The Effects of Extrusion Cooking and Milling on the Instant Properties of Wheat Powders

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Abstract Instant powders that only require mixing with water prior to consumption can be produced by extrusion for use in products such as instant beverages. Both extrusion processing conditions and particle size of powder are important to end-product characteristics. In this study, a twin-screw extruder was used under various processing conditions (feed moisture, barrel temperature, and screw speed) to produce extrudates from soft wheat flour, which were ground to powders with particle size ranges of less than 93, 93-145, and 145-249 μm. Effects of adding soy lecithin to wheat flour before extrusion were also investigated. Water absorption, solubility, suspension viscosity, and dispersibility of wheat powders were related to specific, mechanical energy measured during extrusion. Powder particle size was important to instant properties, especially ease of dispersal in water and stability to sedimentation. Addition of lecithin significantly improved dispersibility of powders.

Keywords: extrusion, instantization, powder, dispersibility, flour

Introduction

Instantization or pregelatinization can be performed on cereal grains to increase the cold water viscosity and solubility of starch obtained from the grains. These instant powders are often used in products that undergo little or no heating prior to use. Production of instant starches is commonly done by drum-drying a 30-40% solids slurry of starch in water, followed by milling into a powder (1).

Pregelatinization can also be achieved by extrusion, through which conditions such as moisture, screw speed, temperature, and screw configuration, and starch properties including water absorption, water solubility, and cold viscosity can be modified (2, 3). Powders with high viscosity and water-binding capacity can be used in products as thickeners, while powders with low viscosity and high water-solubility are suitable for products such as beverages (3).

In terms of evaluating suitability of a particular instant powder, another important characteristic is the effort required to reconstitute and disperse the powder in liquid. According to Schubert (4), these instant properties include wettability, sinkability, dispersibility, and solubility. Some factors that affect instant properties include the dispersing of the liquid, powder composition, and powder particle size.

Instant cereal powders often have poor dispersibility due to starch swelling. Lump formation occurs in fine starch-based powders (which have large surface areas) due to the rapid hydration and gelling of starch on the outer surface of a lump cluster of inadequately mixed particles (1). As swelling occurs, pores for liquid penetration become clogged, leaving a lump with a dry core, known as a "fish eye" (1, 4). Dispersibility is normally controlled in drum-dried starches through the degree of milling. Larger particles, with their relatively less surface area, hydrate

more slowly, resulting in easier dispersion. However, larger particles also are coarser in texture (1) and may sediment more quickly. This may be an important consideration depending on the intended product.

Instantization improves instant properties of a product, and generally falls into either an agglomerative or a non-agglomerative process category (4). The addition of lecithin, a molecule that contains both hydrophilic and hydrophobic regions, is an example of non-agglomerative processing to improve the wetting of dry powders by liquids. Whole powdered milk is an example of a product where both agglomerative and non-agglomerative processes are used (5).

The objectives of the present study were to examine the effects of different extrusion conditions and instant powder particle size, along with the addition of lecithin, on the instant properties of extruded wheat flour.

Materials and Methods

Extrusion Soft white wheat flour (WF) (Star of the West, Frankenmuth, MI, USA) was extruded with an APV co-rotating, twin screw extruder, having a barrel diameter of 19 mm and a barrel length to diameter (LD) ratio of 25:1 (Model MP19T2-25, APV Baker, Grand Rapids, MI, USA). Barrel temperature, screw speed, and dough moisture content were varied to produce eight different extrusion conditions (Table 1), and extrusion was replicated on a different day.

Heating of the barrel was controlled by electric heating elements jacketing the barrel in five zones, with zone one nearest the feed section and zone five nearest the exit die. Moisture was adjusted by injection of water into the barrel using a Brook Crompton E2 Metripump (Hudders Field, England). Dry materials were fed using a K-TRON K2M twin-screw volumetric feeder (K-TRON, Pittman, NJ, USA). Torque was measured as percent of the total motor power (2000 W). The specific mechanical energy (SME) in Watt hours/kg was calculated according to the equation

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Table 1. Extrusion conditions for wheat flour and wheat flour +lecithin[a]

Free Rate (kg/hr)[b]	Total Material Moisture (%)	Screw Speed (rpm)	Barrel Temp. Zomes 1-5(°C)[c]
1.8	25	300	40/50/80/110/120
1.8	25	200	40/50/80/110/120
1.8	35	200	40/50/80/110/120
1.8	35	300	40/50/80/110/120
1.8	35	300	40/60/90/130/145
1.8	35	200	40/60/90/130/145
1.8	25	200	40/60/90/130/145
1.8	25	300	40/60/90/130/145

[a]Screw configuration (feed inlet → die): 8DT, 7 × 30°FKP, 7DT, 4 × 60°FKP, 3 ×30°RKP, 2DS, 6 × 60°FKP, 4 × 30°RKP, 2DS. D = Diameter, T = Twin lead screw, S = Single lead screw, FKP = Forward kneading paddle, SKP= Reverse kneading paddle; 1 Kneading paddle = 0.25D; 1D = 19 mm.
[b]Dry basis.
[c]Zone 5= nearest to exit die.

of Brent *et al.* (6):

SME = [actual screw rpm / rated screw rpm] × [% torque / 100] × [motor power in W / feed rate in kg/hr]
rated screw speed = 500 rpm; motor power = 2000 W.

Extrudate processing The extrudates were dried overnight in a food dehydrator (Proctor and Schwartz Inc., Philadelphia, PA, USA) at 45-50°C. Powders were made by progressively grinding and sieving the WF extrudates to produce particle sizes of 145-249, 93-145, and <93 μm. Grinding was done using a coffee grinder (Braun Inc., Woburn, MA) and an impact mill with 1.0 and 0.50 mm screens (Udy Cyclone Mill, Udy Corp., Fort Collins, CO, USA). Sieving was done with a rotary sifter (Sampl-Sifter, Great Western Mfg. Co., Leavenworth, KS, USA). After milling, the powders were stored at 5°C until analysis.

Wheat flour + lecithin (WFL) Wheat flour was blended with deoiled hydroxylated soy lecithin (Precept 8120, Central Soya, Fort Wayne, IN, USA) to a level of 4 % prior to extrusion. The same extrusion conditions as for the wheat flour alone (Table 1) were followed. A <93 μm powder was produced from the extrudates and analyzed in a similar fashion.

Powder analysis Mean particle size of the powders was determined by laser particle size analysis using a Beckman-Coulter LS 130 laser diffraction instrument (Beckman, Hialeah, FL, USA). Samples were suspended in isopropanol and measured for a 60-sec time interval.

Moisture content of the milled extrudates was determined by drying 1 g powder in an air oven (Model 737F, Fisher Scientific Co., Pittsburgh, PA, USA) at 130°C for 1 hr before re-weighing.

The water absorption and water solubility indices (WAI and WSI) were measured according to the procedure of Jin *et al.* (7) with some modifications. Two grams of powder were mixed with 20 ml distilled water in 30-ml round-bottom centrifuge tubes. The tubes were allowed to sit for 10 min and inverted three times each at 5 and 10 min. After 10 min, the suspensions were centrifuged (Model J2-21M, Beckman Instruments Inc., Fullerton, CA, USA) at
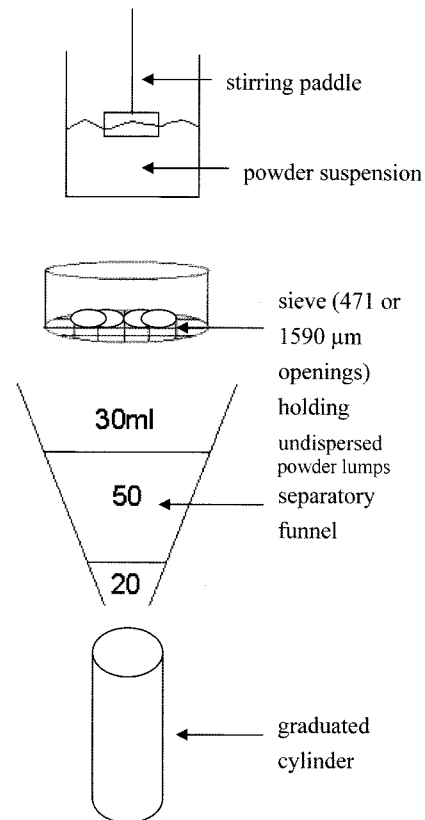

Fig. 1. Schematic for obtaining samples for measuring dispersibility and stability of extruded-milled powders in water.

1000 × g for 15 min. The supernatant was then poured off, and WAI of the powder sample was calculated as:
WAI = weight of pellet / sample weight (dry basis)
WSI was measured by drying the supernatant in an air oven overnight at 60°C. WSI was calculated as:
WSI = weight of dried supernatant / sample weight (dry basis)

Pasting properties were determined using a Rapid Visco Analyzer (RVA Model 4, Newport Scientific Pty. Ltd., NSW, Australia). Before analysis 3.5 g powder sample (14% m.b.) was mixed with 25 ml distilled water by shaking to ensure that no lumps were present. The extrusion 1 (no alcohol) temperature and heating profile of Thermocline for Windows v.1.2 (Newport Scientific) was followed. Cold viscosity was defined as the peak viscosity in Rapid Visco Units (RVU) between 0 and 2 min (holding at 25°C). Hot paste viscosity was measured as the peak viscosity during heating to 95°C between 2 and 7 min followed by holding at this temperature for 3 min.

Dispersibility measured the % total solids that passed through a sieve after mixing the powder in distilled water for a set time. Mixing was done with an overhead mixer (Mixer Head Model 50003-30, Cole-Parmer, Vernon Hills, VA, USA) by a 4 × 2 × 0.1 cm stirring paddle set at 200 rpm (Fig. 1). The stirring paddle was centered with its length horizontal, 1 cm below the liquid surface in a 250-ml beaker containing 100 ml distilled water at 21°C. Mixing time was set at 1 min and 10 sec. Five grams of powder sample were poured into the beaker during the

first 10 sec of mixing. After mixing, the suspension was immediately poured through a wire mesh sieve (Fig. 1). WF and WFL 145-249 and 93-145 μm powder suspensions were poured through a sieve with 1590 mm openings. The suspensions containing <93 μm particle size powder samples of WF and WFL were poured through a sieve with 471 μm openings. For each sample tested, the suspensions were poured through the indicated sieve (to remove undispersed powder lumps) directly into a 250-ml separatory funnel (Fig. 1), with the hole in the stopcock enlarged to aid the passage of the suspension. Twenty milliliters of the suspension were immediately drained through the stopcock, out of which 4 g sample was evaluated for solids content by drying in an air oven (Model 737F, Fisher Scientific Co., Pittsburgh, PA, USA) for 2 hr at 110°C. Dispersibility was calculated as the solids concentration of the suspension passing through the sieve, divided by the solids concentration solids concentration that would be possible if all powder particles had been completely dispersed.

% Dispersibility = [b_{20} / {(g sample dry basis) / (g sample d.b. + 100 g water)}] × 100

b_{20} = solids concentration (w/w) of drained 20 ml

Stability measured the amount of sedimentation in the remaining approximately 80 ml of suspension in the separatory funnel (Fig. 1) by allowing it to settle undisturbed for 2 min, after which 50 ml was then drained and discarded. The remaining portion (about 30 ml), consisting of the upper layer of the suspension, was then drained and a 4-g aliquot was measured for solids content. This was then divided by the solids concentration of the respective 20 ml aliquot initially drained off to measure dispersibility.

% Stability = [t_{30} / b_{20}] × 100

t_{30} = solids concentration (w/w) of drained upper layer

Statistics Statistical differences between extrusion conditions, particle sizes, and raw materials were calculated by the Mixed Method using SAS version 8.01 (SAS Institute, Cary, NC, USA). Correlations between the specific mechanical energy and each of the powder properties were calculated using Microsoft Excel 97 (Microsoft, Redmond, WA, USA).

Results and Discussion

Specific mechanical energy (SME) During extrusion of wheat flour SME was significantly affected by changes in moisture, screw speed, and temperature during extrusion (p<0.05, Table 2). Different combinations of these variables resulted in a range of SME from 83±1 to 190±7 Wh/kg. At lower moisture content and higher screw speed, a significant increase was observed in the mechanical energy input into the extruded materials. The effect of temperature on SME was not as great as those of moisture and screw speed; however, an increase in the extruder barrel temperature at 25% moisture content led to a decrease in SME.

Numerous studies have found similar effects of extrusion conditions on SME. Whalen *et al.* (8) reported a decrease in torque as temperature increased, particularly at 15-25% moisture content, the lower range used in their

Table 2. Specific mechanical energy (SME) during extrusion of wheat flour[a]

M/S/T[b]	SME (Wh/kg)
25/300/120	190±7
25/200/120	144±1
35/200/120	78±8
35/300/120	118±1
25/300/145	173±4
25/200/145	120±1
35/200/145	83±1
35/300/145	118±3
	F value
M	608.94*
S	349.00*
T	15.27*

[a]Standard deviation calculated from two repetitiions of extrusion.
[b]M = Moisture (%), S = Screw speed (rpm), T = Zone 5 temperature (°C).
*Indicates a significant extrusion variable effect (p<0.05)

experiment. Increasing the barrel temperature has also been reported by others to reduce SME (9, 10). Brümmer *et al.* (11) reported SME values that increased from below 100 to over 300 Wh/kg as the moisture content of extruded cornstarch decreased from 32 to 13%. Della Valle *et al.* (12) and Bhattacharya *et al.* (13) also found that SME decreased as moisture content increased. Increasing the screw speed has been reported to both increase (12, 13) and decrease (14) SME. As the screw speed increases, the degree of fill in the barrel decreases and the viscosity of the dough may also decrease, leading to a lowering of SME (15). However, in the present experiments, the increase in screw speed was large enough to overcome a slight reduction in the % torque from the motor, resulting in a higher SME. SME is regarded by Schuchmann and Danner (3) as the most important parameter to control when extruding starchy products.

Particle size analysis The mean particle sizes of the 145-249 im fraction produced by milling and sieving of the WF and WFL extrudates ranged from approximately 210 to 230 μm as measured by a laser (Table 3). The

Table 3. Laser particle size analysis of extruded-milled wheat flour (WF) and wheat flour + lecithin (WFL) powders

Treatment[a] M/S/T rep	145-249 μm Sieve Fraction	93-145 μm Sieve Fraction	<93 μm Sieve Fracton
	Mean Particle Size (μm)		
WF 25/300/145 rep1	210	133	59
WF 25/300/145 rep2	214	129	51
WFL 25/300/120 rep1	219	137	52
WFL 25/300/120 rep2	231	142	57

Raw Wheat Flour = 38 μm
[a]M = Moistue (%), S = Screw speed (rpm), T = Zone 5 temperature (°C).

measured sizes of particles in the 93-145- and <93 μm sieve fractions ranged from 130-140 and 50-60 μm, respectively. Based on appearance and feel, powders of the two largest particle sizes were still somewhat granular, while the powder below 93 μm was finer.

Water absorption index (WAI) Raw wheat flour had WAI of 1.91 g/g, while the extruded WF powders had WAI values that ranged from 6.3±0.21 to 8.48±0.14 g/g (Table 4). Extrusion moisture, screw speed, and barrel temperature had significant effects on WAI (p<0.05, Table 4). Extrusion at higher moisture contents and temperatures led to an increase in WAI, whereas increasing the screw speed led to a decrease in WAI. In addition, WAI significantly decreased as the powder particle size decreased (p <0.05).

These effects of different extrusion conditions on WAI are generally consistent with other published results (7, 16, 17). According to Gomez and Aguilera (16), WAI is dependent on the binding of water by hydrophilic groups and on the ability of macromolecules to form gels. When starch is gelatinized, water absorption increases. However, as greater dextrinization and starch fragmentation occurs, WAI then begins to decrease (17, 18). In this regard, SME is an important variable to consider, because it has been correlated with the degree of starch fragmentation and conversion (3, 12). The importance of mechanical energy input is supported by the negative correlation between SME and WAI in our results (Table 5).

Water solubility index (WSI) Raw wheat flour had WSI of 0.020 g/g, and those of the extruded WF powders ranged from about 0.10 to 0.30 g/g (Table 4). Reducing the extrusion feed moisture content had the largest effect of increasing WSI for the two smallest particle sizes. Increasing the screw speed also led to an increase in WSI, while variation of the temperature did not have a significant effect on the two smallest particle sizes. At the

145-249 μm particle size, the lack of significant extrusion condition effects may have been due to the difficulty in forming a solid pellet after centrifugation during WSI determination, causing difficulty in pouring off the supernatant for drying. This may have led to less accurate results, along with a reduction in the number of data points.

Like water absorption, water solubility is also related to conditions favoring degradation and fragmentation of starch (7, 16). According to Davidson *et al.* (19) and Diosady *et al.* (20), the most important factor regarding the fragmentation of starch is shear stress. Various studies have shown that decreases in temperature and moisture or increases in screw speed during extrusion lead to increases in starch fragmentation (17, 19). Brümmer *et al.* (11) measured the molecular weight of cornstarch after extrusion by size exclusion chromatography and found an exponential decrease in molecular weight as SME increased. In our experiments, it was similarly found that conditions leading to an increase in SME, and presumably greater starch breakdown, resulted in an increase in WSI (Table 5).

In terms of the different particle sizes, no significant differences were noted among their WSI values. This may have been due to the difficulties in analyzing some of the samples, as mentioned previously. However, a general trend appeared to be that water solubility increased as particle size decreased at the upper range of the WSI measured.

Rapid visco analyzer viscosity The cold viscosity of WF powder samples ranged from approximately 55 to over 200 RVU (Table 6, much higher than that of raw wheat flour (3 RVU) at 25°C. Decreasing the extrusion moisture and temperature conditions led to significant decreases in WF powder cold viscosity (p<0.05, Table 6). At the lower screw speed, cold viscosity of the resultant powder was slightly higher.

Table 4. Water absorption index (WAI) and water solubility index (WSI) of extruded-milled wheat flour powders[a] extruded under different conditions

Extrusion Condition	WAI (g/g)			WSI (g/g)		
	Particle Size			Particle Size		
M/S/T[b]	145-249 μm	93-145 μm	<93 μm	145-249 μm	93-145 μm	<93 μm
25/300/120	7.48±0.26	7.09±0.16	6.30±0.21	0.173±0.008	0.233±0.004	0.302±0.028
25/200/120	8.15±0.02	7.79±0.03	7.11±0.25	0.141±0.010	0.175±0.018	0.223±0.016
35/200/120	NT[c]	NT	7.05±0.02	NT	NT	0.083±0.161
35/300/120	NT	NT	6.94±0.11	NT	NT	0.115±0.021
25/300/145	7.64±0.14	7.32±0.20	7.07±0.13	0.157±0.020	0.196±0.009	0.225±0.016
25/200/145	8.23±0.06	7.87±0.07	7.67±0.06	0.119±0.006	0.157±0.012	0.177±0.031
35/200/145	8.48±0.14	8.34±0.26	7.66±0.11	0.125±0.008	0.101±0.020	0.120±0.024
35/300/145	7.76±0.07	7.60±0.08	7.10±0.08	0.128±0.033	0.113±0.004	0.131±0.004
	F value					
M	9.42*	26.91*	4.5	0.98	54.69*	145.69*
S	69.13*	61.34*	54.73*	0.99	7.06*	18.35*
T	NT	NT	55.79*	NT	NT	3.02

[a]Standard deviation calculated between powders produced from two extrusion replicates.
[b]M = Moisture (%), S = Screw speed (rpm), T = Zone 5 temperature (×C).
NT = not tested due to the inability to form a firm pellet upon centrifugation.
*Indicates a significant extrusion variable effect (p<0.05).

Table 5. Correlations between instant wheat flour powder properties and the specific mechanical energy (SME) during extrusion

Instant power property	Correlation coefficient(r) with SME		
	Particle Size		
	145-249 μm	93-145 μm	<93 μm
Water absorption index (g/g)	-0.81	-0.90	-0.62
Water solubility index (g/g)	0.77	0.93	0.92
Cold viscosity (RVU)[a]	-0.65	-0.75	-0.87
Hot paste viscosity (RVU)	-0.90	-0.80	-0.88
Dispersibility (%)	NT	NT	-0.76

[a]Viscosity measured in Rapid Visco Units (RVU).
NT=Not tested because dispersibility was 100% for all extrusion treatments.

Increased cold viscosity is due to the presence of swollen granules and non-granular starch in the form of high molecular weight polymers and dextrins. Cold viscosity increases with the degree of cooking of the starch, while hot paste viscosity decreases. However after reaching a peak, increasing shear and greater breakdown of starch lead to a reduction in the cold viscosity (8). This appeared to be the case in the present study as SME was negatively correlated with cold viscosity, and the hot paste viscosity did not show a higher peak (Tables 5 and 6). Bhattacharya *et al.* (13) found a negative correlation between SME and cold viscosity in an extruded potato and wheat flour blend. Other studies have also related increase in the severity of extrusion conditions to decrease in cold viscosity (8, 16).

Powder particle size of the extruded WF samples was also a significant factor affecting the RVA viscosity (p< 0.05, Table 6). The <93 mm fraction had a significantly lower cold viscosity than the two larger particle size fractions. Similar results were reported in a study by

Becker *et al.* (21), who examined the effects of milling on RVA viscosity profiles. In that study, smaller particle sizes, produced by grinding with different mills followed by sieving, resulted in lower RVA viscosities for extruded corn and wheat pellets.

In addition to the peak viscosity, particle size also had an effect on the hydration speed of the powders. The peak viscosity of the <93 μm particle size WF powder typically occurred at the start of analysis, and the peak for the 93-145 μm particle size occurred shortly thereafter (Fig. 1). However, the 145-249-μm fraction took more than 2 min to reach peak viscosity. Because cold viscosity is, by definition, measured during the first 2 min, before heating occurs, faster hydration would explain why the 93-145 μm fraction had a higher cold viscosity than the 145-249 μm fraction. After 2 min, the heating cycle of RVA began, and the peak viscosity at this time was recorded as the hot paste viscosity. However, this is not a true gelatinization peak that occurs when heating a sample such as raw flour. Once the 145-249 μm fraction was fully hydrated, its viscosity increased and was similar to that of the 93-145 μm fraction. The rate of hydration may play an important factor in relation to dispersibility as discussed later. The lack of a gelatinization peak when comparing the cold and hot paste viscosities also indicates that the powdered extrudates were thoroughly cooked during extrusion, in contrast to the results of flour extruded with lecithin, presented later.

Dispersibility Dispersibility of the WF powders was 100% for the two largest particle sizes, independent of extrusion conditions. Below 93 microns, extrusion moisture and temperature had significant effects (p<0.05, Table 7) on the extruded-milled particles; dispersibility was greater than 90% for those from extrudates formed at the higher temperature and moisture levels. At low extrusion moisture and temperature, many large lumps formed, and powder dispersibility was less than 60%.

In general, conditions which led to an increase in SME

Table 6. Cold and hot paste viscosities of extruded-milled wheat flour powders[a] extruded under different conditions

Extrusion condition	Cold viscosity (RVU)[b]			Hot paste viscosity (RVU)		
	Particle size			Particle size		
M/S/T[c]	145-249 μm	93-145 μm	<93 μm	145-249 μm	93-145 μm	<93 μm
25/300/120	108±5	110±17	54±4	126±1	102±12	47±2
25/200/120	120±10	172±0	65±6	147±9	148±4	55±2
35/200/120	148±7	208±3	143±17	261±1	210±3	139±3
35/300/120	153±2	196±79	133±28	210±16	196±79	12±18
25/300/145	135±20	161±3	94±2	152±30	151±2	84±5
25/200/145	152±29	229±25	111±2	180±31	213±19	97±7
35/200/145	213±23	244±37	156±2	251±21	243±36	141±7
35/300/145	206±9	218±37	132±28	234±6	213±33	121±22
F value						
M	66.93*	7.62*	91.22*	105.24*	13.44*	168.28*
S	1.63*	5.76*	6.05*	11.73*	5.1	10.35*
T	50.43*	5.67*	15.06*	4.43*	5.85	19.77*

[a]Standard deviation calculated for powders produced from two extrusion replicates
[b]Viscosity measured in Rapid Visco Units (RVU)/
[c]M = Moisture (%), S = Screw speed (rpm), T = Zone 5 temperatue (°C).
*Indicates a significant extrusion variable effect (p<0.05).

Table 7. Dispersibility and stability of extruded-milled wheat flour powders[a] extruded under different conditions

Extrusion Condition	Dispersibility (%) Particle Size			Stability (%) Particle Size		
M/S/T[b]	145-249 μm	93-145 μm	<93 μm	145-249 μm	93-145 μm	<93 μm
25/300/120	100	100	58.7±1.8	37.5±2.8	89.8±0.1	80.9±0.9
25/200/120	100	100	57.4±4.5	34.4±9.7	91.4±1.4	77.7±1.5
35/200/120	100	100	93.5±0.1	7.7±0.7	44.1±3.9	74.7±1.6
35/300/120	100	100	93.6±0.4	7.2±0.4	51.8±20.7	78.8±3.1
25/300/145	100	100	74.0±5.4	33.4±2.5	86.0±3.2	82.0±5.5
25/200/145	100	100	73.9±1.1	36.5±0.4	92.3±2.0	84.5±1.4
35/200/145	100	100	87.5±0.4	12.3±1.5	69.8±14.1	87.9±1.9
35/300/145	100	100	89.2±2.9	9.9±2.3	60.5±3.2	83.1±0.3
	F value					
M			322.06*	193.03*	53.28*	0.02
S			0.32	0.06	0.27	0.00
T			14.86*	0.49	2.96	35.38*

[a]Standard deviation calculated for powders produced from two extrusion replicates.
[b]M=Moisture (%), S=Screw speed (rpm), T=Zone 5 temperature (°C)
*Indicates a significant extrusion variable effect (p<0.05).

(Table 2) were associated with subsequent powders with poorer dispersibility, as shown by an inverse correlation between the two (Table 5). The increase in lumps may be a result of stickiness or gumminess, causing the powder particles to stick together. Mercier *et al.* (22) noted that stickiness of extruded products is related to increased water solubility (a characteristic positively correlated with SME in our experiment). Whalen *et al.* (8) found that extruded corn, wheat, and rice products were gummy when extrusion was performed at 15% moisture content, but not when the moisture content was increased. Similarly, in our experiments, dispersibility of powders was poorer when extrusion was performed at lower moisture content.

The effects of particle size reduction on mixing and dispersibility were noted by Anderson *et al.* (23). In their study, extruded corn grits ground to 20 to 40 mesh were judged to be good for use as instant gruels. Particles smaller than 40 mesh had poor dispersibility due to lumping and balling, and were deemed not suitable for use in products such as instant drinks. The particle size for which dispersibility was found to become difficult for corn grits was much larger than that determined for wheat flour in our experiment. Even in the 93-145 μm particle size range, the wheat flour powders dispersed very easily. It was not until a much finer powder (<93 mm) was produced that dispersibility became poor.

Dispersibility may have been more difficult for the <93 mm powder fraction than the two larger particle size fractions, because larger particles generally wet faster than smaller particles. In the bulk material, the pore structure becomes smaller as the powder particle size decreases, making the penetration of water more difficult, thereby slowing the wetting process (4). The contact angle, which is dependent on the interfacial tensions between the solid, liquid, and the surrounding air (24), generally increases as particle size decreases, making wetting more difficult as well (25). According to Schubert (25), interparticle adhesion forces can also cause lump formation in powders with smaller particles due to a larger surface area in

relation to weight. These interparticle forces are also much stronger in wet powders (25). In this (Schubert's?) experiment, the contact angle and interparticle forces would have been strong enough to hinder dispersibility only for the <93 μm powder fraction.

The results seen with the RVA in the current experiment, i.e., that a longer time is needed for hydration of larger particles, may also be important to consider, as a longer hydration time could allow for dispersal to take place before it is limited by swelling.

Stability Although the two largest particle size fractions were easily dispersed, they were not as stable to sedimentation. The 145-249 μm particle size fraction had the poorest stability, with all values below 40% (Table 7). Stability for the 93-145 μm powder fraction covered a wide range from very poor to very good. At <93 μm, there was a smaller range of measured stabilities, with most being around 80%. Moisture was the extrusion variable having the most significant effect, as a decrease was associated with increased stability (p<0.05, Table 7).

According to Stokes' law (4), larger particles would be expected to have poorer stability, as was the case for the 145-249 mm fraction. The velocity of sedimentation (w) is described by the Stokes' law equation $w = \Delta\rho\chi^2/18\ \eta$, where $\Delta\rho$ is the difference in density between the solid and liquid, g is acceleration due to gravity, χ is the particle diameter, and η is the viscosity of the liquid (4). Thus, larger particles sediment more quickly. The increase in stability for particles extruded at lower moisture content may also be related to the increasing water solubility of particles made under these extrusion conditions.

Extrusion of wheat flour with lecithin (WFL) Adding lecithin to the wheat flour resulted in a decrease in SME compared to extrusion without lecithin (p<0.05, Tables 2 and 8). This most likely occurred due to lubrication provided by the lipids in the WFL sample during extrusion.

There were only small differences among WAIs of

Table 8. Instant power properties of extruded-milled wheat flour + lecithin[a] extruded under different conditions

Extrusion condition M/S/T[b]	SME[c] (Wh/kg)	WAI[d] (g/g)	WSI[e] (g/g)	Cold viscosity (RVU)f	Hot paste viscosity (RVU)f	Dispersibility (%)	Stability (%)
25/300/120	165±7	6.63±0.07	0.122±0.001	106±3	10±64	89.7±1.2	73.5±1.3
25/200/120	133±5	6.61±0.4	0.086±0.006	118±19	123±9	91.1±0.9	71.6±0.0
35/200/120	75±1	6.48±0.24	0.047±0.001	52±4	179±1	94.8±2.1	61.0±0.9
35/300/120	112±5	6.41±0.19	0.066±0.006	62±7	151±1	93.7±0.5	65.0±2.5
25/300/145	150±0	6.44±0.08	0.106±0.004	101±1	103±4	92.5±0.4	74.3±0.1
25/200/145	104±1	6.61±0.21	0.066±0.007	85±9	122±12	97.3±0.8	68.8±0.8
35/200/145	69±0	7.19±0.26	0.052±0.002	117±27	145±6	91.0±2.0	79.8±2.3
35/300/145	102±3	7.12±0.03	0.079±0.01	121±16	137±7	89.1±1.3	76.2±0.4

[a]Standard deviation calculated between <93 μm powders produced from two extrusion replicates.
[b]M = moisture (%), S = screw speed (rpm), T = Zone 5 temperatue (°C).
[c]SME = specific mechanical energy in Watt·hours·kg^{-1}.
[d]WAI = water absorption index.
[e]WSI = water solubility index.
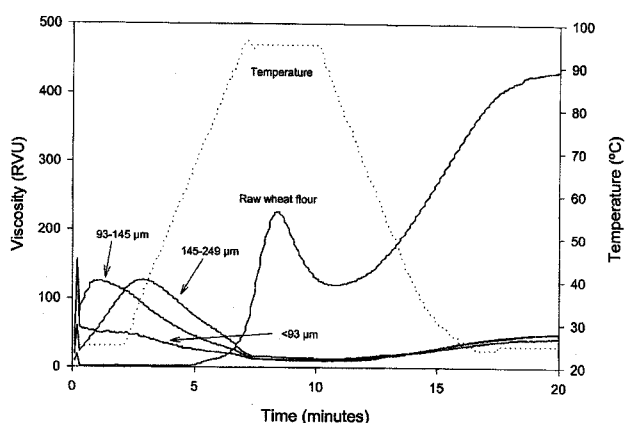[f]Viscosity in Rapid Visco Units (RVU).

Fig. 2. Representative Rapid Visco Analyzer graphs of raw wheat flour and extruded-milled powders with particle size ranges of <93 μm, 93-145 μm, and 145-249 μm. Viscosity reported in Rapid Visco Units (RVU).

because the viscosity of powders from some treatments increased during heating (Table 8). This is in contrast to the <93 μm WF extrudate powder results, which did not show an increase in viscosity during heating.

Dispersibility for the <93 μm WFL samples ranged from 89.1 to 97.3%, which is much greater than that for the WF powders (Tables 8 and 5, respectively). The WFL powders (Table 8) had lower stability than those made from WF, which may be due to the lower water solubility and cold viscosity values of the WFL powders.

It is out of the scope of the present study to determine whether properties specific to lecithin or those attributed to extrusion with lipids in general are responsible for the improved dispersibility. Lecithin-specific effects may have been the improvement of wetting or the addition of electrostatic repulsive forces between the particles (4). The reduction in the severity of extrusion conditions due to the addition of lecithin, as shown by the reduction in SME along with a reduction in water solubility and changes in viscosity, may also be important. However, these changes may occur with the addition of lipids in general and not just with the addition of lecithin.

powdered samples produced under the extrusion conditions studied (Table 8). The WAI values of the WFL powders were generally lower than those of the WF powders, although the difference was not significant.

The WSI values of powders made from extruded WFL were mainly affected by the feed moisture and extruder screw speed; lower moisture content and higher screw speed resulted in higher WSI values (Table 8). Although the general trends of the extrusion conditions on WSI were similar to the results for wheat flour extruded alone, the WSI values were much lower for wheat flour extruded with lecithin. The highest WSI among the WFL samples was 0.122±0.001 g/g compared to 0.302±0.028 g/g for the WF samples made under the same extrusion conditions (Tables 8 and 4, respectively). Lower water solubility may be the result of reduced starch degradation, which is what Colonna *et al.* (26) found when monoglycerides and triglycerides were added to extruded cassava starch. The reduced starch degradation was attributed to the lubricant effect of lipids inside of the extruder. This may also be true for the effect of lecithin in the present study.

The rapid visco analyzer results indicated that some of the WFL extrudate powders were not thoroughly cooked,

Conclusions

Water absorption, solubility, and viscosity of powdered wheat flour extrudates can be controlled through the adjustment of extrusion conditions and degree of extrudate milling. The specific mechanical energy provides a measure of the starch transformations taking place during extrusion and is correlated with final product characteristics, making SME an important parameter to control. The particle size of powders is also important to consider since dispersibility in water becomes much more difficult at lower particle sizes, even though stability to sedimentation is better. The addition of lecithin provides another means to modify instant wheat powders, especially as it relates to the improvement of dispersibility.

Acknowledgments

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