

Effects of Extrusion Variables and Chemicals on the Properties of Starch-Based Binders and Processing Conditions¹

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ABSTRACT

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The effects of extrusion variables (moisture, screw speed, and temperature) and chemicals (urea and sodium bicarbonate) on the properties of starch-based binders (water absorption, bulk density, binder yield, expansion ratio, solubility, pH) and processing conditions (die temperature and pressure, feed rate, and specific mechanical energy) were studied using a central composite design. All quadratic regression models, except the models for bulk density and pH, were significant at the $P \leq 0.06$ level. These models can predict the binder properties and processing conditions

when extrusion variables and the chemical concentrations are known. Optimum combinations of the chemical concentrations (g/100 g of starch) and extrusion variables to achieve high water absorption in the binders were 15–20 g of urea/100 g of starch, 0–4 g of sodium bicarbonate/100 g of starch, 35–40 g of moisture/100 g of starch, 100–120 rpm screw speed, and 185–215°C barrel temperature. The molecular degradation of the starch occurred during extrusion, especially when the moisture content of starch was <30 g/100 g of starch.

Bentonite is a major iron ore binder used in the Midwest region of the United States. However, the use of bentonite introduces contaminants to iron ore and deteriorates the quality of the steel. In addition, bentonite must be shipped from western states to iron ore pellet-producers in the Midwest. Researchers began to investigate the possibility of using organic materials to replace bentonite as the iron ore binder to improve steel quality with low production cost. Organic binders, such as starch-based binders, can be completely removed as CO₂ and H₂O during sinteration and result in pure steel. Corn starch is an inexpensive renewable organic material produced in the Midwest and could be used to produce starch-based binders with attractive binding properties. Haas et al (1988 and 1989) showed that pellets made with carboxymethyl cellulose (CMC) and pregelatinized wheat starches with 760% water absorption could improve steel properties, but the physical characteristics of the ore pellets, such as low wet-strength, were not satisfactory. It was proposed by the same authors that the starch-based binder can perform satisfactorily if the water absorption is improved. The high production cost of CMC and pregelatinized starch is another factor prohibiting them from being used in the steel industry. Therefore, it is necessary to investigate an alternative manufacturing method of starch-based binder for this specific industry need.

We choose extrusion processing to produce the binding materials because extrusion processing is a widely used technology to process starch into food and industrial products with low cost and high efficiency. Extrusion processing can alter the physical and chemical properties of starch (Chinnaswamy and Hanna 1990, Lai 1992). The major variables affecting the performance of the extrudate include temperature, screw speed, moisture content, and the addition of other materials (Chinnaswamy and Hanna 1988). Barrel temperature can change the color, shape, and water absorption of extrudate (Meuser and Widen 1989). Increasing the moisture content of the feed material can significantly reduce the specific mechanical energy (SME) and die pressure. The residence time of the materials in the barrel can be changed by varying the screw speed to achieve an appropriate degree of cooking at a given temperature.

Urea and sodium bicarbonate are commonly used in starch extrusion as a hydrogen bond breaker and as a blowing agent, respectively (Chinnaswamy and Hanna 1988). Starch extrudate is also sensitive to differences in moisture content levels. Increasing moisture content decreases the expansion and softens the texture of starch extrudate (Faubion and Hosenev 1982, Owusu-Ansah and Voort 1984).

Even though extrusion cooking of starch has been studied extensively, no literature can be found on how to produce extrusion-cooked starch with high water absorption for use as iron ore binders. The objective of this study was to investigate the effects of extrusion variables (barrel temperature, screw speed, and moisture content of starch) and concentrations of urea and sodium bicarbonate on the physicochemical properties of starch-based binders and the operating conditions of an extruder.

MATERIALS AND METHODS

Materials and Sample Preparation

Normal corn starch with 11.8% moisture content obtained from American Maize-Products Company (Hammond, IN) was used as the base for the binder. The moisture content was measured by using Corn Refiners Association method (CRA 1983). Urea and sodium bicarbonate were purchased from Fisher Scientific (Pittsburgh, PA).

The binder was prepared by batch of 600 g of starch. The starch was weighed and placed in a kitchen mixer (model K5SS, Kitchen-Aid, St. Joseph, MI). A solution was made by mixing appropriate amounts of urea, sodium bicarbonate, and water and then sprayed onto the starch during mixing to produce a homogenous mixture. A twin-screw extruder (Micro 18, American Leistritz Extruder Corp., Somerville, NJ) with a die diameter of 3.175 mm was used. A low-shear screw set (diameter 1.8 cm, total length 350 cm) consisting of two 2-cm, 90° bilobal kneading segments and conveying elements was used for the study. Different starch mixtures were processed at different screw speeds and temperatures as specified in Table I. A volumetric feeder was set at a constant speed to ensure stable flow at the feed section of the extruder. The feed rate was determined by measuring twice the dried extrudate weight produced in a 2-min period for each test. During extrusion, the die temperature and pressure, and energy consumption data were collected by the data acquisition system of the extruder. The specific mechanical energy (SME), which was defined as the consumed energy per unit weight of dry extrudate, was calculated based on the energy consumption and feed rate.

Physicochemical Property Measurement

The extrudate was dried at room temperature (22–23°C) for 24 hr, and samples were then taken for expansion and density meas-

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urements. The dried extrudate was first coarsely ground with a hammer mill and then finely ground with a cyclone sample mill (Udy Corp., Fort Collins, CO). A 200-g ground sample was sieved using a testing sieve shaker (Ro-Tap, W. S. Tyler Inc. Mentor, OH) with a 100-mesh screen (150 μm) for 10 min. The fine particle products were designated as binders. The ratio of the binder weight (bottom portion, particle sizes <150 μm) to total sample weight before sieving (200 g) was defined as percentage of binder yield, which is normally reversibly correlated to the hardness of the extrudate. Hard extrudate normally needs more energy for grinding to produce required particle sizes. Therefore, binder yield could be used to estimate energy required for grinding the extrudate in production.

In addition to binder yield, other physical properties of the binders measured in this study included the expansion ratio and the bulk density of the extrudate, and the water absorption, water solubility, and the pH of the binder. The expansion ratio of the extrudate was determined as the diameter of dried extrudate divided by the die diameter. The mean diameter of extrudate for each test was an average of 20 measurements. The volume of the expanded sample for bulk density determination was measured by using a 100-mL graduated cylinder and pearl amaranth. The volume of a 5-g sample was measured for each test. The ratio of the sample weight and the replaced volume in the cylinder was calculated as bulk density (g/cm^3). The water absorption test was done by following the Standard Test Method for Water Absorption of Bentonite by the Porous Plate Method (ASTM 1984). A 0.5-g binder sample, 18-hr water absorption time, and the No. 4 filter paper with 9-cm diameter (Whatman, Fairfield, NJ) were used. The water absorption data were reported as percentage of dry binder. Water solubility of the binder was measured following the method of Schoch (1964) with a 5-g binder sample blended in 200 mL of distilled water at room temperature and held for 2 hr. The pH of the solution was measured before centrifugation. The solubility was calculated as the ratio of solid in the supernatant and the total sample weight on dry basis.

Molecular weight distributions of the binders were determined by the gel-permeation chromatography as described by Kasemsuwan and Jane (1994). The total carbohydrate (anthrone-sulfuric acid reaction) and iodine blue values of the fractions were measured by using an Autoanalyzer II (Technicon Instruments Corp., Elmsford, NJ) at 630 and 640 nm, respectively. To determine the degree of starch gelatinization of the binder, selected samples were run in a differential scanning calorimeter equipped with an Intracooler System II (DSC-7, Perkin Elmer, Norwalk, CT).

Experimental Design and Statistical Analysis

A central composite design was used to determine the effects of five independent variables on the properties of the binders and extrusion processing conditions. It allows investigators to determine all the main effects, quadratic effects, and interactions between the independent variables and to develop the regression models between dependent and independent variables (Haaland 1989). The five independent variables were urea and sodium bicarbonate concentrations, moisture content, screw speed, and barrel temperature. Each variable was tested at five levels, as shown in Table I. The five levels were chosen on the basis of preliminary test results. The dependent variables were SME, die pressure, and temperature, water absorption, water solubility, pH, extrudate bulk density, extrudate expansion ratio, feed rate, and binder yield. A total of 30 tests, including four replicates were conducted. The statistical analysis was performed by using the multiple regression model of Statgraphics (Statistical Graphics Corporation, Princeton, NJ).

RESULTS AND DISCUSSIONS

The extrusion conditions and test results are shown in Table I. The binders with high water absorption (>760%) were obtained with low sodium bicarbonate (0–4%) and medium urea concentrations (15–20%), medium screw speed (100–120 rpm), and high moisture content (35–40%) and high temperature (185–215°C) in

TABLE I
Experiment Design and Test Results of Binder Properties and Processing Conditions

Sample	Urea (g/100 g)	Sodium Bicarbon (g/100 g)	Moisture Content (g/100 g)	Screw Speed (rpm)	Temp. (°C)	Water Absorp. (%)	Solubility (%)	Yield (%)	Expansion Ratio	Bulk Density (g/cm^3)	pH	Die Temp. (°C)	SME (kJ/kg)	Pressure (MPa)	Feed Rate (kg/hr)
1	15	2	25	100	200	735	57.0	88.4	1.02	0.33	10.0	177.6	5190.4	189.1	1.18
2	15	2	25	120	170	630	69.9	77.8	1.05	0.41	9.8	165.0	6009.9	186.2	1.01
3	15	2	35	100	170	782	50.8	76.7	0.80	0.69	9.7	161.6	4154.2	126.4	0.50
4	15	2	35	120	200	764	53.7	84.2	0.85	0.54	10.1	178.0	3844.7	162.9	0.60
5	15	6	25	100	170	645	81.9	93.4	1.16	0.58	9.7	162.7	5536.8	184.1	1.12
6	15	6	25	120	200	620	72.7	95.7	1.05	0.36	9.8	178.0	5565.1	197.6	1.07
7	15	6	35	100	200	787	58.7	85.8	0.86	0.48	9.9	178.0	3859.4	172.1	0.64
8	15	6	35	120	170	685	55.1	80.1	0.78	0.65	9.8	161.8	4503.9	134.6	0.59
9	25	2	25	100	170	732	40.5	23.8	1.44	0.73	9.7	165.3	3331.1	165.3	1.44
10	25	2	25	120	200	674	44.0	87.8	0.89	0.51	10.1	181.5	3379.5	171.9	1.29
11	25	2	35	100	200	730	23.5	72.0	0.86	0.54	10.0	179.4	3419.8	154.4	0.65
12	25	2	35	120	170	770	37.2	59.2	0.82	0.77	9.9	163.2	2306.6	119.9	1.08
13	25	6	25	100	200	681	64.9	81.8	0.93	0.40	9.9	179.3	3833.8	168.1	1.13
14	25	6	25	120	170	589	54.2	31.2	1.48	0.80	9.9	163.7	3420.0	156.2	1.40
15	25	6	35	100	170	679	40.0	66.8	0.80	0.65	9.9	161.6	2848.5	127.5	1.04
16	25	6	35	120	200	717	44.3	83.7	0.88	0.55	9.9	179.6	3415.2	153.4	0.80
17	10	4	30	110	185	649	64.5	90.2	0.93	0.37	10.0	171.4	5896.6	175.2	0.77
18	30	4	30	110	185	667	32.1	41.5	0.82	0.60	10.3	168.8	2997.6	132.7	1.00
19	20	0	30	110	185	773	36.6	53.8	0.82	0.57	8.7	173.1	3877.7	176.7	0.92
20	20	8	30	110	185	623	63.3	77.1	0.85	0.43	9.9	169.8	3747.0	154.6	1.05
21	20	4	20	110	185	532	74.4	90.0	1.16	0.32	9.9	172.0	6906.9	202.3	1.08
22	20	4	40	110	185	775	39.3	54.9	0.82	0.57	9.9	168.8	2945.6	134.6	0.65
23	20	4	30	90	185	713	39.0	69.2	0.86	0.43	9.8	168.8	4150.3	149.8	0.97
24	20	4	30	130	185	679	51.6	63.4	0.84	0.52	10.0	168.8	3504.5	148.9	1.10
25	20	4	30	110	155	668	53.5	47.1	0.89	0.50	9.9	153.4	3767.0	136.1	1.13
26	20	4	30	110	215	788	35.4	87.8	0.95	0.37	10.0	184.3	2787.3	181.0	1.40
27	20	4	30	110	185	731	53.7	80.6	0.83	0.50	9.8	171.0	2921.3	159.2	1.34
28	20	4	30	110	185	716	47.9	86.4	0.81	0.57	9.9	167.5	3588.6	149.6	1.14
29	20	4	30	110	185	729	48.9	66.6	0.81	0.55	9.9	167.8	3302.0	148.4	1.22
30	20	4	30	110	185	707	57.3	74.0	0.82	0.59	9.9	166.2	4018.8	143.2	1.18

the experiment ranges. To quantify the relationship between dependent variables and independent variables, regression analysis was based on the test results from the central composite design. The regression model between dependent variable (Y) and independent variables (X_j) can be generally written as:

$$Y = a + \sum_{j=1}^5 (b_j X_j) + \sum_{j=2}^5 (c_j X_1 X_j) + \sum_{j=3}^5 (d_j X_2 X_j) + \sum_{j=4}^5 (e_j X_3 X_j) + f_5 X_4 X_5 + \sum_{j=1}^5 (g_j X_j^2)$$

The significance levels of the regression models and coefficient of each term in the regression models are shown in Table II. All

regression models in the table are significant at $P \leq 0.06$, except the model for bulk density. The correlation (R^2) between observed values and predicted values for most models, except bulk density, feed rate, and yield, were ≥ 0.9 , indicating that the models are appropriate. Therefore, the regression models can be used to predict the properties of the binders and processing conditions when independent variables are known. The significance level of the bulk density regression model is 0.1791. The pH values of the solutions containing 5% binders ranged from 8.7 to 10.2. The regression model for pH values was not significant and was not shown in the table. The degree of significance of each coefficient

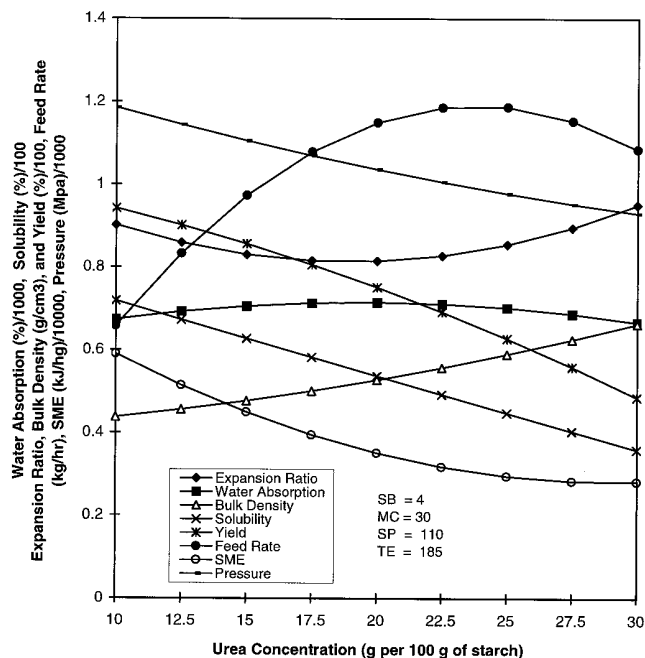


Fig. 1. Effects of urea concentration on binder properties and processing conditions (sodium bicarbonate [SB], moisture content [MC], screw speed [SP], temperature [TE]). Values calculated using the regression models.

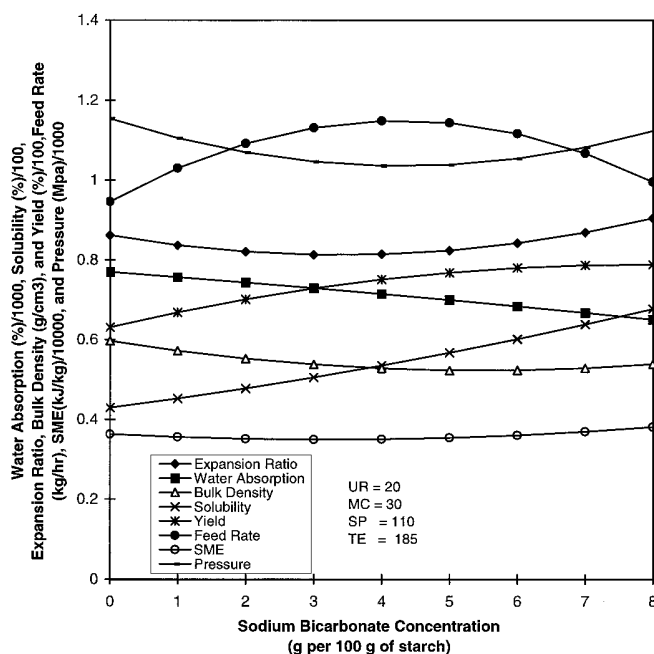


Fig. 2. Effects of sodium bicarbonate concentration on binder properties and processing conditions (urea [UR], moisture content [MC], screw speed [SP], temperature [TE]). Values calculated using the regression models.

TABLE II
Coefficients and Significance of Regression Models^a

Coefficients ^b	Water Absorption (%)	Solubility (%)	Expansion Ratio	Bulk Density (g/cm ³)	Yield (%)	SME (kJ/kg)	Feed Rate (kg/hr)	Die Pressure (MPa)	Die Temperature (°C)
Constant (a)	1,651.7	212.482	18.657	3.0413	139.472	35,799.06	-2.901	1,049.94*	242.10*
UR (b ₁)	27.2243	-7.0175****	0.1141****	0.0436	-28.5336****	-1,124.85**	0.2555***	-1.456	-1.4847
SB (b ₂)	-86.3592****	11.5735	-0.2903****	0.0488	41.7805****	-876.86	0.2064	-7.7471	-3.2454
MC (b ₃)	17.644	-9.9886***	-0.3769*	0.0050	6.6344	-1,208.69**	0.1003	-30.7432*	-2.7362***
SP (b ₄)	-11.6688	0.8115	-0.0710****	-0.0447	-0.4985	-35.79	0.0350	1.4511	-0.5683
TE (b ₅)	-8.4886	0.3163	-0.0894**	-0.0059	0.2610	53.16	-0.0217	-5.2271**	-0.3025
UR × SB (c ₂)	-0.4125	0.1329	-0.0003	-0.0016	-0.0451	5.006	-0.0014	-0.1881****	-0.0219
UR × MC (c ₃)	-0.4195****	0.0115	-0.0010	-0.0015***	0.2142***	9.91***	0.0009	0.1368**	-0.0053
UR × SP (c ₄)	0.2243***	0.0101	0.0002	0.0006****	0.0297	-2.62	0.0006	-0.0294	-0.0006
UR × TE (c ₅)	-0.1088	0.0170	-0.0008*	-0.0003	0.0985*	3.230***	-0.0011**	-0.0096	0.0046
SB × MC (d ₃)	0.3638	-0.1848****	-0.0013	-0.0024	0.0007	2.856	0.0027	0.1906****	0.0281
SB × SP (d ₄)	-0.1244	-0.1628*	0.0029*	0.0010	-0.2663**	4.314	-0.0009	-0.0491	-0.0072
SB × TE (d ₅)	0.4579***	0.0617****	-0.0001	-0.0004	-0.0409	0.691	-0.0003	0.0173	0.0077
MC × SP (e ₄)	0.298**	0.0261	0.0001	0.0001	0.0007	-0.867	0.0004	-0.0186	-0.0016
MC × TE (e ₅)	-0.026	0.0042	0.0012*	0.0002	-0.0705**	0.879	-0.0002	0.0829*	0.0059
SP × TE (f ₅)	0.003	0.0031	0.0000	0.0001	0.0149	-0.195	0.0001	0.0035	0.0001
UR × UR (g ₁)	-0.445***	0.0022	0.0011****	0.0002	-0.0374	8.537**	-0.0028**	0.0317	0.0250**
SB × SB (g ₂)	-0.2744	0.1130	0.0043	0.0025	-0.2585	13.695	-0.0111	0.9291*	0.2403*
MC × MC (g ₃)	-0.492***	0.0877**	0.0022*	-0.0001	0.0282	13.330**	-0.0030*	0.1767*	0.0280**
SP × SP (g ₄)	-0.0156	-0.0070	0.0002	0.0000	-0.0082	0.585	-0.0003	-0.0036	0.0030
TE × TE (g ₅)	0.0283	-0.0040	0.0002**	0.0000	-0.0024	-0.351	0.0001	0.0086	0.0014
Model P -value	0.0070	0.0014	0.0230	0.1791	0.0410	0.0074	0.0550	0.0001	0.00001

^a Significance level of coefficients: * = $P < 0.05$; ** = $P < 0.1$; *** = $P < 0.2$; **** = $P < 0.3$.

^b UR = urea; SB = sodium bicarbonate; MC = moisture content; SP = screw speed; TE = temperature.

in the regression models was examined using the *t* test. If the *t* value of a coefficient was significant at a lower *P* value, it indicated that the term was more important than others in the model and made a significant contribution to the dependent variable.

To illustrate the effects of independent variables on dependent variables with graphs, only one independent variable was varied in the experimental range and four other independent variables were fixed at their central levels. Selected values of dependent variables obtained from the regression models are shown in Figs. 1–5. The solubility and binder yield decreased and bulk density and feed rate increased when the urea concentration increased (Table II, Fig. 1). The function of urea is to break the hydrogen bonds in starch

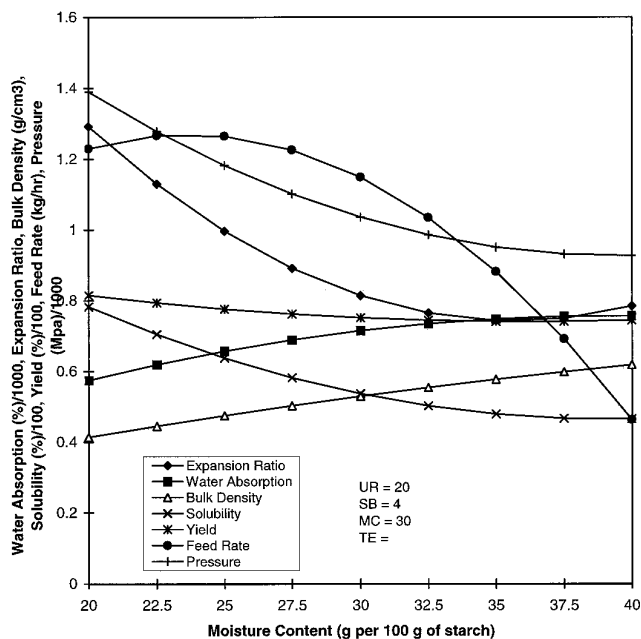


Fig. 3. Effects of moisture content on binder properties and processing conditions (urea [UR], sodium bicarbonate [SB], screw speed [SP], temperature [TE]). Values calculated using the regression models.

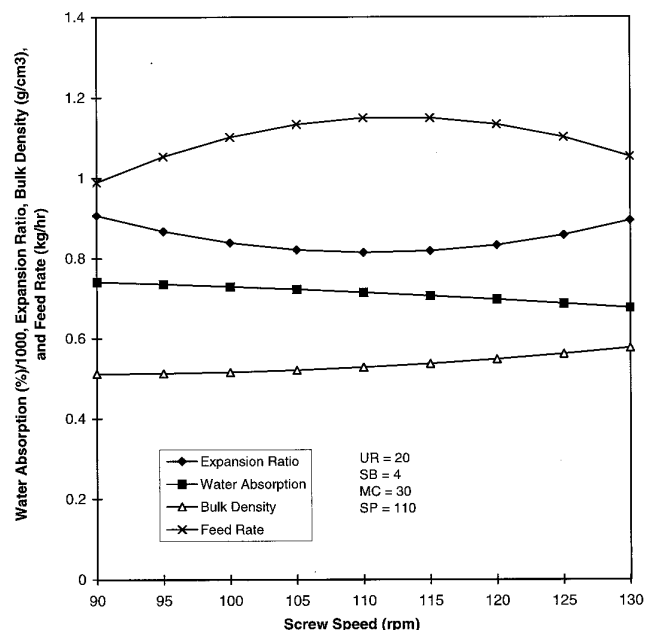


Fig. 4. Effects of screw speed on binder properties and processing conditions (urea [UR], sodium bicarbonate [SB], moisture content [MC], temperature [TE]). Values calculated using the regression models.

and to serve as a plasticizer, which results in reduced resistance to the flow of the starch in the barrel.

Thus, the die pressure and SME were slightly reduced and the feed rate increased (Chinnaswamy and Hanna 1990). The extrudate obtained with a high urea concentration had a high bulk density, which could be translated into great hardness. The hard extrudate was difficult to grind into fine particles and gave a low binder yield. Slightly increased water absorption was obtained at a concentration of ≈ 20 g of urea/100 g of starch. The decrease in solubility of the binder is similar to results obtained by Owusu-Ansah et al (1983) with NaOH. The expansion ratio decreased when urea concentration increased from 10–20 g/100 g of starch, which was similar to the results reported by Chinnaswamy and Hanna (1988). The low solubility of the binder produced with high urea concentration indicated no significant molecular degradation. Chinnaswamy and Hanna (1990) reported that sodium bicarbonate

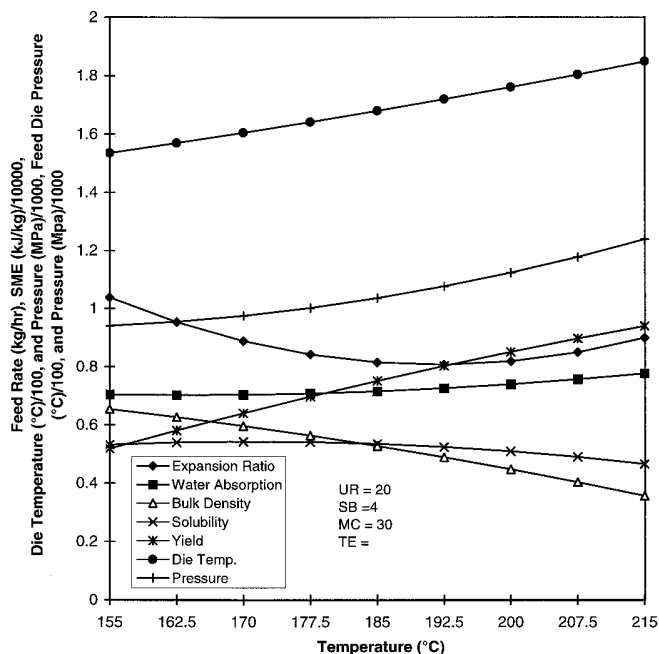


Fig. 5. Effects of temperature on binder properties and processing conditions (urea [UR], sodium bicarbonate [SB], moisture content [MC], screw speed [SP]). Values calculated using the regression models.

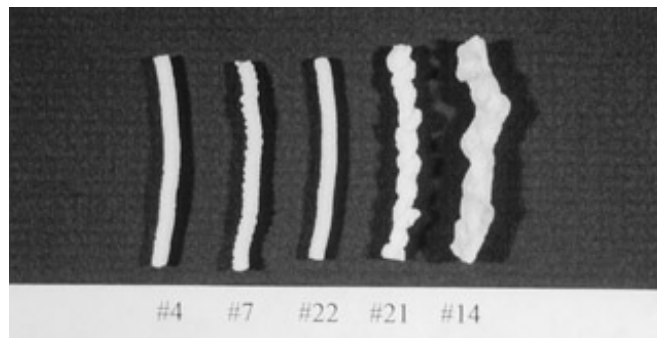


Fig. 6. Appearance of extrudates with high water absorption: sample 4 (15 g of urea, 2 g of sodium bicarbonate, 35% moisture content, 120 rpm; 200°C); sample 7 (15 g of urea, 6 g of sodium bicarbonate, 35% moisture content, 100 rpm; 200°C); sample 22 (20 g of urea, 4 g of sodium bicarbonate, 40% moisture content, 110 rpm; 185°C). Appearance of extrudates with high water absorption: sample 21 (20 g of urea, 4 g of sodium bicarbonate, 20% moisture content, 110 rpm; 185°C); sample 14 (25 g of urea, 6 g of sodium bicarbonate, 25% moisture content, 110 rpm; 170°C). Concentration is grams per 100 g of starch.

degraded starch molecules to a greater extent than did urea when they were present at the same concentration.

Sodium bicarbonate displayed an effect similar to that of urea on the expansion ratio of extrudate (Fig. 2). The solubility of the binders increased with the increase of the sodium bicarbonate concentration, but decreased with the increase of urea concentration, indicating different functions of sodium bicarbonate and urea during extrusion. Sodium bicarbonate also showed different effects on SME and bulk density. A slightly higher binder yield at the high sodium bicarbonate concentration was noted. Water absorption of the binder decreased with the increase of sodium bicarbonate concentration. All these results could be attributed to sodium bicarbonate induced molecular degradation.

It was observed that feed rate of starch in the feed section of the extruder was low when the moisture of the starch was high. Then the feed rate of volumetric feeder was adjusted based on the moisture content and screw speed to ensure a stable feeding in the feed section. Once the starch was fed into the extruder, it flowed well through the extruder barrel because water acted as a plasticizer and a lubricant and reduced the pressure of the die. Die pressure and expansion ratio of the extrudate decreased with the increased moisture content (Fig. 3). High moisture content made the extrudate rubbery so it was not able to maintain the expanded shape. This phenomenon corroborated the report by Della Valle et al (1987) for cooking corn starch with a twin-screw extruder. The increase in water absorption of the binder with the increase of the moisture content was attributed to less molecular degradation. Excess moisture in the extrudate, however, requires more energy to dry. Thus, the moisture content >40 g/100 g of starch is not recommended.

A high screw speed indicates a short residence time of starch in the barrel and resulted in a slightly higher bulk density and lower water absorption (Fig. 4). Barrel temperature played a very important role during extrusion (Fig. 5). As the temperature increased, more gas was generated from sodium bicarbonate, which resulted in a higher pressure in the die and more pores in the extrudate. Therefore, the extrudate bulk density decreased and binder yield increased. Water absorption increased slightly at a high temperature (>200°C).

The most important terms in the water absorption models include the interaction terms of urea and screw speed, sodium bicarbonate and temperature, and moisture content and screw speed, as well as the quadratic terms of urea and moisture. This indicates that the interactions are important in affecting the water absorption of extrudates during the process. Among the total of 30 tests, five of them had high water absorption ranging from 760 to 790%, which is higher than the water absorption of pregelatinized wheat starch tested as a iron ore binder by Hass et al (1989), and two showed low water absorption ranging from 530 to 590%.

To examine the degree of starch gelatinization of the binder, selected samples 21 and 22 were run in a differential scanning calorimeter. No thermal transition peaks were shown in the temperature range from 25 to 120°C. This indicated complete gelatinization of the starch. An examination of the extrudate samples and extrusion conditions revealed that the binders made with starch (100 g) at low moisture content (20–25 g), high urea concentration (20–25 g), and low temperature (170–185°C) had low water absorption, and the samples made with high moisture content (35–40 g), medium urea concentration (15–20 g), and high temperature (185–200°C) produced the binders with high water absorption. The extrudate samples had different appearances (Fig. 6). Gel-permeation chromatographic studies of the three samples with high water absorption and the two samples with low water absorption showed that the samples with high water absorption displayed a low degree of molecular degradation (sample 22, Fig. 7), whereas the samples with low water absorption displayed a high degree of degradation (sample 21, Fig. 7). For sample 14, the extrudate had a high bulk density because of its low moisture content and low extrusion

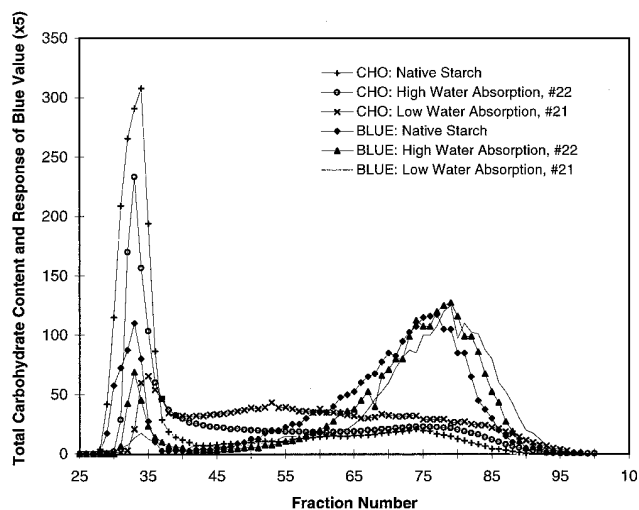


Fig. 7. Chromatographic profile of native starch and starch-based binders with high (sample 22) and low (sample 21) water absorption capabilities.

temperature. For sample 21, with a low moisture content and high extrusion temperature, the extrudate had a low bulk density and the texture was fragile. Although these two samples showed different physical appearances (Fig. 6) and bulk density, both had low water absorption and severe molecular degradation. These indicated that the low moisture content of the starch resulted in the molecular degradation.

On the basis of these results, the optimum chemical concentrations and extrusion variables for high water absorption were 15–20 g of urea, 0–4 g of sodium bicarbonate, 35–40 g of moisture/100 g of starch, 100–120 screw speed rpm, and 185–215°C barrel temperature. Extrusion processing was demonstrated to produce starch binders with good water absorption for making iron ore pellets.

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