

Extrusion of Regular and Waxy Barley Flours for Production of Expanded Cereals

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ABSTRACT

Cereal Chem. 81(1):94–99

Grains of two regular and two waxy barley cultivars were milled into break and reduction stream flours using a wheat milling mill, granulated to facilitate feeding and flow through the barrel, and extruded to form expanded products using a modified laboratory single-screw extruder. As moisture content of barley granules decreased from 21 to 17%, the expansion index of extrudates increased from 1.81 to 2.68, while apparent modulus of compression work (AMCW) decreased from 17.1×10^4 to 7.8×10^4 N/m². Break stream flours of both regular and waxy barley produced extrudates with higher expansion index (2.72–3.02), higher water absorption index (WAI), and lower AMCW than extrudates from reduction stream flours. Extrudates produced from regular barley

had generally higher expansion and lower density than those produced from waxy barley. The specific mechanical energy (SME) was greater during extrusion of regular than of waxy barley. Barrel temperatures of 130, 150, and 170°C for the feeding, compression, and metering sections, respectively, resulted in higher SME, higher expansion index, lower water absorption index and lower AMCW of extrudates compared with a constant extruder barrel temperature of 160°C. Increased screw speed generally resulted in larger expansion index and increased WAI of extrudates. With increased feed rate from 89 to 96 g/min, the expansion index of extrudates decreased from 3.20 to 2.78 in regular barley and 3.23 to 2.72 in waxy barley, and harder extrudates were produced.

Barley is a durable crop grown over a wide range of environmental conditions compared with other cereal grains (Nilan and Ullrich 1993) and is mainly used in making malt to produce beer and for livestock feed (Newman and Newman 1991). Traditionally, utilization of barley for foods has been limited due to social and cultural perceptions that barley is inferior compared with other cereal crops. However, barley is an important cereal grain from a nutritional point of view due to its high dietary fiber content, particularly β -glucans which are beneficial to human health (Lehtonen and Aikasalo 1987; Newman and Newman 1991). Barley grains are commonly pearled to remove hull and bran layers and are often used as a rice extender or in soups. Barley can be milled into flour and used as a major component of baked products and noodles as well as in breakfast cereals.

The food industry extrudes cereal flours and starches to produce expanded snack foods, ready-to-eat (RTE) cereals and dry pet foods (Chinnaswamy and Hanna 1988a). Extrusion cooking is a high temperature, short time process in which food material is cooked by a combination of moisture, pressure, temperature, and mechanical shear (Harper 1981). During extrusion cooking, starch is gelatinized and protein is denatured as food material is mixed, cooked, and forced through a die. Desirable physical characteristics of an extruded, puffed breakfast cereal include a light and crisp texture and a slow absorption rate of milk without sogginess (Fast 1990). In general, a high expansion index, low bulk density and a firm texture with slow water absorption are desirable qualities for RTE breakfast cereals. These physical characteristics of extrudates are governed by properties of feed materials and extrusion cooking parameters such as moisture content, die diameter, temperature, screw speed, and feed rate (Harper 1989; Ali et al 1996).

Currently, limited information is available on extrusion processing of barley flour, especially 100% barley flour, for the production of RTE breakfast cereals. Berglund et al (1994) observed that while breakfast cereals produced by extrusion of 100% barley had limited expansion and high bulk density, the bulk density was reduced by 50% when barley was blended with 50% rice. The objectives of this study were to produce extruded RTE breakfast cereals from barley flours and to determine the effects of type of

barley and flour stream, as well as extrusion conditions, on the extrudate properties.

MATERIALS AND METHODS

Materials

Two waxy hull-less barley cultivars, Merlin and Waxbar, were provided by Western Plant Breeders, Inc. (Bozeman, MT). Two regular, hulled barley cultivars, Baroness and Crystal, were obtained from Wallace Grain & Pea Co. (Palouse, WA). Barley was milled to break and reduction stream flours without tempering using a Miag Multomat roller mill (Buhler, Inc., Braunschweig, Germany), as described by Klaczynski (1998). Flour streams were blended together to obtain break and reduction flours. Composite flour was prepared by combining break and reduction stream flours in proportion to their milling yields.

A granulation device was developed to produce barley granules (Fig. 1). The principle mechanism of the device is to press barley flour dough through a rotary wire screen with small openings to produce granules. The device is equipped with a feeding tube (5.5 cm i.d.) that has close contact with a rotating screen through which barley dough is compressed. The wire screen is 20 cm in diameter with openings of 2.0 mm and is attached to a tripod stand that supports the screen and transfers the rotating motion from the shaft to the screen. The screen is housed by a drum that collects the barley granules. Barley flour (500 g) was mixed with distilled water (270 mL) in a Hobart mixer for \approx 1 min until a uniform dough was formed. The dough was pressed through the feeding tube (Fig. 1) and compressed against the screen, which was rotated at a rate of 65 rpm. Moisture content of collected barley granules was adjusted from 16 to 21% as needed with a forced air dryer at 23°C.

Chemical Analyses

Approved Method 44-15A (AACC 2000) was used to determine moisture content by oven drying for 1 hr at 130°C. Ash content was measured after dry combustion at 580°C for 16 hr according to Approved Method 08-01 (AACC 2000). Protein content (N \times 6.25) was determined by a nitrogen analyzer (Leco Corporation, St. Joseph, MI). Free lipids content was measured according to Approved Method 30-25 (AACC 2000). Starch content was determined after enzymatic conversion to glucose by successive treatment with α -amylase, protease, and amyloglucosidase (Prosky et al 1988). The released glucose was measured colorimetrically using a glucose oxidase-peroxidase reagent (Lloyd and Whelan 1969).

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Extrusion

A laboratory single-screw extruder (C.W. Brabender Instruments, Inc., S. Hackensack, NJ) with a 20:1 barrel length-to-diameter ratio and screw with a compression ratio of 4:1 was used to produce barley extrudate. The die chamber of the extruder was modified by inserting a torpedo, which significantly decreased the volume of the die chamber (Fig. 2). A torpedo helps to facilitate even distribution of food material through the die chamber and enhances flow rate by increasing the residence time of food material in the die chamber. Without the torpedo, barley flour is burned in the die chamber, causing the die channel to plug and cease extrusion operation.

Extrusion conditions of barley granules were feed moisture content 17%, die nozzle diameter 3.0 mm, screw speed 100 rpm, feed rate 93 g/min, and barrel temperature 130-150-170°C, based on our preliminary trials, unless otherwise specified.

Effects of Extrusion Parameters

The effects of feed moisture on barley extrudate properties were tested with reduction flour of barley cultivar Waxbar. Barley flour granules with various moisture contents ranging from 16 to 21% were prepared and extruded. Characteristics of extrudates produced were evaluated as described below.

Break and reduction flours of two regular and two waxy barley cultivars were processed into granules and extruded to determine the effects of mill streams and type of barley on extrudate quality.

The effects of barrel temperature, screw speed and feed rate on extrudate properties were determined independently using composite flours under the extrusion conditions described above. Two different barrel temperature profiles, 130-150-170°C or 160-160-160°C, for the feed, compression, and metering sections, respectively, were tested. To examine the effects of screw speed on extrudate properties, granules of regular and waxy barley were extruded at 50, 75, 100, 125, and 150 rpm screw speed. Various

feed rates of 89, 93, and 96 g/min were also applied for the extrusion of granules of one regular and one waxy barley.

Each experiment for the determination of the effect of extrusion variables on extrudate properties was performed independently, starting with the preparation of barley flour granules, extrusion of granules, evaluation of extrudates, and analysis of data. Torque during extrusion processing was monitored by a sensor mounted to the extruder. From the torque, screw speed, and throughput, specific mechanical energy (SME) was calculated using the equation described by van Lengerich (1990): $SME (J/g) = (\text{torque } (Kg_f \times m) \times \text{screw speed } (\text{rad/sec}) / \text{throughput } (\text{g/sec})) \times 9.8$.

Evaluation of Extrudates

The expansion index of extrudate was determined as described by Rayas-Duarte et al (1998). The diameter of 10 extrudates was measured with a caliper, averaged, and divided by the diameter of the die nozzle. Bulk density was defined as the mass of particles occupied by a unit volume. This measurement accounts for the void space between particles (Singh and Heldman 1993). The bulk density of barley extrudate was measured by rapeseed displacement. Whole extrudate (10 g) was placed in a glass jar (8.0 cm height and 6.5 cm diameter), then filled with rapeseed from a height of 21.5 cm. The jar was leveled off and the volume of displaced rapeseed was measured. The bulk density of the extrudate was expressed as the weight of the extrudate divided by its volume.

Water absorption index of extrudates (WAI) was determined by placing weighed pieces of extrudates in a porous stainless steel tea filter (0.50 mm screen openings) and submerging it completely in 500 mL of distilled water for 60 sec. The tea filter was removed and drained (4 sec), excess water was absorbed with lint paper and the filter was reweighed. The WAI was expressed as: $WAI = (\text{wt of wet extrudate} - \text{wt of dry extrudate}) / (\text{wt of dry extrudate})$.

Textural characteristics of the extrudates were determined using a TX-XT2 texture analyzer (Stable Micro System, Haslemere,

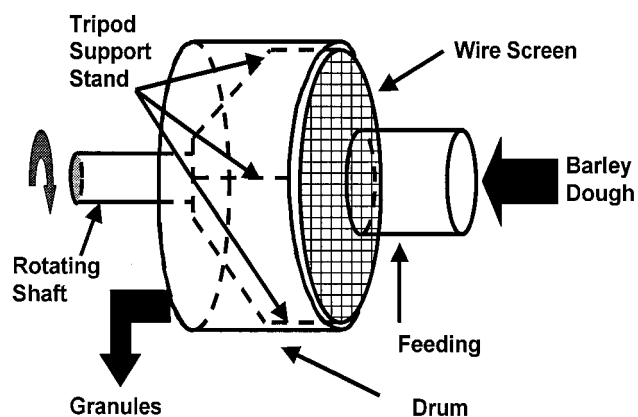


Fig. 1. Granulation device for barley flour dough.

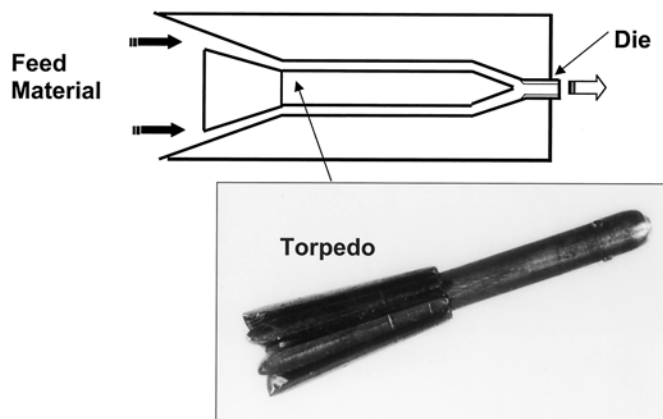


Fig. 2. Torpedo inserted in die chamber.

TABLE I
Chemical Composition of Regular and Waxy Barley Flours^{a,b}

Cultivar	Flour Fraction	Protein (%)	Ash (%)	Free Lipids (%)	Starch (%)	
Regular	Baroness	Break	9.6b	1.0a	0.5a	74.0a
		Reduction	10.8a	1.1a	0.6a	74.1a
	Crystal	Break	9.5b	0.9a	1.3a	84.8a
		Reduction	10.6a	0.8a	1.5a	81.6b
Waxy	Merlin	Break	10.5a	0.6a	1.4b	81.6a
		Reduction	12.0a	0.8a	1.8a	76.7b
Waxbar	Break	10.7b	0.9a	0.8a	82.9a	
	Reduction	12.1a	1.0a	1.2a	76.7b	

^a Means with different letters in the same column within each cultivar are significantly different at the 5% level.

^b Dry weight basis.

England). An extrudate 20.0 mm long was compressed once with a plunger 5.0 cm diameter at a rate of 0.8 mm/sec to 30% of the original height of the extrudate. The compression generated a curve with the force over distance. An apparent modulus of compression work (N/m^2) was calculated from the area under the force-distance curve divided by the volume of the extrudate to normalize the variation due to differences in extrudate dimension.

Statistical Analysis

All physical and chemical measurements were performed at least in duplicate. Analysis of variance (ANOVA) and least significant differences (LSD) were performed by the Statistical Analysis System (SAS Institute, Cary, NC).

RESULTS AND DISCUSSION

Composition of Barley Flours

Chemical composition of break and reduction stream flours of two regular and two waxy barley cultivars are summarized in Table I. Waxy barley cultivars generally had higher protein content of flours compared with regular barely cultivars. Protein content of break flours was consistently lower than for reduction flours, regardless of type and cultivar of barley. Break and reduction flours of regular and waxy barley cultivars exhibited similar ash and free lipids content. Starch content of break flours was usually higher than that of reduction flours, except in cv. Baroness, in which starch content of break and reduction flours were similar.

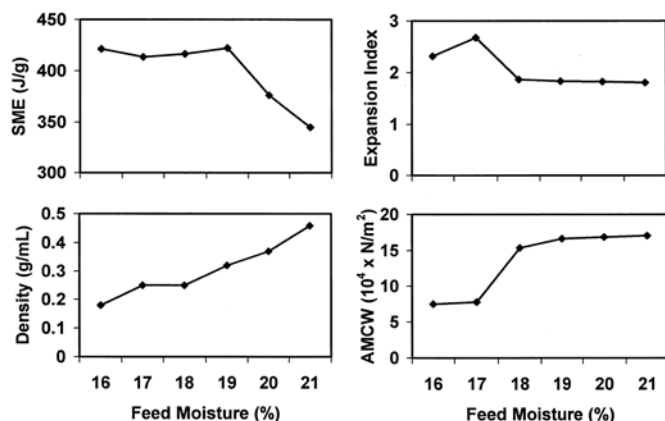


Fig. 3. Effect of feed moisture content of barley granules on specific mechanical energy (SME) and properties of extrudates. Texture property of extrudates was denoted using an apparent modulus of compression work (AMCW). Extrusion conditions included screw speed of 100 rpm; feed rate of 93 g/min; die nozzle diameter of 3.0 mm; barrel temperature of 130-150-170°C.

Starch content of barley flours was much lower in Baroness than in other cultivars.

Effects of Barley Granule Moisture Content

Extrudates produced from barley granules generally exhibited higher expansion, lower bulk density, and less AMCW as moisture content decreased (Fig. 3). The SME was relatively stable at 16–19% feed moisture and dropped considerably as feed moisture increased over 20%. The viscosity of the food material in the screw channel has influenced the torque required to turn the extrusion screw (Harper 1981). The increase in feed moisture probably enhanced the fluidity of the material in the extrusion barrel, subsequently lowering the torque and SME.

Extrudates had the highest expansion index at 17% moisture. The expansion index increased from 1.81 to 2.68 as moisture content decreased from 21 to 17%. At 16% moisture, there was a decrease in the expansion index and an increase in the barrel pressure over the normal range operating limits of the single-screw extruder. The decrease in the expansion index at 16% moisture may have been caused by increased molecular disruption of amylopectin from the high shear rate inside the extruder barrel. van Lengerich (1990) reported that after a shear rate maximum at low moisture content, a decrease in expansion was observed in wheat starch. The effect of moisture content of feeding materials on the bulk density of extrudates was significant ($P < 0.01$) (Fig. 3). Bulk density of barley extrudates linearly increased from 0.18 to 0.46 g/mL as feed moisture content increased from 16 to 21%. While there were no changes in expansion index, the continuous increase in bulk density between 18 and 21% feed moisture could be due to the decrease in longitudinal expansion of the extrudate.

As moisture content decreased from 21 to 16%, AMCW of the extrudates decreased from 17.1×10^4 to $7.5 \times 10^4 N/m^2$. The decrease in AMCW was apparently due to an increase in radial or longitudinal expansion, which led to a consistent decrease in the density of extrudates as feed moisture content decreased. Rayas-Duarte et al (1998) reported that decreased breaking strength of extrudates was associated with high expansion index and low bulk density. Bhattacharya and Hanna (1987) reported similar findings for regular and waxy cornstarch with decreasing feed moisture.

Effects of Barley Type and Flour Milling Fractions

Characteristics of extrudates produced from the break and reduction flours of both regular and waxy barley cultivars are summarized in Table II and Fig. 4. SME during extrusion of regular barley was consistently higher than for waxy barley flours. In both regular and waxy barleys, the expansion index of extrudates was higher in break flour compared with reduction flour. In regular barleys Baroness and Crystal, the expansion index of extrudates ranged from 2.84 to 3.02 in break flour and from 2.52 to 2.72 in reduction flour. The expansion index of waxy barleys

TABLE II
Specific Mechanical Energy (SME) and Extrudate Properties of Break and Reduction Fractions of Barley Cultivars^{a,b}

Cultivar	Flour Fraction	SME (J/g)	Expansion Index	Density (g/mL)	WAI ^c (g/g)	AMCW ^d ($10^4 \times N/m^2$)
Regular						
Baroness	Break	552.7a	2.84a	0.20a	2.46a	15.1b
	Reduction	549.8a	2.72a	0.21a	2.13b	23.7a
Crystal	Break	505.7a	3.02a	0.20b	2.46a	15.2b
	Reduction	520.4a	2.52b	0.28a	2.21b	34.8a
Waxy						
Merlin	Break	293.0b	2.70a	0.18a	2.57a	8.6a
	Reduction	440.0a	2.62b	0.19a	2.36b	10.8a
Waxbar	Break	432.2a	2.92a	0.16b	2.58a	8.4b
	Reduction	373.4b	2.54b	0.23a	2.25b	18.1a

^a Means with different letters in the same column within each cultivar are significantly different at the 5% level.

^b Screw speed of 100 rpm; feed rate of 93 g/min; feed moisture content of 17%; die nozzle diameter of 3.0 mm; barrel temperature of 130-150-170°C.

^c Water absorption index of extrudates.

^d Apparent modulus of compression work.

Merlin and Waxbar ranged from 2.70 to 2.92 in break flour and from 2.54 to 2.60 in reduction flour. Differences in the expansion index of extrudates between regular and waxy barley cultivars could be due to the differences in starch content and characteristics such as the content of amylose as well as protein content. Chinnaswamy and Hanna (1988b) reported that the expansion ratio of corn starch increased from 8 to 16 as amylose content increased from 0 to 50%, and decreased with further increase in starch amylose content. In addition to high starch content in break flour, low protein content may also have contributed to higher expansion in break flour (Table I). Significant influence of the amount and type of protein on expansion and textural properties of wheat flour extrudate was reported by Linko et al (1981). Faubion and Hoseny (1982) also reported that steady decrease in expansion of wheat starch added with wheat gluten as gluten protein content increased from 1 to 11%. The density of extrudates was lower in break flours than in reduction flours in Crystal and Waxbar, but exhibited no differences between break and reduction flours in Baroness and Merlin. In both regular and waxy barley cultivars, extrudates from break flours absorbed more water than extrudates from reduction flours.

Regardless of flour fractions, waxy barley flours produced softer extrudates than regular barley flours (Table II). Because expansion indices of extrudates are similar between regular and waxy barley flours, increase in longitudinal expansion was probably responsible for production of softer extrudates from waxy barley flours. Extrudates from reduction flours required more energy to compress and crush than those from break flours in both barley types. This was probably due to the smaller expansion index and denser extrudate in reduction flours. Higher protein content by 1.1 to 1.5%, as well as lower starch content in reduction flours than in break flours, except in Baroness, probably contributed to the smaller expansion of extrudate in reduction flour.

Effects of Extruder Barrel Temperature

Characteristics of extrudates produced from regular and waxy barley at different extruder temperatures are shown in Table III. The SME was significantly higher during extrusion of barley under nonisothermic temperature conditions of 130-150-170°C than under isothermic conditions of 160-160-160°C. The higher SME at 130-150-170°C produced extrudates with higher expansion than extrudates produced at 160-160-160°C. The constant temperature of 160°C throughout the extruder barrel may have decreased the viscosity and thus reduced the pressure and torque (Colonna et al 1989; van Lengerich 1990). In regular barley, the expansion index ranged from 3.40 to 3.45 at 130-150-170°C but was 3.08 at 160-160-160°C barrel temperature.

In regular barley, bulk density of extrudates ranged from 0.13 to 0.14 g/mL at 130-150-170°C and 0.15 g/mL at 160-160-160°C.

The bulk density of extrudates produced from waxy barley was 0.16 g/mL at 130-150-170°C and ranged from 0.18 to 0.19 g/mL at 160-160-160°C. Regardless of barley type or cultivar, the WAI of barley extrudates was higher at 160-160-160°C than at 130-150-170°C (Table III). Higher WAI was associated with higher expansion index of extrudates, as shown in Tables II. Higher WAI of extrudates at 160-160-160°C, despite lower expansion indices compared with those at 130-150-170°C, could have been caused by differences in the degree of starch gelatinization at two different barrel temperature profiles. At 160-160-160°C, WAI of extrudates ranged from 2.84 to 3.38 g/g in regular barley and from 2.65 to 3.14 g/g in waxy barley. The WAI of extrudates extruded at 130-150-170°C was lower in waxy barley (1.71 to 1.99 g/g) than in regular barley (2.54 to 2.74 g/g). In regular barley, the extrudates produced at 160-160-160°C were harder compared with extrudates produced at 130-150-170°C. Waxy barley extrudates at 130-150-170°C were less hard in Merlin and similar in Waxbar compared with those extruded at 160-160-160°C. The SME correlated negatively with both density and AMCW of extrudates ($P < 0.05$, $n = 8$).

Effects of Extruder Screw Speed

In general, as screw speed increased from 50 to 150 rpm, the SME for both regular and waxy barley extrudates linearly increased (Table IV). The increase in SME was due to the increase in shear rate when the screw speed was raised. An increase in screw speed from 50 to 100 rpm resulted in an increase in the expansion index

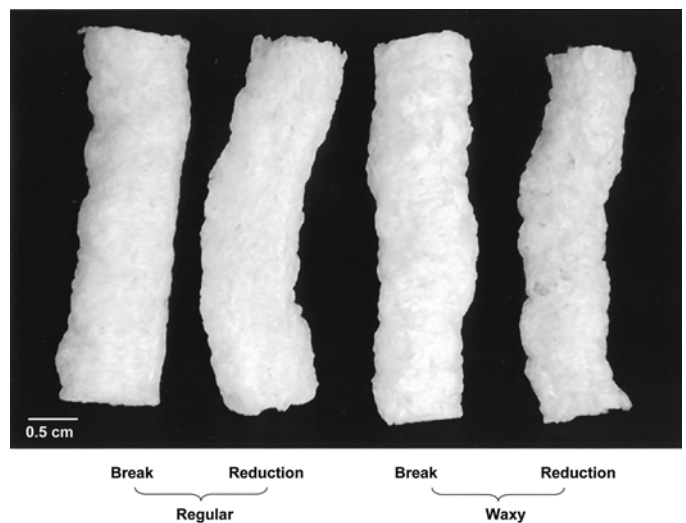


Fig. 4. Extrudates prepared from break and reduction streams of regular and waxy barley.

TABLE III
Effects of Variable Barrel Temperature on Specific Mechanical Energy (SME) and Properties of Extrudates Produced from Blends of Break and Reduction Flours of Regular and Waxy Barley^{a,b}

Cultivar	Temperature Profile (°C)	SME (J/g)	Expansion Index	Density (g/mL)	WAI ^c (g/g)	AMCW ^d (10 ⁴ × N/m ²)
Regular						
Baroness	130-150-170	454.7a	3.40a	0.13a	2.54b	7.8b
	160-160-160	337.1b	3.08b	0.15a	2.84a	14.0a
Crystal	130-150-170	454.7a	3.45a	0.14a	2.74b	10.5b
	160-160-160	279.3b	3.08b	0.15a	3.38a	15.0a
Waxy						
Merlin	130-150-170	440.0a	2.47a	0.16a	1.99b	7.3b
	160-160-160	234.2b	1.84b	0.19a	3.14a	20.0a
Waxbar	130-150-170	410.6a	2.63a	0.16a	1.71b	12.7a
	160-160-160	293.0b	2.10b	0.18a	2.65a	11.0a

^a Means with different letters in the same column within each cultivar are significantly different at the 5% level.

^b Extrusion parameters: screw speed of 100 rpm; feed rate of 93 g/min; feed moisture content of 17%; die nozzle diameter of 3.0 mm.

^c Water absorption index of extrudates.

^d Apparent modulus of compression work.

of extrudates from both types of barley. A further increase in screw speed resulted in no change or in a lower expansion index of extrudates. The bulk density of extrudates was not significantly affected by screw speed.

Extrudates from regular barley exhibited much higher WAI than those of waxy barley (Table IV). As the screw speed increased, the WAI increased in both barley types. The increased SME by the elevated screw speed probably promoted the molecular disruption of barley flour components, leading to the increase in WAI along with the increased expansion of extrudate. The AMCW of extrudates was not consistently affected by changes in screw speed, though the softest extrudate was produced at 100 rpm in both regular and waxy barley cultivars. Both lowering and raising screw speed from 100 rpm generally produced harder extrudates. The SME exhibited positive relationships with expansion index and WAI ($P < 0.01$, $n = 20$).

Effects of Extruder Feed Rate

Effect of feed rate of barley flour granules at 89–96 g/min did not significantly affect SME (Table V). There was no difference in

the expansion index of extrudates between feed rates of 89–93 g/min. A further increase in feed rate to 96 g/min resulted in a significant decrease ($P < 0.05$) in the expansion index of extrudates in both regular and waxy barley. At a feed rate of 96 g/min, the food material flowed too quickly through the extruder barrel, resulting in lower expansion. The expansion index decreased from 3.20 to 2.78 in regular barley extrudates and from 3.23 to 2.72 in waxy barley extrudates as feed rate increased from 89 to 96 g/min.

The bulk density of extrudates made with regular barley Baroness was higher at a feed rate of 96 g/min than at 89 or 93 g/min, mainly due to the decreased expansion. Extrudates made from Merlin, however, exhibited no consistent increase in bulk density as feed rate increased from 89 to 96 g/min. The WAI of extrudates increased from 1.29 to 1.59 g/g in regular barley and from 1.22 to 1.62 g/g in waxy barley extrudates as feed rate increased from 89 to 96 g/min.

The AMCW of extrudates increased with increasing feed rate in both regular and waxy barley, evidently due to the decreased expansion index. AMCW increased from 8.5×10^4 to 25.2×10^4 N/m² in Baroness and from 6.7×10^4 to 11.8×10^4 N/m² in Merlin

TABLE IV
Effects of Screw Speed on Specific Mechanical Energy (SME) and Properties of Extrudates Produced from Blends of Break and Reduction Flours of Regular and Waxy Barley^{a,b}

Screw Speed (rpm)	SME (J/g)	Expansion Index	Density (g/mL)	WAI ^c (g/g)	AMCW ^d ($10^4 \times \text{N/m}^2$)
Baroness					
50	198.0e	2.28c	0.13a	2.50d	13.0b
75	296.9d	2.67b	0.14a	2.52cd	11.6bc
100	402.8c	3.08a	0.13a	2.54bc	8.0c
125	503.7b	2.88a	0.14a	2.58b	9.2c
150	682.1a	2.98a	0.14a	2.70a	15.9a
Crystal					
50	172.5e	2.39d	0.13c	2.21c	32.8a
75	252.8d	2.83c	0.14a	2.20c	24.9bc
100	358.7c	3.27a	0.14c	2.75b	20.3d
125	568.4b	3.22ab	0.16b	3.23a	22.6cd
150	682.1a	3.08b	0.16b	3.28a	26.4b
Merlin					
50	157.8e	2.06d	0.17a	1.26e	8.2ab
75	247.0d	2.52bc	0.18a	1.45d	9.1ab
100	358.7c	2.84a	0.16a	1.65c	6.3b
125	448.8b	2.71ab	0.19a	2.45b	8.8ab
150	659.5a	2.47c	0.19a	2.54a	10.5a
Waxbar					
50	164.6e	1.95c	0.16a	1.45d	14.1bc
75	263.6d	2.21bc	0.17a	1.56c	27.5a
100	358.7c	2.63a	0.16a	1.58c	11.2c
125	476.3b	2.41ab	0.17a	1.67b	18.0b
150	615.4a	2.55a	0.18a	2.06a	20.4b

^a Means with different letters in the same column within each cultivar are significantly different at the 5% level.

^b Extrusion parameters: feed rate of 93 g/min; die nozzle diameter of 3.0 mm; feed moisture content of 17%; barrel temperature of 130-150-170°C.

^c Water absorption index of whole extrudates.

^d Apparent modulus of compression work.

TABLE V
Effects of Feed Rate on Specific Mechanical Energy (SME) and Properties of Extrudates Produced from Blends of Break and Reduction Flours of Regular and Waxy Barley^{a,b}

Cultivar	Feed Rate (g/min)	SME (J/g)	Expansion Index	Density (g/mL)	WAI ^c (g/g)	AMCW ^d ($10^4 \times \text{N/m}^2$)
Regular						
Baroness	89	346.9a	3.20a	0.15b	1.29b	8.5b
	93	323.4a	3.29a	0.15b	1.39ab	9.2b
	96	327.3a	2.78b	0.21a	1.59a	25.2a
Waxy						
Merlin	89	307.7a	3.23a	0.19a	1.22c	6.7b
	93	294.0a	3.35a	0.15b	1.35b	7.0b
	96	267.3b	2.72b	0.21a	1.62a	11.8a

^a Means with different letters in the same column within each cultivar are significantly different at the 5% level.

^b Extrusion parameters: screw speed of 100 rpm; die nozzle diameter of 3.0 mm; feed moisture content of 17%; barrel temperature of 130-150-170°C.

^c Water absorption index of whole extrudates.

^d Apparent modulus of compression work.

as feed rate increased from 89 to 96 g/min. Overall, as feed rate increased to 96 g/min, there was a decrease in expansion index, an increase in WAI and an increase in AMCW of extrudates.

CONCLUSIONS

Characteristics of barley extrudates produced from regular and waxy barley granules using a single-screw extruder were influenced by the type of barley as well as milling streams, moisture content, barrel temperature, feed rate, and screw speed. The type of barley played an important role in the quality of the extrudate due to differences in starch characteristics and protein content. Regular barley had consistently higher SME and pressure during extrusion, and generally produced extrudates with greater expansion index and lower density than waxy barley extrudates. Break stream flours generally produced extrudates with higher expansion index, higher WAI, and lower AMCW than reduction stream flours. An increase in feed moisture content resulted in extrudates with lower expansion, higher bulk density, and increased AMCW. Constant barrel temperature of 160°C resulted in extrudates with lower expansion and higher WAI compared with barrel temperature of 130-150-170°C in both types of barley. The feed rate of >96 g/min produced less expanded extrudates with higher WAI and AMCW. With granulation of barley flour and fine control of extrusion parameters, a readily acceptable expanded RTE cereal can be produced from barley.

ACKNOWLEDGMENTS

This research is part of the IMPACT (International Marketing Programs for Agricultural Commodities and Trade) activities at Washington State University. The financial support of the Washington Barley Commission is gratefully acknowledged.

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[Received February 18, 2003. Accepted July 8, 2003.]