PROPERTIES OF EXTRUDED WHITE CORN FLOUR-HIGH AMYLOSE CORN STARCH PUFFS

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by
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The undersigned, appointed by the Dean of the Graduate School, have examined the thesis entitled

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HIGH AMYLOSE CORN STARCH PUFFS

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ABSTRACT

This study was conducted to determine the effect of high-amylose corn starch in corn puffs on the extrusion parameters, product and textural properties and the glass transition temperature. The data was analyzed in a randomized complete block design (RCBD) in which the treatments were arranged in a 4 x 3 x 3 {high-amylose content (0, 20, 40 and 60%) x moisture content (20, 22, and 18 or 24%) x extruder screw speed (200, 300 and 400 rpm)} factorial arrangement of treatments with two replicants.

The collected results indicate that the maximum amount of expansion occurs when the screw speed and moisture content are both decreased and the high-amylose corn starch content is increased. The puff density increased and the specific volume decreased when screw speed and starch content decreased and moisture content increased. While the original puff breaking strength and hardness were only affected by the moisture content, the puffs containing more high-amylose corn starch exhibited significantly higher breaking strengths at higher water activities. The extruder responded to increases in screw speed and starch content and a decrease in moisture content with increases in temperature and specific mechanical energy. The Gordon-Taylor equation was used to predict the effect of water plasticization on the high-amylose corn puffs.

CHAPTER 1

INTRODUCTION

Many snack foods and breakfast cereals currently on the market are produced by the extrusion process. Our research focused on the study of the use of high-amylose corn starch in corn puff snack products. High-amylose starch is processed as dietary fiber by the body because it is a resistant starch (Liu et al, 2007). For this reason, high-amylose starch could be a valuable ingredient to healthy snack foods on the market. We chose to study high-amylose corn starch because the use of high-amylose rice (Chen and Yeh, 2001), wheat (Van Hung et al, 2006, 2007) and potato (Thuwall et al, 2006) starches in food products have previously been published. The study of the changes to the structure of high-amylose corn starch during extrusion (Lopez-Rubio et al, 2007) as well as its use in packaging materials (Lin et al, 1995) have been published.

One of the main focuses of our study was the analysis on the changes in glass transition temperature and texture at various water activities and high-amylose corn starch contents. Glass transition temperature is an important characteristic for the food manufacturer to know because the food texture varies greatly above and below this temperature. Since the glass transition temperature is dependent on the moisture content, the texture of the food will be dependent on both the moisture content and the product temperature. The Gordon-Taylor equation was used in the analysis of the glass transition temperature.

The dependent variables studied in addition to the glass transition temperature were: extrusion parameters (die and product temperatures, specific mechanical energy and die pressure); product properties (length, width, expansion, per piece weight, bulk density, apparent bulk density, specific volume and color); and texture properties (breaking strength and hardness). The independent variables changed were the ratio of high-amylose corn starch to white corn flour (0, 20, 40 and 60%); the moisture content fed into the extruder (20, 22 and 18 or 24%); and the extruder screw speed (200, 300 and 400 rpm).

CHAPTER 2

LITERATURE REVIEW

2.1 Extrusion

Popcorn was the inspiration behind the initial puffed product extrusion research (Matz, 1976). Before extruders, high-pressure chambers were used to puff whole grains. Extrusion quickly became the preferred method due to the fact that it was a continuous process that allowed for a product with consistent expansion and shape (Hauck, 1980). Once it was discovered that extruders could be used to create an expanded product with a desirable texture, new shapes started becoming available in snack foods and cereals. Ingredients, moisture content, temperature, pressure, screw speed and die design all affect the expanded product's final appearance (Matz, 1993). In addition to lowering the energy requirements and labor costs of the production of expanded products, extrusion cooking also inactivates enzymes, increases the uptake of water in starch for improved digestibility, and pasteurizes the product which ensures a stable shelf life (Smith, 1982). Extrusion cooking tends to favor the Maillard reaction because it uses high temperatures and relatively low moistures (Berset, 1989). The Maillard reaction normally involves reducing sugars and amino acids (Chinachoti, 2000). However, during extrusion the high shear forces can enhance the hydrolysis of starch which can create reducing carbohydrates (Berset, 1989). While most initial extrusion applications used a single-screw extruder, the twin-screw extruder is now often preferred for many situations.

2.1.1 Snack foods

The cereal used more often than any other in expanded snack foods is corn, due to its relatively low cost and superior expandability in extrusion; generally degermed corn is used in extrusion because its lower oil content allows for better expansion (Moore, 1994). Yellow and white corns are both commonly used in snack foods. While more people prefer the taste of white corn to yellow corn, white corn contains significantly less vitamin A than yellow corn (Poneleit, 1994). For this reason, white corn is generally only used in snack foods and not animal feed.

2.1.1.1 *Direct expanded snack products*

The direct expanded snack products are often referred to as second-generation snacks and were once called collets, in reference to the type of extruder that made them (Moore, 1994). They are called direct expanded because they require no additional processing after extrusion to complete the expansion of the product and are said to be the easiest food products to make with an extruder (Sevatson and Huber, 2000). The puffing of the products is fairly simple. The dry ingredients and water are mixed in the extruder and heated to above 100°C; the water remains a liquid however because of the high pressures inside the extruder barrel. Once the product reaches the die opening, the superheated water vaporizes into steam as it comes in contact with the outside atmosphere. This rapid vaporization causes stretching in the starch matrix of the product and results in the expanded, porous product with a characteristic size, shape and texture (Moore, 1994). Due to the fact that there is a continuous flow of product from the die, the extrudates experience the greatest amount of expansion in the radial direction

(Padmanabhan and Bhattacharya, 1989). The final shape of the product will be determined by the die configuration and cutter speed at the die opening (Matson, 1982). Once extruded, these direct expanded products can be finished by either baking or frying (Huber, 2001). Baking gives the products a crisper, lighter, crunchier texture whereas frying gives the products a smoother texture because of the oil uptake (Serna-Saldivar et al, 1994).

2.1.1.2 *Third-generation snack products*

Third-generation snack products are sometimes referred to as indirect expanded products, half products or semi products. There are two main categories of third-generation extruded snacks: pellets and fabricated chips. Neither pellets nor fabricated chips are expanded directly by the extruder. The pellets are shaped by the die at low temperatures to prevent expansion, and the fabricated chip products are extruded as sheets and then cut into desirable shapes (Moore, 1994). Generally these third-generation snack products contain at least 60% starch to achieve maximum expansion during post extrusion processing (Sevatson and Huber, 2000). During further processing, the third-generation snack products can be either expanded by immersion in hot oil or by hot air puffing (Huber and Rokey, 1990). A more recent variant to this further processing is the expansion by infrared or microwave heating (Huber, 2001).

2.1.1.3 *Co-extruded snack products*

Typically co-extruded snacks have an extruded crunchy outer shell and pumpable inner filling that may be added during or after extrusion (Huber and Rokey, 1990). Not many co-extruded snacks have proven themselves successful in the marketplace because of the relatively short shelf life of these products. This short shelf life is largely due to the migration of moisture and lipids from the center filling to the outer shell that should have a much different texture (Huber, 2001). One of the few products that has found a solid footing in the consumer marketplace is produced by Mars Incorporated; Combos have been popular since the early 1980s (Moore, 1994).

2.1.1.4 *Supercritical carbon dioxide puffed snack products*

New research in supercritical fluid extrusion has made possible the production of snacks that have extremely fine cell structures. This extrusion process is conducted at lower temperatures and higher moisture levels than regular extrusion to maintain a high CO_2 solubility (Chen and Rizvi, 2006). The use of supercritical carbon dioxide rather than water as the driving force behind expansion also allows for the use of heat-sensitive dairy products that can not be used in traditional extrusion (Huber, 2001). This can be achieved because puffing with supercritical carbon dioxide can occur at a lower temperature and with less shear than when steam is used. This allows for the production of puffs that are less degraded, and it also causes less machine wear on the extruder (Alavi and Rizvi, 2005).

2.1.2 RTE breakfast cereals

Ready-to-eat (RTE) breakfast cereals are shelf-stable, lightweight to ship and store, and require no further cooking by the consumer (Duensing et al, 2003). The most commonly used cereal grains in RTE breakfast cereals are corn, wheat, rice, oat and barley (Sevatson and Huber, 2000). Of these cereal grains, corn is used more often both alone and in combination with others (Serna-Saldivar et al, 1994). In addition to the cereal grains, RTE cereals are generally enhanced with vitamins and minerals and often flavored and sweetened. The most common types of RTE breakfast cereals include flaked cereals, extrusion puffed cereals, oven puffed cereals, and gun puffed cereals.

2.1.2.1 *Flaked cereals*

Corn flakes were made from the endosperm of the corn kernel as early as 1903 by W.K. Kellogg, who used degermed corn grits (Fast, 1999). During processing, the corn grits are first steamed under pressure in rotary cookers which ensures high gelatinization with little swelling of starch granules (Duensing et al, 2003). Alternatively, corn meal, corn flour, or corn bran can be mixed with other ingredients and extruded into small pieces that can undergo the same flaking process as the corn grits without the need for the rotary cookers (Duensing et al, 2003). In the flaking process, the gelatinized corn grits or the extruded product pieces are smashed and then rolled into continuous sheets. The pieces must possess a degree of fluidity and gelatinization to ensure that they can be fed and reshaped without falling apart (Miller, 1994).

2.1.2.2 *Extrusion puffed cereals*

Like the direct expanded snack products, the extrusion puffed cereals do not require any additional puffing after the extrusion process. The extrusion puffed cereals are generally denser than the direct expanded snacks (Miller, 1994). The current trend in research today is to move away from the oven and gun puffed products and toward the extrusion puffed cereals because of the faster process that ultimately requires less man power (Sevatson and Huber, 2000). Since the early 1980s extrusion technology has progressed, allowing for the development of an increasing number of colors, textures, sizes and shapes of RTE breakfast cereals (Duensing et al, 2003).

2.1.2.3 *Oven puffed cereals*

Extruded cereals are oven puffed when a great degree of expansion is not required because expansion is generally only three to four times the original size (Serna-Saldivar et al, 1994). These products are most often made of rice or a combination of rice and corn. Puffing occurs either on fluidized bed driers or rotary toasting ovens at high temperatures. The rapid heating causes expansion only if the products are well gelatinized and at the proper moisture level (Miller, 1994). The process usually takes about a minute and a half (Rooney and Serna-Saldivar, 2003).

2.1.2.4 *Gun puffed cereals*

Extruded cereals are gun puffed when a great degree of expansion is required because expansion is generally ten to sixteen times the original size (Serna-Saldivar et al, 1994). Changing the temperature and pressure determines the degree of expansion in this process which takes anywhere from five to seven minutes (Rooney and Serna-Saldivar, 2003). These products are most often made of corn or a combination of corn and other cereal grains. Puffing occurs inside a pressurized vessel that is first heated and then suddenly opened. The main difference between gun puffed and extrusion puffed cereals is that the gun puffed products are not exposed to the shear forces of the extruder and therefore retain their original shape (Miller, 1994).

2.2 Corn

The corn kernel, like other cereal grains, is made up of three basic layers: the pericarp, the endosperm and the germ. The pericarp, or bran, is the outer-most layer and functions mainly to protect the grain. In the corn kernel, the pericarp adheres strongly to the endosperm making it a caryopsis type of kernel (Rooney and Suhendro, 2001). Over half of the kernel's dietary fiber is found in the pericarp (Watson, 2003). The endosperm makes up over 80% of the whole corn kernel and is composed of starch granules embedded in a protein matrix (Swanson, 2000). Finally, the germ serves as the source of nutrients and hormones during germination and later as the storage site for over 80% of the kernel's oil (Watson, 2003).

When processing corn, the kernels can either be dry or wet milled. Dry milling separates the different sections of the kernel; the bran and sometimes the germ are removed from the endosperm. Additionally, corn kernels have dark colored tip caps located at the end of the germ which must also be removed to prevent severe discoloration of the flour (Matz, 1976). Dry milling can be further broken down into three specific types: full-fat milling, bolted milling, and tempering-degerming milling (Duensing et al, 2003). The white corn flour used in this project was degermed, meaning both the bran and germ were removed, leaving only the endosperm. Wet milling separates the chemical structures of the kernel. Wet milling is used to isolate starch, oil, protein, and fiber from the kernel to provide purified marketable products (Johnson and May, 2003).

2.2.1 Starch

Starch is the second most abundant naturally occurring organic compound, cellulose being the first (Huang and Rooney, 2001). The starch found in the endosperm of the corn kernel is composed of glucose molecules. The two complex carbohydrates that make up the starch granules are amylose and amylopectin. The amylose is a linear chain of glucose molecules connected by α-(1-4) linkages as shown in Figure 2.2.1. Normally the amylose makes up 25-30% of the total starch found inside the endosperm. However in the high amylose mutant varieties it can make up 60-70% of the total starch (Johnson and May, 2003).

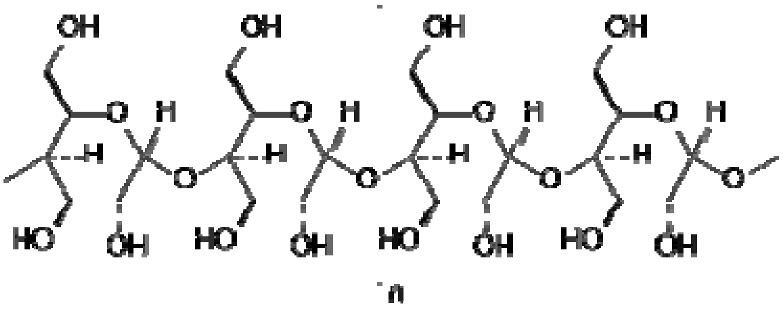

Figure 2.2.1: Amylose structure

Amylopectin is a highly branched structure that normally makes up 70-75% of the total starch. However in waxy mutant varieties it can make up nearly 100% of the total starch in the endosperm (Johnson and May, 2003). The branches of the amylopectin are connected by α-(1-6) linkages while the linear sections are connected by α-(1-4) linkages as in the amylose chains as shown in Figure 2.2.2.

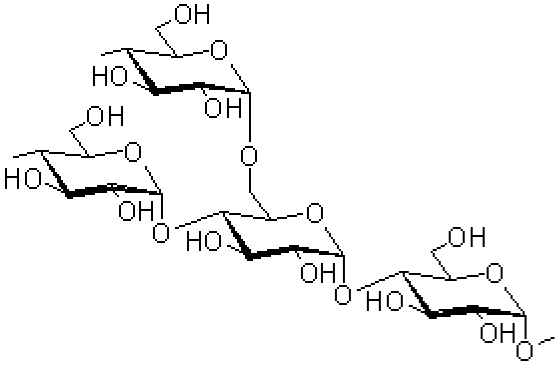

Figure 2.2.2: Amylopectin structure

Corn and wheat starch are made up of simple granules whereas rice and oats are made up of compound granules which contain a number of smaller individual granules (Huang and Rooney, 2001). Starch granules exhibit a crystalline structure which is composed of starch double helices (Jane, 2000). This crystallinity can be seen on the starch granules as a Maltese cross when exposed to polarized light; this phenomenon is referred to as birefringence (White, 1994). It is believed that the amylopectin portions of the starch are responsible for this crystalline network because while waxy mutants exhibit a similar crystalline structure, high-amylose mutants show decreased crystallinity (Boyer and Shannon, 2003). During extrusion cooking, a portion of starch degrades into smaller macromolecules due to shear forces as well as the cooking temperatures and addition of water during extrusion (Diosady, 1986). Additionally, protein-starch complexes tend to form during extrusion as the protein solubility decreases (Wlodarczyk-Stasiak and Jamroz, 2008). In addition to the numerous uses of starch in food applications, many other industries also utilize starch as can be seen in Table 2.2.1.

Table 2.2.1: Industrial uses of starch

Industry	Use of starch/modified starch
Adhesive	Adhesive production
Agrochemical	Mulches, pesticide delivery, seed coatings
Cosmetics	Face and talcum powders
Detergent	Surfactants, builders, cobuilders, bleaching agents and bleaching activators
Food	Viscosity modifier, glazing agent
Medical	Plasma extender/replacers, transplant organ preservation, absorbent sanitary products
Oil drilling	Viscosity modifier
Paper and board	Binding, sizing, coating
Pharmaceuticals	Diluent, binder, drug delivery
Plastics	Biodegradable filler
Purification	Flocculant
Textile	Sizing, finishing and printing, fire resistance

Taken from previously published source (Ellis et al, 1998).

2.2.2 Gelatinization

The gelatinization of starch is very important to the food industry because humans can only digest starch that has been almost fully gelatinized. Feedstuff however should only be partially gelatinized due to the different enzymes found in the digestive tracts of livestock (Van Zuilichem and Stolp, 1987). Gelatinization of starch is irreversible and occurs when the granules are subjected to sufficient heat and water (Huang and Rooney, 2001). It is important to note that during extrusion cooking, less water is required for gelatinization (Hayakawa et al, 1992). Starches with higher amylose content require more severe extrusion cooking than those with higher amylopectin contents to fully gelatinize (Kim and Maga, 1993c). The granules will first swell as they absorb water, and then the amylose begins to leach out of the granules which increases the viscosity of the solution (White, 1994). Additionally during extrusion cooking, the amylose that was released from the granules forms complexes with any lipids that may be present in the extrudate (Strauss et al, 1992). The gelatinization temperature is defined as the time the starch begins to undergo the irreversible changes of gelatinization; this occurs over a temperature range and not at a specific temperature. The extent to which gelatinization occurs during extrusion is dependent upon moisture content, temperature, torque and screw speed of the extruder (Strauss et al, 1992). Increasing the screw speed of the extruder decreases the degree of gelatinization due to the decreased retention time (Chiang and Johnson, 1977). The glass transition temperature is defined by the loss of birefringence or decreased crystallinity, this occurs over a temperature range and not at a specific temperature. Pasting is commonly used interchangeably with gelatinization but in fact is a process that occurs following gelatinization. Pasting is the further dissolution of the starch as the amylose more readily leaches from the granules, forming a more viscous paste (White, 1994).

2.2.3 Retrogradation

The retrogradation of starch occurs after the paste has cooled and the released amylose chains begin to reassociate into a crystalline network (Daniel and Weaver, 2000). The amylose molecules initiate retrogradation by first reattaching to one another and then to the outer edge of the starch granules they leached from during gelatinization. Normal and high-amylose starches have a high tendency to retrograde whereas waxy starches show little if any retrogradation due to their lack of amylose (White, 1994). Additionally, extrudates containing excess water have a greater tendency to retrograde than those extruded under more severe conditions (Lopez-Rubio et al, 2007). Differential scanning calorimetry (DSC) is the preferred method of measuring retrogradation due to the correlation between recrystallization and glass transition (Roos, 2007).

2.2.4 High-amylose corn starch

High-amylose corn starch has a genetic mutation of the amylose-extender (*ae*) allele that increases the amylose content of the endosperm up to and above 50% (Darrah et al, 2003). High-amylose starches tend to be more resistant to digestive enzymes than native cereal starches because it is not susceptible to α-amylases (Lopez-Rubio et al, 2007). Like other resistant starches (RS), high-amylose starch acts as a dietary fiber in the body and can lower plasma cholesterol (Liu et al, 2007). Current research is also studying possible applications of high-amylose wheat starch as a dietary fiber and resistant starch (Van Hung et al, 2006). There are three types of RS: RS1 are physically bound starches, RS2 are granular starches, and RS3 are retrograded starches; high-amylose starch belongs in the RS2 group along with the starch found in green bananas and uncooked potatoes (Mauro et al, 2003).

High-amylose starches are often used in extruded products that will later be fried because they reduce the oil absorption by forming stronger films than regular or waxy starchs (Huang and Rooney, 2001). They are also used in the confectionery industry to stabilize the shape and integrity of candy (Fergason, 1994). High-amylose starches are used to thicken pudding and bind tomato paste. The biodegradable packaging peanuts produced by the National Starch and Chemical Company are composed of 95% high-amylose starch and are referred to as ECO-FOAM™ (Fergason, 1994). Other research is being conducted in the study of biodegradable cushioning and insulation made using high-amylose corn starch (Nabar and Narayan, 2006).

The ratio of amylose to amylopectin in starch is very important to determining the extent of expansion during extrusion. High-amylose corn starches tend to produce less expansion than waxy or native corn starches when used in extruded products (Zhang and Hoseney, 1998); extruded rice pellets also showed decreased expansion with increased amylose content (Chen and Yeh, 2001). Starches with a high-amylopectin content produce more fragile products with a lower density (Matz, 1993). Products containing higher amylose contents tend to have higher gelatinization temperatures than those containing higher amylopectin contents (Van Hung et al, 2007).

2.3 Water Activity

Water activity (a_w) is important to both the microbial and textural stability of food systems. It is defined as the ratio of the vapor pressure of water in the headspace above the food to the vapor pressure of pure water (Chinachoti, 2000). Practically speaking, a_w differs from the moisture content of the food in the fact that it is not simply a measure of the amount of water but rather the amount of water available for microbial growth and other reactions. The water activity can be controlled by placing the food sample in a desiccator containing a saturated salt solution with known a_w.

Changes in a_w are known to have significant effects on the texture of cereal and snack products. These changes in texture occur because the water softens the starch matrix, changing the product to a glassy state and losing the desired crunchy texture (Gondek and Lewicki, 2006). For most cereal and snack products this change occurs between a_w of 0.5 and 0.6 (Hsieh et al, 1990a). Increasing a_w of the product initially causes antiplasticization, and the force required to compress the product increases; however at higher a_w than this critical point, a plasticization of the products takes place, and the force required to compress the product decreases (Gondek and Lewicki, 2006). These changes in a_w are also important to biodegradable packaging products which exhibit a poor spring index at both low (below 0.33) and high (above 0.75) a_w, whereas at intermediate a_w (between 0.33 and 0.75) the product provides suitable cushioning properties for use in packaging applications (Lin et al, 1995).

2.4 Glass Transition Temperature

The glass transition temperature (T_g) of cereal and snack products is important because the desired crunchy texture is only present when the product is in its glassy state. Raising the moisture content and/or temperature enough will cause a transition from a glassy to a rubbery state as the molecular mobility increases (Marzec and Lewicki, 2006). Since the transition from glassy to rubbery state is also dependent on the moisture content, the crunchiness of the product can not be predicted by the T_g alone (Nicholls et al, 1995). It can be difficult to determine the T_g of food systems because products containing multiple components exhibit multiple transitions. The instability of water also complicates the determination of an accurate T_g (Yu and Christie, 2001). A relatively simple extruded amylopectin-sucrose system can be analyzed to find the two T_g of each of the components, however even in this basic system the lack of homogeneous mixing during extrusion prevents the calculation of highly accurate temperatures (Farhat et al, 2003). It is important to note however that the starch within the extrudate is more homogeneously distributed than the protein and lipids (Cremer and Kaletunc, 2003). The glass transition temperature is important to non-crunchy foods as well such as fruit leather which should have a soft rubbery texture when consumed (Huang and Hsieh, 2005).

CHAPTER 3

MATERIALS AND METHODS

3.1 Raw Materials

The two ingredients used to make the corn puffs in this project were white corn flour and high amylose corn starch. The white corn flour was purchased from Bunge Milling Inc. (St. Louis, Missouri, U.S.A.), and its proximate composition is shown in Table 3.1.1. The high amylose corn starch, Hylon VII, was purchased from National Starch (Bridgewater, New Jersey, U.S.A.), and its proximate composition is also shown in Table 3.1.1. The ingredients for each of the four batches were mixed in an 18.9L Hobart Mixer (Hobart Corp., Troy, Ohio, U.S.A.) for 10 minutes to ensure complete blending. The concentrations (dry basis) for each of the four batches are shown in Table 3.1.2.

Table 3.1.1: Proximate composition of ingredients

Component (%)	White Corn Flour	High Amylose Corn Starch
Protein	5.75	0.84
Fat	0.78	0.00
Fiber	0.31	0.18
Moisture	11.32	11.65
Ash	0.55	0.13

Table 3.1.2: Percent composition of the four batches

Batch	1	2	3	4
% White Corn Flour	100	80	60	40
% High Amylose Corn Starch	0	20	40	60

3.2 Experimental Design

This experiment had three independent variables: the high amylose corn starch concentration, moisture content, and extruder screw speed. Each of the four batches were extruded at three moisture levels and three screw speeds and each sample was collected in duplicate. A total of 36 (4x3x3) treatments were extruded and collected. Varying the high amylose starch concentration in the batches changed the stability of the extruded product at different moisture levels. For this reason, after preliminary work, we discovered that the four batches could not be run at the same three moisture levels. This was not a great surprise because previous studies have reported that high-amylose starch can be more difficult to extrude due to its higher melt viscosity compared to native starches; this problem can be overcome by increasing the moisture content (Thuwall et al, 2006).

Each of the treatments was assigned a four digit code. The first digit corresponds to the batch (1-4). The second digit corresponds to the moisture content (1-3), these assignments varied between batches is explained in Table 3.2.1. The third digit corresponds to screw speed (1-3, where 1 = 200 rpm, 2 = 300 rpm, and 3 = 400 rpm). The fourth digit corresponds to the replicant (1-2).

Table 3.2.1: Moisture content code assignments

Code	Batch	Moisture Content (%)
11	1	18
12	1	20
13	1	22
21	2	20
22	2	22
23	2	24
31	3	20
32	3	22
33	3	24
41	4	20
42	4	22
43	4	24

3.3 Extrusion

The white corn flour and high amylose corn starch puffs were extruded using an APV Baker MPF 50/25 twin-screw extruder (APV Baker, Grand Rapids, Michigan, U.S.A.) The extruder was set up for a diameter-to-length ratio of 1:25, where the diameter of the screw was 50 mm. The raw materials were fed into the extruder using a K-tron type T-35 twin screw volumetric feeder (K-tron Corp, Pitman, New Jersey, U.S.A.) at a rate of 45.4 kg/hr. Due to the fact that a volumetric feeder was used, each of the batches had to be calibrated with the feeder because of their varying densities. Water was injected into the extruder using an Ivek Digifeeder (Ivek, Springfield, Vermont, U.S.A.) pump system at ambient temperature. The puffs were extruded using the screw profile shown in Table 3.3.1.

Table 3.3.1: Screw profile

Length (mm)	Screw type
225	twin lead feed screw
25	2x90° paddles
50	single lead feed screw
162.5	13x30° forward paddles
150	twin lead feed screw
25	2x90° paddles
100	single lead feed screw
50	4x30° reverse paddles
125	single lead feed screw
25	2x90° paddles
100	twin lead feed screw
100	8x30° forward paddles
62.5	5x30° reverse paddles
50	single lead feed screw
1250	Total barrel length

The temperatures at each of the barrel zones in the extruder were controlled and can be seen in Table 3.3.2.

Table 3.3.2: Extruder barrel zone temperatures

Zone	Temperature, °C
3	26.7
4	37.8
5	51.7
6	93.3
7	115.6
8	121.1
9	121.1

The following extruder responses were recorded for use in the analysis: die temperature, product temperature, torque and die pressure. The puff products exited the extruder through two 3.18 mm diameter die and were immediately cut by a four blade fixed steel cutter. The specific mechanical energy of the extruder was then calculated using the following formula (Hsieh et al, 1990b and Garber et al, 1997):

$$SME = \frac{rpm(run)}{rpm(rated)} * \frac{\%Torque}{100} * \frac{HP(rated)}{feedrate}$$

where rpm(rated) = 500, HP(rated) = 28kW, and feed rate = 0.01261 kg/sec.

Samples were collected after the extruder had reached steady state for each of the treatment levels, this occurred after approximately seven minutes. The puffs were collected onto two large baking sheets and placed in a fluidized bed drier at 65°C for five minutes. After this drying period, all the puffs had moisture contents of 2-3%. The samples were then removed and allowed to reach room temperature before being stored in sealed plastic bags. The plastic bags were stored at ambient temperature until needed for testing.

3.4 Analysis of Product Properties

3.4.1 Length, width and expansion

The length and width of the corn puffs were determined by measuring fifty random puffs from each of the treatments with a digital caliper (Mitutoyo, Japan). The fifty measurements were averaged and reported in this study. The expansion was calculated by dividing the width of the puff by the diameter of the die opening, 3.18 mm.

3.4.2 Per piece weight

Per piece weight was calculated by measuring the weight of fifty random puffs and dividing the total weight by fifty. This test was conducted in triplicate.

3.4.3 Bulk density

To measure the bulk density, the corn puffs were first ground in a Waring blender (Torrington, Connecticut, U.S.A.). The ground sample was then placed in a pre-weighed graduated cylinder and tapped three times to remove air pockets. The weight and volume of the sample were recorded. This test was conducted in triplicate.

3.4.4 Apparent bulk density

The apparent bulk density was measured by filling a container of known weight and volume (1.6L) with corn puffs. The apparent bulk density was calculated as the weight of the corn puffs divided by the volume of the container. This test was conducted in triplicate.

3.4.5 Specific volume

The specific volume was calculated using a rapeseed displacement method. First the volume of the container was determined by weighing it empty and then again filled with water. The bulk density of the rapeseed was then determined by weighing the filled container. To determine the specific volume of the extrudate, sample puffs were placed in the container and weighed. Then the container was filled with rapeseed and weighed again. The specific volume was calculated in triplicate.

3.4.6 Color

The color of the corn puffs was measured using a Konica-Minolta colorimeter (Mahwah, New Jersey, U.S.A.). The corn puffs were first ground in a Waring blender (Torrington, Connecticut, U.S.A.) and then packed between two Petri dishes. Two readings were taken for each of the samples. The second measurement was taken after rotating the colorimeter 90°. This test was conducted in triplicate, for a total of six readings. The colorimeter measured L, a, and b values. The L value is a measure of the degree of lightness of the sample. An L value of 100 represents white and 0 represents black. The a value is a measure of red and green. A positive a value indicates redness and a negative value indicates greenness. The b value is a measure of yellow and blue. A positive b value indicates yellowness and a negative value indicates blueness. For both the a and b values, a measurement with a higher absolute value represents a greater intensity of color.

3.5 Texture Profile Analysis

A TA-HDi (Texture Technologies, Scarsdale, New York, U.S.A.) analyzer was used to collect the data for the texture analysis. The puffs were cut using a scalpel into 1 cm thick cross sections in preparation for the compression portion of the texture profile analysis. The compression testing calculated the hardness. This test was conducted using a probe which would compress the sample to thirty percent of its original thickness, raise away from the sample, and then compress the sample again to thirty percent of its compressed height. This test was conducted in triplicate.

The shear testing portion of the texture profile analysis calculated the force required to shear the sample puff in two. This test was conducted using a 50 kg load cell. The breaking strength was calculated by dividing the force required to shear the sample by the average cross sectional area of that treatment. Ten sample puffs were sheared from each of the treatments.

3.6 Controlled Water Activity Analysis

3.6.1 Sample preparation at controlled water activity

To determine the effect of water activity on the texture analysis and glass transition temperature, whole puff and ground samples were equilibrated over seven different salt solutions which can be seen in Table 3.6.1. The samples were allowed to equilibrate in the desiccators for six weeks. The exact water activities were measured using a CX-2 AquaLab Water Activity Meter (Decagon Devices, Pullman, Washington, U.S.A.) and are also shown in Table 3.6.1.

Table 3.6.1: Saturated salt solutions

Salt Solution	Water Activity
KAc	0.233
$MgCl_2$	0.334
K_2CO_3	0.446
NaBr	0.555
KI	0.646
NH4Cl	0.702
$Sr(NO_3)_2$	0.797

3.6.2 Texture profile analysis at controlled water activity

The samples were cut into cross sections as described above in preparation for the compression testing. Once again the sample was compressed by thirty percent of its thickness twice. The treatments were all tested in triplicate at each of the seven water activities.

Once again the whole puff was used for the shear testing. The 50 kg load cell was again used to shear the samples. Ten samples from all of the treatments were tested at each of the seven water activities.

3.6.3 Glass transition

To determine the glass transition temperatures a Perkin Elmer 7 DDSC (DDSC, Perkin Elmer, Norwalk, Connecticut, U.S.A.) was used. DDSC stands for dynamic differential scanning calorimetry. Before testing the samples, baselines were generated using empty aluminum pans. Once the baselines had been established, the equilibrated ground samples were weighed (varied from 2mg to 4mg) and sealed in the aluminum DSC pans. Dynamic mode was used during operation. The sample was scanned from 20°C to 112°C, with amplitude of 2°C and equilibrating time of 30 seconds. Scans were conducted in duplicate, though several samples had to be run in triplicate to ensure more accurate results.

The Gordon-Taylor equation is often used to predict water plasticization:

$$T_g = \frac{w_1 * T_{g1} + k * w_2 * T_{g2}}{w_1 + k * w_2}$$

In the Gordon-Taylor equation T_g, T_{g1}, and T_{g2} are the glass transition temperatures of the mixture, solids, and water; w_1 and w_2 are the weight percentages of solids and water; and k is a constant. A temperature of -135°C is used as the T_{g2} for pure water (Li et al, 1998). Ground samples were dehydrated and used to measure T_{g1}. By inserting the experimental values into the Gordon-Taylor equation, the k value was estimated.

3.7 Data Analysis

The data was analyzed in a randomized complete block design (RCBD) in which the treatments were arranged in a 4 x 3 x 3 (high-amylose content x moisture content x extruder screw speed) factorial arrangement of treatments. The mean difference was calculated using the Fischer's protected least significant difference (LSD) method ($P \leq 0.05$). All data was analyzed using SAS software (version 9.1). To determine the effects of the independent variables on the dependent variables the Generalized Linear Model (GLM) procedure was used. Within this procedure standard error was used to calculate the significant difference between treatments. Note that when analyzing the effects of starch content on the various dependent variables, only the data from puffs extruded at 20% and 22% moisture were used in order to maintain a balanced analysis.

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Extruder Responses

4.1.1 Die temperature

The relationship between high-amylose corn starch, moisture content, extruder screw speed and die temperature can be seen in Table 4.1.1. Increasing the screw speed significantly increased the die temperature. For each of the four batches the two lower moisture contents did not have significantly different die temperatures, but the highest moisture content had a significantly lower die temperature. The changes in starch level did not have as significant an effect on the die temperature as the screw speed. Over all, the die temperature of puffs containing 60% starch was significantly higher than that of the puffs containing no starch, but there was not a significant change between each of the starch levels.

4.1.2 Product temperature

This temperature reading is taken in the extruder barrel immediately before the extruder die. The relationship between high-amylose corn starch, moisture content, extruder screw speed and product temperature can be seen in Table 4.1.2. Increasing the screw speed significantly increased the product temperature. Generally increasing the moisture content significantly decreased the product temperature. However, there was not a significant difference between products extruded at 18% and 20% moisture, the two lowest moisture contents. The changes in starch level did not have as significant an effect on product temperature as screw speed and moisture content. Over all, the product temperature of puffs containing 60% starch was significantly higher than that of the puffs containing no starch, but there was not a significant change between each of the starch levels.

4.1.3 Torque

The relationship between high-amylose corn starch, moisture content, extruder screw speed and torque can be seen in Table 4.1.4. The torque significantly decreased when the screw speed was increased. The torque also significantly decreased when the moisture content was increased. Both of these decreases in torque have been previously reported (Mohamed, 1990). This decrease in torque can be directly related to the fact that the viscosity of the melt inside the extruder decreases with increasing moisture content. There was not a significant difference in torque between puffs containing 0% and 20% starch. However, as starch content was increased from 20% to 40% the torque significantly increased. This increase in torque with increasing amylose content has been reported before (Kim and Maga, 1993b).

4.1.4 Specific mechanical energy

The relationship between high-amylose corn starch, moisture content, extruder screw speed and specific mechanical energy (SME) can be seen in Table 4.1.5. Increasing the screw speed significantly increased the specific mechanical energy. This data agrees with previously published material concerning corn meal (Garber et al, 1997). Increasing the moisture content significantly decreased the specific mechanical energy. Increasing the starch content significantly increased the specific mechanical energy.

4.1.5 Die pressure

The relationship between high-amylose corn starch, moisture content, extruder screw speed and die pressure can be seen in Table 4.1.6. Increasing the screw speed significantly decreased the die pressure of the extruder. Increasing the moisture content also significantly decreased the die pressure of the extruder. Both of these decreases in die pressure have been previously reported (Mohamed, 1990). This decrease in pressure can be directly related to the fact that the viscosity of the melt inside the extruder decreases with increasing moisture content (Blanche and Sun, 2004). There was not a general trend of die pressure changes with starch levels. The puffs containing 60% starch had significantly higher die pressers than the rest of the puffs. While the die pressure decreased with increasing starch levels from 0% to 40%, there was not a significant difference in die pressure between each of the three lower starch levels.

Table 4.1.1: Effects of high-amylose corn starch, moisture content, and screw speed on the die temperature (°C)

	High-amylose starch content (%)												
	0			20			40			60			
	Moisture (%)			Moisture (%)			Moisture (%)			Moisture (%)			
Screw speed (rpm)	**18%**	**20%**	**22%**	**20%**	**22%**	**24%**	**20%**	**22%**	**24%**	**20%**	**22%**	**24%**	**RPM Mean**
200	137.5	138.43	134.7	136.48	137.39	132.37	136.36	137.6	132.54	142.31	144.72	140.28	137.56^{X}
300	142.93	142.92	135.79	141.55	141.43	134.27	142.46	143.98	134.85	148.32	150.34	142.02	141.74^{Y}
400	150.02	148.75	139.85	147.74	146.83	138.28	151.01	149.08	140.72	153.99	154.58	146.2	147.25^{Z}
Mean	143.48	143.37	136.78	141.92	141.88	134.97	143.28	143.55	136.04	148.21	149.88	142.83	
Batch mean		140.07^{A}		141.90^{AB}			143.42^{B}			149.04^{C}			

At α=0.05 level, LSD=3.13. Samples with differences less than 3.13 are not significantly different. Batch mean considers only moisture contents of 20% and 22%.

Table 4.1.2: Effects of high-amylose corn starch, moisture content, and screw speed on product temperature (°C)

	High-amylose starch content (%)												
	0			20			40			60			
	Moisture (%)			Moisture (%)			Moisture (%)			Moisture (%)			
Screw speed (rpm)	**18%**	**20%**	**22%**	**20%**	**22%**	**24%**	**20%**	**22%**	**24%**	**20%**	**22%**	**24%**	**RPM Mean**
200	160.42	161.51	157.15	160.11	156.25	149.04	163.2	157.36	150.67	165.01	165.41	157.29	158.62^{X}
300	166.75	166.74	158.43	167.69	160.49	152.4	172.23	164.17	155.23	183.14	173.22	163.78	165.36^{Y}
400	175.03	173.54	163.16	176.65	170.14	161.56	180.77	173.2	165.95	187.66	183.56	173.33	173.71^{Z}
Mean	167.4	167.26	159.58	168.15	162.29	154.33	172.07	164.91	157.28	178.6	174.06	164.8	
Batch mean		163.42^{A}		165.22^{AB}			168.49^{B}			176.33^{C}			

At α=0.05 level, LSD=3.30. Samples with differences less than 3.30 are not significantly different. Batch mean considers only moisture contents of 20% and 22%.

Table 4.1.3: Effects of high-amylose corn starch, moisture content, and screw speed on torque (%)

	High-amylose starch content (%)												
	0			20			40			60			
	Moisture (%)			Moisture (%)			Moisture (%)			Moisture (%)			
Screw speed (rpm)	**18%**	**20%**	**22%**	**20%**	**22%**	**24%**	**20%**	**22%**	**24%**	**20%**	**22%**	**24%**	**RPM Mean**
200	71.93	61.84	57.56	65.06	58.17	53.83	69.83	63.04	58.94	85.03	80.38	75.88	66.79^X
300	60.59	52.2	47.54	55.15	49.06	45.15	58.97	52.4	48.31	67.96	63.54	58.25	54.93^Y
400	54	49.03	44.4	49.71	44.86	41.28	52.09	46.84	43.85	59.44	59.01	51.93	49.70^Z
Mean	62.17	54.36	49.83	56.64	50.7	46.75	60.3	54.09	50.37	70.81	67.64	62.02	
Batch mean		52.10^A		53.67^A			57.20^B			69.23^C			

At α=0.05 level, LSD=3.13. Samples with differences less than 3.13 are not significantly different. Batch mean considers only moisture contents of 20% and 22%.

Table 4.1.4: Effects of high-amylose corn starch, moisture content, and screw speed on specific mechanical energy (kJ/kg)

	High-amylose starch content (%)												
	0			20			40			60			
	Moisture (%)			Moisture (%)			Moisture (%)			Moisture (%)			
Screw speed (rpm)	**18%**	**20%**	**22%**	**20%**	**22%**	**24%**	**20%**	**22%**	**24%**	**20%**	**22%**	**24%**	**RPM Mean**
200	523.9	439.4	398.8	462.3	403.0	363.4	496.2	436.7	397.9	604.2	556.9	512.2	466.2^X
300	661.9	556.4	494.0	587.8	509.8	457.2	628.5	544.5	489.2	724.3	660.3	589.8	575.3^Y
400	786.6	696.8	615.2	706.4	621.6	557.3	740.2	649.0	592.0	844.7	817.6	701.1	694.0^Z
Mean	657.5	564.2	502.7	585.5	511.5	459.3	621.6	543.4	493.0	724.4	678.3	601.0	
Batch mean		533^A		548^A			583^B			701^C			

At α=0.05 level, LSD=33.0. Samples with differences less than 33.0 are not significantly different. Batch mean considers only moisture contents of 20% and 22%.

Table 4.1.5: Effects of high-amylose corn starch, moisture content, and screw speed on die pressure (kPa)

	High-amylose starch content (%)												
	0			20			40			60			
	Moisture (%)			Moisture (%)			Moisture (%)			Moisture (%)			
Screw speed (rpm)	**18%**	**20%**	**22%**	**20%**	**22%**	**24%**	**20%**	**22%**	**24%**	**20%**	**22%**	**24%**	**RPM Mean**
200	72.3	60.7	55.5	58.2	51.8	44.6	56.9	50.0	44.5	68.1	62.8	57.2	56.9^{X}
300	52.9	47.0	43.7	45.7	39.8	36.9	44.4	38.1	36.1	51.4	48.7	44.5	44.1^{Y}
400	40.0	37.6	37.2	36.0	32.5	30.8	34.3	30.1	28.4	38.9	39.4	35.8	35.1^{Z}
Mean	55.1	48.4	45.5	46.6	41.4	37.4	45.2	39.4	36.3	52.8	50.3	45.9	
Batch mean		47.0^{B}		44.0^{BC}			42.3^{C}			51.55^{A}			

At α=0.05 level, LSD=3.6. Samples with differences less than 3.6 are not significantly different. Batch mean considers only moisture contents of 20% and 22%.

4.1.6 Extrusion parameter correlations

The correlations between each of the extrusion parameters can be seen in Table 4.1.6.1. As expected the die and product temperatures were highly correlated. The temperatures were also correlated to the specific mechanical energy. This correlation can be explained by an increase in energy with increasing temperature. Finally, the pressure and torque were correlated because they are both dependent on the viscosity of the extrudate as described earlier.

The correlations between each of the extrusion parameters and each of the product and textural properties can be seen in Table 4.1.6.2. The pressure and torque were correlated to the expansion and width because they are all dependent on the viscosity of the extrudate. The correlation between the specific mechanical energy and the puff length can be explained by the fact that at a higher energy, the extrudate is moving through the extruder at a faster speed which therefore results in longer puffs. The specific mechanical energy was positively correlated to the specific volume and negatively correlated to the densities because of their dependence on the viscosity of the extrudate. This was also the reason that the die and product temperatures were positively correlated to length and specific volume and negatively correlated to the densities.

Table 4.1.6.1: Correlations between extrusion parameters

	Pressure	**Torque**	**SME**	**Die Temperature**	**Product Temperature**
Pressure		0.8766	-0.3551	-0.3025	-0.2732
Torque	0.8766		-0.0736	-0.0058	-0.0066
SME	-0.3551	-0.0736		0.9250	0.9420
Die Temperature	-0.3025	-0.0058	0.9250		0.9400
Product Temperature	-0.2732	-0.0066	0.9420	0.9400	

Table 4.1.6.2: Correlations between extrusion parameters and product and textural properties

	Pressure	Torque	SME	Die Temperature	Product Temperature
Expansion	0.8208	0.8860	-0.2446	0.4487	-0.1025
Length	-0.2111	0.1898	0.8683	0.8646	0.8664
Width	0.8174	0.8864	-0.2346	-0.1294	-0.0929
Per Piece Weight	0.2348	0.5974	0.3295	0.3780	0.3197
Apparent Bulk Density	-0.1887	-0.5024	-0.6965	-0.7577	-0.7670
Bulk Density	0.1467	-0.2041	-0.8035	-0.8663	-0.7931
Specific Volume	0.2574	0.5618	0.7079	0.7460	0.7787
Color: L	-0.0983	0.1101	-0.2664	-0.1494	-0.2105
Color: a	0.0324	-0.0524	0.5752	0.4793	0.5441
Color: b	0.1805	-0.2455	-0.4256	-0.4279	-0.3817
Breaking Strength	-0.5801	-0.5312	-0.0711	-0.1897	-0.1883
Hardness	-0.6110	-0.6126	-0.2165	-0.2858	-0.3645

4.2 Product Properties

Shown below are views of the whole products and their cross sections in Figures 4.2.1 – 4.2.8:

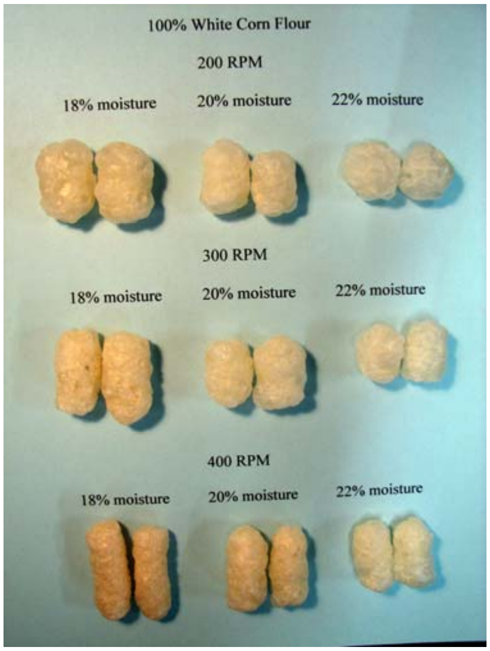

Figure 4.2.1: Puffs containing 0% high-amylose corn starch

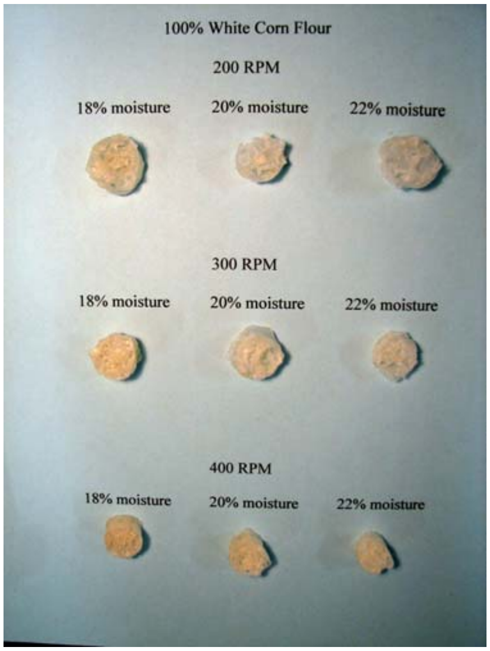

Figure 4.2.2: Cross sections of puffs containing 0% high-amylose corn starch

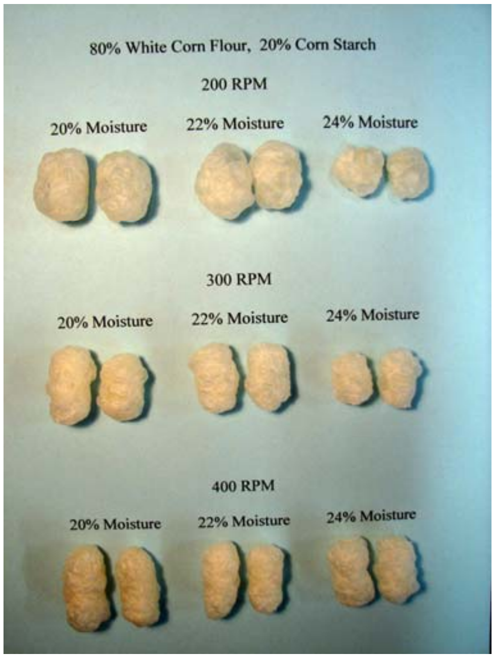

Figure 4.2.3: Puffs containing 20% high-amylose corn starch

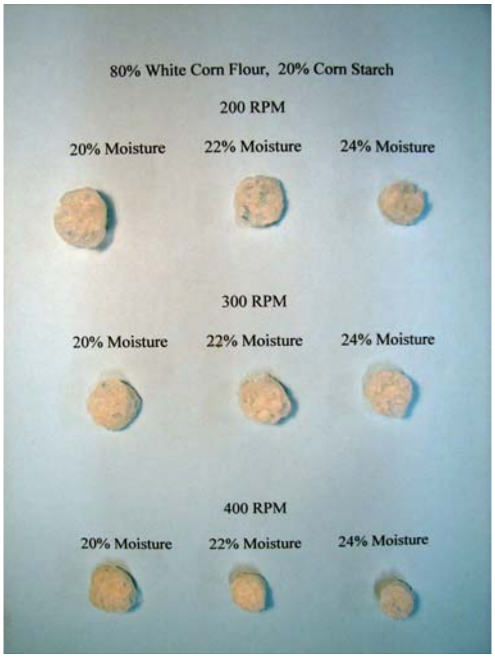

Figure 4.2.4: Cross sections of puffs containing 20% high-amylose corn starch

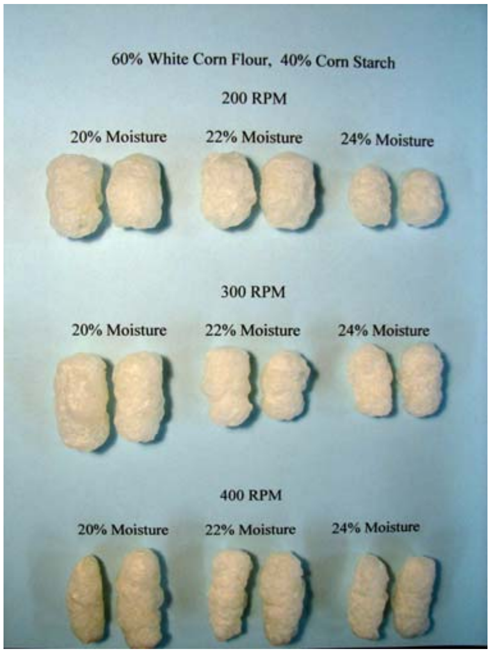

Figure 4.2.5: Puffs containing 40% high-amylose corn starch

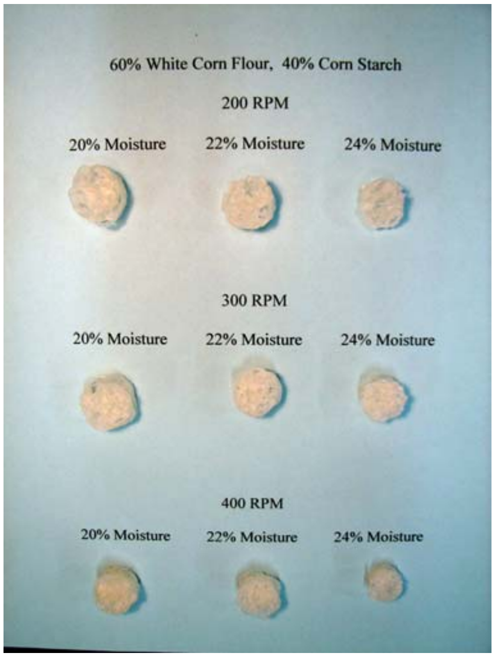

Figure 4.2.6: Cross sections of puffs containing 40% high-amylose corn starch

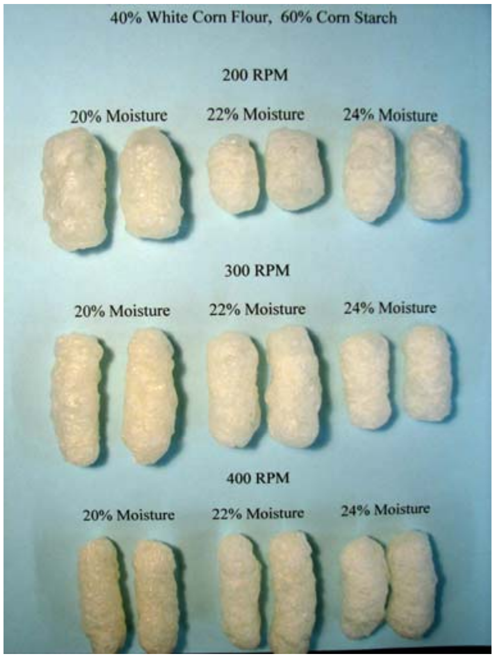

Figure 4.2.7: Puffs containing 60% high-amylose corn starch

Figure 4.2.8: Cross sections of puffs containing 60% high-amylose corn starch

4.2.1 Length and width

The relationship between high-amylose corn starch, moisture content, extruder screw speed and length can be seen in Table 4.2.1 and width in Table 4.2.2. Puffs that were extruded at a higher screw speed were significantly longer in length and narrower in width, which results in a lower bulk density (Mulvaney et al, 1992). There was a greater difference in length between puffs extruded at 300 and 400 rpm than puffs extruded at 200 and 300 rpm. The width of the puffs did not always change significantly between screw speeds, but the puffs extruded at 400 rpm were significantly narrower in width than those extruded at 200 rpm for each of the moisture contents and starch levels. Increasing the moisture content decreased the length of the extruded product; however there was not a consistent significant effect on the width. The puffs containing 20% and 40% starch did show a significant decrease in width with increased moisture content. Increasing the starch content of the puffs significantly increased the puff length; however, there was not a consistent significant effect on the width.

4.2.2 Expansion

The relationship between high-amylose corn starch, moisture content, extruder screw speed and expansion can be seen in Table 4.2.3. The puffed product showed a significant decrease in expansion when extruded at a higher screw speed. Only the products containing 20% and 40% starch showed a significant decrease in expansion with increased moisture content. Similar results were found in expanded corn starch (Chinnaswamy and Hanna, 1988), extruded corn grits (Gujral et al, 2001), expanded rice products (Ding et al, 2005) and expanded wheat-based snacks (Ding et al, 2006). This decrease in expansion is related to the decreased viscosity at higher moisture contents which results in decreased torque and die pressure (Blanche and Sun, 2004). The products with higher initial moisture contents had less structural integrity and therefore suffered from a greater degree of collapse because they could not hold their shape as well as the puffs with lower moisture contents (Kim and Maga, 1993a). Similar results were found in extruded cowpea meal (Phillips et al, 1984), corn grits (Mohamed, 1990) and cornstarch (Blanche and Sun, 2004). The puffs containing 0% and 60% starch did not show a significant change with moisture contents. The puffs containing 60% starch expanded a significant amount more than puffs containing no starch. This data supports reports that pure starch produces the best expansion (Colonna et al, 1989). However there was not a significant difference in expansion between the two intermediate starch levels, 20% and 40% starch. Previously reported sources have also pointed out that the moisture content has a greater effect on the product expansion than the ratio of amylose to amylopectin (Harper and Tribelhorn, 1992).

4.2.3 Per piece weight

The relationship between high-amylose corn starch, moisture content, extruder screw speed and per piece weight can be seen in Table 4.2.4. The changes of screw speed and moisture content did not significantly effect the per piece weight of the samples. The puffs containing 60% starch were significantly heavier than the puffs containing less starch, but there was not a significant difference in weight between the puffs containing 0%, 20%, and 40% starch.

4.2.4 Bulk density

The relationship between high-amylose corn starch, moisture content, extruder screw speed and bulk density can be seen in Table 4.2.5. Increasing the screw speed significantly decreased the bulk density of the product. Generally, increasing the moisture content of the puffs significantly increased the bulk density. Similar results were found in expanded wheat-based snacks (Ding et al, 2006). Changing the starch levels of the products had a more complex effect on the bulk density of the products. Puffs extruded at 22% moisture content had bulk densities that significantly decreased with increasing starch level which supports previous reports (Nabar and Narayan, 2006). However, puffs extruded at 20% moisture content only showed a significant decrease in bulk density with starch levels increasing from 20% to 40% starch. Previous reports have pointed out that the bulk density decreases as the product expansion increases (Blanche and Sun, 2004); these results agree with this claim as the amylose and moisture content are changed, however the bulk density and expansion both decrease with increasing screw speed.

4.2.5 Apparent bulk density

The relationship between high-amylose corn starch, moisture content, extruder screw speed and apparent bulk density can be seen in Table 4.2.6. Generally puffs extruded at 200 rpm had a significantly higher apparent bulk density than those extruded at 400 rpm. However for puffs containing 20% moisture content at starch levels of 20% and 40% there was not a significant change in apparent bulk density between the extreme screw speeds. Increasing the moisture content significantly increased the apparent bulk density of the puffs. However, this was not the case for each of the moisture contents in samples containing 60% starch. For these puffs, there was not a significant difference between 18% and 20% moisture; however the puffs containing 22% moisture did have a significantly higher apparent bulk density. There was a significant decrease in apparent bulk density with each increased starch level.

4.2.6 Specific volume

The relationship between high-amylose corn starch, moisture content, extruder screw speed and specific volume can be seen in Table 4.2.7. Increasing the screw speed did not have a consistent effect on the specific volume in the puffs containing 0% and 20% starch. However, as the screw speed was increased for the puffs containing 40% and 60% starch the specific volume significantly increased. Increasing the moisture content of the product significantly decreased the specific volume. Similar results have previously been reported (Wu et al, 2007; Liu et al, 2000). Increasing the starch content of the puffs significantly increased the specific volume.

4.2.7 Color

4.2.7.1 *Lightness (L)*

The relationship between high-amylose corn starch, moisture content, extruder screw speed and lightness can be seen in Table 4.2.8. Increasing the screw speed only had a significant effect on the lightness of the puffs at the two lowest moisture contents (18% and 20%). At these lower moisture contents, puffs extruded at 200 rpm were lighter than puffs extruded at 400 rpm. However at the higher moisture contents (22% and 24%), there was no significant difference between the screw speed levels. The puffs containing no starch showed a significant increase in lightness with increasing moisture content. The puffs containing the three different starch levels only showed a significant increase in lightness with increasing moisture content at 400 rpm. Generally, increasing the starch level significantly increased the puff lightness.

4.2.7.2 *Redness (a)*

The relationship between high-amylose corn starch, moisture content, extruder screw speed and red/green (*a*) color can be seen in Table 4.2.9. Increasing the screw speed significantly increased the intensity of red and decreased that of green. The intensity of red decreased and green significantly increased as the moisture content increased. Similar results were previously reported (Liu et al, 2000). Generally, increasing the starch level significantly decreased the intensity of red and increased that of green color with the exception of the puffs containing 60% starch.

4.2.7.3 *Yellowness (b)*

The relationship between high-amylose corn starch, moisture content, extruder screw speed and yellow/blue (*b*) color can be seen in Table 4.2.10. All of the extruded puffs had a positive *b* value, meaning they all had a yellow rather than blue color. It can be seen that changing the screw speed and the moisture content of the product did not significantly affect the intensity of this yellow color. Similar results were previously reported (Wu et al, 2007). However, increasing the starch level did significantly decrease the intensity of the yellow color.

Table 4.2.1: Effects of high-amylose corn starch, moisture content and screw speed on puff length(mm)

	High-amylose starch content (%)												
	0			20			40			60			
	Moisture (%)			Moisture (%)			Moisture (%)			Moisture (%)			
Screw speed (rpm)	18%	20%	22%	20%	22%	24%	20%	22%	24%	20%	22%	24%	RPM Mean
200	22.37	21.22	19.56	24.03	22.49	18.84	28.01	26.03	22.28	32.61	33.77	31.78	24.66^{X}
300	28.15	22.75	19.83	27.35	23.27	20.83	30.90	28.38	25.06	39.96	35.24	33.50	27.43^{Y}
400	36.49	29.91	23.68	32.19	28.80	24.98	37.70	34.04	30.17	51.42	47.15	40.37	34.23^{Z}
Mean	29.00	24.63	21.02	27.86	24.85	21.55	32.20	29.48	25.84	41.33	38.72	35.22	
Batch mean		22.83^{A}		26.36^{B}			30.84^{C}			40.03^{D}			

At α=0.05 level, LSD = 2.15mm. Samples with differences less than 2.15mm are not significantly different. Batch mean considers only moisture contents of 20% and 22%.

Table 4.2.2: Effects of high-amylose corn starch, moisture content, and screw speed on puff width(mm)

	High-amylose starch content (%)												
	0			20			40			60			
	Moisture (%)			Moisture (%)			Moisture (%)			Moisture (%)			
Screw speed (rpm)	18%	20%	22%	20%	22%	24%	20%	22%	24%	20%	22%	24%	RPM Mean
200	17.23	17.15	15.92	18.15	17.76	15.42	18.67	17.3	15.3	18.77	18.87	18.41	17.41^{X}
300	15.51	15.22	15.15	16.71	14.77	14.95	16.76	15.16	14.66	17.71	16.79	16.83	15.85^{Y}
400	13.53	13.87	13.29	15.03	14.34	13.51	14.93	14.62	13.26	15.54	16.22	16.26	14.53^{Y}
Mean	15.42	15.41	14.79	16.63	15.62	14.63	16.79	15.69	14.41	17.34	17.29	17.17	
Batch mean		15.10^{A}		16.13^{AB}			16.24^{AB}			17.32^{B}			

At α=0.05 level, LSD=1.36mm. Samples with differences less than 1.36mm are not significantly different. Batch mean considers only moisture contents of 20% and 22%.

Table 4.2.3: Effects of high-amylose corn starch, moisture content, and screw speed on puff expansion

	High-amylose starch content (%)												
	0			20			40			60			
	Moisture (%)			Moisture (%)			Moisture (%)			Moisture (%)			
Screw speed (rpm)	**18%**	**20%**	**22%**	**20%**	**22%**	**24%**	**20%**	**22%**	**24%**	**20%**	**22%**	**24%**	**RPM Mean**
200	5.418	5.393	5.007	5.708	5.586	4.850	5.872	5.439	4.811	5.904	5.934	5.789	5.476^{X}
300	4.879	4.787	4.764	5.256	4.645	4.702	5.269	4.769	4.609	5.568	5.280	5.292	4.985^{Y}
400	4.256	4.363	4.180	4.727	4.509	4.249	4.694	4.597	4.171	4.888	5.010	5.113	4.563^{Y}
Mean	4.851	4.848	4.650	5.230	4.913	4.600	5.278	4.935	4.530	5.453	5.408	5.398	
Batch mean		4.749^{A}		5.072^{AB}			5.107^{AB}			5.431^{B}			

At α=0.05 level, LSD=0.425. Samples with differences less than 0.425 are not significantly different. Batch mean considers only moisture contents of 20% and 22%.

Table 4.2.4: Effects of high-amylose corn starch, moisture content, and screw speed on per piece weight (g)

	High-amylose starch content (%)												
	0			20			40			60			
	Moisture (%)			Moisture (%)			Moisture (%)			Moisture (%)			
Screw speed (rpm)	**18%**	**20%**	**22%**	**20%**	**22%**	**24%**	**20%**	**22%**	**24%**	**20%**	**22%**	**24%**	**RPM Mean**
200	0.2763	0.2607	0.2567	0.2683	0.2723	0.272	0.2733	0.2763	0.2943	0.335	0.351	0.3547	0.2909^{X}
300	0.2587	0.2453	0.2433	0.258	0.2607	0.277	0.2793	0.2733	0.2807	0.335	0.331	0.3187	0.2801^{X}
400	0.2673	0.2543	0.244	0.2613	0.2607	0.2643	0.2793	0.2753	0.272	0.3407	0.3337	0.3457	0.2832^{X}
Mean	0.2674	0.2534	0.248	0.2625	0.2646	0.2711	0.2773	0.275	0.2823	0.3369	0.3386	0.3397	
Batch mean		0.2507^{A}		0.2636^{A}			0.2761^{A}			0.3377^{B}			

At α=0.05 level, LSD=0.0280. Samples with differences less than 0.0280 are not significantly different. Batch mean considers only moisture contents of 20% and 22%.

Table 4.2.5: Effects of high-amylose corn starch, moisture content, and screw speed on bulk density (g/mL)

	High-amylose starch content (%)												
	0			20			40			60			
	Moisture (%)			Moisture (%)			Moisture (%)			Moisture (%)			
Screw speed (rpm)	**18%**	**20%**	**22%**	**20%**	**22%**	**24%**	**20%**	**22%**	**24%**	**20%**	**22%**	**24%**	**RPM Mean**
200	0.4552	0.4668	0.566	0.4703	0.4775	0.5718	0.3863	0.406	0.489	0.3092	0.2985	0.3602	0.4381^{X}
300	0.3615	0.3185	0.5102	0.386	0.4188	0.4967	0.356	0.34	0.4298	0.3062	0.157	0.3033	0.3653^{Y}
400	0.3043	0.2993	0.4673	0.3328	0.3942	0.4362	0.2897	0.3195	0.364	0.2538	0.2593	0.278	0.3332^{Y}
Mean	0.3737	0.3615	0.5145	0.3964	0.4302	0.5016	0.344	0.3552	0.4276	0.2897	0.2383	0.3138	
Batch mean		0.4380^{A}		0.4133^{A}			0.3496^{B}			0.2640^{C}			

At α=0.05 level, LSD=0.0586. Samples with differences less than 0.0586 are not significantly different. Batch mean considers only moisture contents of 20% and 22.

Table 4.2.6: Effects of high-amylose corn starch, moisture content, and screw speed on apparent bulk density (g/L)

	High-amylose starch content (%)												
	0			20			40			60			
	Moisture (%)			Moisture (%)			Moisture (%)			Moisture (%)			
Screw speed (rpm)	**18%**	**20%**	**22%**	**20%**	**22%**	**24%**	**20%**	**22%**	**24%**	**20%**	**22%**	**24%**	**RPM Mean**
200	39.10	45.13	56.42	35.99	45.87	71.16	30.93	38.97	55.59	26.06	26.18	33.56	42.08^{X}
300	36.19	46.20	55.97	34.13	47.31	63.66	28.10	36.95	53.04	23.26	24.75	31.90	40.12^{X}
400	33.72	41.22	52.13	34.26	34.45	60.52	28.01	35.51	47.40	20.57	22.04	27.75	36.47^{Y}
Mean	36.34	44.18	54.84	34.79	42.54	65.11	29.01	37.14	52.01	23.30	24.32	31.07	
Batch mean		49.51^{A}		38.67^{B}			33.08^{C}			23.81^{D}			

At α=0.05 level, LSD=3.27. Samples with differences less than 3.27 are not significantly different. Batch mean considers only moisture contents of 20% and 22%.

Table 4.2.7: Effects of high-amylose corn starch, moisture content, and screw speed on specific volume (mL/g)

	High-amylose starch content (%)												
	0			20			40			60			
	Moisture (%)			Moisture (%)			Moisture (%)			Moisture (%)			
Screw speed (rpm)	**18%**	**20%**	**22%**	**20%**	**22%**	**24%**	**20%**	**22%**	**24%**	**20%**	**22%**	**24%**	**RPM Mean**
200	23.88	21.66	17.87	24.8	20.78	14.85	26.75	22.29	16.77	29.66	29.47	24.47	22.77^{X}
300	24.35	21.19	18.82	24.52	19.93	15.91	27.33	22.99	17.62	31.38	30.19	25.16	23.28^{XY}
400	25.65	22.97	19.79	24.03	20.63	16.39	27.49	24.02	18.44	33.87	31.52	27.98	24.40^{Y}
Mean	24.63	21.94	18.83	24.45	20.45	15.72	27.19	23.1	17.61	31.64	30.4	25.87	
Batch mean		20.38^{A}		22.45^{B}			25.15^{C}			31.02^{D}			

At α=0.05 level, LSD=1.60. Samples with differences less than 1.60 are not significantly different. Batch mean considers only moisture contents of 20% and 22%.

Table 4.2.8: Effects of high-amylose corn starch, moisture content, and screw speed on color (L)

	High-amylose starch content (%)												
	0			20			40			60			
	Moisture (%)			Moisture (%)			Moisture (%)			Moisture (%)			
Screw speed (rpm)	**18%**	**20%**	**22%**	**20%**	**22%**	**24%**	**20%**	**22%**	**24%**	**20%**	**22%**	**24%**	**RPM Mean**
200	75.47	78.26	79.4	80.75	81.18	79.96	81.6	82.37	81.78	82.22	83.72	82.94	80.80^{X}
300	74.45	78.03	79.74	79.81	82.59	80.63	80.8	83.56	82.79	80.83	82.75	83.78	80.81^{X}
400	73.04	75.6	79.2	77.68	81.03	81.27	78.35	82.16	83.12	79.04	81.58	83.42	79.62^{Y}
Mean	74.32	77.3	79.45	79.41	81.6	80.62	80.25	82.7	82.56	80.7	82.68	83.38	
Batch mean		78.37^{A}		80.51^{B}			81.47^{BC}			81.69^{C}			

At α=0.05 level, LSD=1.13. Samples with differences less than 1.13 are not significantly different. Batch mean considers only moisture contents of 20% and 22%.

Table 4.2.9: Effects of high-amylose corn starch, moisture content, and screw speed on color (a)

	High-amylose starch content (%)												
	0			20			40			60			
	Moisture (%)			Moisture (%)			Moisture (%)			Moisture (%)			
Screw speed (rpm)	**18%**	**20%**	**22%**	**20%**	**22%**	**24%**	**20%**	**22%**	**24%**	**20%**	**22%**	**24%**	**RPM Mean**
200	2.792	1.251	0.154	0.566	-0.017	-0.443	0.083	-0.523	-0.688	0.247	-0.510	-0.678	0.186^{X}
300	3.315	1.708	0.380	1.228	0.185	-0.394	1.008	-0.237	-0.554	1.238	-0.130	-0.761	0.582^{Y}
400	3.722	2.773	1.180	2.092	0.831	-0.127	1.933	0.517	-0.348	2.061	1.070	-0.285	1.285^{Z}
Mean	3.276	1.911	0.571	1.295	0.333	-0.321	1.008	-0.081	-0.530	1.182	0.143	-0.575	
Batch mean		1.241^{A}		0.814^{B}			0.464^{C}			0.663^{BC}			

At α=0.05 level, LSD=0.233. Samples with differences less than 0.233 are not significantly different. Batch mean considers only moisture contents of 20% and 22%.

Table 4.2.10: Effects of high-amylose corn starch, moisture content, and screw speed on color (b)

	High-amylose starch content (%)												
	0			20			40			60			
	Moisture (%)			Moisture (%)			Moisture (%)			Moisture (%)			
Screw speed (rpm)	**18%**	**20%**	**22%**	**20%**	**22%**	**24%**	**20%**	**22%**	**24%**	**20%**	**22%**	**24%**	**RPM Mean**
200	15.865	15.820	15.338	14.899	14.760	14.859	14.216	14.069	14.633	13.603	13.537	13.578	14.598^{X}
300	14.964	16.174	15.378	14.938	15.012	14.343	14.043	14.278	13.843	13.684	13.132	13.116	14.409^{X}
400	14.416	15.054	15.444	14.800	14.741	14.370	13.906	14.238	13.908	13.303	13.340	12.821	14.195^{X}
Mean	15.082	15.683	15.387	14.879	14.838	14.524	14.055	14.195	14.128	13.530	13.336	13.172	
Batch mean		15.535^{A}		14.858^{B}			14.125^{C}			13.433^{D}			

At α=0.05 level, LSD=0.462. Samples with differences less than 0.462 are not significantly different. Batch mean considers only moisture contents of 20% and 22%.

4.2.8 Product property correlations

The correlations between each of the product and textural properties can be seen in Table 4.2.8.1 and Table 4.2.8.2. The expansion was highly correlated to the width because the width was used to calculate the expansion. The length was positively correlated to the specific volume and negatively correlated to the densities because there was more variation in puff length than per piece weight. For this reason the per piece weight was not as strongly correlated to the specific volume and densities. The apparent bulk density and bulk density were highly correlated to each other as expected and inversely correlated to the specific volume because the densities are a measure of mass per unit volume while the specific volume is a measure of volume per unit mass. The puff color lightness was highly correlated to the greenness in color. The blueness in color was highly correlated to the length and per piece weight. Finally the textural properties, breaking strength and hardness, were correlated to each other. They were also positively correlated to the apparent bulk density and negatively correlated to the expansion, width and specific volume as expected. These properties were correlated because the puffs with more expansion and therefore lower density were easier to mechanically crush or cut.

Table 4.2.8.1: Correlations between product and textural properties

	Expansion	Length	Width	Per Piece Weight	Apparent Bulk Density	Bulk Density
Expansion		0.0736	0.9996	0.5215	-0.4433	-0.0831
Length	0.0736		0.0855	0.6839	-0.8112	-0.8341
Width	0.9996	0.0855		0.5289	-0.4502	-0.0896
Per Piece Weight	0.5215	0.6839	0.5289		-0.5922	-0.5590
Apparent Bulk Density	-0.4433	-0.8112	-0.4502	-0.5922		0.8257
Bulk Density	-0.0831	-0.8341	-0.0896	-0.5590	0.8257	
Specific Volume	0.4809	0.8411	0.4891	0.6630	-0.9524	-0.7992
Color: L	0.3005	0.0831	0.3030	0.4746	-0.0692	-0.0829
Color: a	-0.2559	0.2349	-0.2545	-0.3031	-0.2830	-0.2421
Color: b	-0.2388	-0.7336	-0.2455	-0.8216	0.5512	0.6197
Breaking Strength	-0.5613	-0.0128	-0.5634	0.0061	0.5042	0.2198
Hardness	-0.5924	-0.2171	-0.5942	-0.0965	0.6280	0.3134

Table 4.2.8.2: Correlations between product and textural properties (continued)

	Specific Volume	Color: L	Color: a	Color: b	Breaking Strength	Hardness
Expansion	0.4809	0.3005	-0.2559	-0.2388	-0.5613	-0.5924
Length	0.8411	0.0831	0.2349	-0.7336	-0.0128	-0.2171
Width	0.4891	0.3030	-0.2545	-0.2455	-0.5634	-0.5942
Per Piece Weight	0.6630	0.4746	-0.3031	-0.8216	0.0061	-0.0965
Apparent Bulk Density	-0.9524	-0.0692	-0.2830	0.5512	0.5042	0.6280
Bulk Density	-0.7992	-0.0829	-0.2421	0.6197	0.2198	0.3134
Specific Volume		0.0200	0.3017	-0.5605	-0.4383	-0.6282
Color: L	0.0200		-0.9090	-0.5756	0.2006	0.2570
Color: a	0.3017	-0.9090		0.3840	-0.3192	-0.4248
Color: b	-0.5605	-0.5756	0.3840		-0.1841	-0.1379
Breaking Strength	-0.4383	0.2006	-0.3192	-0.1841		0.8111
Hardness	-0.6282	0.2570	-0.4248	-0.1379	0.8111	

4.3 Texture Profile Analysis

4.3.1 Breaking strength

The relationship between high-amylose corn starch, moisture content, extruder screw speed and breaking strength can be seen in Table 4.3.1. Changing the screw speed and starch level did not have a significant effect on the breaking strength of the puffs. The puffs containing 24% moisture had significantly higher breaking strengths than those extruded at 20% and 22% moisture for puffs containing 20% and 40% starch. However, for the puffs containing 0% and 60% starch, there was not a significant difference in breaking strength for varying moisture contents. Note that the data for puffs extruded at 400 rpm, containing 60% starch and 20% moisture appeared unusually high, but was confirmed by multiple samples.

4.3.2 Hardness

The relationship between high-amylose corn starch, moisture content, extruder screw speed and hardness can be seen in Table 4.3.2. Changing the screw speed and starch level did not have a significant effect on the hardness of the puffs. The puffs containing 20% and 40% starch showed significant increases in hardness with increasing moisture content. Similar results were found in expanded rice products (Ding et al, 2005), expanded wheat-based snacks (Ding et al, 2006), and wheat flour and whole cornmeal extrudates (Ryu and Ng, 2001). This increase in hardness may be a result of decreased expansion at the higher moisture contents (Liu et al, 2000). The puffs containing 24% moisture had significantly higher hardness than those extruded at 20%

and 22% moisture for puffs containing 60% starch. However, the puffs containing 0% starch showed no significant difference in hardness for varying moisture contents.

Table 4.3.1: Effects of high-amylose corn starch, moisture content, and screw speed on breaking strength (g/mm^2)

	High-amylose starch content (%)												
	0			20			40			60			
	Moisture (%)			Moisture (%)			Moisture (%)			Moisture (%)			
Screw speed (rpm)	**18%**	**20%**	**22%**	**20%**	**22%**	**24%**	**20%**	**22%**	**24%**	**20%**	**22%**	**24%**	**RPM Mean**
200	4.39	5.53	9.51	4.35	6.75	18.17	3.98	7.14	20.09	4.58	5.13	7.65	8.11^{X}
300	5.85	6.52	12.76	5.32	9.70	20.73	5.45	12.25	21.48	5.29	7.40	11.33	10.34^{X}
400	8.26	8.37	11.12	6.45	10.66	25.01	8.09	9.96	19.01	26.01	7.40	12.22	12.71^{X}
Mean	6.17	6.81	11.13	5.37	9.04	21.30	5.84	9.79	20.19	11.96	6.64	10.40	
Batch mean		8.97^{A}		7.21^{A}			7.81^{A}			9.30^{A}			

At α=0.05 level, LSD=7.58. Samples with differences less than 7.58 are not significantly different. Batch mean considers only moisture contents of 20% and 22%.

Table 4.3.2: Effects of high-amylose corn starch, moisture content, and screw speed on hardness (g)

	High-amylose starch content (%)												
	0			20			40			60			
	Moisture (%)			Moisture (%)			Moisture (%)			Moisture (%)			
Screw speed (rpm)	**18%**	**20%**	**22%**	**20%**	**22%**	**24%**	**20%**	**22%**	**24%**	**20%**	**22%**	**24%**	**RPM Mean**
200	1460	1502	2219	1174	1755	3064	1126	1897	2627	1572	1432	2019	1821^{X}
300	1468	1549	2225	1438	2374	3909	1730	2634	3362	1678	1826	2278	2206^{X}
400	2218	1961	2024	1849	2546	3100	1764	2175	2777	1966	1795	2447	2219^{X}
Mean	1715	1671	2156	1487	2225	3358	1540	2235	2922	1739	1684	2248	
Batch mean		1913^{A}		1856^{A}			1888^{A}			1712^{A}			

At α=0.05 level, LSD=491. Samples with differences less than 491 are not significantly different. Batch mean considers only moisture contents of 20% and 22%.

4.4 Controlled Water Activity Analysis

4.4.1 Equilibrated moisture content

Isotherms illustrate the relationship between water activity and equilibrated moisture content. Figure 4.4.1 shows that the high-amylose starch content did not have a significant effect on the equilibrated moisture content. This indicates that at the tested parameters, high-amylose starch content did not have an effect on the degree to which the puffs adsorbed water.

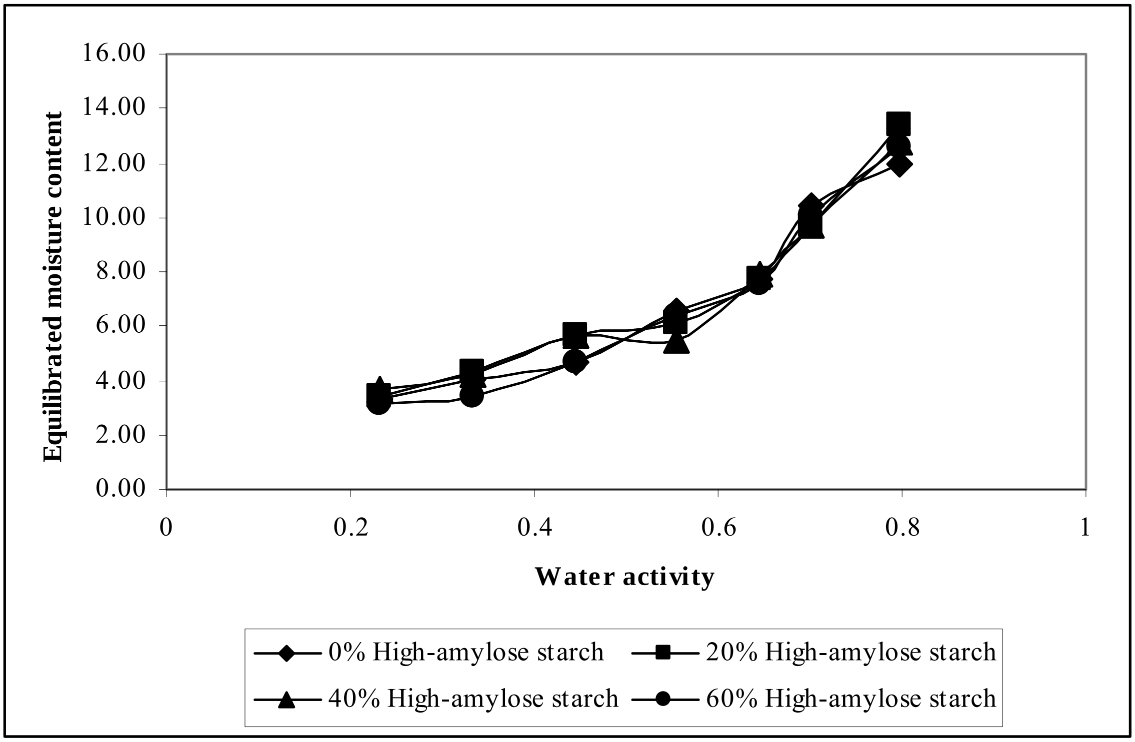

Figure 4.4.1: Isotherms as a function of high-amylose starch content

4.4.2 Breaking strength

The relationship between high-amylose corn starch, water activity (a_w) and breaking strength can be seen in Table 4.4.2 and Figure 4.4.2. For a_w above 0.446, increasing the starch content of the puffs significantly increased the breaking strength, however there was not a significant difference between puffs containing 0% and 20% starch. For a_w below 0.446, increasing the starch content of the puffs had no significant effect on the breaking strength. There was not a significant difference in breaking strength between the two lowest a_w. The breaking strength significantly increased with increased a_w and reached a peak at a_w of 0.555 or 0.646 and then significantly decreased with continued increases in a_w. The lowest breaking strengths of the puffs at the maximum a_w were still higher than the breaking strengths at the two lowest a_w. Puffed rice cakes have been found to undergo a dramatic change in texture between a_w of 0.44 and 0.57 (Hsieh et al, 1990a). For the four highest water activities it seems intuitive that as the puffs absorb more water, they become more 'soggy' and thus the breaking strength decreases. It is also important to note another reason for this change in texture, as the water activity increases, the puffs get closer to their glass transition temperature as seen in Figure 4.4.4.

4.4.3 Hardness

The relationship between high-amylose corn starch, water activity (a_w) and hardness can be seen in Table 4.4.3 and Figure 4.4.3. There was not a consistent significant change in hardness with changing starch content. Several of the mid-range a_w showed higher hardness at 20% and 40% starch, but this trend did not exist for all the a_w. There hardness generally significantly increased with increasing a_w and reached a peak at a_w of 0.555 or 0.646 and then significantly decreased with continued increases in a_w. Though there was not a significant difference between each of the water activities, this trend generally applied to each of the starch levels. The most likely explanation for why the breaking strength exhibited a clearer trend between texture and a_w is that the puffs must be compressed twice to measure hardness. For this reason, hardness is not as good a measure of texture in products that are crunchy (snack products) as those that are softer (meat products).

Table 4.4.2: Effects of high-amylose corn starch and water activity on breaking strength

	Starch content (%)				
Water Activity (Aw)	0	20	40	60	Mean
0.233	7.35	9.75	8.71	7.55	8.34^{V}
0.334	8.31	10.89	10.81	8.85	9.71^{V}
0.446	10.23	13.57	18.07	43.83	21.42^{W}
0.555	22.31	33.56	49.62	60.42	41.48^{Y}
0.646	23.90	29.45	44.17	55.53	38.26^{Y}
0.702	22.37	22.77	41.66	49.92	34.18^{XY}
0.797	19.70	22.95	34.36	40.38	29.35^{X}
Mean	16.31^{A}	20.42^{A}	29.63^{B}	38.07^{C}	

At α=0.05 level, LSD=7.77. Samples with differences less than 7.77 are not significantly different.

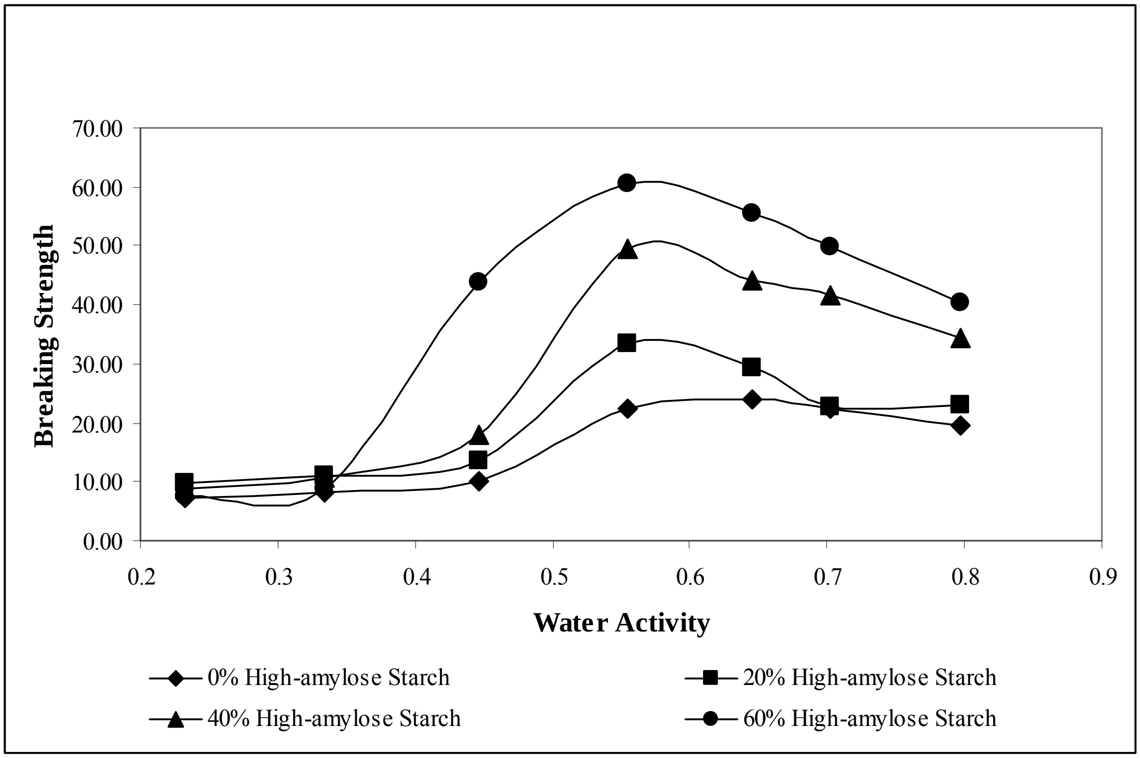

Figure 4.4.2: Effects of high-amylose corn starch and water activity on breaking strength

Table 4.4.3: Effects of high-amylose corn starch and water activity on hardness

	Starch content (%)				
Water Activity (Aw)	0	20	40	60	Mean
0.233	1249	1855	2220	1752	1769^{VW}
0.334	1797	2179	1926	2140	2011^{VWX}
0.446	1719	2947	2746	2054	2366^{X}
0.555	2444	2717	2417	1733	2328^{WX}
0.646	2360	2555	2568	1783	2316^{WX}
0.702	2382	1727	1760	1516	1846^{VWX}
0.797	1909	1676	1836	1329	1687^{V}
Mean	1980^{A}	2236^{A}	2211^{A}	1758^{A}	

At α=0.05 level, LSD=591. Samples with differences less than 591 are not significantly different.

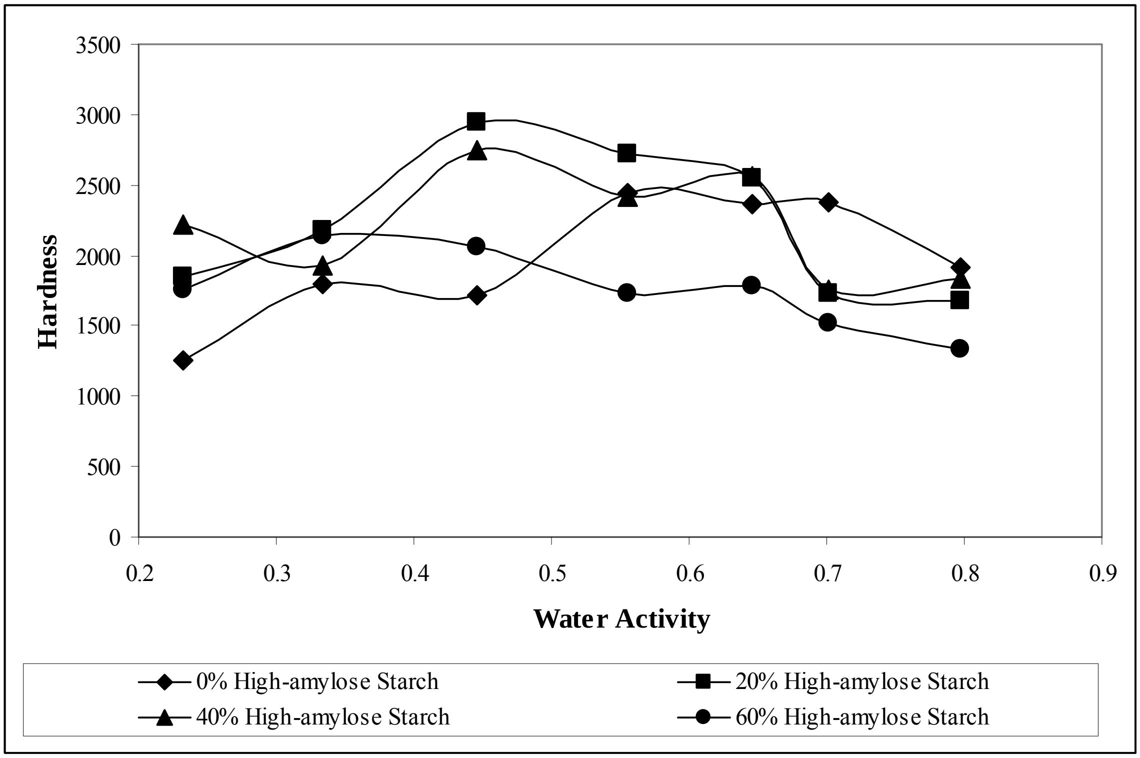

Figure 4.4.3: Effects of high-amylose corn starch and water activity on hardness

4.4.4 <u>Glass transition</u>

In order to use the Gordon-Taylor equation, the equilibrated moisture contents rather than the water activities were used in calculations and therefore reported below. The relationship between equilibrated moisture content and glass transition temperature, along with the Gordon-Taylor equation goodness-of-fit can be seen in Table 4.4.4 and Figure 4.4.4. Increases in water activity, and corresponding equilibrated moisture content decreased the glass transition temperature of the ground samples. Similar decreases in glass transition temperature with increased water activity have previously been reported in native and gelatinized rice starches (Chung et al, 2002; Bindzus et al, 2002; Chen and Yeh, 2001; Chen and Yeh, 2000). The high-amylose starch content had no significant effect on the glass transition temperature. The Gordon-Taylor predicted k-value was calculated to be 2.86. At an $\alpha = 0.04$ level, there is not a significant difference between the measured and Gordon-Taylor predicted glass transition temperatures. Similar k-values have been reported for yellow (2.58) and white (2.39) corn cakes made of cracked dent corns (Li et al, 1998).

Table 4.4.4: Effects of equilibrated moisture content on glass transition temperature and Gordon-Taylor equation goodness-of-fit

Equilibrated Moisture Content	Glass Transition Temperature	Predicted Glass Transition Temperature
0.0000	124.77	N/A
0.0341	104.09	100.95
0.0400	96.06	97.11
0.0517	86.95	89.73
0.0614	78.24	83.83
0.0772	57.37	74.62
0.0996	50.21	62.34
0.1267	50.92	48.59

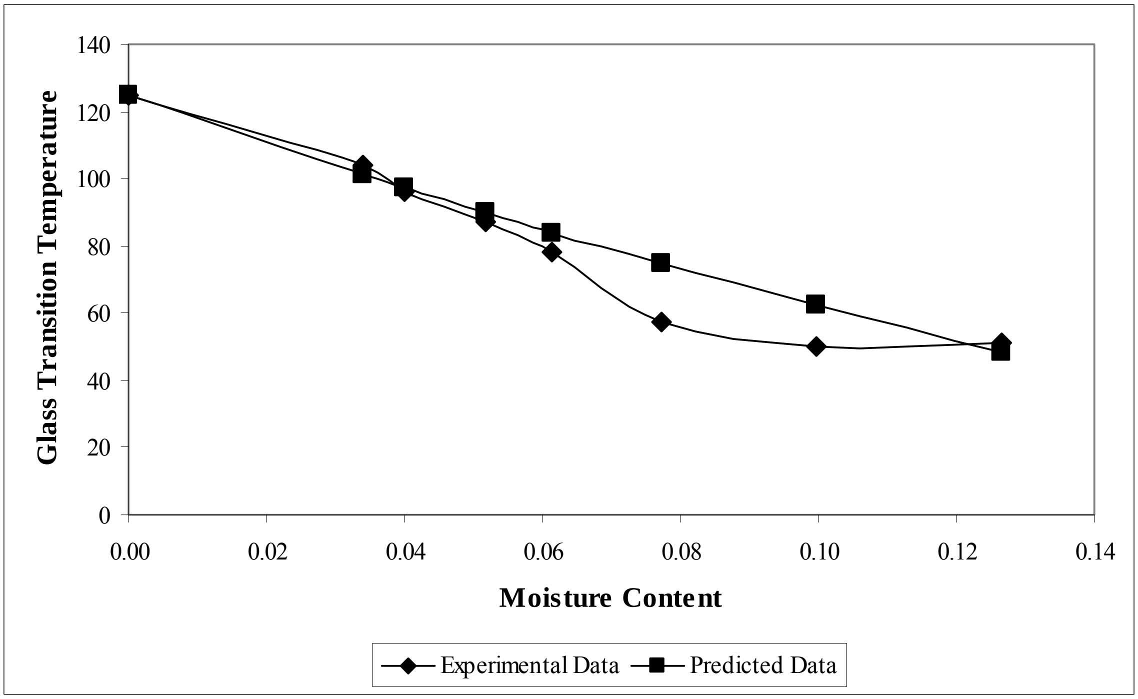

Figure 4.4.4: Effects of equilibrated moisture content on glass transition temperature

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

1. The collected results indicate that the maximum amount of expansion occurs when the screw speed and moisture content are both decreased and the high-amylose corn starch content is increased.

2. As expected, the high-amylose starch content did not have a significant effect on the texture analysis of the puffs at their original extruded water activities. However, the puffs containing more high-amylose corn starch exhibited significantly higher breaking strengths at higher water activities.

3. The Gordon-Taylor equation was applied to the experimental glass transition temperature data and a k-value of 2.86 was calculated. This k-value predicted data that was not significantly different than the measured glass transition temperatures. As previously reported, increasing the water activity decreased the glass transition temperature.

4. Increases in the extruder screw speed corresponded with the following significant changes in the extrusion parameters and product properties:

   - Increases in die temperature, product temperature, specific mechanical energy, puff length, specific volume and redness
   - Decreases in torque, die pressure, puff width, expansion, bulk density, apparent bulk density and lightness

5. Increases in the moisture content corresponded with the following significant changes in the extrusion parameters and product properties:

- Increases in bulk density, apparent bulk density, lightness, breaking strength and hardness
- Decreases in die temperature, product temperature, torque, specific mechanical energy, die pressure, puff length, expansion, specific volume and redness

6. Increases in the high-amylose starch content corresponded with the following significant changes in the extrusion parameters and product properties:

- Increases in die temperature, product temperature, torque, specific mechanical energy, puff length, expansion, per piece weight, specific volume and lightness
- Decreases in apparent bulk density, redness and yellowness

5.2 Recommendations

1. Compare the ratio of amylose to amylopectin by using waxy (high-amylopectin) starch as well as high-amylose starch.

2. Perform texture analysis above and below the glass transition temperature. For our study, only analysis at room temperature was available.

3. Submit the product to a sensory panel to determine which textural characteristics are most important to consumers.

4. Analyze the fracturability and other textural properties in a more complete texture analysis.

APPENDIX A

GLM PROCEDURES FOR SAS

A.1 Extruder responses GLM

```
Options ls=100 ps=70;
Data extrusion;
Title1 'Extrusion Data';
Options pagesize=52;

Infile 'F:/eeextrusion.prn' missover;
Input mix water speed rep product p9 p8 torque psi cutter feed;

Proc sort;
By mix water speed rep;
Proc means noprint;
By mix water speed rep;
Var product p9 p8 torque psi cutter feed;
Output out=newextrusion mean=product p9 p8 torque psi cutter feed;

Data newextrusion;
Set newextrusion;
Trt=compress(mix||water);
Proc print;

Proc glm;
      Classes rep trt speed;
      Model product p9 p8 torque psi cutter feed=rep trt|speed;
      Means trt|speed/lsd lines;
      Lsmeans trt|speed/s p;
Run;
```

A.2 Product properties GLM

A.2.1 Length, width and expansion

```
Options ls=100 ps=70;
Data lwexp;
Title1 'Length, Width and Expansion';
Options pagesize=52;

Infile 'F:\ecwcfcslw.prn' missover;
Input mix water speed rep l w exp;
Proc sort;
By mix water speed rep;
Proc means noprint;
By mix water speed rep;
Var l w exp;
Output out=newlwexp mean=l w exp;

Data newlwexp;
Set newlwexp;
Trt=compress(mix||water);
Proc print;

Proc glm;
      Classes rep trt speed;
      Model l w exp=rep trt|speed;
      Means trt|speed/lsd lines;
      Lsmeans trt|speed/s p;
Run;
```

A.2.2 Per piece weight, bulk density and apparent bulk density

```
Options ls=100 ps=70;
Data density;
Title1 'Per Piece Weight, Apparent Bulk Density, Bulk Density';
Options pagesize=52;

Infile 'F:/ecdensity.prn' missover;
Input sample code mix water speed rep ppw abd bd;
Proc sort;
By mix water speed rep;
Proc means noprint;
By mix water speed rep;
Var ppw abd bd;
Output out=newdensity mean=ppw abd bd;

Data newdensity;
Set newdensity;
Trt=compress(mix||water);
Proc print;

Proc glm;
      Classes rep trt speed;
      Model ppw abd bd=rep trt|speed;
      Means trt|speed/lsd lines;
      Lsmeans trt|speed/s p;
Run;
```

A.2.3 Specific volume

```
Options ls=100 ps=70;
Data sv;
Title1 'Specific Volume';
Options pagesize=52;

Infile 'F:\spv.prn' missover;
Input mix water speed rep sv;
Proc sort;
By mix water speed rep;
Proc means noprint;
By mix water speed rep;
Var sv;
Output out=newsv mean=sv;

Data newsv;
Set newsv;
Trt=compress(mix||water);
Proc print;

Proc glm;
      Classes rep trt speed;
      Model sv=rep trt|speed;
      Means trt|speed/lsd lines;
      Lsmeans trt|speed/s p;
Run;
```

A.2.4 Color

```
Options ls=100 ps=70;
Data color;
Title1 'Color';
Options pagesize=52;

Infile 'F:\eccolor.prn' missover;
Input sample code mix water speed rep L a b;
Proc sort;
By mix water speed rep;
Proc means noprint;
By mix water speed rep;
Var L a b;
Output out=newcolor mean=L a b;

Data newcolor;
Set newcolor;
Trt=compress(mix||water);
Proc print;

Proc glm;
      Classes rep trt speed;
      Model L a b=rep trt|speed;
      Means trt|speed/lsd lines;
      Lsmeans trt|speed/s p;
Run;
```

A.3 Texture profile GLM

```
Options ls=100 ps=70;
Data texture;
Title1 'Texture';
Options pagesize=52;

Infile 'F:\ectexture.prn' missover;
Input mix water speed rep force strength hard cohesiv spring gum chew;
Proc sort;
By mix water speed rep;

Proc means noprint;
By mix water speed rep;
Var force strength hard cohesiv spring gum chew;
Output out=newtexture mean=force strength hard cohesiv spring gum chew;

Data newtexture;
Set newtexture;
Trt=compress(mix||water);
Proc print;

Proc glm;
      Classes rep trt speed;
      Model force strength hard cohesiv spring gum chew=rep trt|speed;
      Means trt|speed/lsd lines;
      Lsmeans trt|speed/s p;
Run;
```

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