially or completely depending on the amylose-amylopectin ratio and extrusion variables. At extrusion temperatures $>100^{\circ}\text{C}$, the structure was completely destroyed, leading to an X-ray pattern typical of an amorphous state. Figure 2 shows the diffractograms of analyzed samples and their respective crystallinity values. For native starch, strong peaks were observed at 2θ values of 15.1, 16.4, 17.5, and 22.6 \AA , corresponding to d -spacings of 5.95, 5.39, 5.2, 4.7, and 3.9 \AA , respectively. This pattern closely matches reported values for A-type cereal starches (Zobel 1964, 1988). The modification of the physical structure of starch granules observed by X-ray diffraction showed that the combined action of feed moisture, barrel temperature, and calcium hydroxide modified starch crystallinity. The addition of 0.15% calcium hydroxide at 130 and 150°C barrel temperatures increased the crystallinity of corn meal extrudates from 5.0 to 7.2% (b and c) and from 5.0 to 6.8% (d and e), respectively. However, increasing calcium hydroxide from 0.25 to 0.35% at 130°C barrel temperature reversed the trend (f and g). With increases in feed moisture from 16 to 20% at 130°C barrel temperature and addition of 0.35% calcium hydroxide, crystallinity remained constant (g and i). Increasing barrel temperature from 130 to 150°C at 20% feed mc and addition of 0.00% calcium hydroxide reduced crystallinity from 6.4 to 5.0% (j and d). However, with addition of 0.35% calcium hydroxide, crystallinity increased from 4.9 to 5.1% (i and h). The lowest crystallinity values were observed for samples i and g, and the highest value was for sample c.

Mercier et al (1979) reported that commercial corn starch at 22% feed mc extruded at 135°C formed a new type of structure characterized by three main peaks on X-ray diffraction patterns; the major peak was located at $9^{\circ} 54'$. The spectrum corresponds to the butanol-amylose complex spectrum, known as the V-amylose type structure.

Extrusion cooking of corn meal with added calcium hydroxide showed peaks at 12.7, 14.2, and 19.8 \AA and may have been due to the starch-calcium complex, as revealed by an increase in crystallinity. Kalentunc and Breslauer (1993) reported that the original, unprocessed, high-amylopectin corn flour possessed a crystalline structure that was destroyed by the extrusion process. Acidification of doughs increased depolymerization of starch during extrusion (Kim and Hamdy 1987).

CONCLUSIONS

The highest values ($P < 0.05$) for radial expansion and the lowest values for density and breaking force of extrudates were found for the treatment with 0.00% calcium hydroxide extruded at 16% feed mc and 130°C barrel temperature. This treatment was statistically different from the other treatments. The best values for radial expansion of samples extruded with added calcium hydroxide were for samples with 0.15% calcium hydroxide at 18% feed mc and 130°C barrel temperature, followed by the sample with 0.35% calcium hydroxide at 16% feed mc and 130°C barrel temperature.

The combined action of calcium hydroxide and extrusion conditions increased extrudate yellowness. Such extrusion treatments produced significant ultrastructural changes, and both cold-water absorption and solubility increased. Microscopic observations showed large numbers of flattened and sheared granules. The organized structure of starch was modified during the extrusion process. Interesting changes in the crystallinity of starch were observed on diffractograms of analyzed samples. Increasing crystallinity of starch granules was observed when samples were extruded with calcium hydroxide, suggesting the formation of starch-calcium complexes. Extruded products were softer and crisper after puffing.

ACKNOWLEDGMENTS

This study was financially supported by the National Council of Science and Technology, México—Project 211085-5-1336BP.

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[Received September 19, 1997. Accepted July 7, 1998.]