Factors Affecting the Viscosity of Extrusion-Cooked Wheat Starch[1]

W. R. MASON[2] and R. C. HOSENEY[3]

ABSTRACT

Cereal Chem. 63(5):436–441

The factors responsible for the cold and hot paste viscosities of extrusion-cooked wheat starch were investigated. Hot paste viscosity was affected by die temperature and an interaction between screw speed and barrel temperature. Cold paste viscosity was affected by an interaction between moisture of the feed and throughput rate. The area of a peak on the descending amylograph heat cycle curve was measured. This "swell peak area" was highly correlated with cold paste viscosity. It was shown that the swell peak area corresponded to the quantity of starch that, although completely gelatinized, can undergo further swelling upon heating in water.

Moreover, the swell peak area reflected the presence of insoluble starch, which absorbs water but excludes solubles, thus concentrating the soluble phase. Cold paste viscosity was shown to vary with the concentration of the soluble phase and the volume of insolubles that exclude solubles. The latter was measured with a dye-labeled soluble dextran. Water absorption index and water solubility index were negatively correlated with cold paste visocosity. Hot paste viscosity was found to be correlated with molecular degradation as measured with capillary viscometry.

Starch is most commonly used as a thickener or bodying agent in foods (Sterling 1978). Pregelatinized starches are useful in a variety of prepared and convenience products because of their relatively high viscosities at fairly low concentrations in products that are not heated. Extruders offer an efficient means for the preparation of pregelatinized starches (Millauer and Weidmann 1984). Varying the conditions of starch extrusion produces extrudates with a range of paste qualities (Anderson et al 1969, Lawton et al 1972, Meuser et al 1984). Unfortunately, efforts to completely account for variations of paste viscosity in extruded starches have been unsuccessful (Colonna and Mercier 1983, Davidson et al 1984).

This investigation was designed to associate cold and hot paste viscosity with extrusion conditions. In addition, several starch parameters were correlated with the hot and cold paste viscosity of the extruded products.

MATERIALS AND METHODS

Materials

A Brabender 19-mm model 2403 extruder was used for the laboratory experiments (C. W. Brabender Co. , Hackensack, NJ). When larger quantities of extruded sample were required, a Wenger X-20 was used (Wenger Manufacturing, Sabetha, KS). The Brabender extruder has been described by Faubion (1980). More recently, it was fitted with a feeder designed by Timbers and coworkers (1976) and manufactured at the Kansas State University instrument shop. In all of the laboratory extrusion experiments a 4:1 compression screw and a 6.35-mm die cap were employed. The die cap was attached to a 10-cm extender, which had the same internal diameter as the Brabender die cap mount (10 mm). The extender was found to give a more uniform flow when the die cap was attached to the extender. Power consumption was recorded by a recording ampere meter on the extruder drive motor.

The Wenger X-20 was set up with five heads including the barrel segments, screw elements, and steam locks depicted in Table I. A back-up die with a single 12.7-mm hole was used. The final die had three 4.75-mm openings. Amperage consumption by the 22.4-kW U.S. Motors (Milford, CT) drive was monitored with an Amprobe Instruments (Lynbrook, NY) recording ampere meter fitted at the breaker box.

Commercial grade wheat starch was obtained from Midwest Solvents Inc. of Atchison, KS. Silicon dioxide was obtained from the Degussa Corp. of Teterboro, NJ.

Moisture Measurement

Moisture determinations were made by AACC method 44-19 (1983).

Tempering Wheat Starch for Extrusion with the Brabender Extruder

For laboratory extrusion, 2 kg of wheat starch was placed in a tempering drum 50 cm long and 50 cm in diameter. Water was added as a mist into the drum as it was turned. Sufficient Aerosil 200 silicon dioxide to make 0.1% based on the total starch was mixed with 100 g of starch in a Waring Blendor. The mixture was then added to the 2-kg sample and blended for 1 hr in a V-mixer (Patterson Kelly Co., East Stroudsberg, PA). Sample moisture levels were confirmed by oven moisture determinations and adjusted when necessary by adding water or 10% moisture starch. Samples were allowed to equilibrate at 4° C for at least three days before extrusion.

Operation of Brabender Extruder

The Brabender extruder has three zones, which may be heated or air-cooled. In all cases, the feed zone was set at 30° C, the middle zone at 125° C, and the end zone was set at the desired temperature (165–215° C). The treatments employed are given in Table II. These represent a three-variable, five-level (Table III) central composite response-surface methodology design, as described in Cochran and Cox (1957). The feed rate was adjusted to 35 g/min and monitored during the run. Start-up was achieved with a mixture of 30% soy meal in wheat starch at 25% moisture. Once the extruder was running smoothly under the desired treatment conditions, 10 min was allowed to pass before samples or data were collected. Samples were collected as straight ropes up to 1 m long. Each rope corresponded to 10, 15, or 20 sec running time, depending upon the axial flow rate. Ten ropes were collected for

TABLE I
Wenger X-20 Barrel and Screw Configurations
Used to Extrude Wheat Starch
(Including Manufacturer's Part Numbers)

Barrel Segment	Screw Element	Steam Lock
Spiral (68372-001)	Single flight (68327-001)	Small (68364-001)
Spiral (68372-001)	Single flight (68327-001)	Small (68364-001)
Straight (68318-001)	Double flight (68326-001)	Intermediate (68324-001)
Straight (68318-001)	Double flight (68326-001)	Intermediate (68324-001)
Spiral cone (68350-001)	Triple flight shallow cone (68387-001)	

each treatment. The remainder of the extruded starch was collected for grinding and starch analysis.

Operation of the Wenger Extruder

A screw speed of 400 rpm was used. Wheat starch containing 0.1% silicon dioxide was processed at 55 kg/hr. The addition of water to the feed stream at the barrel throat was monitored with a Brooks flow meter. Two samples were produced for this study; these are characterized in Table IV. Once the extruder was running, each of the barrel segments was cooled with water except the last zone, which required steam to maintain the desired barrel temperature in some cases.

Drying and Grinding of Samples

Extrudates were dried 2 hr at 100°C in a forced draft oven and sealed in plastic bags after cooling. Samples were ground first in a Waring Blendor then in a Udy cyclone mill (Udy Corp., Boulder, CO) fitted with a 0.5-mm screen.

Process Measurements

Barrel and die temperatures. Die temperature was measured with a surface probe (Omega Engineering, Stamford, CT) attached to the die cap. Barrel temperatures were determined with bayonet thermocouple probes.

Throughput rate. The throughput rate (g/min) was determined for the dry-basis weights of individually timed ropes collected as described above.

Specific energy. The ampere load and voltage of the extruder drive was used to calculate the watt hours consumed. Together with the throughput data, these values were used to calculate the specific energy (kWhr per kg throughput) with the equation:

$$\text{Specific energy} = (\text{amperes} \times \text{volts})/(\text{kg/hr throughput}).$$

Product Measurements

Axial and radial expansion and bulk density. Axial expansion (or flow rate) was measured from the individually timed ropes corresponding to 10, 15, or 20 sec of extrusion. The flow rate thus calculated was expressed in centimeters per minute. A dial caliper was used to determine the diameter of the extruded rope. Radial expansion was simply expressed as the diameter of the rope. Bulk density was determined by dividing the weight of a sample by its calculated volume. The volume was determined by multiplying average cross-sectional area times the rope length.

Analysis of changes in starch during extrusion. For amylography, 600 g of a 10% dry basis slurry was prepared by blending appropriate amounts of 30°C distilled water and sample. The slurry was then shaken for 2 hr in a 30°C water bath, and 500 g of the slurry was weighed into the bowl of a Brabender amylograph. The torque on the stirring spindle was recorded as the slurry was stirred at 75 rpm, and the temperature was increased at 1.5°C/min up to 95°C. Although the amylograph does not measure viscosity in the true sense, the torque measurements will be called viscosities as this is the convention. The following data were read from the curves in each of two tests: initial or cold paste viscosity, viscosity at 95°C, and the area under a peak occurring on the down-sloping amylograph curve (swell peak area). Swell peaks are evident on amylograms appearing in several publications (Anderson et al 1969, Gomez and Aguilera 1983, Kim 1983). To measure the area under the peak, a line was drawn tangentially from the inflections at the beginning and end of the peak (Fig. 1). The peak area was then determined with a planimeter.

Cold paste viscosity of dissolved materials. To investigate the effect of solubles on cold paste viscosity in extruded samples, the following experiment was performed. Samples were chosen to represent a range in cold paste viscosity and relative viscosity (defined under capillary viscometry). These samples were dissolved at 10% dry basis by stirring 20 min in 1N sodium hydroxide. Subsequently, their 30°C amylograph viscosities were determined at pH 13.5, 13, 12.5, 12, 11.5, 11, 10, 9, and 6.5. Unfortunately, it was not possible to separate neutralization and dilution effects.

TABLE II
Experimental Design for Brabender Extrusion

Sample I.D.	Feed Moisture (%)	Screw Speed (rpm)	Barrel Temperature (°C)
A	22.5	120	205
B	22.5	160	205
C	21.0	140	215
D	21.0	107	190
E	22.5	160	175
F	21.0	140	190
G	23.5	140	190
H	22.5	120	175
I	19.5	160	205
J	19.5	120	175
K	21.0	140	190
L	21.0	140	190
M	18.5	140	190
N	19.5	120	205
O	21.0	140	190
P	19.5	160	175
Q	21.0	173	190
R	21.0	140	190
S	21.0	140	165
T	21.0	140	190

TABLE III
Central Composite Design Employed in Study: Level of Variables ($n = 20$ Treatment Combinations)[a]

Block	X-Variable 1	2	3
I	−1	−1	1
	1	−1	−1
	−1	1	−1
	1	1	1
	0	0	0
	0	0	0
II	−1	−1	−1
	1	−1	1
	−1	1	1
	1	1	−1
	0	0	0
	0	0	0
III	−1.633	0	0
	1.633	0	0
	0	−1.633	0
	0	1.633	0
	0	0	−1.633
	0	0	1.633
	0	0	0
	0	0	0

[a] Adapted from Cochran and Cox 1957.

TABLE IV
A Comparison of Samples Used in the Reconstitution Study

Variable	Sample I	II
Extrusion conditions:		
Barrel temperature	160°C	175°C
Feed moisture	27%	20%
Specific energy	0.088 kWhr/kg	0.136 kWhr/kg
Starch characteristics:		
Relative viscosity	0.838	0.781
Amylograph cold paste viscosity	700 BU	480 BU
Swell peak area	3,290 BU min	1,440 BU min
Hot paste viscosity	85 BU	50 BU
BDEV/g[a]	4.38 ml/g	3.79 ml/g

[a] BDEV/g is the blue dextran exclusion volume per gram.

However, the samples were always between 9 and 10% dry basis, and the greatest volume of acid was added above pH 11.5. Because gelation was evident below pH 10, the rate of thickening in the solubilized materials was monitored for several hours after they were adjusted to pH 6.5. The viscosity of the solutions was determined after the pH 6.5 slurry had been shaken 0.5, 1.0, and 2 hr at 30° C.

Capillary viscometry. Samples were prepared for capillary viscometry according to the method of Leach (1963). Starch (1 g) was suspended in 20 ml of water. This suspension was heated for 30 min in a boiling water bath. The samples were cooled and adjusted to make 2 g/L starch in 1 N base. Cannon-Fenske no. 50 tubes were used to determine the kinematic viscosities of these solutions. The relative viscosity of sample solutions was calculated by dividing the kinematic viscosity of the sample by that of a solution of the parent starch. The Cannon-Fenske tubes were calibrated against water and 20% sucrose at 30, 35, and 40° C.

Estimation of insoluble volume. This experiment was performed to estimate the volume of the insolubles that absorb water but exclude solubilized starch. Hereafter, this will be referred to as the blue dextran exclusion volume (BDEV). A sample weighing 1.25 g was shaken 11 hr in 24 ml of 5% aqueous blue dextran (Sigma Chemical, St. Louis). The slurry was centrifuged at $1,000 \times g$ for 10 min and the absorbance of the supernatant at 660 nm was determined. To correct for turbidity, the absorbance of a sample containing water in place of blue dextran was measured. This value was subtracted from the former to obtain net absorbance. BDEV was calculated from:

$$BDEV \text{ per gram} = (24 \text{ ml}) - [(24 \text{ ml}) \cdot (As/Abd)] / 1.25 \text{ g},$$

where As is the net absorbance of the sample and Abd is the absorbance of the 0.5% blue dextran solution.

Water absorption and water solubility indexes. Water absorption index (WAI) and water solubility index (WSI) were determined as described by Anderson et al (1969). A 2.5-g sample of ground product was suspended in 30 ml of water at 30° C. The sample was shaken for 30 min with intermittent agitation on a vortex mixer (Scientific Products, McGraw Park, IL) then centrifuged at $1,000 \times g$ for 10 min. The supernatant was dried and the amount of solubles expressed as a percent of the original dry sample weight (WSI). The ratio between the total weight of the pellet and the weight of the solids in the pellet is the calculated WAI.

Reconstitution study to evaluate model for factors influencing cold paste viscosity. An experiment was performed to test whether solubles concentration and BDEV of the insolubles control the cold paste viscosity of an extruded starch. In the same study, the effect of holding time on cold paste viscosity was also investigated. The concentration of solubles and insolubles was adjusted by extracting solubles and reconstituting diluted solubles with either extracted insolubles or granular extrudate.

For this study, two samples were prepared on the Wenger X-20 extruder (Table IV). In the sample with lower solubles (sample I), water-extracted materials were simply added to granular extrudate. The sample extruded at lower moisture (sample II) had a much higher solubles content, so it was generally necessary to dilute solubles and add them back to water-extracted centrifugate.

The formulated samples comprised a central composite design of three variables (including holding time) at five levels. The experimental designs for the two samples are shown in Tables V and VI. The quantities of water, solubles, and insolubles required to achieve the experimental levels were calculated from a measurement of the amount of starch solubilized and from an estimation of the volume of solubles within the extracted insolubles. The volume of solubles remaining in the pellet was calculated as the total volume less the BDEV.

TABLE V
Experimental Design for Solubles and Insolubles Reconstitution Study with Extruded Sample I

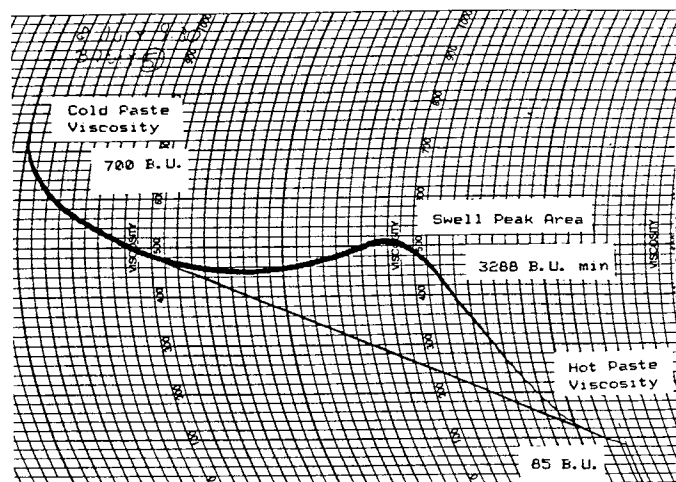| Number	Holding Time (hr)	Solubles (%)	Insolubles (%)	Dry Basis (%)
1	4.0	2.11	8.50	10.61
2	4.0	2.11	8.50	10.61
3	4.0	2.11	9.50	11.61
4	4.0	3.11	8.50	11.61
5	4.0	2.11	8.50	10.61
6	4.0	1.11	8.50	9.61
7	2.75	1.50	9.11	10.61
8	2.75	1.50	7.89	9.39
9	2.75	2.72	9.11	10.61
10	2.0	2.11	8.50	10.61
11	5.25	2.72	9.11	11.83
12	4.0	2.11	8.50	10.61
13	4.0	2.11	8.50	10.61
14	6.0	2.11	8.50	10.61
15	5.25	1.50	9.11	10.61
16	4.0	2.11	7.50	9.61
17	4.0	2.11	8.50	10.61
18	5.25	1.50	7.89	9.39
19	2.75	2.72	7.89	10.61
20	5.25	2.72	7.89	10.61

Fig. 1. An amylogram (30–95° C) of extruded wheat starch showing the "swell peak area."

TABLE VI
Experimental Design for Solubles and Insolubles Reconstitution Study with Extruded Sample II

Number	Holding Time (hr)	Solubles (%)	Insolubles (%)	Dry Basis (%)
1	2.75	2.72	9.11	11.83
2	4.0	2.11	8.50	10.61
3	4.0	2.11	9.50	11.61
4	2.0	2.11	8.50	10.61
5	2.75	1.50	7.89	9.39
6	2.75	2.72	7.89	10.61
7	4.0	3.11	8.50	11.61
8	4.0	2.11	8.50	10.61
9	6.0	2.11	8.50	10.61
10	4.0	2.11	8.50	10.61
11	4.0	2.11	8.50	10.61
12	4.0	2.11	7.50	9.61
13	4.0	2.11	8.50	10.61
14	5.25	1.50	7.89	9.39
15	5.25	2.72	9.11	11.83
16	4.0	2.11	8.50	10.61
17	5.25	1.50	9.11	10.61
18	2.75	1.50	9.11	10.61
19	4.0	1.11	8.50	9.61
20	5.25	2.72	7.89	10.61

RESULTS AND DISCUSSION

The first phase of this study was designed to associate cold and hot paste viscosity with extrusion conditions. The independent variables included screw speed, barrel temperature, and feed moisture. The process measurements taken included power consumption, die temperature, actual throughput rate, axial flow rate, and extrudate diameter.

Effect of Extrusion Conditions on Hot Paste Viscosity

Hot paste viscosity was found to be influenced by die temperature and an interaction between screw speed and barrel temperature (Table VII). Davidson et al (1984) observed a shift in the molecular weight distribution of extruded starch towards larger molecular fragments (less degradation) when lower screw speeds and higher temperatures were used. They ascribed this to an increased importance of thermal degradation as the dough temperature increased. At higher temperatures, mechanical degradation was less pronounced as the dough viscosity decreased, whereas the kinetics of thermal degradation became more favorable.

Factors Controlling Hot Paste Viscosity in the Product

Hot paste viscosities significantly correlated with capillary viscometry and appeared to reflect molecular degradation (Table VIII). Similar findings are reported for wheat starch (Colonna et al 1983), wheat flour (Kim 1983), and corn grits (Gomez and Aquilera 1983).

Effect of Extrusion Conditions on Cold Paste Viscosity

Cold paste viscosity was influenced by the interaction between moisture and throughput rate (Table VII). This agrees with the observation of Meuser et al (1982) that cold paste viscosity achieves a maximum at low rates of specific energy input. The same authors found that increased feed moisture and increased throughput rate decreased specific energy. Figure 2 shows the relationship between cold paste viscosity and the two variables, feed moisture and barrel temperature, for the present data.

Starch Analyses

The starch analyses used in the study were examined to gain insight into the factors controlling cold paste viscosity (Table VIII). Cold paste viscosity was highly correlated with swell peak area, water absorption index, and water solubility index. The WAI and WSI data concurred with the findings of Anderson et al (1969). It was not clear how to interpret the WSI and WAI data or what mechanism was responsible for cold paste viscosity. The correlation with swell peak area, however, suggested that the presence of meta-stable associations of starch might be important. Because swell peak area decreased with increasing specific energy input (Table IX), it appeared that starch granules remaining ungelatinized after extrusion might account for the swell peak area. However, no gelatinization endotherm was found when samples with large swell peaks were examined by differential scanning calorimetry. Therefore, the swell peak area was not attributable to starch granules that escaped cooking. Instead, it
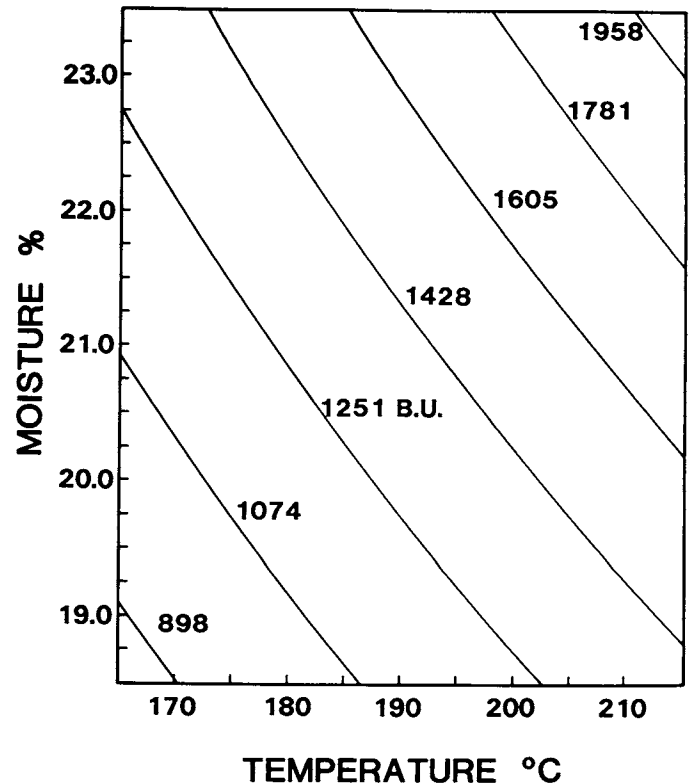
TABLE VII
Regression Equations
for Starch Analyses Versus Laboratory Extrusion Conditions

Dependent Variable	Independent Variable[a]	Intercept and Coefficient[b]	Prob >F	R^2
Cold paste viscosity		−320.2[b]		
	W × G	2.40	0.0001	0.59
Hot paste viscosity		615.8[b]		
	D	−2.25	0.0764	0.49
	R × T	−0.016	0.0239	
Swell peak area		−3,387.6[b]		
	W × D	1.42	0.0001	0.70
Relative viscosity		1.08[b]		
	T	−0.0017	0.001	0.67
	W × G	0.00012	0.0147	
Water absorption index		20.06[b]		
	W	−0.39	0.001	0.69
	R × T	−0.000064	0.0180	
Water solubility index		0.34[b]		
	W × G	−0.00027	0.0035	0.39
Blue dextran exclusion volume		−18.18[b]		
	W × D	0.0018	0.0007	0.48

[a] W = moisture (%), T = barrel temperature (°C), D = die temperature (°C), G = dry basis throughput (g/min), and R = screw speed.
[b] Denotes intercept value.

Fig. 2. Contour plot of cold paste viscosity (BU) as a function of feed moisture and barrel temperature.

TABLE VIII
Correlation Coefficients Between Starch Analyses Used to Characterize Laboratory-Extruded Wheat Starch

Starch Analyses	Cold Paste Viscosity	Hot Paste Viscosity	Swell Peak Area	Relative Viscosity	Water Absorption Index	Water Solubility Index
Hot paste viscosity	−0.047	···	···	···	···	···
Swell peak area	0.633**[a]	0.004	···	···	···	···
Relative viscosity	0.016	0.541*	0.164	···	···	···
Water absorption index	−0.755**	0.057	−0.843**	−0.112	···	···
Water solubility index	−0.647**	0.131	−0.619**	−0.039	0.594*	···
Blue dextran exclusion volume	0.459*	0.085	0.724*	0.152	−0.598**	−0.374

[a] *, ** Significant at 95 and 99%, respectively.

appears that the peak is caused by the presence of gelatinized but incompletely disorganized granular remnants. Presumably, these can continue to swell when heated in water at temperatures below the gelatinization temperature. It was not possible to determine whether the structures responsible for the swell peak are vestiges of starch granules or structures formed during extrusion.

Studies with wheat starch solubilized in alkali demonstrated the relationship between viscosity and the concentration of a starch solution (Table X). Because a starch solution's viscosity increased markedly with concentration, it was conceivable that the structures responsible for the swell peak area were concentrating the soluble phase. This would be possible if water but not the solubilized starch could enter the insoluble starch matrix.

The WAI and WSI data supported this hypothesis. Cold paste viscosity was negatively correlated with WAI and WSI (Table VIII). Further support for this hypothesis came from blue dextran exclusion data. A dye-labeled soluble dextran was used to estimate the volume of insolubles that would absorb water but exclude solubles. This BDEV was found to correlate with cold paste viscosity in the 20 samples from laboratory extrusion (Table VIII).

Testing the Model for Cold Paste Viscosity

A model for cold paste viscosity was proposed that included two parts, assuming, first, that the concentration of the solubles controls the viscosity of the suspension, and second, that the concentration of the soluble phase is influenced by the volume of insolubles that preferentially absorb water but exclude soluble starch. In order to test this model, samples were prepared that varied in the concentration of their soluble phase and in the quantity of insolubles present. The concentration of the soluble phase was calculated using three values: a measure of the solubles in the extract, a measure of the solubles in the insoluble source, and an estimate of the volume of the insolubles into which water but not solubles can diffuse. If the proposed model for cold paste viscosity were sound, then variation among the samples would be accounted for by the independent variables used in the study. The independent variables included holding time in addition to solubles and insolubles concentrations. In experiments with alkali solubilized starch, holding time affected cold paste viscosity of neutralized solutions.

The regression equations for the model experiment appear on Table XI. The R^2 of 0.89 indicates that the model effectively explains the variation in cold paste viscosity for sample I. The most significant term according to stepwise regression analysis was the interaction between soluble concentration and insoluble concentration. Apparently, the effect of either term was increased by an increase in the other variable. Higher concentration of solubles (the second independent variable in the model) lowered the cold paste viscosity. This may reflect delayed or decreased solubilization of granular materials when the concentration of the reconstituted solubles was high. Figure 3 shows how the cold paste viscosity of the suspensions reconstituted from sample I responded to changes in solubles and insolubles concentrations. Sample II had an R^2 of 0.74. This lower value may reflect a change in the BDEV during successive extractions of the insoluble material. At the lowest solubles level, there was an increase in the predicted viscosity. In both studies, models were significant, and the weight and volume of solubles appeared to be controlling factors in the cold paste viscosity of extruded wheat starch. The relationship between the cold paste viscosity and the concentrations of solubles
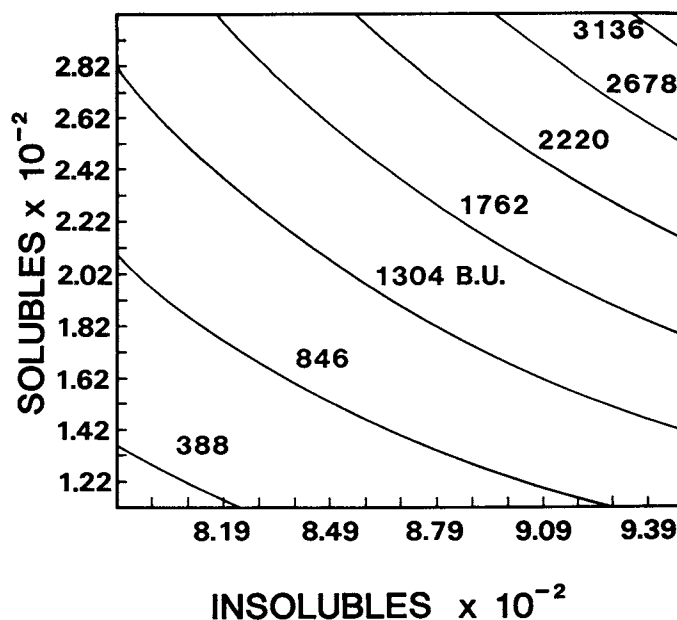
TABLE IX
Correlation Coefficients for Laboratory Extrusion Proces Measurements and Starch Analyses

Starch Analyses	Specific Energy	Linear Flow Rate	Extrudate Diameter	Specific Volume
Cold paste viscosity	−0.324	0.155	−0.284	−0.365
Hot paste viscosity	−0.164	−0.399	0.605**[a]	−0.006
Swell peak area	−0.558**[a]	0.137	−0.076	0.045
Relative viscosity	−0.505*	−0.310	0.602**	−0.142
Water absorption index	0.397	−0.324	0.321	−0.198
Water solubility index	0.087	−0.053	0.152	−0.238
Blue dextran exclusion volume	−0.368	0.280	0.026	−0.152

[a] *, ** Significant at 95 and 99%, respectively.

TABLE X
The Effect of Concentration on Cold Paste Viscosity of Alkali-Solubilized Wheat Starch

Dry Basis Concentration (%)	Cold Paste Viscosity (BU)
3.0	10
4.0	40
5.0	60
6.0	75
7.0	170
8.0	250
9.0	470
10.0	1,260

TABLE XI
Regression Coefficients for Cold Paste Viscosities for Reconstituted Extruded Wheat Starch Solubles and Insolubles

Sample	Independent Variable[a]	Intercept and Coefficient	Prob > F	R^2
I	···	−468.9[b]	···	0.89
	Sol	−240377.6	0.0001	
	Sol × Ins	3803890.1	0.0001	
II	···	−1119.9[b]	···	0.74
	Sol	−162549.7	0.0080	
	Sol × Sol	4477795.8	0.0026	
	Ins	36089.5	0.0003	

[a] Sol = solubles concentration, Ins = insolubles concentration, Sol × Sol = second order effect of solubles concentration, and Sol × Ins = interaction between solubles and insolubles concentration.
[b] Denotes intercept value.

Fig. 3. Contour plot of cold paste viscosity (BU) as a function of solubles and insolubles concentration for reconstitution study I.
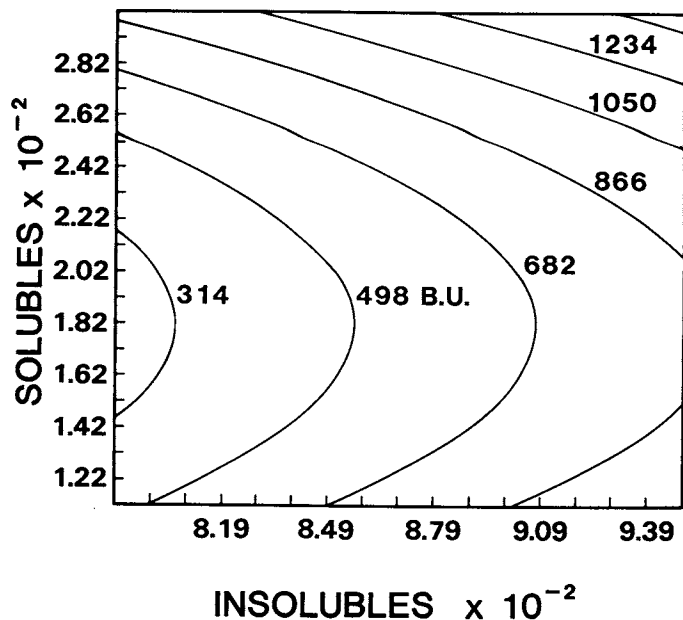
Fig. 4. Contour plot of cold paste viscosity (BU) as a function of solubles and insolubles concentration for reconstitution study II.

and insolubles in suspensions reconstituted from sample II is depicted in Figure 4.

Holding time did not appear to influence cold paste viscosity. This may be because the amylograph measurement, with its rapid stirring, destroyed gels as they were formed. Holding time had a dramatic influence on cold paste viscosity, when alkali-solubilized extruded starches were shaken to 30°C and measured in the amylograph after 0, 0.5, 1.0, and 2.0 hr (Table XII). The samples with the lowest relative viscosity (Table XIII) set up more rapidly, possibly because the increased degradation allowed for more mobility and, therefore, faster gelation. It is unclear whether the differences between the samples would have persisted with longer holding times. At least under the conditions of this experiment, holding time and, therefore, gelation, did not influence the cold paste viscosity of the samples.

CONCLUSIONS

A measurement of "swell peak area" was found to be correlated with cold paste viscosity. This swell peak area was shown to quantitate starch which, when slurried, can undergo further swelling during heating. Moreover, the swell peak area correlated with the extent to which an extruded starch can absorb water but not soluble starch, thus, concentrating the solubles phase. In a reconstituted system, cold paste viscosity was found to depend upon the concentration of solubles in the continuous phase of the suspension. Based on these findings, a model was proposed for factors controlling the cold paste viscosity of an extruded starch. In this study, time was not found to be an important variable in controlling viscosity. This would suggest that, under these conditions, viscosity was not dependent upon gelation.

With regard to extrusion conditions, cold paste viscosity was found to be influenced by an interaction between feed moisture and throughput rate. The swell peak area was found to be greater in starch extruded at higher moistures and higher die temperatures. Hot paste viscosity was found to be influenced by an interaction between extrusion screw speed and throughput rate and die temperature.

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TABLE XII
The Effect of Holding Time on the Viscosity of Alkaline-Solubilized Laboratory-Extruded Samples at pH 6.5[a]

Holding Time (hr)	Starch	Samples[b] B	E	I	S
0		80	120	70	105
0.5		420	140	230	130
1.0		520	150	420	160
2.0	1,255	600	200	550	290

[a] Data reported in BU.
[b] Letters designate samples listed in Table II.

TABLE XIII
Relative Viscosity,[a] Cold Paste Viscosity, Hot Paste Viscosity, and Cold Paste Viscosity Following Alkali Solubilization for Wheat Starch and Several Laboratory-Extruded Samples

Starch Analyses	Starch	Sample[c] B	E	I	S
Relative viscosity	1.0	0.810	0.876	0.801	0.900
Cold paste viscosity[b]	⋯	1,960	1,820	1,130	1,205
Hot paste viscosity[b]	⋯	80	175	72.5	175
Dissolved cold paste[b]	1,260	80	120	70	120

[a] Relative viscosity is the ratio between sample and parent starch kinematic viscosities.
[b] Hot paste and cold paste data are reported as BU.
[c] Letters designate samples listed in Table II.