Reactive processing and mechanical properties of cross-linked maize starch

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Relative effect of particle size on the physical properties of corn meal extrudates: Effect of particle size on the extrusion of corn meal ☆

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ABSTRACT

Corn meal of various particle sizes ranging from 180 to 710 μm were processed in a twin-screw extruder to produce directly expanded extrudates. The extrusion process effects on the specific mechanical energy (SME), expansion indexes (radial, longitudinal and volumetric), pasting viscosity, water absorption index (WAI) texture properties, and microstructure were determined. Increasing the particle size decreased the SME input. Extrudates produced with corn meal of higher particle sizes expanded more than extrudates produced with smaller particle sizes. For all treatments there was no peak viscosity at 95 °C. But expanded corn meal extrudate from the 180 μm fraction showed a discontinuous gel matrix phase. Increasing corn meal particle size decreased WAI values. The mechanical resistance of the extrudates from the smallest particle size was significantly higher ($p < 0.05$) than that of the largest particle size. The microstructure of raw corn meal revealed large fractured particles with small rounded particles adhering to the surface.

1. Introduction

Particle size distribution is intimately linked to milling process. Mathew et al. (1999) working with Corn meal for pet food found that particle size and type of mill affect expansion properties and texture of pet food. Similar findings were also described by Carvalho and Ascheri (1999). They found that milled fractions of white maize grits from different mills expanded differently depending on the particle size distribution. The maize grits produced in roller mills experienced higher starch conversion and produced more expanded extrudates than those from hammer mills. The authors attributed these findings to the differences in particle size and shape of the particles produced by the mills, which was already evident from the observation that roller milled particles flowed better than hammer mill.

The effect of different starch sources and particle size on extrusion has been reported. For instance, in the work of Ryu and Lee (1988) rice flour expansion was found to decrease as the particle size decreased, but the internal cell distribution was more uniform. Garber et al. (1997) and Mohamed (1990) reported similar effects for corn meal. Mohamed (1990) observed significant decrease in starch conversion and SME with larger particle sizes (1622 μm) and high moisture content (22%), which lead to a decrease in expansion and an increase in bulk density of the final extrudates. Recently, Altan et al. (2009) showed that raw barley properties interacted with extruder screw configuration resulting in a more severe mixing and increased thermal energy inputs to the material thereby increasing starch conversion. Previously, Zhang and Hoseney (1998) showed that corn meal with larger particles produced extrudates of higher expansion. These authors also reported poor expansion for corn meal with high count of glassy particles. Their explanation for this was that large glassy particles result in poor water distribution, non-uniform melting, and less expansion.

The effects of particle size distribution of cereal grits on the final properties of extrudates has been studied to an extent already (Altan et al., 2009; Carvalho and Ascheri, 1999; Mathew et al., 1999; Desrumaux et al., 1998; Garber et al., 1997; Ryu and Lee, 1988). According to Konstance and Onwulata (2006) narrowing the particle size distribution improves the expansion of expanded extrudates. These authors working with addition of whey protein powder on corn meal of different particle sizes found that the smaller particles of corn meal matching those of whey protein concentrate powder, the more expanded the extrudates were, with improved breaking strength. Corn meal without added whey showed higher radial expansion, but no expansion differences were found when powdered whey was added in the formulation

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regardless corn meal size (Konstance and Onwulata, 2006). The objective of this work was to investigate the effect of extrusion cooking on the physical properties of expanded products made from corn meal separated mechanically into various sizes.

2. Material and methods

2.1. Materials

Commercial corn meal of three particle size grades, classified as fine, medium and coarse, were purchased from Agricor (Marion, Industries). From these lots six particle size fractions designated as 180, 300, 420, 500, 600, 710 and 850 μm, were produced by sieving with a Retsch AS 200 Digit sieve shaker (Retsch GmbH, Haan, Germany). These fractions represented material retained on U.S. Standard sieve numbers 80, 50, 40, 35, 30, 25, 20, respectively.

2.2. Procedures

2.2.1. Material analyses and measurements

The proximate composition of each fraction was determined according to AOAC (2000) standards: moisture content (Method 930.15), protein content (Method 990.03), fat content (Method 920.39), ash content (Method 942.05) and crude fiber content (Method 962.09).

The particle size distribution of each fraction was determined using the Accusizer Optical Particle Sizer Model 780 (Particle Sizing Systems, Santa Barbara, Calif., USA) equipped with a LE5000-20 EXT sensor that was held constant at the threshold particle size of 22.76 μm for all measurements.

2.2.2. Extrusion processing

Extrusion was performed on a ZSK-30 twin-screw extruder (Werner and Pfleiderer, Ramsey, NJ, USA) operated at 300 rpm. The extruder had nine barrel sections each with its individual temperature control and it was fitted with two 3.18 mm rounds dies. The screw configuration and thermal controlled zones with their respective temperature settings are shown in Fig. 1. The solid material of known moisture content was fed into the extruder using a series K2-MV-T 35 twin screw volumetric feeder (K-Tron International, Inc., Pitman, NJ) operated at a constant setting of 700 rpm yielding a feed rate that varied according to the particle size. The liquid feed rate was kept constant at 1.2 L h^{-1} by using an electronic metering pump (Milton Roy, Ivyland, Pa.). Mass flow rate through the extruder (production rate) was measured by collecting extruded product over a 1 min period and weighing the collection then repeating this a number of times. The moisture content of the extrudate is needed in calculating the longitudinal expansion index (LEI) and so this was measured.

2.2.3. Extrudate sample preparation

The expanded extrudates were placed in a convection oven (Model 40B-350, Corbett Industries, Inc., Waldwick, NJ, USA) with a 1200 ft^3 min^{-1} airflow rate that and a 60 °C setting to dry overnight. Some of the dried were packaged in hermetic plastic for later analysis and the rest was milled in a roller mill having corrugated rollers (Kice Industries, Wichita, Kan., USA). The milled extrudates were then sieved for 2 min using a plan sifter (Great Western Manufacturing Co., Leavenworth, Kan., USA) to obtain particles sized between 107 and 249 μm. The expanded extrudates set aside were used for texture analysis while the milled extrudates were analysed for paste viscosity, water absorption, and solubility indexes.

2.2.4. Specific mechanical energy and expansion indexes

Specific mechanical energy (SME) was calculated following the methodology described by Onwulata et al. (1994) dividing the total flow rate by the net mechanical energy input. Expansion was determined using the method of Alvarez-Martinez et al. (1988). Sectional expansion index (SEI), longitudinal expansion index (LEI), and volumetric expansion index (VEI) were calculated. Triplicate measurements were made on 10 randomly chosen pieces of extrudate from each run to calculate the foregoing process–product parameters. Density was evaluated using the methods described by Fan et al. (1996a). Equations for the calculations are presented below

$$\text{Sectional expansion index (SEI)} = \left[\frac{D}{D_0}\right]^2 \quad (1)$$

$$\text{Longitudinal expansion index (LEI)} = \left[\frac{\rho_d}{\rho_e}\right]\left[\frac{1}{\text{SEI}}\right]\left[\frac{1-M_d}{1-M_e}\right] \quad (2)$$

$$\text{Volumetric expansion index (VEI)} = \text{SEI}\cdot\text{LEI} \quad (3)$$

$$\text{Density } (\rho_e) = \frac{4m}{\pi D^2 L} \quad (4)$$

In the equations, m is the mass of a length L of extrudate with diameter D after cooling and D_0 is the diameter of the die. Bulk density of the dough (ρ_d) behind the die was considered 1400 kg m^{-3}. The moisture content (M_e, w.b.) of the extrudates and the moisture content of the dough inside the extruder (M_d, w.b.) were measured by drying 2–3 g in a vacuum oven at 70 °C until constant weight was reached. What was used in the calculations was the average of three measurements.

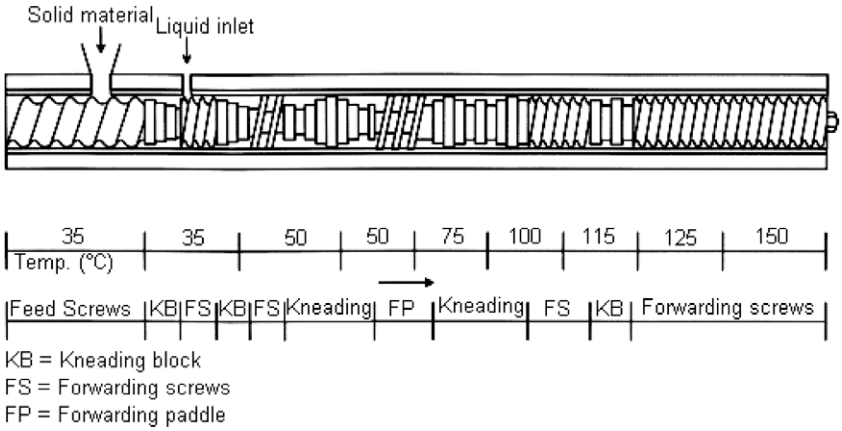

Fig. 1. Schematic representation of screw configuration with each temperature zone.

2.2.5. Paste viscosity

The degree of starch cooking also known as starch conversion was investigated by determining the apparent paste viscosity of the milled and sieved extrudates. A Rapid Visco Analyser (RVA, Newport Scientific Pty Ltd., Warriewood, NSW, Australia) was used to measure the apparent viscosity of samples as a function of temperature. Approximately 3 g extrudate specimen adjusted to 10% solids concentration was added to 25 g distilled water and this was loaded into the RVA. The time–temperature profile included initially mixing and holding the specimen with the paddles rotating at 160 rpm at 25 °C for 4 min (to investigate the cold-swelling starch peak), heating to 95 °C at a constant rate of 14 °C/min, holding 95 °C for 3 min, and then cooling to 25 °C in 5 min at the same rate. The readings from the paste curve generated were maximum viscosity peak at 25 °C (MV25), minimum viscosity after heating (MV95), breakdown (MV95-MV25), final viscosity (FV) and set back viscosity (FV-MV95).

2.2.6. Water absorption index

Water absorption (WAI) indexes were carried out according to the methodology described by Anderson et al. (1969) with modifications. The procedure followed involved weighing 0.5 ± 0.001 g of sample in a test tube, adding 5 mL of deionized water, mixing for 1 min in a vortex shaker (Genie Scientific Industries, Bohemia, NY, USA), and allowing the mixture to stand overnight to allow complete hydration. The gels formed were centrifuged using a Dupont Sorvall® Instruments EconoSpin (Boston, Mass., USA) at 3800 rpm (2394 g) for 30 min. WAI was expressed as the weight of the precipitate per gram of sample.

2.2.7. Texture analysis

Since the expanded extrudates had different water content, the dried extrudates were stored in hermetic bags. The texture was preliminarily determined using the methodology described by Bouvier et al. (1997), although it was modified according to the sample characteristic described as follow. Texture testing was accomplished on a Texture Analyser TA.XT 2i (Stable Micro Systems, Surrey, UK) interfaced with a PC computer that was fitted with a 5 kg load cell attached and a 3 mm diameter stainless steel cylinder probe. For each test the diameter of an extrudate specimen was first measured with a Vernier caliper. The specimen was then penetrated in the Texture Analyzer at a cross head speed of 1 mm/s until the probe had sunk into the specimen to a depth of 75% of the radius. For each of the six feed particle size treatments were made on 36 representative specimens that were 30 mm long. According to Bouvier et al. (1997), the following criteria were applied to evaluate crispness:

– Frequency of structural ruptures (mm^{-1}):

$$N_{sr} = \frac{N_0}{d} \tag{5}$$

– Average specific force of structural ruptures (N):

$$F_{sr} = \sum \frac{\Delta F}{N_0} \tag{6}$$

– Average of compression force (N):

$$F = \frac{A}{d} \tag{7}$$

– Crispness work (N.mm):

$$W_c = \frac{F}{N_{sr}} \tag{8}$$

In the foregoing equations, N_0 is the total number of peaks in the Texture Analyzer force–deformation curve output; d is the distance of compression (mm); ΔF is the individual force drops for each peak (N); A is the area under the force deformation curve (mm^2); N_{sr} is the frequency of ruptures; F_{sr} the average specific force of ruptures; F is the average compression force and W_c is the crispness work.

2.2.8. Microstructure analysis

As cold swelling peak in the RVA analysis is one of the main characteristic of expanded extrudates. This occurrence was investigated by examining the microstructure of the gel produced from an extrudate at the point of peak viscosity in comparison to a gel produced from raw corn meal (starch not subjected to extrusion) at its peak viscosity through scanning electron microscopy. The difference in microstructure should be the result of the extrusion process, more specifically the starch shearing that occurs during extrusion. For this comparison, corn meal from the 180 fraction was used. The maximum viscosity at 25 °C or cold swelling peak occurred at approximately 4 min into a RVA run. Gels made from ground extrudate and corn meal were thereby prepared in the RVA and collected at the 4 min mark. Depending on the solidity of the fresh gel, the sample was either pipetted into a dialysis tube using a syringe or cut into pieces with a stainless steel razor blade. Both types of samples were immersed in a solution of 2.5% glutaraldehyde–0.1 M imidazole buffer (pH 7.0) overnight and further processed by freeze-fracture (Brooks et al., 1975).

For the scanning electron microscopy (SEM), the samples were dehydrated in a graded ethanol series (50, 70, 90 and 100%) and frozen in liquid nitrogen. After 5 min of freezing, samples were fractured manually with the edge of a cooled scalpel blade. Sample fragments were thawed in absolute ethanol and critical-point dried from liquid carbon dioxide. Dry fragments were mounted on aluminum specimen stubs with colloidal silver adhesive (Electron Microscopy Sciences, Ft. Washington, Pa.) and coated with a thin layer of gold by DC sputtering. Images of topographical features in fracture faces were made using a Quanta F200 scanning electron microscope (FEI Company, Hillsboro, Ore) at an accelerating voltage of 10 kV.

2.2.9. Statistical analysis

Analysis of variance (ANOVA) for the effect corn meal particle size on extrudate properties was accomplished using the mixed procedure of the Statistical Analysis System (SAS, 2004). Significant differences among treatment least-squares means were separated by Fisher's least significant difference at the 5% significance level.

3. Results and discussion

3.1. Chemical composition and particle size distribution

Proximate chemical composition of corn meal fractions (Table 1) showed protein content ranging from 6.15 to 8.04 g/100 g, crude fat varying from 0.57 to 0.79 g/100 g and carbohydrate content

Table 1
Proximate chemical composition of Corn meal fractions (g/100 g)[a].

	Average particle size (μm)					
	180	300	420	500	600	710
Protein	7.7	6.1	6.9	7.5	7.9	8.0
Crude fiber	<0.2	<0.2	0.2	<0.2	<0.2	<0.2
Crude fat	0.6	0.8	0.8	0.6	0.6	0.6
Ash	0.3	0.4	0.4	0.3	0.3	0.3
Moisture	10.3	10.6	11.2	11.0	10.8	10.8
Carbohydrate[b]	80.8	81.2	80.4	80.0	80.1	80.1

[a] Proximate composition derived from analyses performed by ingredient manufacturer per specification.
[b] By difference.

above 80%. The particle size distributions of the fractions produced by sieving corn meal are shown in Fig. 2. It was observed that the smaller fractions presented a less broad particle size distribution than the larger particles greater than 300 μm. The 180 μm, the smallest fraction produced, had particles varying from 100 to 750 μm while the 710 μm fraction had sizes ranging from 500 to 1500 μm, which was very similar to the particle distribution of 600 μm fraction. There was a tendency for the average particles to be larger than the values measured by sieves (Table 2). A possible explanation for this broad distribution might be attributed to the smaller particles adhering to the surface of the big ones. As the more sensitive particle size analyzer uses a disaggregation device, it would be expected that the small particles would be detected. On the other hand, the detection of larger particles above the average size aperture size could be explained by particle shape shadow effect as the particles pass through the laser beam (Mühlenweg and Dan Hirleman, 1998). This could also explain the slight difference in particle size distribution (Fig. 1) between the larger fractions (600 and 710 μm). Another explanation for this finding could be attributed to the small difference in sieve size aperture of the sieves 710 and 800 μm, which was only 90 μm.

3.2. Specific mechanical energy and expansion indexes

The specific mechanical energy (SEM) and expansion index (SEI, LEI and SEI) in extrusion of corn meal of various particle sizes are presented in Table 3. The SEM is a good quantitative descriptor in extrusion processes and the amount of mechanical energy delivered to the extruded material determines the extent of macromolecular transformations and interactions that takes place, i.e. starch conversion, and consequently, the rheological properties of the melt (Moraru and Kokini, 2003). The calculated specific mechanical energy (SME) of corn meal extrusion ranged from 528 to 719 kJ/kg. These findings show that SME input was significantly affected by the particle average size ($p < 0.05$) and that increasing particle size decreased the SME input. Similar results were also reported by Altan et al. (2009) who showed the reduction in SME during extrusion of barley flour when compared to that of barley grits attributing the influence of particle size on melt viscosity during the process. Large particles have less contact area both in relation to particle to particle and to the barrel and, consequently, are less affected by barrel temperature than finer particles as reported by Konstance and Onwulata (2006) and Desrumaux et al. (1998). The finer particles would heat more rapidly and reach the melt transition temperature faster than coarser particles resulting in lower viscosity and hence reduce SME. Also, energy expended to reduce the size of the particles in the extruder may not be available for starch conversion.

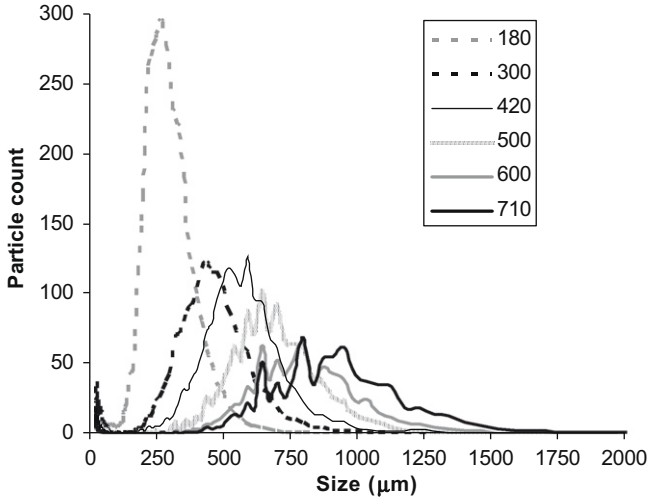

Fig. 2. Particle size distribution of raw corn meal fractions.

Table 2
Average particle size measured by particle size analyzer and solid feed rate at 700 rpm of corn meal of varied sizes.

Fraction	Sieve aperture size (μm)	Average particle size (μm)	Solid feed rate (kg h^{-1})
180	300	249.4 ± 6.83	5.7 ± 0.02
300	420	388.1 ± 8.44	6.4 ± 0.05
420	500	519.3 ± 7.83	6.8 ± 0.06
500	600	636.8 ± 12.85	7.3 ± 0.05
600	710	733.7 ± 13.05	7.5 ± 0.10
710	800	834.7 ± 15.92	7.7 ± 0.10

The SEI values varied from 7.5 and 10.8 (Table 3). SEI of 180 and 300 particle sizes were statistically different ($p < 0.05$) from particles of higher sizes (500 fractions). Extrudates produced from higher particle size expanded more than those from smaller particle sizes. As LEI is inversely proportional to SEI (Alvarez-Martinez et al., 1988), higher SEI value resulted in lower LEI values, the reason may be that as the extrudates emerged from the die, the forward momentum favored longitudinal over radial expansion. VEI, which is a product of LEI, reduced with an increase of particle size. Altan et al. (2009) concluded that the particle form of raw material (grits or flour) affected SEI and bulk density of extrudate, is inversely related to volumetric expansion, but disproportionally favors longitudinal expansions. Ding et al. (2005) reported that increasing feed rate significantly increased the extrudate expansion. Our results in Table 2 agrees with Ding et al. (2005) on the effect of increased feed rate on expansion, but further, we demonstrate that the aggregate or average particle size also influences the extrudate expansion. Increased feed rate influences the degree of fill and residence time, inducing greater degradation of starch molecules networks due to increased particle to particle shear effects, which may change the melt rheology characteristics, thus leading to greater extensible bubbles during expansion water vapor flashing off due to a reduction of melt viscosity, which results in extrudates of low density and increased expansion (Fan et al., 1996b).

3.3. Paste viscosity and water absorption index

The viscosity of a paste depends to a large extent on the degree of gelatinization of the starch granules and the rate of molecular breakdown. Viscosity parameters of Corn meal extrudates from particles of various sizes are shown in Table 4. High values of cold paste viscosity (MV25) indicates high shearing during the extrusion (Becker et al., 2001), which is translated into greater starch breakdown as more hydrophilic sites of the sheared starch molecules are exposed to water and forms a three-dimensional network at ambient temperature. Extrudates from the 180 sieve corn meal

Table 3
Specific mechanical energy (SME) and expansion indexes (SEI, LEI, VEI) of Corn meal extrusion of varied particle sizes*.

Fractions	SME (kJ/kg)	SEI	LEI	VEI
180	719.2^{a}	8.2^{b}	0.12^{a}	0.70^{a}
300	$655.5^{a,b}$	$7.6^{b,c}$	0.10^{b}	0.61^{b}
420	$605.9^{b,c}$	7.5^{c}	0.09^{b}	0.57^{c}
500	553.3^{c}	10.1^{a}	0.05^{c}	0.44^{d}
600	566.2^{c}	10.8^{a}	0.04^{c}	$0.40^{d,e}$
710	528.0^{c}	10.1^{a}	0.04^{c}	0.40^{e}

* Values with different superscripts letters in the same column are statistically significant at $p < 0.05$.

Table 4
Paste viscosity and WAI of Corn meal extrudates from various particle sizes*.

Fractions	MV25 (cP)	MV95 (cP)	Breakdown viscosity (cP)	FV (cP)	Setback viscosity (cP)	WAI (g/g)
180	669.5^{a}	74.3^{a}	595.2^{a}	462.6^{a}	388.3^{a}	11.1^{a}
300	555.3^{b}	52.4^{b}	502.8^{a,b}	324.4^{c}	272.0^{d}	9.8^{b}
420	461.9^{b,c}	49.7^{b}	412.1^{b,c}	277.3^{d}	227.6^{e}	8.7^{b}
500	484.4^{b,c}	58.1^{b}	416.1^{b,c}	413.1^{b}	344.8^{b}	8.6^{c}
600	354.6^{c}	54.1^{b}	300.5^{c}	340.9^{b}	286.8^{c}	8.4^{c}
710	384.7^{c}	54.2^{b}	330.6^{c}	378.9^{b}	324.7^{b,c}	8.5^{c}

* Values with different superscripts letters in the same column are statistically significant at $p < 0.05$.

Table 5
Texture aspects of Corn meal extrudates from various particle sizes*.

Fractions	N_{sr} (N)	F_{sr} (N)	F (N)	W_c (N.mm)
180	7.0^{a}	2.0^{a}	2.8^{a}	0.5^{a}
300	7.4^{a}	1.3^{b}	2.2^{a}	0.4^{b}
420	7.2^{a}	1.1^{b,c}	2.1^{a}	0.3^{b,c}
500	5.5^{b}	1.0^{b,c}	1.4^{b}	0.3^{b,c}
600	5.7^{b}	0.9^{b,c}	1.3^{b}	0.2^{b,c}
710	5.7^{b}	0.7^{c}	1.2^{b}	0.2^{c}

* Values with different superscripts letters in the same column are statistically significant at $p < 0.05$.

fraction showed the highest MV25 value, whereas the larger particle fractions (>180) showed the least values, clearly indicating that the higher the particle size the higher the chance of starch conversion. As expected, for all treatments there were no peak viscosity at 95 °C (typical of raw and intermediary cooked starch based materials), as a result of the severe condition necessary to produce directly expanded extrudates. The average particle sizes present no effect on the MV95 values. MV95 indicates the start of cooling period and may represents the extent of converted starches forms that are unable to keep their structure integrity and entanglements with vicinal dispersed starch molecules thus a reduction of paste viscosity occurs (Ozcan and Jackson, 2005). When hot pastes are cooled, the extent of increase in viscosity is governed by the re-association tendency of the starch as reported by Hagenimana et al. (2006). The re-association was reported for extruded rice flour.

WAI of extrudates ranged from 8.4 to 11.1 g/g (Table 4) and it was observed that as particle size increased, WAI values decreased. This finding differs from those of Altan et al. (2009) that showed that raw material properties had no effect on WAI. These findings suggest that smaller starch particles have a greater contact area for shear fragmentation during extrusion which leads to increased dextrinization and improves its water absorption capacity. The WAI estimates the amount of water absorbed by starch and can be used as an index of gelatinization, since it is known that disrupted starch granule binds more water (Ding et al., 2006).

3.4. Texture analysis

The textural properties of corn meal extrudates of different particle sizes were determined by measuring the frequency of ruptures (N_{sr}), the average specific force of ruptures (F_{sr}), the average compression force (F) and the crispness work (W_c) (Table 5). Mechanical resistance of the lowest particle size (180) specimen was significantly higher than that of the highest particle size (710) in contrasting to what was reported by Desrumaux et al. (1998), but agreeing with the findings of Altan et al. (2009). Both authors agree that increasing particle size produced extrudates with slightly larger cell sizes and lower cell density. Ding et al. (2005, 2006) found that increasing feed rate associated results in extrudates with a higher expansion whereas and increased in hardness was observed when increasing feed rate was associated with an increase of feed moisture. The hardness and crispness of expanded extrudate is a perceptible to consumers, and may be correlated with the expansion and cell structure of the product, independent of the feed moisture content (Ding et al., 2005). In fact, excess water acts to over plasticize starch reducing its viscosity and mechanical energy dissipation capacity in the extruder, leading to a dense hard extrudate product with compressed cell structures; crispness of such extrudate is reduced. Therefore, when the feed rate increases, excess moisture is reduced (Table 2), an inverse effect was observed in a crispness values (Table 5).

3.5. Microstructure analysis

SEM of raw and expanded corn meal extrudate specimen from the 180 sieve fraction subset from cold viscosity peak (MV25) are shown in Figs. 3 and 4. Microstructure of raw corn meal revealed large fractured particles (250×) with the smaller rounded particles, possibly intact starch granules released during milling, adhering to the surface (Fig. 3a). The higher magnification (2500×) surface image showed irregular individual cells (Fig. 3b) with no evidence of damage to the integrity of the cell wall.

Generally, the cold viscosity of extrudates increase due to pregelatinization effect and then decrease due to dextrinization and granule rupture when the degree of cook increases (Singh et al., 2009), as a result of severity of starch shearing. The raw corn meal microstructure (Fig. 3b) contrasts with the expanded corn meal

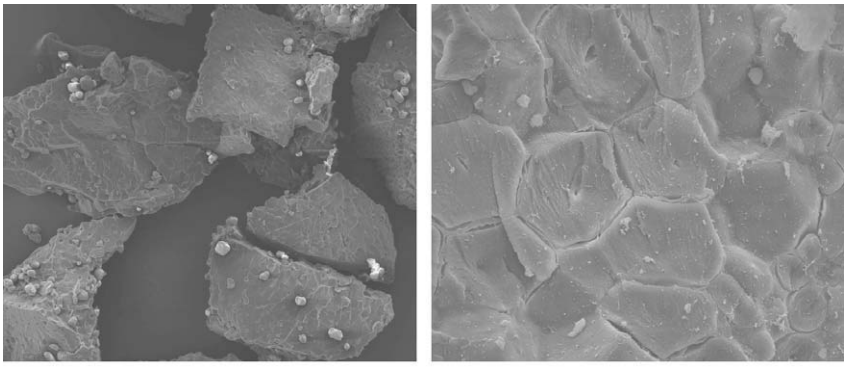

Fig. 3. Scanning electron micrographs of raw corn meal fraction 180: (a) 250× magnification and (b) 2500× magnification.

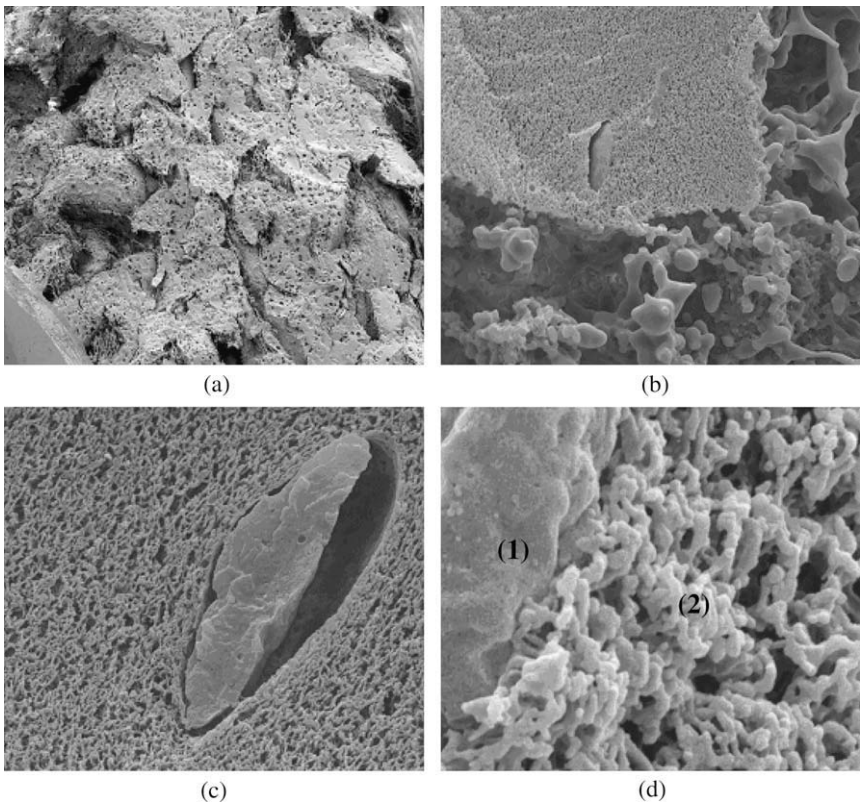

Fig. 4. Scanning electron micrographs of expanded corn meal extrudate 180 fraction from cold viscosity peak (MV25): (a) 100×, (b) 2500×, (c) 10,000×, and (d) 50,000× magnification.

(180 sieve fraction) (Fig. 4b) showing an absence of individual cells and very little particles, suggesting this specimen to be a discontinuous phase gel matrix. By increasing the magnification (Fig. 4c and d), the clear difference in network structure of a compact structure phase (1) and a random coarser aggregate with different porous sizes (2) became apparent; the smaller granules disappeared. Increased SME input was also considered responsible for fragmentation of starch molecules during low moisture extrusion (Moraru and Kokini, 2003; Meuser et al., 1992). Grooper et al. (2002) using SEM showed that starch granules were still present in extrudates produced at SME = 142 kJ/kg, but were no longer observable at SME = 299 kJ/kg, and thus corroborating with our previous results (Table 3). SME input plays an important role in starch conversion, since it catalyzes the gelatinization process by rupturing intermolecular hydrogen bonds and leads to starch granule breakage during heating under shear stress; these changes can be documented with SEM analysis of starch conversion.

4. Conclusion

The properties of corn meal extrudates depend on particle size distribution. SME input was significantly affected by the particle size distribution ($p < 0.05$). Increasing the particle size decreased the SME input, hence reduced starch conversion. SEI of 180 and 300 fractions were statistically different ($p < 0.05$) from those of particle sizes greater than the 500 fraction. Extrudates produced with larger particle size exhibited higher expansion than extrudates produced with particles of smaller size. Therefore, average particle size influences the extrudate expansion. As expected, for all treatments there were no peak viscosity at 95 °C (typical of raw and intermediary cooked starch based materials), as a result of the severe condition necessary to produce directly expanded extrudates. The average particle sizes present no effect on the MV values, except to 180 fraction. Mechanical resistance of the smallest particle size (180) was significantly higher than that of the largest particle size. Microstructure of raw corn meal revealed large fractured particle sizes with small rounded particles adhered to the surface and there was no evidence of gel formation. In contrast, expanded extrudate from 180 fraction had an absence of individual cells and very little particles. This is the likely a result of the severity of starch shear stress that led to a discontinuous phase of gel matrix. The results of our study may attest valuable in the selection of suitable corn meal based on the average particle size for pursuing desirable characteristics during extrusion process.

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