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THE EFFECTS OF EXTRUSION COOKING AND MILLING ON THE INSTANT PROPERTIES OF WHEAT AND SOY POWDERS

presented by

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has been accepted towards fulfillment
of the requirements for the

Master of Science degree in Food Science

Major Professor's Signature

Dec. 5, 2002

Date

THE EFFECTS OF EXTRUSION COOKING AND MILLING ON THE INSTANT PROPERTIES OF WHEAT AND SOY POWDERS

By

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A THESIS

Submitted to
Michigan State University
in partial fulfillment of the requirements
for the degree of

MASTER OF SCIENCE

Department of Food Science and Human Nutrition

2002

ABSTRACT

THE EFFECTS OF EXTRUSION COOKING AND MILLING ON THE INSTANT PROPERTIES OF WHEAT AND SOY POWDERS

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Instant powders, which require only reconstitution in liquid for use in products such as beverages, can be produced by extrusion cooking. Powders with good instant properties should disperse easily, without lumps. Instant cereal and soy powders are often difficult to disperse because of swelling and fine grinding, respectively. In this study, extrusion was done using a twin-screw extruder and varying the dough moisture content, barrel temperature, and screw speed. The extrudates were then milled to produce powders with different particle size ranges. The specific mechanical energy (SME), water absorption index (WAI), water solubility index (WSI), viscosity, ease of dispersibility, and stability to sedimentation were measured. The WAI and suspension viscosity of instant wheat powders were negatively correlated with the SME, and decreased with particle size. The WSI of wheat powders increased with the SME. The WAI and WSI of instant soy powders were not strongly influenced by the extrusion conditions used. Wheat powders with larger particle sizes were easily dispersed, however below 93 μm, dispersibility was inversely correlated with the SME. The addition of lecithin improved dispersibility. Soy powders displayed poor dispersibility when the particle size was reduced to approximately 15 μm. Stability to sedimentation was greater as particle size decreased for both wheat and soy powders.

ACKNOWLEDGEMENTS

I would like to express thanks to my advisor, Dr. P.K.W. Ng for his guidance and patience throughout the completion of my program. His providing of resources and time are greatly appreciated. Dr. K.D. Dolan and Dr. J.N. Cash are also to be acknowledged for providing advice and direction while serving on my committee. Special thanks are given to R.J. Wolthuis for his knowledge and skill regarding much of the equipment used in the studies. Without the aid of D. Ngo during sample preparation, and the laser particle size analysis results from Dr. G.A. Hareland of the USDA/ARS Wheat Quality Lab at North Dakota State University, this work would have been much more difficult to accomplish. The help of E.B. Smith with statistical analysis is also deeply appreciated. Most importantly I would like to thank those mentioned above along with the other members of the cereal science lab for providing friendship and making my time much more enjoyable.

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I Introduction

Extrusion processing is commonly used in the food industry because of its versatility. Processing conditions can be altered depending on the raw materials and on the desired qualities of the end product. Examples of extruded products include puffed cereals for breakfast or snacks, pet foods, and texturized meat analogs made from soy.

Extruders can also be used as cookers to produce instant food powders that need only reconstitution in liquid. The starches in cereals, such as wheat and corn, can be pregelatinized to improve their cold water properties. The advantage of extrusion cooking is that it can modify the characteristics of starch, such as solubility and viscosity. The instant powders can then be used for products such as gruels or beverages. Extrusion has also been used to make low cost, nutritious soy powders for aid programs. However, soy is not widely accepted in the United States due to objectionable characteristics such as poor flavor and mouthfeel.

In addition to being ready to use without further cooking, instant powders should also be easily reconstituted. This is especially important for powders that are meant to be consumed at home, like instant beverage bases. A powder with good instant properties should disperse easily into liquid and should not sediment too quickly. Some factors affecting instant properties include the type of powder and liquid, along with the particle size of the powder.

Cereal powders can be difficult to reconstitute because of swelling, which can lead to the formation of lumps. Soy powders are another case where problems can occur because of the difficulty in mixing fine powders. Various processes are used to instantize

or improve the instant properties of powders, including agglomeration to make larger particles, and the addition of lecithin to improve wetting.

The objectives of these studies were to determine the effects of different extrusion conditions and powder particle sizes on the instant properties of wheat and soy powders, to delineate the effects of lecithin on instant properties, and to develop blends of wheat and soy powders that are suitable for an instant beverage base.

II Literature Review

2.1. Extrusion

Extruders work by mixing materials into a viscous dough-like mass and forcing it through a restricted opening. The ingredients are fed into a cylindrical barrel, which contains either one or two rows of flighted screws (Harper, 1981). As the screw(s) turn, the materials are mixed and conveyed down the barrel. The lengths of barrels are described by the ratio of the barrel length to its diameter (L/D), and typically range from 1:1 to 20:1 (Harper, 1981). Changes in the geometry of the screws, along with the restricted die opening at the end of the barrel, cause the material to be compressed and the pressure to increase. As the material makes its way down the barrel, these forces cause the material to become a plasticized dough, which is subject to the mixing and shearing forces of the turning screw(s). The mechanical energy imparted by the screws is dissipated in the form of heat. Additional heat can be applied through heating of the extruder barrel or direct injection of steam. Extruders can be considered high temperature/short time cookers because temperatures can reach as high as 200°C with residence times ranging from only 5-10 seconds to over 1 minute. The shear rate and temperature are typically highest at the end of the barrel near the exit die, and this is where most of the cooking and product transformation takes place. Upon exiting the die, moisture in the extrudate flashes off causing expansion and cooling of the product (Harper, 1981). During extrusion, some of the changes that take place in the raw material include starch gelatinization and transformation, protein denaturation and alignment, killing of microbes, development of colors and flavors, inactivation of antinutritional factors, and the destruction of vitamins and other nutrients (Harper, 1981).

Important advantages of extruders include their ability to produce a wide range of products and their high production capacity. Producing foods with extruders is also low cost due to efficiencies in labor, floor space and energy consumption. Processing can be done at lower moistures, reducing the amount of heat needed during processing and drying of the product (Harper, 1981).

2.1.1. Single- and Twin-Screw Extruders

The two main types of extruders are the single- and twin-screw extruders. Single-screw extruders rely on one set of screws to convey materials down the barrel by drag flow (Frame, 1994). For this extruder to function, the material must have enough friction with the barrel wall so that the material does not rotate with the screws.

Twin-screw extruders consist of two sets of intermeshing screws which can either rotate in the same (co-rotating) or opposite (counter-rotating) direction. The more common co-rotating twin screw extruders convey materials by both drag and positive displacement flow (Frame, 1994). Materials are transferred from one screw to the other, which enhances mixing and allows the twin-screw extruder to handle a wider variety of materials than a single-screw extruder.

2.1.2. Independent Variables

Independent variables are the operating conditions that can be controlled to produce the desired extrudate characteristics. One variable that can be changed is the screw geometry at different positions along the barrel. The flight on a screw refers to the portion that forms the helical pattern that conveys material when the screw is turned

(Harper, 1981). The number, depth, and angle of the flights affects the conveying capacity of the screw. For example, at the feed section, screws typically have less shallow flights than screws near the die. These deeper flights have greater conveying capacity while the more shallow flights have more pumping ability, the latter needed to force material through the die (Frame, 1994). Mixing elements such as paddles, screws with cut flights, and reverse pitch screws that convey materials in the opposite direction can also be used (Harper, 1986). In addition to mixing, these types of elements provide additional shear and alter the residence time of the material in the extruder. Other independent variables include the raw materials, moisture content of the ingredients, die design, barrel temperature, screw speed, and feed rate (Harper, 1986).

2.1.3. Dependent Variables

Dependent variables are affected by changes in the independent variables. One of the most important dependent variables is the specific mechanical energy (SME). It is a measure of the amount of work being put into the material during extrusion and is a function of the feed rate, screw speed, and rheological properties of the extruded material (Frame, 1994). The SME has been correlated with many product characteristics and is one of the most important variables to consider for scale up (Levine, 1989; Schuchmann and Danner, 2000). The shear rate is another important variable and it is affected by the screw speed, screw geometry, die geometry, and the rheological properties of the extruded material (Harper, 1981). Other dependent variables include pressure, which can reach over 1000 psi at the die, viscosity of the material, and residence time (Harper, 1981). The most important dependent variables are the actual product characteristics.

These include product expansion, color, texture, water solubility, and many other measurable parameters.

2.2. Wheat Flour

Wheat flour can be extruded to make a variety of products including breakfast cereals, snacks, and instant powders. It is primarily composed of protein and starch. Depending on the wheat variety, protein content in flour can range from 7-15% at a 14% moisture basis (Atwell, 2001). Wheat flour is comprised of approximately 63-72% starch on a 14% moisture basis (Atwell, 2001), and is regarded as the main functional component in extruded flour products (Colonna et al., 1989; Guy and Horne, 1988). It is composed of amylose and amylopectin, which are α-1,4 and α-1,6 linked polymers of glucose, respectively (Thomas and Atwell, 1999). Amylose is a straight chain polymer which can take the form of a helix with a hydrophobic core. This allows it to bind free fatty acids and some alcohols. Amylopectin is a branched chain polymer and accounts for approximately 75% of the starch in wheat. These components of starch are arranged in discrete, semicrystalline granules, which are approximately 1-45 microns in size. Starch granules are highly ordered and show birefringence when viewed under polarized light (Hoseney, 1994).

One of the main functional properties of starch is its ability to absorb water and increase the viscosity of suspensions. However, native starch in cold water has very low water solubility and water absorption. It is not until heating takes place that starch begins to increase the viscosity of suspensions. The irreversible changes that starch undergoes during heating in water are referred to as gelatinization and pasting (Thomas and Atwell,

1999). During gelatinization, starch granules lose their ordered structure and birefringence. They also begin to swell and increase in solubility (Atwell et al., 1988). As this occurs, the viscosity of the starch/water suspension increases. Gelatinization occurs over a range of temperatures [52-85°C for wheat starch (Thomas and Atwell, 1999)], leading to a steady increase in viscosity. A peak viscosity is reached when the majority of starch granules are swollen and still intact. The swollen granules eventually begin to break down and exude their components, a process referred to as pasting. Once allowed to cool, the starch components, primarily amylose, can re-associate and form a gel. The Amylograph and Rapid Visco Analyzer (Figure 2.1) are two instruments that produce pasting curves of starch by measuring the relative viscosity of starch suspensions during programmed heating and cooling cycles.

2.2.1. Pregelatinization

Instantization or pregelatinization is processing to make starches with higher cold water viscosity and solubility. These instant powders are often used in products that undergo little or no heating prior to use. Some functions of pregelatinized starch are binding and the addition of viscosity and texture. Production of instant starches is commonly done by drum drying a 30-40% solids slurry of starch in water (Thomas and Atwell, 1999). The dried product is then ground into a powder.

Extrusion can also be used to pregelatinize starches and has advantages over drum drying because starch properties such as water absorption, water solubility, and cold viscosity can be modified (Colonna et al., 1984). Experiments comparing drum dried and extruded wheat starches have shown that extrusion cooking produces starch with lower

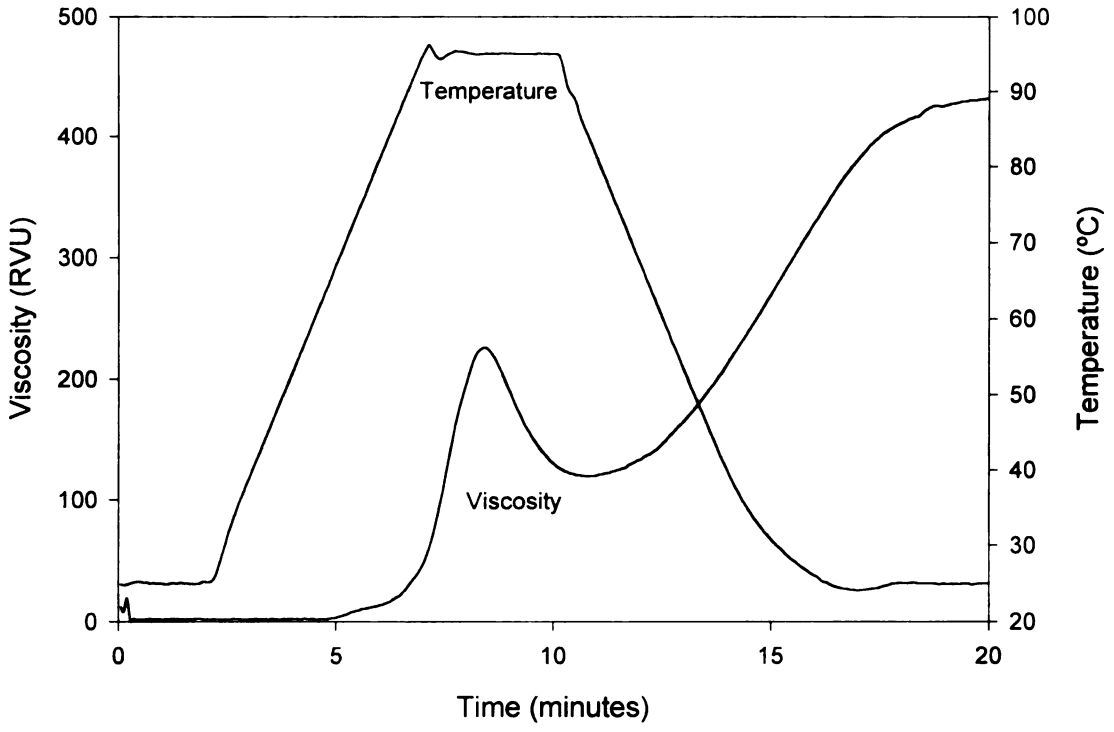

Figure 2.1. Rapid Visco Analyzer pasting curve of soft wheat flour. Viscosity in Rapid Visco Units (RVU).

viscosities and water absorptions, and higher water solubilities (Colonna et al., 1984; Doublier et al., 1986). Colonna et al. (1984) found that as the water absorption decreased, the cold water solubility of the extruded starch increased to 60-80% compared to a solubility of only 14-25% for the drum dried starch. Extrusion led to the disruption of starch granules and the macromolecular degradation of amylose and amylopectin. Anderson et al. (1969) observed that the water solubility of extruded corn grits was positively correlated with extrusion temperature and negatively correlated with the feed moisture during extrusion. Higher shear conditions were found to lower the viscosity of starch/water slurries.

2.2.2. Extruded Instant Cereal Powders

Schuchmann and Danner (2000) identified extrusion conditions that produced instant corn powders for use as thickeners and beverages. High barrel temperature and extrusion moisture, low screw speed, and medium to low shear conditions produced powders with high suspension viscosity and high water binding capacity. These powders were judged to be good for use as instant thickeners. To make powders suitable for products such as infant formulas, conditions were adjusted to produce powders with low suspension viscosities and high water solubilities. Low extrusion moisture, temperature, and screw speed, and a high-shear screw configuration produced powders with these characteristics. Lower suspension viscosity and higher water solubility was correlated with higher SME. The SME was regarded by Schuchmann and Danner (2000) as the most important parameter to control.

Anderson et al. (1970) produced extruded corn grit powders with a range of characteristics. Extrusion at 25% moisture and 188°C produced a powder suitable for gruel, while extrusion at 14% moisture and 188°C produced a powder suitable for a beverage. The latter powder had a lower viscosity and higher solubility in water. Grinding the extrudate to pass through a 40 mesh screen gave a powder with good dispersibility and a smooth mouthfeel. Although grinding to a smaller particle size gave a smoother drink, it also made dispersibility more difficult.

2.3. Soybean Utilization

The United States is the largest producer of soybeans in the world with 95% of its domestic utilization going towards oil production. Soybeans have become a major oilseed due to their low cost and high oil content, which is of good quality (Liu, 1997a). After oil extraction, the remaining defatted meal is used primarily for animal feed. Less than 5% of the meal is further processed for use in human food (Traina and Breene, 1994). One of the reasons for the limited acceptance of soyfoods in the U.S. is flavor (Liu, 2000). Products like soymilk are often referred to as having a beany or grassy flavor, which is objectionable to people unaccustomed to it. Another factor is the relatively high costs of soy due to limited sales volumes. Additionally, sales are mostly through specialty health food stores. However, as more people consume soy products, prices should decrease along with increased availability (Liu, 2000).

Soybeans are commonly processed into soy flour, soy protein concentrates, and isolates for use as food ingredients. Soy flour is available in either full fat or defatted forms. Soy protein concentrates and isolates are produced from defatted soy flakes, and

are defined as containing no less than 70% protein (N x 6.25) or no less than 90% protein (N x 6.25), respectively, on a dry basis (Ohren, 1981). Soy powders with a range of functionalities can be produced by controlling the degree of heat treatment. The protein dispersibility index (PDI) is one measure of heat treatment that soy products have undergone. As heating is prolonged or done at higher temperatures and moistures, the PDI decreases. Cooking of soy also serves to kill microorganisms, destroy antinutritional factors and remove bitter or beany flavors (Fulmer, 1989; Heiser and Trentelman, 1989; Johnson and Kikuchi, 1989). Some functional uses of soy include emulsification, foaming, fat and water absorption, gelation, flavor binding, and color control. Baked goods, baby foods, protein beverages, meat products, and hydrolyzed vegetable proteins are examples of foods to which soy is added (Fulmer, 1989; Wolf, 1970).

2.3.1. Nutritional Value of Soy Protein

The high content and quality of protein in soybeans makes it a good source to meet dietary needs. Although soy protein contains all of the essential amino acids, it is low in sulfur-containing amino acids such as methionine (Scrimshaw, 1981; Torun et al., 1981). However, soy proteins are high in lysine relative to cereal proteins (Horan, 1973; Graham et al., 1972). Thus, these two plant sources of protein are complementary and, when blended, can provide a source of complete protein.

To obtain the full nutritional value of soy, heat treatment must be done to inactivate antinutritional compounds. These include trypsin inhibitors, goitrogens, antivitamins, and phytates (Liener, 1981). Of these, trypsin inhibitors have been the most widely studied. An early study by Rackis (1978) found that the inactivation of trypsin inhibitor

(TI) activity correlated with an increase in the protein efficiency ratio (PER), measured as the weight gain of young rats relative to the amount of protein consumed (Liener, 1981; Liu, 1997b). Although heat treatment can increase protein quality, excess heat should be avoided to minimize the destruction and biological inactivation of amino acids (DelValle, 1981).

The consumption of soy foods is increasing and this has been due largely to awareness of the soybean's health benefits (Liu, 2000). In 1999, the U.S. Food and Drug Administration (FDA) approved labeling for a health claim regarding the role of soy protein in reducing the risk of coronary heart disease (FDA, 1999). The ruling came in response to studies showing that the consumption of 25 grams of soy protein per day significantly reduced blood cholesterol levels. Based on this, foods containing at least 6.25 grams of soy protein per serving were ruled eligible to make the claim.

Isoflavones are another component of soybeans that have received attention, due to studies showing that they may inhibit the growth of cancer cells and reduce blood cholesterol levels (Messina, 1997). Isoflavones have a chemical structure similar to estrogen and have also been used to treat post-menopausal women (Barnes, 1998; Setchell and Cassidy, 1999).

Soy can also be a good source of fiber, as the crude fiber contents of defatted soybean meal and defatted, dehulled soybean meal are 8.2% and 4.3%, respectively (Fulmer, 1989). Potential health benefits of soy fiber include increased bowel function, lowering of serum cholesterol, and influence on blood glucose levels and insulin response (Riaz, 2001; Slavin, 1991).

2.3.2. Soy Drinks

Soymilk is one of the most common soy foods and consists of the water-extractable portion of soybeans (Chen, 1989). Many different procedures exist to make soymilk, but the basic steps involve the grinding of soybeans in water and subsequent filtration to remove okara, the non-water-extractable portion. There must also be a cooking step to destroy microbes and antinutritional factors like trypsin inhibitors. Some other processing steps may involve dehulling, soaking before grinding, adding of flavoring, and homogenization (Chen, 1989). The main goals are to produce a high yield of soymilk with good flavor. The yield of soybean solids in soymilk typically is 55-60% of the starting material with 70-80% of the protein being extracted (Chen, 1989). The remaining unextracted solids comprise what is termed okara. The Illinois process for soymilk production is a method which incorporates the whole soybean by using grinding and homogenization to reduce the particle size enough so that there is an acceptable mouthfeel and good stability of the beverage (Nelson et al., 1976).

Another process utilizing the whole soybean to produce a beverage was developed by Mustakas et al. (1971), in which the soybeans were cooked by extrusion. The resulting full fat soy flour was then wet milled and spray dried to make a beverage base.

Other soy-based beverages that can commonly be found in health food stores are dry powder mixes. Many of these powders are marketed as protein supplement beverages or shakes and utilize soy protein concentrate or isolate. These powders can be expensive because the production cost per pound of isolate is greater than 10 times the cost to make one pound of soy flour (Langsdorf, 1981).

A disadvantage of some of these beverages and powders, aside from their cost, is that the whole soybean is not utilized. Okara, the byproduct from soymilk processing, has found limited use as a human food due to its high fiber content (O'Toole, 1999). Its disposal is also difficult since for every kilogram of soybeans processed, about 1.1 kilograms of okara is produced (Khare et al., 1995). Dry powders based on soy protein concentrates and isolates also do not utilize the whole soybean and contain lower amounts of some nutrients like fiber. These powders also are often inconvenient to use because they may require a blender for reconstitution.

2.3.3. Mouthfeel

Incorporating the whole soybean into a beverage is difficult because it can result in a grainy mouthfeel. Chalkiness, graininess, or a "catch throat" sensation, each refer to an unfavorable mouthfeel characteristic that can occur in soy-based drinks. This has been found to be especially true for soymilk produced by the Illinois method, which incorporates the whole soybean (Kuntz et al., 1978). To reduce the chalkiness of soymilk produced by this method, Kuntz et al. (1978) tried different pretreatments for the soybeans, different homogenization pressures, and adjustments of the soybean soaking pH. They found that soaking the beans in 0.25% $NaHCO_3$ and homogenization of the soymilk at higher pressures resulted in greater particle size reduction and less chalkiness.

Mustakas et al. (1971) also found that soy flour produced by extrusion had a coarse mouthfeel when suspended in water. After colloid milling and homogenization, the mouthfeel was judged to be good. Scanning electron micrograph results showed that the particle size of the soy powder was reduced from about 75 microns to 20 microns.

Traina and Breene (1994) evaluated eight commercially available full fat soy flours for graininess when suspended in water. They found all eight to be grainy even though one claimed to be milled superfine to eliminate the chalkiness. Laser particle size analysis showed that this flour did not meet the manufacturer's claim that 80% of the particles were smaller than 30 microns.

2.3.4. Extrusion of Soy

Extrusion has been investigated as an alternative to cooking with steam for the production of full fat soy flour (Bookwalter et al., 1971a; Mustakas et al., 1964; Mustakas et al., 1970). These early works demonstrated that extrusion cooking could be used to economically process dehulled flakes or grits into high quality, full fat soy flour. By adjusting extrusion conditions such as moisture and temperature, trypsin inhibitors (TI) could be inactivated and beany and bitter flavors removed, leaving a bland tasting flour. Of the extrusion conditions tested by Mustakas et al. (1964), extrusion of the feed materials at 20% moisture and 135°C resulted in 89% TI inactivation and the highest PER. A study by Lorenz et al. (1980) found that extrusion at 143°C resulted in the highest protein quality as measured by the PER, but only 57% TI inactivation. Extrusion at 149°C resulted in 74% TI inactivation, but a lower PER. They also found that TI inactivation increased with the moisture of the extruded raw material.

2.4. Extrusion of Soy and Cereal Blends

The extrusion of blends of soy and cereals has been studied as a low cost method of producing instant foods for international aid programs. The combination of cereal and

soy protein is complementary, and is a good source of complete protein from a nutritional and economic standpoint. Numerous studies have shown that the nutritional quality of these blends are comparable to that of casein (Bookwalter et al., 1971b; Bressani et al., 1978; Horan, 1973; Jansen et al., 1978; Molina et al., 1983; Torun et al., 1981). Calories from carbohydrates and oil provide additional nutritive value (Bressani and Elias, 1966). The starch from cereals also has the functional effect of adding viscosity and texture. Gruels can be made by choosing extrusion conditions which make starch with high suspension viscosities while starch with low suspension viscosities are suited for beverages (Anderson et al., 1970; Bookwalter et al., 1971b; Jansen et al., 1978; Konstance et al., 1998; Molina et al., 1983).

2.5. Instant Powder Properties

In addition to being ready to use without further cooking, the term instant also refers to the ease of reconstitution of a powder. However, defining what instant should mean in this respect is difficult due to the wide range of products possible (Jensen, 1973). A definition would need to take into account the intended use of the product and the reconstitution process. For example, a powder that is mixed in a processing plant with strong agitation would not need instant properties as good as those of a powder intended for home use and mixing by hand. In general, there are four characteristics to consider when evaluating instant properties of powders. They are wettability, sinkability, dispersibility, and solubility (Jensen, 1973; Schubert, 1979; Schubert, 1993).

2.5.1. Wettability

Wettability refers to the ability of water to penetrate into the bulk powder (Schubert, 1993). It is affected by particle size, porosity of the powder, and the contact angle between the particle and the liquid. In general, faster wetting is favored by larger particles. Powders with smaller particle sizes have narrower pore structures in the bulk material, making the penetration of water more difficult, slowing wetting. Conversely, if particles are too large, penetration of liquid will take too long due to the formation of gas inclusions in the pores (Schubert, 1993).

The contact angle between the liquid and the particle also affects wetting. For a powder sitting on top of a liquid, the contact angle is dependent on the interfacial tensions between the solid, liquid, and the surrounding air (Walstra, 1996). If the contact angle is too large, little or no wetting will occur. This is the case for powders that contain fats such as cocoa powder. The contact angle also generally increases as particle size decreases, making wetting more difficult (Schubert, 1979).

2.5.2. Sinkability

Sinkability describes how well particles sink below the surface of the liquid. Schubert (1993) has found that particles greater than 100 microns and having a density of 1.5 g/cm^3 have good sinkability. Powders with poor sinkability may float on the surface, resulting in a poor product appearance. Sinking is also important to allow for water to more easily penetrate into a powder.

2.5.3. Solubility

Powders that are soluble should dissolve quickly and with a minimum of undissolved particles. There are also powders such as cocoa powder that are not soluble, but instead form suspensions, and this property is therefore not applicable (Jensen, 1973).

2.5.4. Dispersibility

A powder with good dispersibility should mix easily and without lumps in the liquid. It also describes how well the particles remain suspended in the liquid. Dispersibility can be considered the most important property because it encompasses the other instant properties and has the most practical importance.

One factor that affects dispersion is particle size. As particles become smaller, interparticle adhesion becomes greater, causing the formation of lumps (Schubert, 1979). The ratio of the force of particle adhesion (F), to the weight of the particle (W), is inversely proportional to the square of the particle size (Schubert, 1987). Thus, 1 μm particles have 10^6 greater F/W ratios than 1 mm particles. According to Schubert, most food powders are non-cohesive only at particle sizes above 100 μm. Additionally, interparticle forces are much stronger in wet powders.

Instant cereal powders present additional difficulties and often have poor instant properties because of starch swelling. Lump formation often occurs in fine powders, which have large surface areas, due to quick hydration and gelling of starch on the outer surface of a lump (Thomas and Atwell, 1999). Swelling also occurs, clogging pores and further impeding wetting (Schubert, 1993). This prevents water from penetrating, leaving a lump of particles with a dry core, known as a "fish eye" (Thomas and Atwell, 1999).

Larger particles having less surface area hydrate more slowly, resulting in easier dispersion. Dispersibility is usually controlled in drum dried starches through the degree of milling. Powders with larger particle sizes are easier to disperse, but do not yield products with as smooth texture (Thomas and Atwell, 1999). In addition to controlling the degree of milling, agglomeration is another method used to produce starch with good instant properties (Schubert, 1993).

Settling of particles is related to particle size and the difference in density between the particle and liquid (Schubert, 1993). The velocity of sedimentation (w) is described by the Stokes' law equation $w = \Delta\rho\, g\, \chi^2/18\, \eta$, where $\Delta\rho$ is the difference in density between the solid and liquid, g is acceleration due to gravity, χ is the particle diameter, and η is the viscosity of the liquid (Schubert, 1993). Thus, larger particles with higher density, sediment more quickly. One way to decrease sedimentation is by increasing the viscosity of the liquid. The viscosity of water can be increased 10-100 fold by stabilizers such as starch and colloids without adversely affecting sensory attributes (Schubert, 1993).

2.6. Instantization

The process of instantization describes the enhancing of the instant properties of a powder. This is often necessary because of the difficulty in dispersing fine or hydrophobic powders in water. Instantization generally falls into either agglomerative or non-agglomerative processes (Schubert, 1993).

Agglomeration improves instant properties by loosely bonding together individual particles to make a larger, granular structure. Once the agglomerate is mixed with liquid, the bonds should then disintegrate so the powder can disperse. This improves wettability

and reduces lump formation (Schubert, 1993). Wet agglomeration is done with a condensing vapor or liquid spray. This results in the formation of solid bridges holding particles together after drying. Spray drying is another commonly used method for agglomeration (Schubert, 1993).

Non-agglomerative processes describe methods that do not involve aggregation of individual particles. These types of processes usually involve either reducing the contact angle or increasing the solubility of particles (Schubert, 1993).

The addition of lecithin is a commonly used method to reduce the contact angle. Lecithin consists of a mixture of phospholipids, mainly refined from vegetable oils. Plant sources include cottonseed, corn, sunflower, and rapeseed. However, the majority of commercially available lecithin comes from the soybean (List, 1989). Lecithin contains both hydrophilic and hydrophobic portions, allowing it to be surface active (Schmitt, 1995). Thus, lecithin can bind to hydrophobic powders and also improve their wetting by liquids. Modification of lecithin by hydroxylation is done to further enhance its water dispersing and emulsifying properties (List, 1989).

Both agglomerative and non-agglomerative processes are often used to produce instant drink mixes. A typical formula for a protein-based drink may include whey protein concentrate, fructose and other flavorings, and 2% lecithin (Sander, 1989). The production of whole powdered milk with the addition of lecithin combined with spray drying is an example where both types of instantization processes are used (Pisecky, 1978).

2.7. Evaluation of Instant Properties

How instant powders are produced and evaluated are dependent upon many factors related to its end use. Considerations include the ease of dispersal required along with the type of liquid that the powder is to be dispersed in (Sander, 1989). The stability of particles to sedimentation is another factor that depends on the type of product. Therefore, one set of standard procedures will not be acceptable for all powders. Evaluation methods need to be practical, simple, and fast to allow for routine analysis.

The International Dairy Federation (IDF) has written a set of standard procedures for the evaluation of powdered milk instant properties. According to IDF-Standard 87:1979, wettability is measured by dropping powdered milk on the surface of water in a beaker and measuring the time it takes for all of the particles to sink below the surface. This type of method requires that the powder be spread evenly over the surface of the water. Various methods of dropping the powder onto the liquid surface have been proposed and it is recognized that spreading the powder evenly is very difficult (Schubert, 1979). This method may also be more representative of sinkability than wettability.

Another method to measure wettability, proposed by Schubert (1993), calls for the placement of powder into a container with a sieve on the bottom. The container is then attached to a balance from above and lowered onto the surface of a liquid. The change in force measures how much liquid is imbibed.

According to IDF Standard 87:1979, dispersibility is measured by stirring powdered milk in water for a standard time before allowing it to stand still. A portion of the milk is then poured through a 150 micron sieve and the total solids of the filtrate are measured.

Schubert (1993) developed a device to remove the middle portion of a drink, which has been stirred and allowed to stand. The solids content of this portion is then measured along with the remaining portion, which consists of the top and bottom of the drink. The degree of dispersion is measured by dividing the solids concentration of the middle portion by the solids concentration of the remaining portions.

According to Sander (1989), dispersibility can be measured by mixing the powder in a beaker with a magnetic stirring bar. The mixing is standardized by measuring the height of the liquid caused by the vortex. The time to disperse the powder is then measured. Further characterization can include pouring the drink over a sieve and counting the number of lumps that remain.

III Materials and Methods

3.1. Raw Materials

Five different raw materials were extruded:

WF: Soft white wheat flour (Star of the West, Frankenmuth, MI).

WFL: 96% soft white wheat flour (dry basis) and 4% deoiled hydroxylated soy lecithin (Precept 8120, Central Soya, Fort Wayne, IN).

SF: Raw defatted soy flour (Nutrisoy 7B, Archer Daniels Midland, Decatur, IL).

SFL: 96% raw defatted soy flour (dry basis) and 4% deoiled hydroxylated soy lecithin.

S-Blend: 50:50 blend of raw defatted soy flour with raw dehulled full fat soy flakes (Thumb Oil Seed Producers' Cooperative, Bad Axe, MI).

3.2. Extrusion

Extrusion was done with an APV co-rotating, twin screw extruder, with a barrel diameter of 19 mm and barrel length to diameter (LD) ratio of 25:1 (Model MP19T2-25, APV Baker, Grand Rapids, MI). Heating of the barrel was controlled by electric heating elements jacketing the barrel. Heating was divided into five zones along the length of the barrel, with zone one nearest the feed section and zone five nearest the exit die. Moisture was adjusted to the dough moisture content during extrusion by injection of water into the barrel using a Brook Crompton E2 Metripump (Hudders Field, England). Dry materials were fed using a K-TRON K2M twin-screw volumetric feeder (K-TRON, Pittman, NJ). Die pressure was measured by a pressure transducer (Model EPR3-3M, Dynisco, Sharon, MA) placed before the die. Torque was measured as % of the total motor power (2000 W).

Moisture, screw speed, and temperature were each varied at two levels, for a total of 8 different combinations. The dry material feed rate was kept constant along with the screw configuration (listed in Table 3.1). The extrusion conditions for WF and WFL are listed in Table 3.1 and conditions for SF, SFL, and S-Blend are listed in Table 3.2. Extrusion of each raw material was repeated on a different day.

3.3. Post Extrusion Processing

The extrudates were dried overnight in a food dehydrator (Proctor and Schwartz Inc., Philadelphia, PA) at 45-50°C. Powders with different particle size ranges were produced from the extrudates by milling and sieving. After milling, the powders were stored at 5°C until analysis.

3.3.1. Milling: Wheat Flour (WF) and Wheat Flour + Lecithin (WFL)

The WF and WFL extrudates were progressively ground and sieved to produce particle sizes of 145-249 μm, 93-145 μm, and <93 μm. Grinding was done using a coffee grinder (Braun Inc., Woburn, MA) and an impact mill with 1.0 mm and 0.50 mm screens (Udy Cyclone Mill, Udy Corp., Fort Collins, CO). Sieving was done with a rotary sifter (Sampl-Sifter, Great Western Mfg. Co, Leavenworth, KS).

3.3.2. Milling: Defatted Soy Flour (SF) and Defatted Soy Flour + Lecithin (SFL)

The SF and SFL extrudates were progressively ground and sieved to produce particle sizes of 93-145 μm and <93 μm. Grinding was done using a coffee grinder and an impact mill with 1.0 mm and 0.50 mm screens. Sieving was done with a rotary sifter. A

Table 3.1. Extrusion Conditions for Wheat Flour and Wheat Flour + Lecithin

Feed Rate (kg/hr)[a]	Total Material Moisture (%)	Screw Speed (rpm)	Barrel Temp. Zones 1-5 (°C)[b]
1.8	25	300	40/50/80/110/120
1.8	25	200	40/50/80/110/120
1.8	35	200	40/50/80/110/120
1.8	35	300	40/50/80/110/120
1.8	35	300	40/60/90/130/145
1.8	35	200	40/60/90/130/145
1.8	25	200	40/60/90/130/145
1.8	25	300	40/60/90/130/145
Screw Configuration (feed inlet → die): 8DT, 7x30°FKP, 7DT, 4x60°FKP, 3x30°RKP, 2DS, 6x60°FKP, 4x30°RKP, 2DS. D = Diameter, T = Twin Lead Screw, S = Single Lead Screw, FKP = Forward Kneading Paddle, RKP = Reverse Kneading Paddle; 1 Kneading Paddle = 0.25D; 1D = 19 mm			

[a] Dry basis.
[b] Zone 5 = nearest to exit die.

Table 3.2. Extrusion Conditions for Defatted Soy Flour, Defatted Soy Flour + Lecithin, and Blend of Defatted Soy Flour with Full Fat Soy Flakes

Feed Rate (kg/hr)[a]	Total Material Moisture (%)	Screw Speed (rpm)	Barrel Temp. Zones 1-5 (°C)[b]
1.8	30	200	40/50/80/110/120
1.8	30	300	40/50/80/110/120
1.8	40	300	40/50/80/110/120
1.8	40	200	40/50/80/110/120
1.8	30	300	40/60/90/130/145
1.8	30	200	40/60/90/130/145
1.8	40	200	40/60/90/130/145
1.8	40	300	40/60/90/130/145
Screw Configuration (feed inlet → die): 8DT, 7x30°FKP, 7DT, 4x60°FKP, 3x30°RKP, 2DS, 6x60°FKP, 4x30°RKP, 2DS. D = Diameter, T = Twin Lead Screw, S = Single Lead Screw, FKP = Forward Kneading Paddle, RKP = Reverse Kneading Paddle; 1 Kneading Paddle = 0.25D; 1D = 19 mm			

[a] Dry basis.
[b] Zone 5 = nearest to exit die.

portion of the <93 μm fraction was further ground using a jet mill (Model 00 Jet-O-Mizer Mill, Fluid Energy Aljet, Telford, PA) to produce a third, finer particle size.

3.3.3. Milling: Blend of Raw Defatted Soy Flour with Full Fat Soy Flakes (S-Blend)

The S-Blend extrudates were ground with an impact mill through a 1.0 mm screen. They were then sieved through a 93 μm screen. Only one particle size was produced due to difficulties grinding and sieving because of the high fat content.

3.4. Analysis

Similar analyses (see below) were performed in duplicate for all of the extruded powders unless indicated otherwise.

3.4.1. Laser Particle Size Analysis

Mean particle sizes of the milled fractions were determined by laser particle size analysis with a Beckman-Coulter LS 130 laser diffraction instrument (Beckman, Hialeah, FL). Samples were suspended in isopropanol and measured for a 60 second time interval.

3.4.2. Specific Mechanical Energy (SME)

The SME in during extrusion in Watt hours/kg was calculated according to the equation of Brent et al. (1997):

SME = [actual screw rpm / rated screw rpm] x [% torque / 100] x [motor power in W / feed rate in kg/hr] [1]

rated screw speed = 500 rpm, motor power = 2000 W

3.4.3. Moisture

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

3.4.4. Water Absorption Index (WAI) and Water Solubility Index (WSI)

The water absorption and water solubility indexes were measured according to the procedure of Jin et al. (1995) with some modifications. Two grams of powder were mixed with 20 ml of distilled water in 30 ml round bottom centrifuge tubes. The tubes were allowed to sit for 10 minutes and were inverted 3 times each at 5 and 10 minutes. After 10 minutes, the suspensions were centrifuged (Model J2-21M, Beckman Instruments Inc., Fullerton, CA) at 1000 x g for 15 minutes. The supernatant was then collected and the WAI was calculated as:

WAI = weight of pellet / sample weight (dry basis) [2]

The water solubility index was measured by drying the supernatant in an air oven overnight at 60°C. WSI was calculated as:

WSI = weight of dried supernatant / sample weight (dry basis) [3]

3.4.5. Rapid Visco Analyzer Viscosity of WF and WFL

Pasting properties were determined using a Rapid Visco Analyzer (RVA Model 4, Newport Scientific Pty. Ltd., NSW, Australia). A 3.5 g sample of powder (14% m.b.) was mixed with 25 ml of distilled water by shaking to ensure that no lumps were present before analysis. The temperature profile and analysis definitions are listed in Table 3.3.

Table 3.3. Rapid Visco Analyzer Temperature Profile and Analysis Definitions

Temperature (°C)	Time (minutes)
25	0
25	2
95	7
95	10
25	15
25	20
Paddle Speed (rpm): 160	
Analysis Definitions[a]	
Cold Viscosity	Peak Viscosity at 0.2 – 2 Minutes
Hot Paste Viscosity	Peak Viscosity at 2 – 10 Minutes
Hold	Trough Viscosity at 10 – 19 Minutes
Breakdown	Hot Paste Viscosity – Trough Viscosity
Final Viscosity	Viscosity at End of Test
Setback	Final Viscosity – Trough Viscosity
Peak Time	Time of Peak Viscosity (Minutes)

[a] Viscosity in Rapid Visco Units (RVU).

3.4.6. Dispersibility

Dispersibility measured the % total solids that passed through a sieve after mixing the powder in distilled water. Mixing was done with an overhead mixer (Mixer Head Model 50003-30, Cole-Parmer, Vernon Hills, VA) by a 4 x 2 x 0.1 cm paddle set at 200 rpm. The paddle was centered with its length horizontal, 1 cm below the liquid surface in a 250 ml beaker containing 100 ml of distilled water at 21°C. Mixing time was set at 1 minute and 10 seconds. Five grams of powder were poured into the beaker during the first 10 seconds of mixing. After mixing, the suspension was immediately poured through a wire mesh sieve. The WF and WFL 145-249 μm and 93-145 μm powders and the 93-145 μm SF and SFL powders were poured through a sieve with 1.59 mm openings. The <93 μm particle size fractions for WF, WFL, SF, and SFL were poured through a sieve with 471 μm openings. The SF and SFL jet milled powders were also poured through a sieve with 471 μm openings. The S-Blend powders were poured through a 1.59 mm-mesh sieve. For each sample tested, the suspensions were poured through the indicated sieve and into a 250 ml separatory funnel with an enlarged stopcock to aid the passage of the suspension. Twenty ml of the suspension were immediately drained and 4 g were measured for solids content by drying in an air oven (Model 737F, Fisher Scientific Co., Pittsburgh, PA) for 2 hours at 110°C. Dispersibility was calculated as the solids concentration of the suspension passing through the sieve, divided by the solids concentration possible if all of the particles were evenly dispersed in the suspension.

% Dispersibility = [b_{20} / (g sample dry basis) / (g sample d.b. + 100 g water)] x 100 [4]

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

3.4.7. Stability

Stability measured the amount of sedimentation in the remaining approximately 80 ml of suspension in the separatory funnel. This remaining suspension was allowed to settle undisturbed for 2 minutes. Fifty ml was then drained and discarded. The remaining portion, consisting of the upper layer of the suspension, was then drained and a 4 g aliquot was measured for solids content. This was then divided by the solids concentration of the respective 20 ml aliquot initially drained off to measure dispersibility.

$$\% \text{ Stability} = [t_{30} / b_{20}] \times 100 \quad [5]$$

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

3.4.8. Trypsin Inhibitor Inactivation of SF, SFL, and S-Blend

Trypsin inhibitor inactivation (TII) was measured according to Hamerstrand et al. (1981). This assay is based on the increase in absorbance at 410 nm when trypsin (Type 1, from Bovine Pancreas, Sigma Chemical Co., St. Louis, MO) is incubated with the substrate benzoyl-DL arginine (BAPA) (Sigma Chemical Co., St. Louis, MO). The presence of TI results in a decrease in absorbance. The <93 μm particle size fraction was used for the assay. S-Blend powders were first defatted with 10 ml of hexane per 1 g of powder. A dilution factor of 1/2500 was used for the raw samples and a factor of 1/156.3 was used for the extruded samples. The percent inactivation of trypsin inhibitor for the extruded samples was calculated as:

$$\% \text{ TII} = \{1 - [(\text{mg TI / g extruded sample}) / (\text{mg TI / g raw sample})]\} \times 100 \quad [6]$$

3.5. Blending of Different Powders

After analyses (Section 2.4) of the powders, 50:50 blends were made between various wheat and soy powders. The powders chosen for blending represented a range of instant properties related to their use for instant beverage bases. These blends were measured for viscosity, dispersibility, and stability.

3.6. Statistics

Statistical differences between extrusion conditions, particle sizes, and raw materials were calculated by the mixed method with SAS version 8.01 (SAS Institute, Cary, NC). Correlations between variables were calculated using Microsoft Excel 97 (Microsoft, Redmond, WA)

IV Results and Discussion

4.1. Extrusion of Wheat Flour (WF) and Wheat Flour + Lecithin (WFL)

After extrusion of the WF and WFL, the extrudates were dried overnight and ground to produce powders with three particle sizes: 145-249 μm, 93-145 μm, <93 μm. The following are results along with analysis and discussion regarding the instant properties measured for all extruded wheat flour samples.

4.1.1. Particle Size Analysis

The mean particle sizes of the 145-249 μm fraction produced by milling and sieving of the WF and WFL extrudates ranged from approximately 210 μm to 230 μm as measured by laser particle size analysis (Table 4.1). The measured size of the 93-145 μm sieve fraction ranged from 130-140 μm and the <93 μm sieve fraction ranged from 50-60 μm. It should be noted that if any swelling occurred when the powders were dispersed in isopropanol for the laser analysis, the particle size measurements would be inflated. Based on appearance and feel, powders of the two largest particle sizes were still somewhat granular, while the powder below 93 μm was finer.

4.1.2. Specific Mechanical Energy (SME) During Extrusion of Wheat Flour

The SME was significantly affected by changes in moisture, screw speed, and temperature during extrusion ($p<0.05$, Table 4.2). The different combinations of these variables resulted in a range of SME from 83±1 Wh/kg to 190±7 Wh/kg. At lower moisture content and higher screw speed, there was a significant increase in the mechanical energy input into the extruded materials. The effect of temperature on the

Table 4.1. Laser Particle Size Analysis of Extruded and Milled Wheat Flour (WF) and Wheat Flour + Lecithin (WFL) Powders

	145 - 249 μm Sieve Fraction	93 - 145 μm Sieve Fraction	<93 μm Sieve Fraction
Treatment[a] M/S/T rep	**Mean Particle Size (μm)**		
WF 25/300/145 rep 1	210	133	59
WF 25/300/145 rep 2	214	129	51
WFL 25/300/120 rep 1	219	137	52
WFL 25/300/120 rep 2	231	142	57
Raw Wheat Flour = 38 μm			

[a] M = moisture (%), S = screw speed (rpm), T = zone 5 temperature (°C). Each repetition extruded on a different day.

Ta

M
Sl
*

Table 4.2. Specific Mechanical Energy (SME) and Statistical Relationships During Extrusion of Wheat Flour (WF) and Wheat Flour + Lecithin (WFL)

Extrusion Conditions M/S/T	WF	WFL
	SME (Wh/kg)	
25/300/120	190±7	165±7
25/200/120	144±1	133±5
35/200/120	78±8	75±1
35/300/120	118±1	112±5
25/300/145	173±4	150±0
25/200/145	120±1	104±1
35/200/145	83±1	69±0
35/300/145	118±3	102±3
	WF	**WFL**
	F value	
M	608.94*	1371.74*
S	349.00*	782.09*
T	15.27*	127.39*
M*S	6.33*	2.34
M*T	25.86*	30.51*
S*T	0.07	3.47
M*S*T	1.52	12.46*
	Least Squares Means	
M: 25% - 35%	**Estimate of Difference (Wh/kg)**	
200 rpm, 120°C	67*	51*
200 rpm, 145°C	37*	35*
300 rpm, 120°C	73*	53*
300 rpm, 145°C	55*	48*
S: 200 rpm - 300 rpm		
25%, 120°C	-46*	-32*
25%, 145°C	-53*	-46*
35%, 120°C	-40*	-37*
35%, 145°C	-36*	-33
T: 120°C - 145°C		
25%, 200 rpm	25*	29*
25%, 300 rpm	18	15*
35%, 200 rpm	-5	5
35%, 300 rpm	-1	10

M = moisture (%), S = screw speed (rpm), T = zone 5 temperature (°C).
Standard deviation measured beteween repetitions of extrusion.
* Significant at $p<0.05$.

SME was not as great as that of moisture and screw speed, but an increase in barrel temperature at 25% moisture and a screw speed of 200 rpm led to a significant decrease in the SME that was not seen with an increase in temperature at 35% moisture with the same screw speed.

Numerous studies have found similar effects of extrusion conditions on SME. Whalen et al. (1997) reported a decrease in torque as temperature increased, especially at 15-25% moisture, the lower range used in their experiment. Increasing the barrel temperature has also been reported by others to reduce the SME (Bhattacharya and Hanna, 1987; Bruin et al., 1978). Brummer et al. (2002) reported SME values that increased from below 100 Wh/kg to over 300 Wh/kg as the moisture content of extruded corn starch decreased from 32% to 13%. Bhattacharya et al. (1999) and Della Valle et al. (1989) also found that the SME decreased as moisture content increased.

These results can be explained by the effects of moisture and temperature on dough rheology. As either moisture or temperature increase, dough viscosity decreases (Harper, 1981). A dough with lower viscosity requires less motor power to extrude, resulting in a lower SME.

Increasing the screw speed has been reported to both increase (Bhattacharya et al., 1999; Della Valle et al., 1989) and decrease (Van Zuilichem et al., 1983) the SME. As the screw speed increases, the degree of fill in the barrel decreases and the viscosity of the dough may also decrease, leading to a lowering of the SME (Frame, 1994). However, in the present experiments the increase in screw speed was large enough to overcome the slight reduction in torque from the motor, resulting in a higher SME (Appendix IIa).

4.1.3. SME During Extrusion of Wheat Flour with Lecithin

The different extrusion variables affected the SME of the wheat flour + lecithin formulation in a similar manner to their effect on SME of wheat flour alone. Lower temperature, lower moisture, and higher screw speed all had significant effects of increasing the SME ($p<0.05$, Table 4.2). However, adding lecithin to the wheat flour resulted in an overall decrease in the SME ($p<0.05$, Table 4.3). This most likely occurred due to lubrication provided by the lipids in the WFL sample during extrusion. The replacement of 4% of the wheat flour may have also added to the reduction of the SME.

4.1.4. Water Absorption Index (WAI) of Extruded Wheat Flour

Raw wheat flour had a WAI of 1.91 g/g while the extruded WF powders had WAI values that ranged from 6.3±0.21 g/g to 8.48±0.14 g/g (Table 4.4). The WAI was dependent on both the extrusion conditions and powder particle size. Extrusion moisture, screw speed, and barrel temperature all had significant effects on the WAI ($p<0.05$, Table 4.4). Extrusion at higher moisture and temperature led to an increase in the WAI, but increasing the screw speed led to a decrease in the WAI. There was also a significant decrease in the WAI as the powder particle size decreased ($p<0.05$, Table 4.4, Figure 4.1).

These effects of different extrusion conditions on the WAI are generally consistent with other published results (Anderson et al., 1969; Gomez and Aguilera, 1983; Jin et al., 1995; Wen et al., 1990). During extrusion, the WAI increases up to a maximum, corresponding to an increase in the degree of starch damage. As greater dextrinization occurs, the WAI then decreases (Colonna et al., 1989). According to Gomez and

Table 4.3. Comparison[a] Between Properties of Extruded and Milled Wheat Flour (WF) and Wheat Flour + Lecithin (WFL) Powders

	Estimate of Difference
	WF - WFL
SME (Wh/kg)	14*
WAI (g/g)	0.43*
WSI (g/g)	0.095*
Cold Viscosity (RVU)	16*
Hot Paste Viscosity (RVU)	-33*
Dispersibility (%)	-13.9*
Stability (%)	9.9*

[a] Comparison done for <93 μm particle size.
SME = specific mechanical energy, WAI = water absorption index, WSI = water solubility index, RVU = Rapid Visco Units.
* Significant at $p<0.05$.

Table 4.4. Water Absorption Index (WAI) and Statistical Relationships of Extruded and Milled Wheat Flour Powders

	Particle Size		
Extrusion Conditions M/S/T	145-249 μm	93-145 μm	<93 μm
	WAI (g/g)		
25/300/120	7.48±0.26	7.09±0.16	6.30±0.21
25/200/120	8.15±0.02	7.79±0.03	7.11±0.25
35/200/120	NT	NT	7.05±0.02
35/300/120	NT	NT	6.94±0.11
25/300/145	7.64±0.14	7.32±0.20	7.07±0.13
25/200/145	8.23±0.06	7.87±0.07	7.67±0.06
35/200/145	8.48±0.14	8.34±0.26	7.66±0.11
35/300/145	7.76±0.07	7.60±0.08	7.10±0.08
Raw Wheat Flour = 1.91 g/g			
	Particle Size		
	145-249 μm	93-145 μm	<93 μm
	F value		
M	9.42*	26.91*	4.5
S	69.13*	61.34*	54.73*
T	NT	NT	55.79*
M*S	0.33	0.38	6.87*
M*T	NT	NT	3.92
S*T	NT	NT	0.76
M*S*T	NT	NT	5.45*
	Least Squares Means		
M: 25% - 35%	**Estimate of Difference (g/g)**		
200 rpm, 120°C	-0.30*	-0.51*	0.06
200 rpm, 145°C			0.01
300 rpm, 120°C	-0.20	-0.40*	-0.64*
300 rpm, 145°C			-0.03
S: 200 rpm - 300 rpm			
25%, 120°C	0.63*	0.63*	0.81*
25%, 145°C			0.60*
35%, 120°C	0.72*	0.74*	0.11
35%, 145°C			0.56*
T: 120°C - 145°C			
25%, 200 rpm	NT	NT	-0.56*
25%, 300 rpm	NT	NT	-0.77*
35%, 200 rpm	NT	NT	-0.61*
35%, 300 rpm	NT	NT	-0.16
Particle Size	**C - B**	**C - A**	**B - A**
Estimate (g/g)	-0.56*	-0.85*	-0.29

M = moisture (%), S = screw speed (rpm), T = zone 5 temperature (°C).
Standard deviation measured between powders produced from repetition of extrusion.
NT = not tested due to the inability to form a firm pellet after centrifugation.
A = 145-249μm particle size, B = 93-145μm particle size, C = <93μm particle size.
* Significant at $p<0.05$.

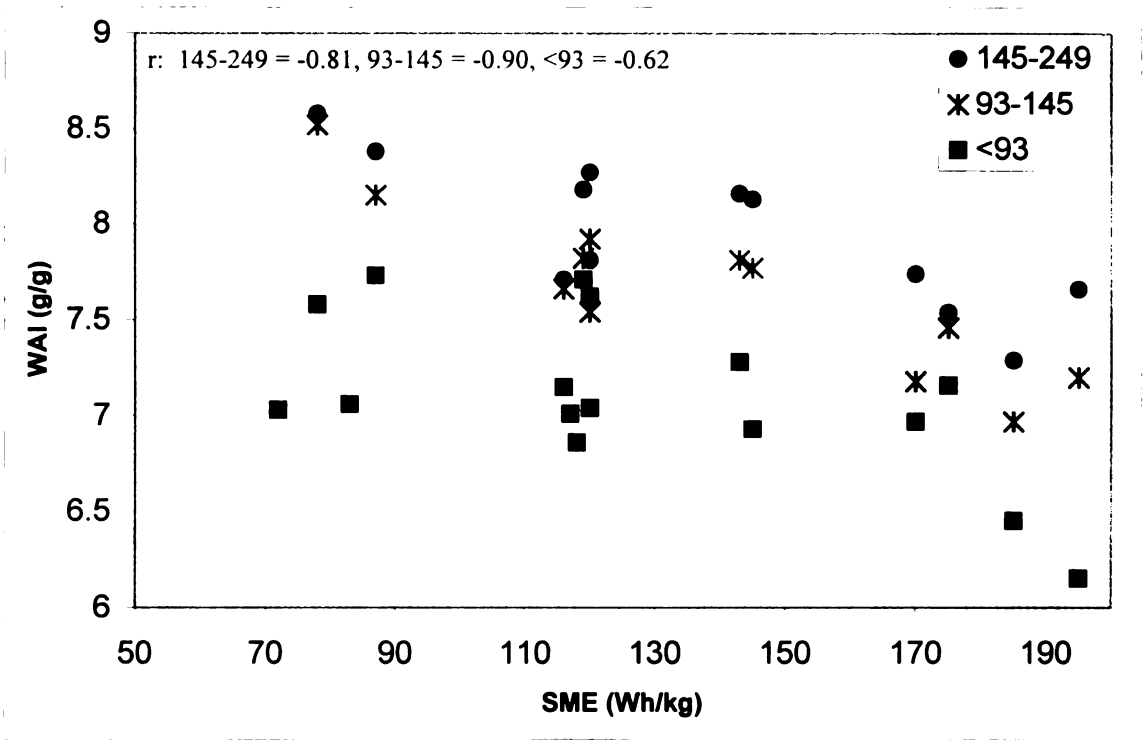

Figure 4.1. Relationship between the specific mechanical energy (SME) and the water absorption index (WAI) for extruded and milled wheat flour powders.

Aguilera (1983), the WAI is dependent on the binding of water by hydrophilic groups and on the ability of macromolecules to form gels. More highly dextrinized starches having lower water absorption capabilities. Decreased WAI measurements were also noted by Wen et al. (1990) to be consistent with an increase in starch fragmentation. Colonna et al. (1984) compared the effects of drum drying versus extrusion on wheat starch. They found that extrusion led to greater depolymerization of amylose, and especially amylopectin, than did drum drying. In a subsequent study this group compared the water swelling capability of drum-dried and extruded wheat starch (Doublier et al., 1986). They found that drum-dried starches had higher cold water swelling capacities than the extruded starches. This was attributed to low water accessibility of extruded starches due to their compact structure.

The SME is an important variable to consider since its increase has been correlated with a greater degree of starch fragmentation and conversion (Brummer et al., 2002; Della Valle et al., 1989; Klingler et al., 1986; Kokini, 1993; Schuchmann and Danner, 2000). Brummer et al. (2002) measured the molecular weight of corn starch after extrusion by size exclusion chromatography and found an exponential decrease in weight as the SME increased. The role of mechanical energy input is supported by the negative correlation between the SME and WAI for all three particle size fractions (Figure 4.1). The conditions of moisture, screw speed, and temperature that increased the WAI, decreased the SME. That starch fragmentation is reduced at lower SME values is also supported by the water solubility index data (see section 4.1.6).

4.1.5. WAI of Extruded Wheat Flour with Lecithin

The WAI and water solubility index were not measured for some milled and sieved extrudates in the 145-249 μm and 93-145 μm particle size fractions because a firm pellet could not be formed. At <93 μm, there were only small differences in the WAIs of samples produced under different extrusion conditions (Table 4.5). There was a significant interaction between moisture and temperature ($p<0.05$). At 145°C, the WAI increased as moisture increased, but at 120°C, an increase in moisture led to a decrease in the WAI.

These results may represent conditions which span the increase of the WAI up to a maximum and then its decrease. At 145°C the combination of thermal and mechanical energy may have fully cooked the starch. The extrusion conditions would have then been severe enough to where the WAI was beyond its maximum. Thus, increasing the moisture content and the resultant decrease in the SME would result in less degradation of the starch, and a higher WAI. At 120°C, the starch may not have been fully cooked due to the presence of lecithin and its lowering effect on the SME. Under these conditions, the maximal WAI may not have been reached. Conditions which reduced the amount of starch damage would then have the opposite effect on the WAI as they would for a fully cooked starch. This would explain why an increase in feed moisture in this case led to a decrease in the WAI. This hypothesis is supported by RVA data presented in section 4.1.9.

The WAI values of wheat flour + lecithin were generally lower than that of wheat alone, although there was not a large difference (Table 4.3).

Table 4.5. Water Absorption Index (WAI),Water Solubility Index (WSI), and Statistical Relationships of Extruded and Milled Wheat Flour + Lecithin Powders (<93 μm Particle Size Fraction)[a]

Extrusion Conditions M/S/T		
	WAI (g/g)	**WSI (g/g)**
25/300/120	6.63±0.07	0.122±0.001
25/200/120	6.61±0.04	0.086±0.006
35/200/120	6.48±0.24	0.047±0.001
35/300/120	6.41±0.19	0.066±0.006
25/300/145	6.44±0.08	0.106±0.004
25/200/145	6.61±0.21	0.066±0.007
35/200/145	7.19±0.26	0.052±0.002
35/300/145	7.12±0.03	0.079±0.001
	Raw Wheat Flour + Lecithin = 2.05 g/g	Raw Wheat Flour + Lecithin = 0.073 g/g
	WAI	**WSI**
	F value	**F value**
M	7.69*	421.28*
S	0.75	333.52*
T	13.78*	1.67
M*S	0	10.45*
M*T	23.95*	48.29*
S*T	0.31	11.52*
M*S*T	0.39	0.94
	Least Squares Means	
M: 25% - 35%	**Estimate of Difference (g/g)**	
200 rpm, 120°C	0.13	0.039*
200 rpm, 145°C	-0.58	0.015*
300 rpm, 120°C	0.23	0.046*
300 rpm, 145°C	-0.69*	0.028*
S: 200 rpm - 300 rpm		
25%, 120°C	-0.03	-0.027*
25%, 145°C	0.17	-0.040*
35%, 120°C	0.08	-0.020*
35%, 145°C	0.07	-0.027*
T: 120°C - 145°C		
25%, 200 rpm	0.00	0.020*
25%, 300 rpm	0.20	0.006
35%, 200 rpm	-0.71*	-0.005
35%, 300 rpm	-0.72*	-0.013

[a] 145-249 μm and 93-145 μm fractions did not form firm pellets after centrifugation and were not measured.

M = moisture (%), S = screw speed (rpm), T = zone 5 temperature (°C).

Standard deviation measured between powders produced from repetition of extrusion.

* Significant at $p<0.05$.

4.1.6. Water Solubility Index (WSI) of Extruded Wheat Flour

The WSI of the extruded powders ranged from about 0.10 g/g to 0.30 g/g (Table 4.6). Extrusion feed moisture had the most significant effect on the WSI. The WSI increased when the moisture was reduced from 35% to 25% at the 93-145 μm and <93 μm particle size ranges ($p<0.05$). Increasing the screw speed also led to an increase in the WSI for the 93-145 and <93μm particle sizes ($p<0.05$). Temperature did not have a significant effect.

Like water absorption, water solubility is also related to conditions which favor the degradation and fragmentation of starch (Jin et al., 1995; Gomez and Aguilera, 1983). However, the inverse relationship exists to water absorption, as increased fragmentation leads to greater water solubility. According to Diosady et al. (1985) and Davidson et al. (1984), the most important factor regarding the fragmentation of starch is shear stress. Various studies have shown that increases in temperature or moisture during extrusion lead to decreases in starch fragmentation, while increases in screw speed lead to increasing amounts of fragmentation (Davidson et al., 1984; Wen et al., 1990). Davidson et al. (1984) states that for polymers, the main effect of increasing temperature is a decrease in viscosity, which results in a decrease in shear stress. An increase in feed moisture would also have the effect of lowering viscosity, while increasing the screw speed increases the shear rate (Harper, 1981).

The conditions of moisture, temperature and screw speed that led to an increase in SME, also resulted in an increased WSI value. The SME was positively correlated with the WSI for all three particle size fractions (Figure 4.2). There were not significant differences in WSI among the particle sizes. This may be due in part to missing data; at

Table 4.6. Water Solubility Index (WSI) and Statistical Relationships of Extruded and Milled Wheat Flour Powders

	Particle Size		
Extrusion Conditions M/S/T	145-249 μm	93-145 μm	<93 μm
	WSI (g/g)		
25/300/120	0.173±0.008	0.233±0.004	0.302±0.028
25/200/120	0.141±0.010	0.175±0.018	0.223±0.016
35/200/120	NT	NT	0.083±0.161
35/300/120	NT	NT	0.115±0.021
25/300/145	0.157±0.020	0.196±0.009	0.225±0.016
25/200/145	0.119±0.006	0.157±0.012	0.177±0.031
35/200/145	0.125±0.008	0.101±0.020	0.120±0.024
35/300/145	0.128±0.033	0.113±0.004	0.131±0.004
Raw Wheat Flour = 0.020 g/g			
	Particle Size		
	145-249 μm	93-145 μm	<93 μm
	F value		
M	0.98	54.69*	145.69*
S	0.99	7.06*	18.35*
T	NT	NT	3.02
M*S	1.24	2.67	4.48
M*T	NT	NT	19.89*
S*T	NT	NT	1.72
M*S*T	NT	NT	0.06
	Least Squares Means		
M: 25% - 35%	**Estimate of Difference (g/g)**		
200 rpm, 120°C	-0.620	0.065*	0.141*
200 rpm, 145°C			0.057
300 rpm, 120°C	0.037	0.102*	0.188*
300 rpm, 145°C			0.094
S: 200 rpm - 300 rpm			
25%, 120°C	-0.035	-0.048*	-0.079
25%, 145°C			-0.048
35%, 120°C	0.622	-0.012	-0.032
35%, 145°C			-0.011
T: 120°C - 145°C			
25%, 200 rpm	NT	NT	0.046
25%, 300 rpm	NT	NT	0.077
35%, 200 rpm	NT	NT	-0.038
35%, 300 rpm	NT	NT	-0.017
Particle Size	**C - B**	**C - A**	**B - A**
Estimate (g/g)	0.010	0.031	0.023

M = moisture (%), S = screw speed (rpm), T = zone 5 temperature (°C).
Standard deviation measured between powders produced from repetition of extrusion.
NT = not tested due to the inability to form a firm pellet after centrifugation.
A = 145-249μm particle size, B = 93-145μm particle size, C = <93μm particle size.
* Significant at $p<0.05$.

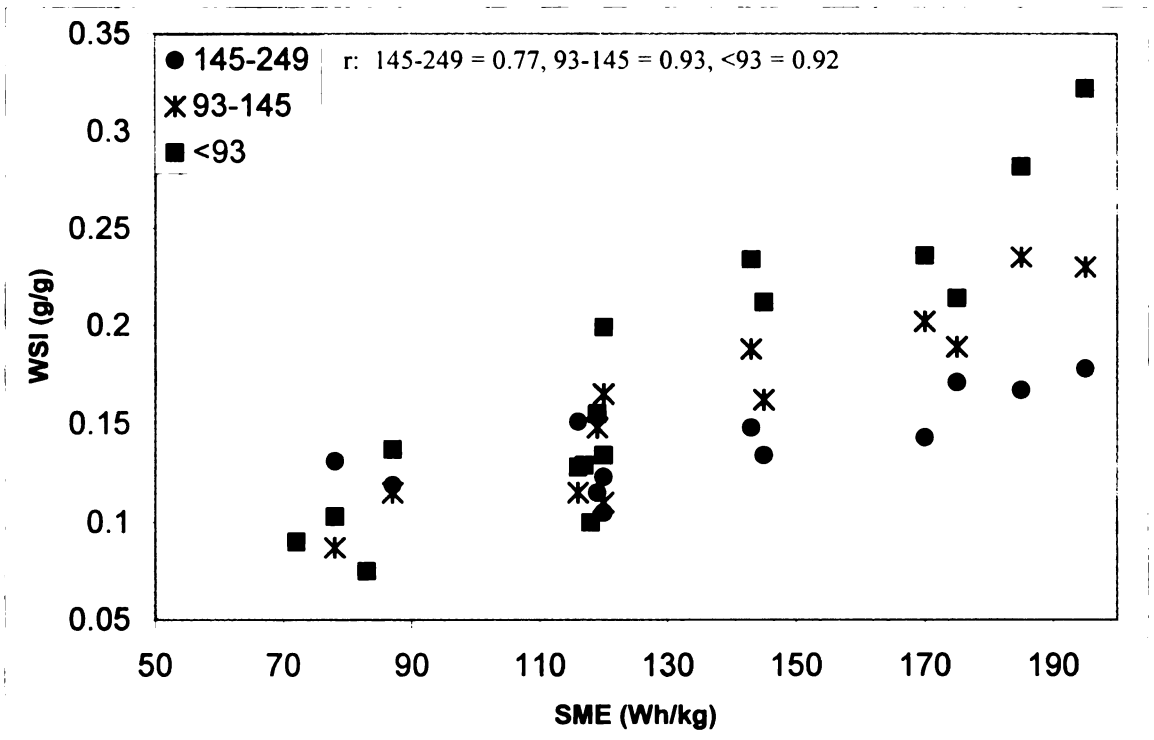

Figure 4.2. Relationship between the specific mechanical energy (SME) and the water solubility index (WSI) for extruded and milled wheat flour powders.

the particle sizes of 145-249 μm and 93-145 μm, solid pellets would not form during the measurement of the WSI of powders from some of the extrusion treatments, resulting in unobtainable data. However, it appeared that water solubility was higher as particle size decreased at the upper range of the WSI measured.

4.1.7. WSI of Extruded Wheat Flour with Lecithin

The WSI values of powders made from extruded WFL were mainly affected by the feed moisture and extruder screw speed. Lower moisture content and higher screw speed resulted in a higher WSI (Table 4.5). Although the general effects of the extrusion conditions were similar to the results for wheat flour extruded alone, the WSI was significantly lower when WF was extruded with lecithin ($p<0.05$, Table 4.3). The WSI for the WFL only reached a maximum of 0.122±0.001 g/g compared to 0.302±0.028 g/g for the WF (Tables 4.5, 4.6).

A decrease in the water solubility of extruded cereals when lipids are added has been attributed to two different effects. Colonna et al. (1983) found that extrusion of cassava starch with added monoglycerides and triglycerides resulted in less starch degradation. This was attributed to the lubricant effect of lipids inside of the extruder. Experiments by Schweizer et al. (1986) and Mercier et al. (1980) found that lipid complexation inside of the amylose helix decreased the water solubility of starches. However, Mercier et al. (1980) also found that only free fatty acids and monoglycerides could form the complex. Fats such as soy lecithin were not able to complex because they were too large to fit into the helix.

4.1.8. Rapid Visco Analyzer Viscosity of Extruded Wheat Flour

Depending on extrusion conditions and particle size, cold viscosity values of WF powder samples ranged from approximately 55 RVU to over 200 RVU (Table 4.7). These viscosities were much greater than that of raw wheat flour at 25°C. Decreasing the extrusion moisture and temperature led to decreases in cold viscosity ($p<0.05$). However, at the lower screw speed, the cold viscosity was slightly higher. These results were also inversely correlated with the SME, as greater mechanical energy input was related to a decrease in the cold viscosity (Figure 4.3).

According to Whalen et al. (1997), cold viscosity is due to the presence of swollen granules and non-granular starch in the form of high molecular weight polymers and dextrins. Drum drying, which involves much less shear than extrusion cooking, was found to produce much higher viscosity starch suspensions than extruded ones (Doublier et al., 1986). The decrease in viscosity after extrusion was attributed to lower swelling capacity and lower molecular size of amylose and amylopectin in extruded starches. Additional studies have also related increases in the severity of extrusion conditions and decreases in cold viscosity (Whalen et al., 1997; Gomez and Aguilera, 1983). Bhattaycharya et al. (1999) was able to correlate the SME and cold viscosity for an extruded potato and wheat flour blend. A negative correlation was found in their study as well as in the current study. The positive correlation of the WSI and negative correlation of the cold viscosity with the SME provides additional evidence of the relationship between increased starch breakdown and lower cold viscosity (Figures 4.2 and 4.3

Powder particle size of the extruded WF samples was also a significant factor affecting the RVA viscosity ($p<0.05$, Table 4.7, Figure 4.3). The <93 μm fraction had

Table 4.7. Cold Viscosity and Statistical Relationships of Extruded and Milled Wheat Flour Powders

	Particle Size		
	145-249 μm	93-145 μm	<93 μm
Extrusion Conditions M/S/T	**Cold Viscosity (RVU)**		
25/300/120	108±5	110±17	54±4
25/200/120	121±10	172±0	65±6
35/200/120	148±7	208±3	143±17
35/300/120	153±2	196±79	133±28
25/300/145	135±20	161±3	94±2
25/200/145	152±29	229±25	111±2
35/200/145	213±23	244±37	156±2
35/300/145	206±9	218±37	132±28
Raw Wheat Flour = 3 RVU			
	Particle Size		
	145-249 μm	93-145 μm	<93 μm
	F value		
M	66.93*	7.62*	91.22*
S	1.63*	5.76*	6.05*
T	50.43*	5.67*	15.06*
M*S	1.18	1.68	0.06
M*T	5.84*	0.52	8.45*
S*T	0.40	0.08	0.61
M*S*T	0.06	0.01	0.10
	Least Squares Means		
M: 25% - 35%	**Estimate of Difference (RVU)**		
200 rpm, 120°C	-27	-37	-78*
200 rpm, 145°C	-61*	-15	-45
300 rpm, 120°C	-44	-86	-79*
300 rpm, 145°C	-71*	-57	-38
S: 200 rpm - 300 rpm			
25%, 120°C	12	62	11
25%, 145°C	18	68	17
35%, 120°C	-4	13	10
35%, 145°C	7	26	24
T: 120°C - 145°C			
25%, 200 rpm	-32	-58	-46
25%, 300 rpm	-27	-51	-40
35%, 200 rpm	-65*	-36	-13
35%, 300 rpm	-54*	-22	1
Particle Size	**C - B**	**C - A**	**B - A**
Estimate (RVU)	**-81***	**-43***	**38***

M = moisture (%), S = screw speed (rpm), T = zone 5 temperature (°C).
Viscosity measured in Rapid Visco Units (RVU).
Standard deviation measured between powders produced from repetition of extrusion.
A = 145-249μm particle size, B = 93-145μm particle size, C = <93μm particle size.
* Significant at $p<0.05$.

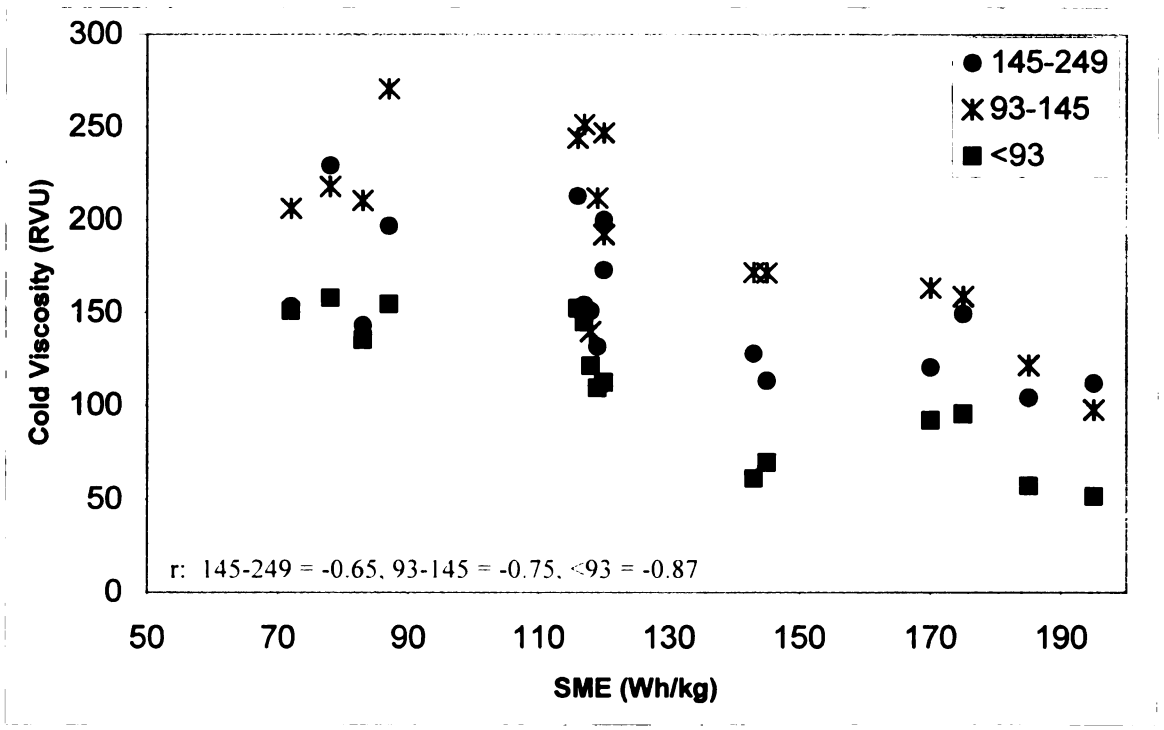

Figure 4.3. Relationship between the specific mechanical energy (SME) and cold viscosity for extruded and milled wheat flour powders.

significantly lower cold viscosity than the two larger particle size fractions. Similar results were reported in a study by Becker et al. (2001), who examined the effects of milling on RVA viscosity profiles. Smaller particle sizes produced by grinding with different mills and sieving resulted in lower RVA viscosities for extruded corn and wheat pellets.

In addition to the peak viscosity, particle size also had an effect on the hydration of the powders. As shown in Figure 4.4, the time to reach peak viscosity increased as the particle size increased. The peak viscosity of the <93 μm particle size WF powder typically occurred at the start of analysis, while the 145-249 μm fraction took more than 2 minutes to reach peak viscosity. This would explain why the 93-145 μm fraction had a higher cold viscosity than the 145-249 μm fraction (Figure 4.3). After 2 minutes, the heating cycle of the RVA began and the peak viscosity at this time was recorded as the hot paste viscosity. However, this was not a true gelatinization peak that would occur when heating raw starch. Once the 145-249 μm fraction was fully hydrated, its viscosity increased and was similar to the 93-145 μm fraction (Figure 4.5). The lack of a gelatinization peak when comparing the cold and hot paste viscosities, also indicates that the powders were fully cooked (Tables 4.7, 4.8).

4.1.9. Rapid Visco Analyzer Viscosity of Extruded Wheat Flour with Lecithin

When examining RVA viscosities of powders from extruded WFL, a significant interaction was noted between feed moisture and extruder temperature ($p<0.05$, Table 4.9). At 35% moisture, increasing the temperature to 145°C caused the cold viscosity to increase while at 25% moisture, the effect of temperature was not significant. Increasing

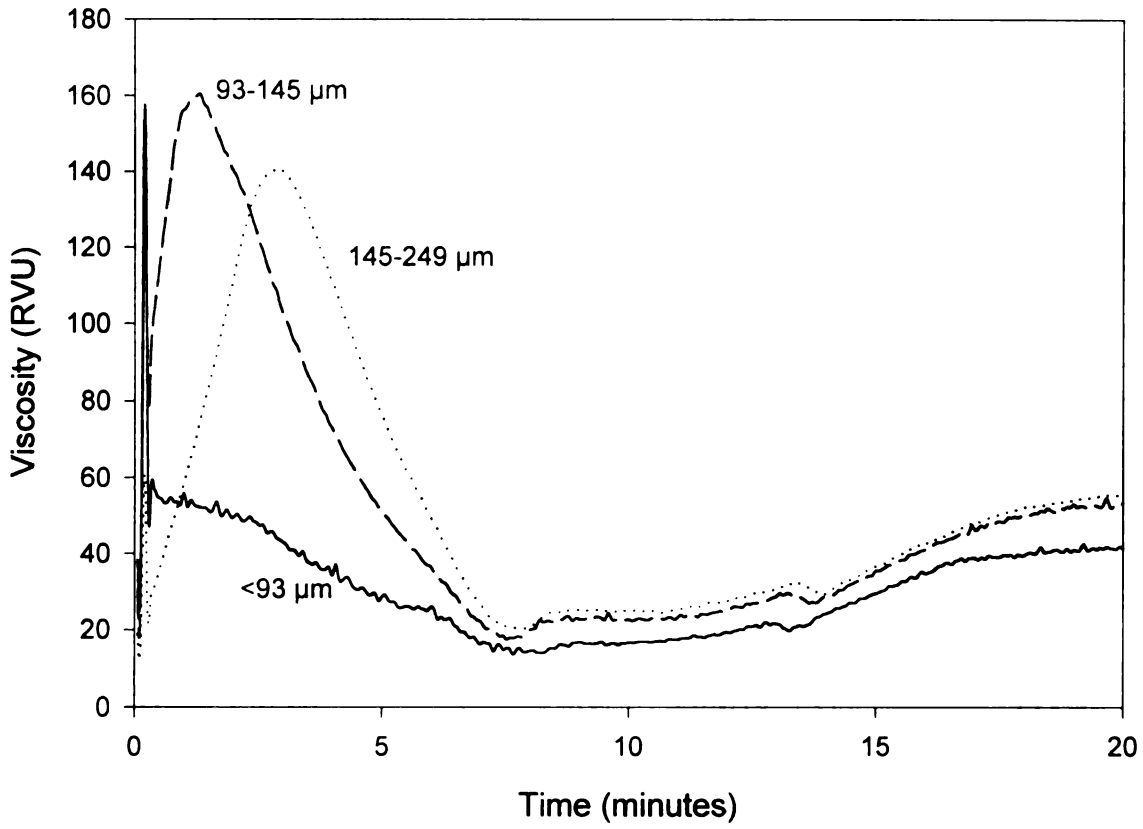

Figure 4.4. Representative Rapid Visco Analyzer pasting curve of extruded and milled wheat flour powders. Viscosity in Rapid Visco Units (RVU).

Table 4.8. Hot Paste Viscosity and Statistical Relationships of Extruded and Milled Wheat Flour Powders

	Particle Size		
	145-249 μm	93-145 μm	<93 μm
Extrusion Conditions M/S/T	**Hot Paste Viscosity (RVU)**		
25/300/120	126±1	102±12	47±2
25/200/120	147±9	148±4	55±2
35/200/120	261±1	210±3	139±3
35/300/120	210±16	196±79	121±8
25/300/145	152±30	151±2	84±5
25/200/145	180±31	213±19	97±7
35/200/145	251±21	243±36	141±7
35/300/145	234±6	213±33	121±22
Raw Wheat Flour = 226 RVU			
	Particle Size		
	145-249 μm	93-145 μm	<93 μm
	F value		
M	105.24*	13.44*	168.28*
S	11.73*	5.10	10.35*
T	4.43	5.85	19.77*
M*S	0.34	0.89	0.79
M*T	1.74	0.84	17.47*
S*T	0.67	0.23	0.15
M*S*T	1.40	0	0.04
	Least Squares Means		
M: 25% - 35%	**Estimate of Difference (RVU)**		
200 rpm, 120°C	-114*	-61	-84*
200 rpm, 145°C	-71*	-31	-44*
300 rpm, 120°C	-84*	-94	-74*
300 rpm, 145°C	-81*	-62	-37*
S: 200 rpm - 300 rpm			
25%, 120°C	21	46	8
25%, 145°C	27	62	13
35%, 120°C	51	14	18
35%, 145°C	17	30	20
T: 120°C - 145°C			
25%, 200 rpm	-32	-64	-42*
25%, 300 rpm	-26	-49	-37*
35%, 200 rpm	10	-34	-2
35%, 300 rpm	-24	-17	0
Particle Size	**C - B**	**C - A**	**B - A**
Estimate (RVU)	-84*	-95*	-11

M = moisture (%), S = screw speed (rpm), T = zone 5 temperature (°C).
Viscosity measured in Rapid Visco Units (RVU).
Standard deviation measured between powders produced from repetition of extrusion.
A = 145-249μm particle size, B = 93-145μm particle size, C = <93μm particle size.
* Significant at $p<0.05$.

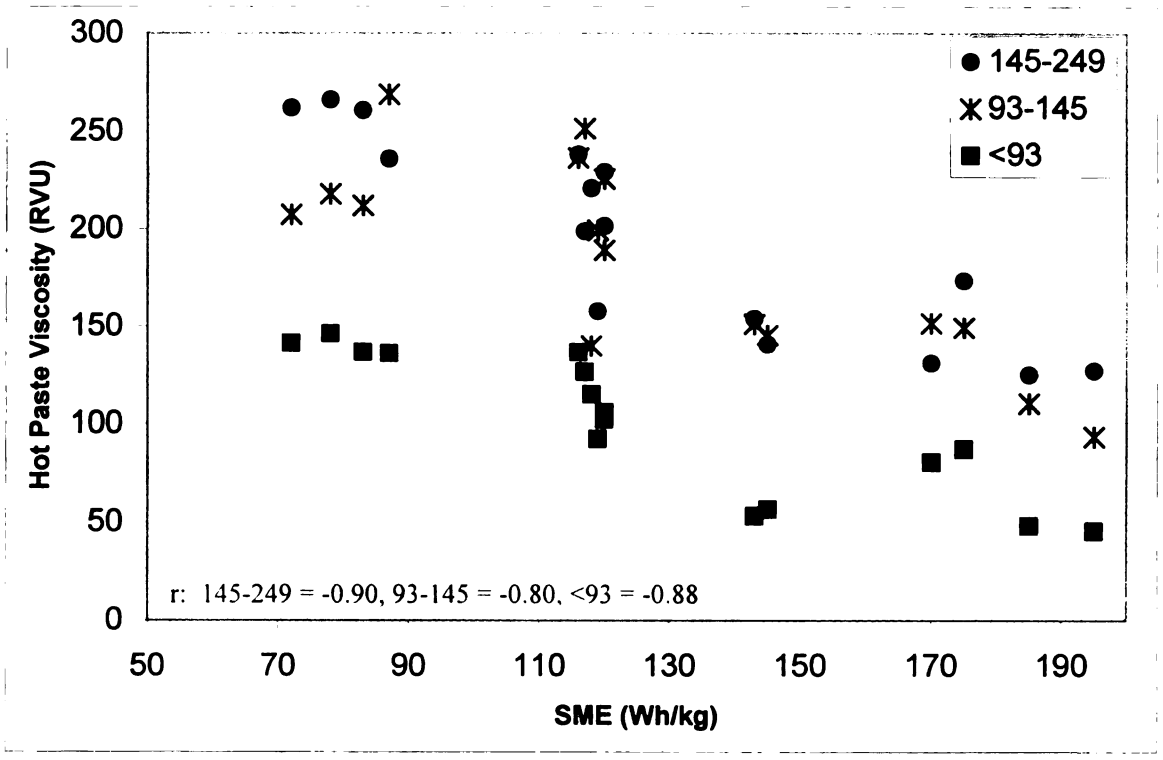

Figure 4.5. Relationship between the specific mechanical energy (SME) and hot paste viscosity for extruded and milled wheat flour powders.

Table 4.9. Cold Viscosity and Statistical Relationships of Extruded and Milled Wheat Flour + Lecithin Powders

	Particle Size		
	145-249 μm	93-145 μm	<93 μm
Extrusion Conditions M/S/T	**Cold Viscosity (RVU)**		
25/300/120	136±7	241±8	106±3
25/200/120	128±6	239±0	118±19
35/200/120	71±1	160±12	52±4
35/300/120	90±1	168± 11	62±7
25/300/145	127±6	235±3	101±1
25/200/145	122±6	233±21	85±9
35/200/145	207±2	216±8	117±27
35/300/145	177±11	166±5	121±16
Raw Wheat Flour + Lecithin = 4 RVU			
	Particle Size		
	145-249 μm	93-145 μm	<93 μm
	F value		
M	7.29*	134.28*	4.38
S	0.01	3.58	0.41
T	321.21*	4.15	9.35
M*S	4.39	5.01	0.10
M*T	416.42*	10.50*	34.62*
S*T	19.90*	7.89*	0.59
M*S*T	15.92*	7.46*	1.50
	Least Squares Means		
M: 25% - 35%	**Estimate of Difference (RVU)**		
200 rpm, 120°C	57*	79*	66*
200 rpm, 145°C	-85*	17	-33
300 rpm, 120°C	46*	73*	45
300 rpm, 145°C	-50*	68*	-20
S: 200 rpm - 300 rpm			
25%, 120°C	-8	-2	12
25%, 145°C	-5	-1	-16
35%, 120°C	-19	-7	-10
35%, 145°C	30*	50*	-3
T: 120°C - 145°C			
25%, 200 rpm	6	6	33
25%, 300 rpm	7	7	6
35%, 200 rpm	-137*	-55*	-65*
35%, 300 rpm	-87*	1	-59*
Particle Size	**C - B**	**C - A**	**B - A**
Estimate (RVU)	-112*	-37*	75*

M = moisture (%), S = screw speed (rpm), T = zone 5 temperature (°C).
Viscosity measured in Rapid Visco Units (RVU).
Standard deviation measured between powders produced from repetition of extrusion.
A = 145-249μm particle size, B = 93-145μm particle size, C = <93μm particle size.
* Significant at $p<0.05$.

the moisture from 25% to 35% at 120°C resulted in a decrease in the cold viscosity for the 145-249 μm and <93 μm particle sizes. At 145°C, there was an increase in the cold viscosity as feed moisture increased.

These trends were similar to those observed for the WAI and changes in cold viscosity may be explained by similar reasons. The decrease in viscosity at 120°C when moisture was raised from 25% to 35% may occur because the starch was not fully cooked at this point. The decrease in SME as moisture increased would result in less mechanical breakdown of the starch. If mechanical energy input was more important than moisture to the cooking of starch, a decrease in the SME would lead to a decrease in the WAI. A gelatinization peak, which is evident when comparing the cold and hot paste viscosities at these extrusion conditions, supports this (Tables 4.9, 4.10). Additional gelatinization and starch damage would lead to an increase in cold viscosity up to a maximum. After being fully cooked, starch damage would result in decreasing viscosity. This may have been the case for the powders at 145°C. Since there was no gelatinization peak for these samples, it can be inferred that increasing the moisture would decrease the amount of starch degradation, and result in higher cold viscosity values.

The effects of particle size on cold viscosity for WFL were similar to those for WF, where the smallest particle size had the lowest cold viscosity (Table 4.9). The cold viscosity of the 93-145 μm fraction was higher than that of the 145-249 μm fraction. This was probably again due to a hydration effect (section 4.1.8) since the hot paste viscosities were similar for the two particle size fractions (Table 4.10).

Table 4.10. Hot Paste Viscosity and Statistical Relationships of Extruded and Milled Wheat Flour + Lecithin Powders

	Particle Size		
	145-249 μm	93-145 μm	<93 μm
Extrusion Conditions M/S/T	**Hot Paste Viscosity (RVU)**		
25/300/120	225±7	242±8	106±4
25/200/120	238±6	244±0	123±9
35/200/120	342±1	353±12	179±1
35/300/120	306±1	281±11	151±1
25/300/145	228±6	237±3	103±4
25/200/145	288±6	258±21	122±12
35/200/145	314±2	221±5	145±6
35/300/145	260±11	169±7	137±7
Raw Wheat Flour + Lecithin = 213 RVU			
	Particle Size		
	145-249 μm	93-145 μm	<93 μm
	F value		
M	57.12*	4.55	149.50*
S	25.45*	56.21*	31.35*
T	0.44	144.16*	15.98*
M*S	0.3	26.30*	0
M*T	15.72*	167.84*	11.21*
S*T	4.30	0	2.04
M*S*T	0.84	3.81	2.97
	Least Squares Means		
M: 25% - 35%	**Estimate of Difference (RVU)**		
200 rpm, 120°C	-104*	-108*	-56*
200 rpm, 145°C	-26	37	-23
300 rpm, 120°C	-81*	-39	-45*
300 rpm, 145°C	-32	68*	-34*
S: 200 rpm - 300 rpm			
25%, 120°C	12	2	17
25%, 145°C	60	21	19
35%, 120°C	36	71*	28*
35%, 145°C	54	52*	8
T: 120°C - 145°C			
25%, 200 rpm	-51	-14	2
25%, 300 rpm	-3	5	3
35%, 200 rpm	28	132*	34*
35%, 300rpm	46	112*	14
Particle Size Estimate (RVU)	**C - B**	**C - A**	**B - A**
	-118*	-142*	-24

M = moisture (%), S = screw speed (rpm), T = zone 5 temperature (°C).
Viscosity measured in Rapid Visco Units (RVU).
Standard deviation measured between powders produced from repetition of extrusion.
A = 145-249μm particle size, B = 93-145μm particle size, C = <93μm particle size.
* Significant at $p<0.05$.

4.1.10. Wettability

Various procedures were attempted in preliminary experiments. These included brushing powder samples through a sieve, as is done with cocoa powder (Anonymous), and dropping powder through a funnel as described by the International Dairy Federation Standard Method 87:1979. However, for any method to be meaningful and reproducible, the powder must be spread evenly on the liquid surface because even small areas of unevenness can lead to large differences in wetting time. None of the methods gave acceptable evenness of powder spreads, and due to the poor reproducibility using the attempted methods, wettability was not measured in this study.

4.1.11. Development of Dispersibility Procedure

Preliminary experiments found that the few methods published describing procedures to measure dispersibility (Sander, 1989; IDF 87:1979) did not suit the products being measured in the current study. Since the main concerns regarding the powders produced in this study were the formation of lumps during mixing with water and sedimentation of particles, the method that was designed needed to take these properties into account.

Mixing: An overhead stirrer was chosen because it could provide consistent mixing at a defined speed. The paddle was placed with one half beneath the surface of the water so that as it turned, the powder would be more evenly spread on the surface. With the entire paddle below the surface, the action of the vortex would be to pull all of the powder into one lump in the center of the liquid.

Mixing time: One minute was chosen as the mixing time after determining the time needed for some commercial products that had acceptable instant properties. Although this method is not able to discriminate among powders that may completely disperse prior to one minute, all powders that did disperse before this time would probably be considered acceptable.

Separation of undispersed solids: After mixing, the suspensions were poured through sieves to remove any lumps. A powder with many lumps that did not disintegrate would have fewer dispersed solids making it through the sieve and there would be a lower solids concentration in the sieved suspension. A larger sieve mesh size was needed for some of the larger particle size powders because of swelling. The smallest sieve size that would allow for free passage of the suspension without blockage of the sieve was chosen. The use of a separatory funnel was chosen to allow for undisturbed drainage.

Measurement of dispersibility: Twenty ml of the sieved suspension were immediately drained so that sedimentation did not occur and an aliquot was measured for solids concentration on a g/g basis. An aliquot of approximately 4 g was taken to reduce the drying time.

Measurement of stability: Two minutes was chosen as the time to allow the remaining approximately 80 ml of the sieved suspension to remain undisturbed because this time was found to be enough to discriminate among samples in preliminary experiments. It also allowed for a faster assay and was within reasonable expectations for a product.

Fifty ml were drained to remove many of the solids that had sedimented. The remaining top portion was chosen to be measured for solids content because a solution with a large amount of sedimentation would have a lower solids content near the top.

4.1.12. Dispersibility of Extruded Wheat Flour

Dispersibility was 100% for the two largest particle sizes, independent of extrusion conditions. Below 93 microns, extrusion moisture and temperature had significant effects ($p<0.05$, Table 4.11). Dispersibility was greater than 90% at the higher temperature and moisture levels. At low moisture and temperature, many large lumps formed and powder dispersibility was less than 60%.

The effects of particle size reduction on mixing and dispersibility were noted by Anderson et al. (1969). In their study, extruded corn grits ground to 20 to 40 mesh were judged to be good for instant gruels. Particles smaller than 40 mesh had poor dispersibility because of lumping and balling and were deemed not suitable for use in products such as instant drinks. The particle size for which dispersibility was found to become difficult for corn grits was much larger than that determined for wheat flour in this experiment. Even at the 93-145 μm particle range, the wheat flour powders dispersed very easily. It was not until a much finer powder (<93 μm) was produced that dispersibility became poor.

The effect of particle size may be due to many of the factors listed in section 2.5. These include an increase in the strength of interparticle forces, an increase in the contact angle, and a decrease in the bulk powder pore size as powder particles become smaller (Schubert, 1987; Schubert, 1993).

Table 4.11. Dispersibility[a] and Statistical Relationships of Extruded and Milled Wheat Flour (WF) and Wheat Flour + Lecithin (WFL) Powders

Extrusion Conditions M/S/T	WF Dispersibility (%)	WFL Dispersibility (%)
25/300/120	58.7±1.8	89.7±1.2
25/200/120	57.4±4.5	91.1±0.9
35/200/120	93.5±0.1	94.8±2.1
35/300/120	93.6±0.4	93.7±0.5
25/300/145	74.0±5.4	92.5±0.4
25/200/145	73.9±1.1	97.3±0.8
35/200/145	87.5±0.4	91.0±2.0
35/300/145	89.2±2.9	89.1±1.3
Raw Wheat Flour = 83.8%		Raw Wheat Flour + Lecithin = 92.2 %
	WF F value	**WFL F value**
M	322.06*	0.51
S	0.32	12.86*
T	14.86*	0.06
M*S	0	1.49
M*T	57.93*	45.25*
S*T	0	2.59
M*S*T	0.24	1.06
	Least Squares Means	
M: 25% - 35%	**Estimate of Difference (%)**	
200 rpm, 120°C	-36.2*	-3.8
200 rpm, 145°C	-13.6*	6.3*
300 rpm, 120°C	-35.0*	-4.0
300 rpm, 145°C	-15.2*	3.4
S: 200 rpm - 300 rpm	-1.3	1.4
25%, 120°C	-0.1	4.8
25%, 145°C	-0.1	1.2
35%, 120°C	-1.7	1.9
35%, 145°C		
T: 120°C - 145°C	-16.6*	-6.2*
25%, 200 rpm	-15.4*	-2.8
25%, 300 rpm	6.0	3.8
35%, 200 rpm	4.5	4.6
35%, 300 rpm	4.5	4.6

[a] Results for <93 μm fraction. 145-249 μm and 93-145 μm fractions had dispersibility of 100%.
M = moisture (%), S = screw speed (rpm), T = zone 5 temperature (°C).
Standard deviation measured between powders produced from repetition of extrusion.
A = 145-249μm particle size, B = 93-145μm particle size, C = <93μm particle size.
* Significant at $p<0.05$.

The rate of hydration may also be an important factor to consider in relation to particle size. As shown by the RVA data (Table 4.7, Figure 4.4), the <93μm size particles hydrated and reached peak viscosity much more quickly than the particles of larger sizes. Swelling reduces dispersibility by clogging pores in the powder, limiting the penetration of water (Schubert, 1993). A delay in the hydration of larger sized particles may allow for dispersal to take place before it is limited by swelling. Thomas and Atwell (1999) also noted that formation of lumps often occurs in fine powders, which have large surface areas, due to quick hydration and gelling of starch on the outer surface of a lump.

Although it is known that dispersibility of starch-containing powders is more difficult because of swelling, it was not known what the effects of the starch modifications that take place during extrusion would be on dispersibility. In general, conditions which led to an increase in the SME, made powder dispersibility poorer. There was an inverse correlation between dispersibility and the SME for the <93 μm powder fraction (Figure 4.6). It is also important to note that the SME was inversely correlated to the WAI and cold viscosity (Figures 4.1 and 4.3), but positively correlated to the WSI (Figure 4.2). Dispersibility was higher in powders with high WAI and high cold viscosity, and low WSI.

These results run counter to what might be expected since dispersibility is more difficult in viscous liquids (Schubert, 1993). Increasing water solubility of powders might be thought to improve dispersibility by reducing the amount of particles that could cause lumps. One hypothesis for the differences noted in dispersibility is that the rate of hydration may be quicker for poorly dispersible powders. If conditions that increase

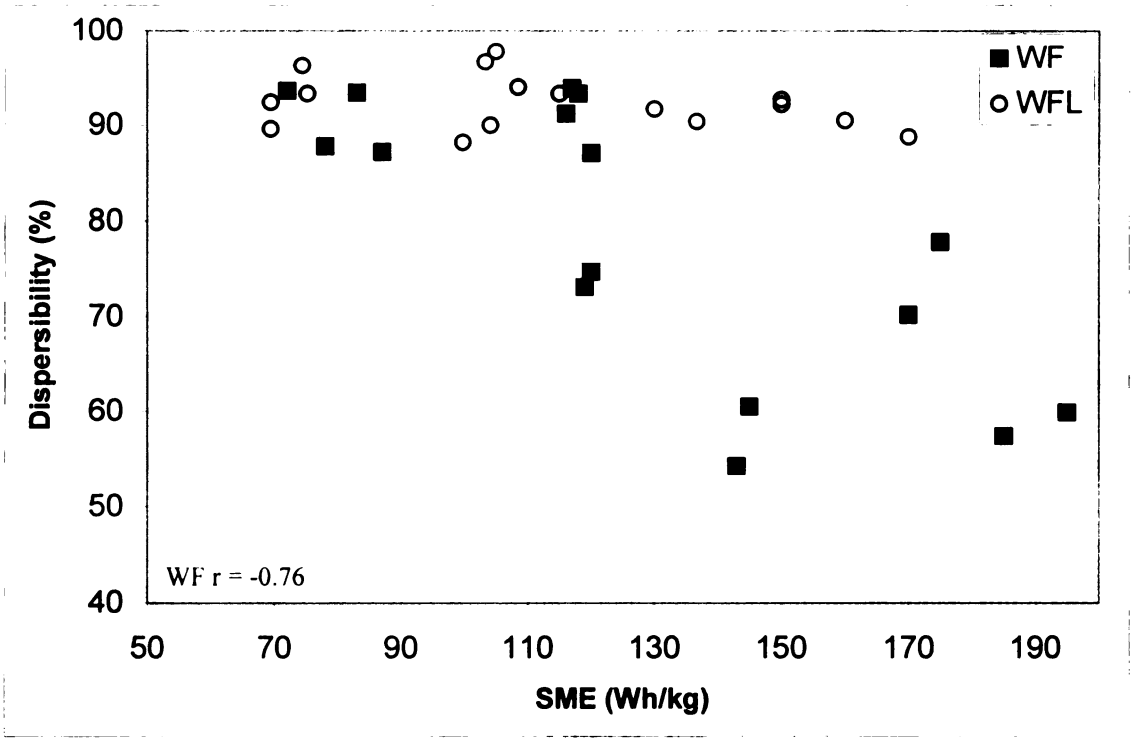

Figure 4.6. Relationship between the specific mechanical energy (SME) and dispersibility for extruded and milled wheat flour powders with (WFL) and without (WF) lecithin.

water solubility and starch granule breakdown also increase the rate of hydration, swelling and gelling could occur before dispersion of the particles is able to take place. This would then lead to the formation of lumps. It is also interesting to note that stickiness of extruded products has been related to increased water solubility (Mercier et al., 1980). Dextrinized starches could stick together more, possibly resulting in more lumps. This could explain why dispersibility was poorer at higher SME and higher water solubility.

4.1.13. Dispersibility of Extruded Wheat Flour with Lecithin

As with the wheat flour, the 145-249 μm and 93-145 μm particle sizes were 100% dispersible for the WFL powders. Dispersibility for the <93 μm samples ranged from 89.1% to 97.3%, significantly greater for the WFL than for the WF ($p<0.05$, Tables 4.3, 4.11). However it is not clear if the properties specific to lecithin or properties attributed to extrusion with lipids are responsible for the improved dispersibility. Lecithin-specific effects may have been the improvement of wetting or the addition of electrostatic repulsive forces between the particles (Schubert, 1993). The changes in water absorption, water solubility, and viscosity when lecithin was added to the wheat flour may also be important. However, these changes may occur with the addition of lipids in general and not just with the addition of lecithin. Further work in this area to clarify the observation is needed.

4.1.14. Stability of Extruded Wheat Flour

Although the two largest particle size fractions were easily dispersed, they were not as stable to sedimentation. The 145-249 μm particle size fraction had the poorest

stability and all of its values were below 40% (Table 4.12, Figure 4.7). Moisture was the only extrusion variable to have a significant effect, as a decrease was associated with increased stability ($p<0.05$, Table 4.12). Stability at 93-145 μm covered a wide range from very poor to very good. Moisture was the only significant variable and stability was greater after extrusion at 25% than at 35% ($p<0.05$). At <93 μm, there was a smaller range measured of stabilities, with most being around 80%.

According to Stokes' law (Schubert, 1993), larger particles would be expected to have poorer stability, as was the case for the 145-249 μm fraction. Stability to sedimentation would be expected to be greater at higher cold viscosity, but there was not a correlation between the two. This may occur because as particles sediment, viscosity would then also decrease. It is also important to keep in mind that the RVA measures viscosity with a paddle, which keeps particles suspended. Changes in particle size and density due to water uptake and swelling should also be considered. The increase in stability at lower moisture extrusion may also be related to increasing solubility at these conditions.

4.1.15. Stability of Extruded Wheat Flour with Lecithin

There were again large differences in stability among the different particle size fractions (Table 4.13). Stability was highest for the <93 μm fraction and in this case, it was correlated with cold viscosity (Figure 4.8). As the cold viscosity increased, stability improved from 60% to over 75%. Overall, WFL had lower stability than WF ($p<0.05$, Table 4.3). This may be due to the lower water solubility and cold viscosity of the WFL

Table 4.12. Stability and Statistical Relationships of Extruded and Milled Wheat Flour Powders

	Particle Size		
Extrusion Conditions M/S/T	145-249 μm	93-145 μm	<93 μm
	Stability (%)		
25/300/120	37.5±2.8	89.8±0.1	80.9±0.9
25/200/120	34.4±9.7	91.4±1.4	77.7±1.5
35/200/120	7.7±0.7	44.1±3.9	74.7±1.6
35/300/120	7.2±0.4	51.8±20.7	78.8±3.1
25/300/145	33.4±2.5	86.0±3.2	82.0±5.5
25/200/145	36.5±0.4	92.3±2.0	84.5±1.4
35/200/145	12.3±1.5	69.8±14.1	87.9±1.9
35/300/145	9.9±2.3	60.5±3.2	83.1±0.3
Raw Wheat Flour = 6.3%			
	Particle Size		
	145-249 μm	93-145 μm	<93 μm
	F value		
M	193.03*	53.28*	0.02
S	0.06	0.27	0
T	0.49	2.96	35.38*
M*S	0.06	0.12	0.09
M*T	1.51	4.17	4.91
S*T	1.45	1.42	11.60*
M*S*T	0.20	0.45	0.56
	Least Squares Means		
M: 25% - 35%	**Estimate of Difference (%)**		
200 rpm, 120°C	27.2*	47.4*	3.0
200 rpm, 145°C	24.2*	22.6	-3.4
300 rpm, 120°C	29.8*	38.1*	2.1
300 rpm, 145°C	23.5*	25.5	-1.1
S: 200 rpm - 300 rpm			
25%, 120°C	-3.1	1.6	-3.2
25%, 145°C	3.1	6.4	2.5
35%, 120°C	-0.5	-7.7	-4.2
35%, 145°C	2.4	9.3	4.8
T: 120°C - 145°C			
25%, 200 rpm	-2.1	-0.9	-6.9
25%, 300 rpm	4.1	3.9	-1.2
35%, 200 rpm	-5.1	-25.7	-13.2*
35%, 300 rpm	-2.2	-8.7	-4.3
Particle Size	**C - B**	**C - A**	**B - A**
Estimate (%)	8.0	58.8*	50.9*

M = moisture (%), S = screw speed (rpm), T = zone 5 temperature (°C).
Standard deviation measured between powders produced from repetition of extrusion.
A = 145-249μm particle size, B = 93-145μm particle size, C = <93μm particle size.
* Significant at $p<0.05$.

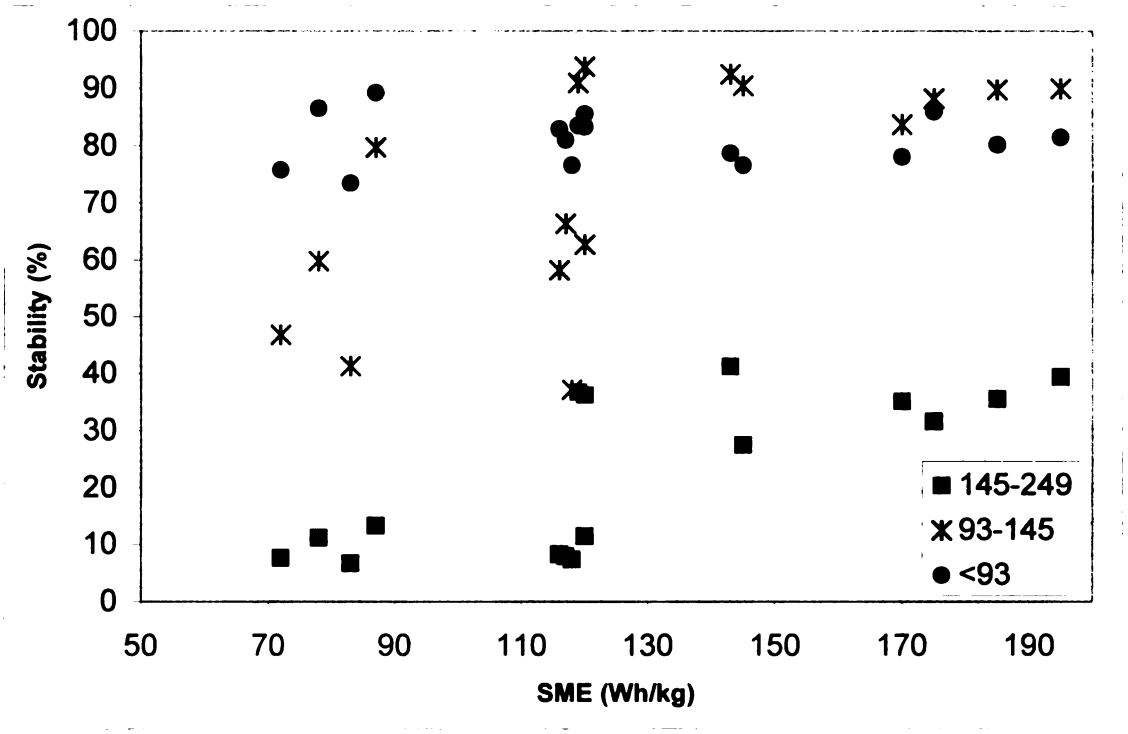

Figure 4.7. Relationship between the specific mechanical energy (SME) and stability for extruded and milled wheat flour powders.

Table 4.13. Stability and Statistical Relationships of Extruded and Milled Wheat Flour + Lecithin Powders

	Particle Size		
Extrusion Conditions M/S/T	145-93 μm	93-145 μm	<93 μm
	Stability (%)		
25/300/120	6.2±0.3	49.6±0.8	73.5±1.3
25/200/120	5.4±0.1	56.6±6.9	71.6±0.0
35/200/120	6.3±0.1	28.5±19.1	61.0±0.9
35/300/120	6.5±0.1	41.8±3.5	65.0±2.5
25/300/145	6.3±0.1	43.2±9.5	74.3±0.1
25/200/145	5.3±0.1	51.5±5.9	68.8±0.8
35/200/145	7.1±0.1	45.4±1.6	79.8±2.3
35/300/145	7.4±0.0	46.5±0.0	76.2±0.4
Raw Wheat Flour + Lecithin = 7.6%			
	Particle Size		
	145-249 μm	93-145 μm	<93 μm
	F value		
M	262.44*	5.73*	5.50
S	88.36*	0	8.42*
T	49.00*	0.39	108.57*
M*S	25.00*	3.41	6.98*
M*T	49.00*	4.23	142.69*
S*T	1.00	0.70	2.22
M*S*T	0.04	0.46	17.68*
	Least Squares Means		
M: 25% - 35%	**Estimate of Difference (%)**		
200 rpm, 120°C	-0.9*	28.1	10.7*
200 rpm, 145°C	-1.8*	6.1	-11.1*
300 rpm, 120°C	-0.3	7.8	8.6*
300 rpm, 145°C	-1.2*	-3.4	-1.9
S: 200 rpm - 300 rpm			
25%, 120°C	-0.9*	7.1	-1.9
25%, 145°C	-1.0*	8.3	-5.6*
35%, 120°C	-0.2*	-13.3	-4.0
35%, 145°C	-0.4	-1.1	3.7
T: 120°C - 145°C			
25%, 200 rpm	0.1	5.2	2.9
25%, 300 rpm	-0.1	6.4	-0.8
35%, 200 rpm	-0.8*	-16.9	-18.9*
35%, 300 rpm	-1.0*	-4.7	-11.2*
Particle Size	**C - B**	**C - A**	**B - A**
Estimate (%)	25.9*	65.0*	39.1*

M = moisture (%), S = screw speed (rpm), T = zone 5 temperature (°C).
Standard deviation measured between powders produced from repetition of extrusion.
A = 145-249μm particle size, B = 93-145μm particle size, C = <93μm particle size.
* Significant at $p<0.05$.

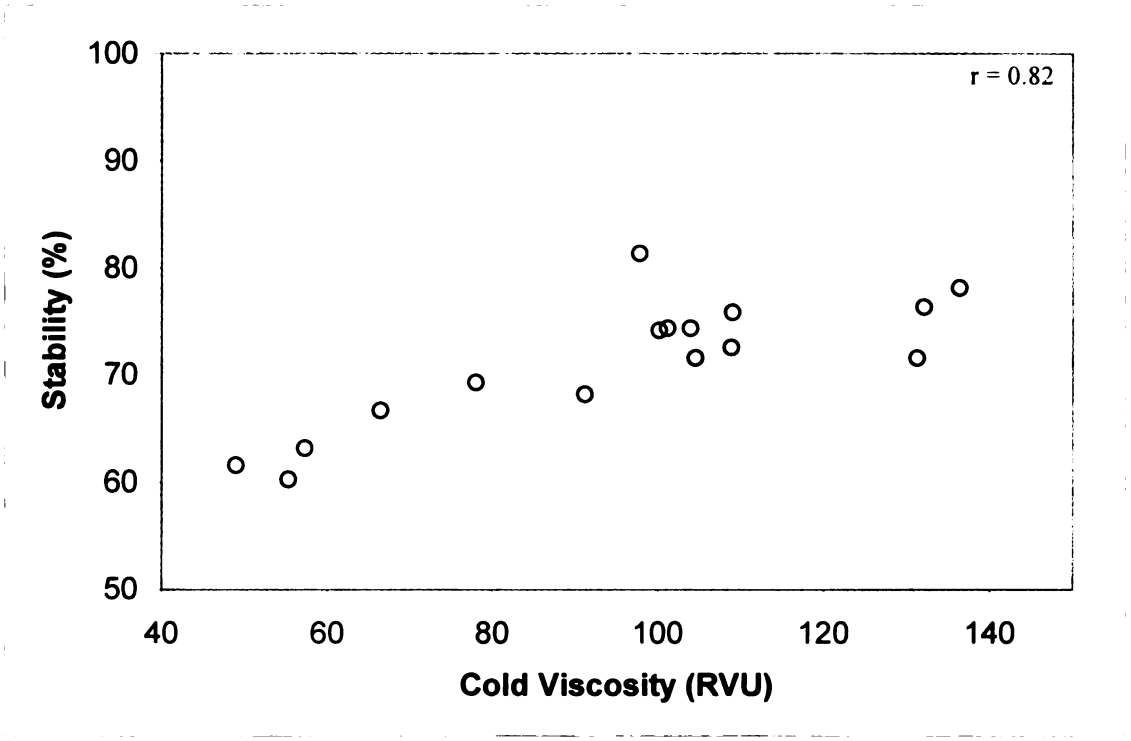

Figure 4.8. Relationship between cold viscosity and stability for extruded and milled wheat flour + lecithin powders.

4.2. Extrusion of Defatted Soy Flour (SF), Defatted Soy Flour with Lecithin (SFL), and Blend of Defatted Soy Flour with Full Fat Soy Flakes (S-Blend)

After extrusion of SF, SFL, and S-Blend samples, the extrudates were dried overnight and ground to produce soy powders of three particle size fractions: 93-145 μm, <93 μm, and jet milled. The following are results along with analysis and discussion regarding the instant properties of extruded soy.

4.2.1. Particle Size Analysis of Extruded and Milled Soy

The mean particle sizes, measured by laser diffraction of the 93-145 μm SF and SFL powder fractions were approximately 150 μm (Table 4.14). The particle size measured by laser light scattering may be larger than the sieve size due to differences in the way that particle sizes are measured. Particles that are not spherical or which scatter light in different ways can affect the results of laser particle size analysis and give different results than physically sieving with a mesh screen (Webb, 2001). The mean particle sizes of the <93 μm SF and SFL fractions produced by sieving were approximately 50 μm (Table 4.14). The S-Blend powders had slightly larger average particle sizes. Jet milling of the SF and SFL extrudates reduced them to powders with mean particle sizes of ≈15 μm (Table 4.14).

4.2.2. Specific Mechanical Energy of Soy During Extrusion

The specific mechanical energy (SME) during extrusion of the SF ranged from 120±8 Wh/kg to 362±16 Wh/kg depending on the conditions (Table 4.15). Moisture had the most significant effect on the SME, followed by screw speed, and temperature (Table 4.15). Higher moisture and temperature resulted in a lower SME while increasing the

Table 4.14. Laser Particle Size Analysis of Extruded and Milled Soy Powders

	93 - 145 μm Sieve Fraction	<93 μm Sieve Fraction	Jet Milled Fraction
Treatment[a] M/S/T rep	**Mean Particle Size (μm)**		
SF 30/300/120 rep 1	155	58	19
SF 30/300/120 rep 2	153	56	17
SF 40/200/120 rep 1		58	19
SF 40/200/120 rep 2		51	16
SF 40/200/145 rep 1		54	14
SF 40/200/145 rep 2		57	15
SFL 30/300/120 rep 1	150	57	15
SFL 30/300/120 rep 2	146	56	13
SFL 40/300/120 rep 1		54	12
SFL 40/300/120 rep 2		54	11
SFL 40/200/145 rep 1		50	15
SFL 40/200/145 rep 2		56	9
S-Blend 30/300/120 rep 1	-	68	-
S-Blend 30/300/120 rep 2	-	67	-
S-Blend 30/200/145 rep 1	-	64	-
S-Blend 30/200/145 rep 2	-	73	-
Raw Defatted Soy Flour = 25 μm			

[a] M = moisture (%); S = screw speed (rpm); T = zone 5 temperature (°C). Each repetition extruded on a different day.
SF = defatted soy flour, SFL = defatted soy flour + lecithin, S-Blend = blend of defatted soy flour with full fat soy flakes.

Table 4.15. Specific Mechanical Energy (SME) and Statistical Relationships During Extrusion of Soy

Extrusion Conditions M/S/T	SF	SFL	S-Blend
	SME (Wh/kg)		
30/300/120	361±16	227±10	126±0
30/200/120	253±16	167±6	89±2
40/200/120	146±11	106±13	71±9
40/300/120	188±11	156±23	93±4
30/300/145	324±30	168±6	115±4
30/200/145	238±37	137±4	84±5
40/200/145	120±8	99±8	69±16
40/300/145	164±6	152±3	98±3
	SF	SFL	S-Blend
	F value		
M	218.00*	212.50*	50.05*
S	55.38*	233.51*	104.83*
T	7.49*	60.49*	1.42
M*S	8.23*	0.95	1.87
M*T	0	36.70*	2.90
S*T	0.27	4.29	1.01
M*S*T	0.42	6.45*	1.24
	Least Squares Means		
M: 30% - 40%	Estimate of Difference (Wh/kg)		
200 rpm, 120°C	107*	61*	185
200 rpm, 145°C	118*	39*	15
300 rpm, 120°C	174*	71*	33*
300 rpm, 145°C	160*	16	17
S: 200 rpm - 300 rpm			
30%, 120°C	-109*	-61*	-37*
30%, 145°C	-87*	-31*	-31*
40%, 120°C	-42	-51*	-23
40%, 145°C	-45	-54*	-30*
T: 120°C - 145°C			
30%, 200 rpm	16	30*	5
30%, 300 rpm	38	59*	12
40%, 200 rpm	27	7	2
40%, 300 rpm	24	4	-5

SF = defatted soy flour, SFL = defatted soy flour + lecithin, S-Blend = blend of defatted soy flour with full fat soy flakes.
M = moisture (%); S = screw speed (rpm); T = zone 5 temperature (°C).
Standard deviation measured beteween repetitions of extrusion.
* Significant at $p<0.05$.

screw speed increased the SME. The effects of changes in these extrusion conditions on SME were similar to those noted for the extruded wheat flour and can be explained similarly. Moisture and temperature affect the rheological properties of dough in the extruder, and increasing the screw speed adds mechanical energy.

The addition of lecithin to the defatted soy flour resulted in a significant decrease in the SME during extrusion when compared to that of the soy flour alone ($p<0.05$ Table 4.16). This may be due to a lubrication effect, which was also seen when lecithin was added to wheat flour (see section 4.1.3). The low end of the range of SME values for SFL was similar to the SME of soy flour without lecithin, but the high end of the range of SME only reached 227±10 Wh/kg (Table 4.15). Changes in moisture, screw speed, and temperature during extrusion of SFL had similar effects on the direction of change in the SME as during extrusion of SF, but in the case of SFL extrusion, screw speed had the most significant effect.

Blending the defatted soy flour with full fat soy flakes resulted in a further lowering of the SME. The different extrusion conditions also had less effect on the SME when extruding S-Blends, resulting in a much smaller range of SME values (69±16 Wh/kg to 126±0 Wh/kg, Table 4.15). Increasing the screw speed had the largest effect of increasing the SME followed by decreasing the moisture (Table 4.15). Varying the temperature did not have a significant effect on the SME.

4.2.3. Trypsin Inhibitor Inactivation of Extruded Soy

Trypsin inhibitor inactivation was greater than 90% for all of the extrusion conditions and among each of the three raw material formulations (Table 4.17). Decreased moisture

Table 4.16. Comparison of Properties Between Soy Powder[a] Formulations

	Estimate of Difference		
	A - B	**A - C**	**B - C**
SME (Wh/kg)	73*	131*	58*
TII (%)	0.1	0.6	0.5
WAI (g/g)	0.043	0.13	0.08
WSI (g/g)	-0.019*	0.011*	0.008*
Dispersibility (%)	4.9*	0	-4.9*
Stability (%)	-4.5*	-1.7*	2.9*

[a] Comparison done for <93 μm particle size.
A = defatted soy flour, B = defatted soy flour + lecithin, C = blend of defatted soy flour with full fat soy flakes.
SME = specific mechanical energy, TII = trypsin inhibitor inactivation, WAI = water absorption index, WSI = water solubility index.
* Significant at $p<0.05$.

Table 4.17. Trypsin Inhibitor Inactivation (TII) and Statistical Relationships of Extruded and Milled Soy Powders

Extrusion Conditions M/S/T	SF	SFL	S-Blend
	Inactivation (%)		
30/300/120	94.7±1.2	95.0±0.9	92.4±0.8
30/200/120	94.4±1.0	93.4±1.8	93.3±0.8
40/200/120	91.5±0.7	92.2±1.0	91.0±0.9
40/300/120	92.1±1.2	92.7±1.5	91.1±1.0
30/300/145	95.9±0.4	95.2±0.0	94.7±0.8
30/200/145	95.4±0.8	94.8±0.1	95.3±0.5
40/200/145	93.6±0.5	92.9±1.0	94.1±0.3
40/300/145	93.6±0.8	93.8±0.2	94.0±1.7
Raw SF = 30.4 mg/g		Raw S-Blend = 23.2 mg/g	
	SF	SFL	S-Blend
	F value		
M	263.18*	22.14*	46.29*
S	4.67	5.41	3.29
T	93.24*	5.13	160.19*
M*S	0.07	0.07	3.52
M*T	4.38	0.02	3.62
S*T	0.39	0.39	0.02
M*S*T	1.36	1.14	0.26
	Least Squares Means		
M: 30% - 40%	Estimate of Difference (%)		
200 rpm, 120°C	2.8*	1.3	2.2*
200 rpm, 145°C	1.9*	2.0	1.3
300 rpm, 120°C	2.6	2.3	1.3
300 rpm, 145°C	2.3*	1.4	0.7
S: 200 rpm - 300 rpm			
30%, 120°C	-0.3	-1.6	0.9
30%, 145°C	-0.4	-0.3	0.6
40%, 120°C	-0.5*	-0.6	-0.1
40%, 145°C	-0.0	-0.9	0.1
T: 120°C - 145°C			
30%, 200 rpm	-1.0	-1.7	-2.1
30%, 300 rpm	-1.2*	-0.2	-2.3*
40%, 200 rpm	-2.0	-0.7	-3.0*
40%, 300 rpm	-1.5*	-1.0	-2.9*

SF = defatted soy flour, SFL = defatted soy flour + lecithin, S-Blend = blend of defatted soy flour with full fat soy flakes.
M = moisture (%), S = screw speed (rpm), T = zone 5 temperature (°C).
Standard deviation measured between powders produced from repetition of extrusion.
* Significant at $p<0.05$.

and higher temperature had significant, but small effects of increasing the inactivation. Greater than 90% destruction of trypsin inhibitors after extrusion of full fat soy flours has also been reported by various authors (Bookwalter and Mustakas, 1971a; Harper, 1979; Konstance et al., 1998). Inactivation of trypsin inhibitors is mainly caused by temperature. Van den Hout et al. (1998) did not find evidence of the involvement of shear forces.

4.2.4. Water Absorption Index (WAI) of Extruded Soy

Increasing the temperature from 120°C to 145°C resulted in a small decrease in the WAI of the SF, while changes in the other extrusion conditions had almost no effect (Table 4.18). The WAI decreased as particle size decreased ($p<0.05$), however there was not a large decrease when compared to the raw soy flour. Traina and Breene (1994) found large differences in water absorption among commercial full fat soy flours produced by different methods. Of the samples they measured, the water absorption ranged from 0.3-2.3 ml/g. They also found an inverse relationship between the protein dispersibility index (PDI) and water absorption.

Extrusion of the SFL and S-Blend samples also did not produce any large differences in the WAI values (Tables 4.19 and 4.20). This occurred even though the SME was much lower with the addition of lipids. The factor with the greatest effect on the WAI of SFL was again, particle size (Table 4.19).

4.2.5. Water Solubility Index (WSI) of Extruded Soy

Extrusion of the different soy flour formulations led to large decreases in the WSI values compared to those of the respective raw materials. The raw materials had WSI

Table 4.18. Water Absorption Index (WAI) and Statistical Relationships of Defatted Soy Flour Powders

	Particle Size		
Extrusion Conditions M/S/T	93-145 μm	<93 μm	≈15 μm (Jet Milled)
	WAI (g/g)		
30/300/120	3.90±0.071	3.72±0.00	3.44±0.07
30/200/120	3.96±0.03	3.85±0.00	3.48±0.01
40/200/120	4.21±0.10	3.88±0.01	3.43±0.01
40/300/120	4.03±0.07	3.78±0.00	3.40±0.09
30/300/145	3.87±0.21	3.69±0.01	3.42±0.15
30/200/145	3.87±0.23	3.67±0.00	3.39±0.18
40/200/145	3.77±0.057	3.52±0.01	3.28±0.10
40/300,145	3.86±0.08	3.63±0.00	3.30±0.08
Raw Defatted Soy Flour = 3.71 g/g			
	Particle Size		
	93-145 μm	<93 μm	≈15 μm (Jet Milled)
	F value		
M	1.38	0.99	6.93*
S	0.48	0.83	0.01
T	10.36*	35.75*	8.29*
M*S	0.02	0.83	0
M*T	4.54	6.21*	1.33
S*T	1.94	8.45*	0.82
M*S*T	0.83	0.34	0.03
	Least Squares Means		
M: 30% - 40%	**Estimate of Difference (g/g)**		
200 rpm, 120°C	-0.25	-0.04	0.05
200 rpm, 145°C	0.10	0.15	0.11
300 rpm, 120°C	-0.13	0.10	0.04
300 rpm, 145°C	0.01	0.06	0.12
S: 200 rpm - 300 rpm			
30%, 120°C	0.06	0.13	0.04
30%, 145°C	0.01	-0.02	-0.03
40%, 120°C	0.18	0.11	0.03
40%, 145°C	-0.09	-0.11	-0.02
T: 120°C - 145°C			
30%, 200 rpm	0.09	0.18	0.09
30%, 300 rpm	0.04	0.04	0.02
40%, 200 rpm	0.44	0.36	0.15
40%, 300 rpm	0.18	0.15	0.10
Particle Size	**C - B**	**C - A**	**B - A**
Estimate (g/g)	-0.33*	-0.54*	-0.22

M = moisture (%), S = screw speed (rpm), T = zone 5 temperature (°C).
Standard deviation measured between powders produced from repetition of extrusion.
A = 93-145 μm particle size, B = <93μm particle size, C = ≈15 μm (jet milled).
* Significant at $p<0.05$.

Table 4.19. Water Absorption Index (WAI) and Statistical Relationships of Defatted Soy Flour + Lecithin Powders

	Particle Size		
Extrusion Conditions M/S/T	93-145 μm	<93 μm	≈15 μm (Jet Milled)
	WAI (g/g)		
30/300/120	3.86±0.03	3.81±0.21	3.32±0.12
30/200/120	4.06±0.07	3.93±0.11	3.34±0.08
40/200/120	3.95±0.05	3.61±0.05	3.24±0.04
40/300/120	4.07±0.01	3.71±0.17	3.22±0.06
30/300/145	3.87±0.11	3.57±0.11	3.17±0.08
30/200/145	3.85±0.04	3.71±0.02	3.42±0.17
40/200/145	4.14±0.07	3.61±0.02	3.21±0.01
40/300/145	3.91±0.08	3.45±0.00	3.17±0.05
Raw Defatted Soy Flour + Lecithin = 4.16 g/g			
	Particle Size		
	93-145 μm	<93 μm	≈15 μm (Jet Milled)
	F value		
M	10.77*	20.38*	5.46
S	4.84	5.09	3.56
T	1.83	25.79*	0.67
M*S	0.25	1.99	1.46
M*T	3.29	1.99	0.01
S*T	1.09	3.90	2.06
M*S*T	20.40	3.36	1.20
	Least Squares Means		
M: 30% - 40%	**Estimate of Difference (g/g)**		
200 rpm, 120°C	0.12	0.33	0.11
200 rpm, 145°C	-0.30*	0.10	0.21
300 rpm, 120°C	-0.21	0.10	0.10
300 rpm, 145°C	-0.04	0.13	0.01
S: 200 rpm - 300 rpm			
30%, 120°C	0.20	0.13	0.03
30%, 145°C	-0.03	0.14	0.25
40%, 120°C	-0.13	-0.11	0.02
40%, 145°C	0.24	0.17	0.02
T: 120°C - 145°C			
30%, 200 rpm	0.22	0.23	-0.08
30%, 300 rpm	-0.01	0.24	0.15
40%, 200 rpm	-0.20	-0.01	0.03
40%, 300 rpm	0.17	0.27	0.06
Particle Size	**C - B**	**C - A**	**B - A**
Estimate (g/g)	-0.41*	-0.70*	-0.29*

M = moisture (%), S = screw speed (rpm), T = zone 5 temperature (°C).
Standard deviation measured between powders produced from repetition of extrusion.
A = 93-145 μm particle size, B = <93μm particle size, C = ≈15 μm (jet milled).
* Significant at $p<0.05$.

Table 4.20. Water Absorption Index (WAI), Water Solubility Index (WSI), and Statistical Relationships of Blend of Defatted Soy Flour with Full Fat Soy Flakes (S-Blend) Powders

Extrusion Conditions M/S/T	WAI (g/g)	WSI (g/g)
30/300/120	3.58±0.08	0.235±0.002
30/200/120	3.61±0.13	0.236±0.004
40/200/120	3.50±0.16	0.240±0.004
40/300/120	3.57±0.10	0.237±0.009
30/300/145	3.68±0.01	0.236±0.001
30/200/145	3.70±0.07	0.235±0.004
40/200/145	3.53±0.22	0.234±0.006
40/300/145	3.56±0.12	0.233±0.004
Raw S-Blend WAI = 3.627 g/g, WSI = 0.408 g/g		
	WAI	**WSI**
	F value	**F value**
M	3.17	0.01
S	0.04	0.27
T	0.81	0.88
M*S	0.46	0.17
M*T	0.66	1.09
S*T	0.02	0.17
M*S*T	0.04	0.01
	Least Squares Means	
M: 30% - 40%	**Estimate of Difference (g/g)**	
200 rpm, 120°C	0.11	-0.004
200 rpm, 145°C	0.18	0.001
300 rpm, 120°C	0.01	-0.002
300 rpm, 145°C	0.12	0.004
S: 200 rpm - 300 rpm		
30%, 120°C	0.03	0.002
30%, 145°C	0.03	-0.001
40%, 120°C	-0.07	0.003
40%, 145°C	-0.03	0.002
T: 120°C - 145°C		
30%, 200 rpm	-0.10	0.001
30%, 300 rpm	-0.10	-0.002
40%, 200 rpm	-0.03	0.005
40%, 300 rpm	0.02	0.004

M = moisture (%), S = screw speed (rpm), T = zone 5 temperature (°C).
Standard deviation measured between powders produced from repetition of extrusion.
* Significant at $p<0.05$.

values of around 0.4 g/g while the extruded powders had WSI values ranging from approximately 0.21-0.26 g/g (Tables 4.20-4.22). As with the WAI, there were only small differences in the WSI among the extrusion conditions. Changes in particle size produced significant differences in the WSI ($p<0.05$, Tables 4.20-4.22). As the particle size decreased, there was a small decrease in the WSI.

The decrease in the WSI of samples after extrusion is largely due to a decrease in the solubility of the soy protein since it makes up a little over 50% of the defatted soy flour. The nitrogen solubility index (NSI), a measure of protein solubility, has been found to decrease below 20% after extrusion of full-fat soy flour (Harper, 1979). Bookwalter et al. (1971a) produced extruded full-fat soy flours with NSI values ranging from 50% to 16%. In the present study, although extrusion was able to cook the soy, as shown by trypsin inhibitor inactivation, it was not able to do so without significantly decreasing the WSI under the extrusion conditions used. Conditions which increase the water solubility of the soy carbohydrates and proteins could be advantageous especially for use in products such as beverages.

4.2.6. Dispersibility of Extruded Soy

In the current study, dispersibility was found to be mainly a function of particle size and not of the extrusion conditions as the SF particle size fractions 93-145 μm and <93 μm were 100% dispersible. However, the ≈15 μm (jet milled) SF powders had dispersibilities from 80% to 90% (Table 4.23). Surprisingly, the SF powders with lecithin had poorer dispersibility. The 93-145 μm SFL powders still had 100% dispersibility, however the <93 μm fractions had dispersibilities of approximately 95%

Table 4.21. Water Solubility Index (WSI) and Statistical Relationships of Extruded and Milled Defatted Soy Flour Powders

	Particle Size		
Extrusion Conditions M/S/T	93-145 μm	<93 μm	≈15 μm (Jet Milled)
	WSI (g/g)		
30/300/120	0.214±0.006	0.230±0.001	0.249±0.003
30/200/120	0.210±0.004	0.224±0.001	0.234±0.013
40/200/120	0.194±0.007	0.213±0.006	0.241±0.004
40/300/120	0.211±0.015	0.222±0.001	0.239±0.007
30/300/145	0.226±0.011	0.232±0.013	0.251±0.013
30/200/145	0.218±0.000	0.232±0.002	0.245±0.015
40/200/145	0.207±0.001	0.224±0.008	0.238±0.016
40/300/145	0.210±0.001	0.224±0.003	0.241±0.009
Raw Defatted Soy Flour = 0.454 g/g			
	Particle Size		
	93-145 μm	<93 μm	≈15 μm (Jet Milled)
	F value	**F value**	**F value**
M	10.35*	14.19*	1.21
S	4.55	2.37	1.46
T	4.55	6.76	0.38
M*S	0.26	0.14	1.21
M*T	0.33	0.14	0.52
S*T	0.41	2.37	0.06
M*S*T	1.41	0.14	0.45
	Least Squares Means		
M: 30% - 40%	**Estimate of Difference (g/g)**		
200 rpm, 120°C	0.016	0.012	-0.007
200 rpm, 145°C	0.012	0.008	0.007
300 rpm, 120°C	0.004	0.008	0.010
300 rpm, 145°C	0.165	0.008	0.011
S: 200 rpm - 300 rpm			
30%, 120°C	-0.004	-0.006	-0.015
30%, 145°C	-0.008	0.000	-0.007
40%, 120°C	-0.017	-0.009	0.002
40%, 145°C	0.007	0.000	-0.003
T: 120°C - 145°C			
30%, 200 rpm	-0.008	-0.008	-0.011
30%, 300 rpm	-0.012	-0.003	-0.002
40%, 200 rpm	-0.125	-0.012	0.003
40%, 300 rpm	0.007	-0.003	-0.002
Particle Size	**C - B**	**C - A**	**B - A**
Estimate (g/g)	0.017*	0.031*	0.014*

M = moisture (%), S = screw speed (rpm), T = zone 5 temperature (°C).
Standard deviation measured between powders produced from repetition of extrusion.
A = 93-145μm particle size, B = <93μm particle size, C = ≈15 μm (jet milled).
* Significant at $p<0.05$.

Table 4.22. Water Solubility Index (WSI) and Statistical Relationships of Extruded and Milled Defatted Soy Flour + Lecithin Powders

	Particle Size		
Extrusion Conditions M/S/T	93-145 μm	<93 μm	≈15 μm (Jet Milled)
	WSI (g/g)		
30/300/120	0.218±0.003	0.244±0.005	0.268±0.002
30/200/120	0.210±0.001	0.235±0.001	0.257±0.001
40/200/120	0.217±0.002	0.241±0.001	0.258±0.001
40/300/120	0.215±0.004	0.239±0.002	0.257±0.002
30/300/145	0.221±0.003	0.252±0.001	0.271±0.001
30/200/145	0.218±0.001	0.250±0.001	0.268±0.001
40/200/145	0.213±0.001	0.241±0.004	0.262±0.003
40/300/145	0.221±0.001	0.2490±0.000	0.265±0.001
Raw Defatted Soy Flour + Lecithin = 0.415 g/g			
	Particle Size		
	93-145 μm	<93 μm	≈15 μm (Jet Milled)
	F value		
M	0.18	10.59*	46.39*
S	26.69*	22.29*	21.10*
T	12.19*	101.15*	65.26*
M*S	2.36	1.40	15.68*
M*T	7.04*	14.79*	0.23
S*T	1.58	0.79	1.23
M*S*T	16.40*	28.35*	13.27*
	Least Squares Means		
M: 30% - 40%	**Estimate of Difference (g/g)**		
200 rpm, 120°C	-0.007	-0.006	-0.001
200 rpm, 145°C	0.005	0.010*	0.005
300 rpm, 120°C	0.003	0.005	0.011*
300 rpm, 145°C	0.001	0.003	0.006
S: 200 rpm - 300 rpm			
30%, 120°C	-0.009*	-0.009*	-0.011*
30%, 145°C	-0.004	-0.002	-0.003
40%, 120°C	0.002	0.002	0.002
40%, 145°C	-0.008	-0.009*	-0.003
T: 120°C - 145°C			
30%, 200 rpm	-0.008*	-0.016*	-0.015*
30%, 300 rpm	-0.003	-0.008*	-0.003
40%, 200 rpm	0.004	0.000	-0.004
40%, 300 rpm	-0.006	0.024*	-0.008*
Particle Size	**C - B**	**C - A**	**B - A**
Estimate (g/g)	0.019*	0.047*	0.027*

M = moisture (%), S = screw speed (rpm), T = zone 5 temperature (°C).
Standard deviation measured between powders produced from repetition of extrusion.
A = 93-145μm particle size, B = <93μm particle size, C = ≈15 μm (jet milled).
* Significant at $p<0.05$.

Table 4.23. Dispersibility and Statistical Relationships of Extruded and Milled Defatted Soy Flour Powders

Extrusion Conditions M/S/T	≈15 μm (Jet Milled)[a] Dispersibility (%)
30/300/120	84.6±1.4
30/200/120	82.3±2.6
40/200/120	92.8±1.6
40/300/120	80.5±0.6
30/300/145	91.0±0.6
30/200/145	86.0±2.2
40/200/145	80.5±0.3
40/300/145	87.0±3.3
	Raw Defatted Soy Flour = 77.8%
	F value
M	12.16*
S	9.36*
T	14.50*
M*S	0.75
M*T	2.44
S*T	9.36*
M*S*T	2.70
	Least Squares Means
M: 30% - 40%	**Estimate of Difference (%)**
200 rpm, 120°C	-0.6
200 rpm, 145°C	5.5
300 rpm, 120°C	4.2
300 rpm, 145°C	4.0
S: 200 rpm - 300 rpm	
30%, 120°C	-2.4
30%, 145°C	-5.0
40%, 120°C	2.4
40%, 145°C	-6.5
T: 120°C - 145°C	
30%, 200 rpm	-3.7
30%, 300 rpm	-6.4
40%, 200 rpm	2.3
40%, 300 rpm	-6.5

[a] 93-145 μm and <93 μm fractions had 100% dispersibility.
M = moisture (%), S = screw speed (rpm), T = zone 5 temperature (°C).
Standard deviation measured between powders produced from repetition of extrusion.
* Significant at $p<0.05$.

and the ≈15 μm (jet milled) fractions had dispersibilities below 80% (Table 4.24). The SFL powders had a tendency to form many small lumps that did not disperse. The blend of defatted soy flour with full fat soy flakes was 100% dispersible.

Wettability was not measured, though it influences dispersibility, and is affected by surface charges along with the size and shape of proteins (Hägerdal and Löfqvist, 1978). Paulsen and Horan (1965) found that wetting was related to heat treatment and the protein dispersibility index (PDI) of defatted soy flour. The contact angle was lower as the PDI decreased, indicating better wetting after heat treatment. Dispersibility is also affected by the ionic composition and pH of the liquid in which the proteins are being dispersed (Kinsella, 1976). The results of the current experiment indicated that particle size was the most important factor affecting dispersibility at the extrusion conditions used.

4.2.7. Stability of Extruded Soy

Stability was also mainly a function of particle size and not the extrusion conditions. The 93-145 μm particle size fractions of the SF samples had stability levels below 40% (Table 4.25). The <93 μm fractions had a stabilities of approximately 55%, and the ≈15 μm (jet milled) powders had stabilities ranging from 74% to 81%. Stabilities for the SFL samples were slightly higher, but demonstrated a similar dependence on particle size (Table 4.26). The S-Blend powders had stability levels similar to the <93 μm fractions for the SF and SFL powders (Table 4.27).

Table 4.24. Dispersibility[a] and Statistical Relationships of Extruded and Milled Defatted Soy Flour + Lecithin Powders

Extrusion Conditions M/S/T	Particle Size	
	<93 μm	≈15 μm (Jet Milled)
	Dispersibility (%)	
30/300/120	96.0±1.3	79.9±2.1
30/200/120	96.3±0.4	75.0±0.2
40/200/120	93.6±2.4	72.4±1.0
40/300/20	96.0±0.0	71.7±2.5
30/300/145	94.4±1.6	78.2±4.7
30/200/145	94.6±0.2	76.5±3.5
40/200/145	94.3±3.2	76.3±2.3
40/300/145	95.9±1.6	73.9±3.9
Raw Defatted Soy Flour + Lecithin = 74.9%		
	Particle Size	
	<93 μm	≈15 μm (Jet Milled)
	F value	
M	0.20	9.58*
S	1.15	0.51
T	0.69	1.40
M*S	1.79	3.98
M*T	1.35	1.65
S*T	0.03	1.04
M*S*T	0.07	0.09
	Least Squares Means	
M: 30% - 40%	Estimate of Difference (%)	
200 rpm, 120°C	2.7	2.6
200 rpm, 145°C	0.3	0.2
300 rpm, 120°C	0.0	8.2
300 rpm, 145°C	-1.5	4.3
S: 200 rpm - 300 rpm		
30%, 120°C	0.3	-5.0
30%, 145°C	0.2	-1.7
40%, 120°C	-2.4	0.7
40%, 145°C	-1.7	2.5
T: 120°C - 145°C		
30%, 200 rpm	1.8	-1.5
30%, 300 rpm	1.6	1.8
40%, 200 rpm	-0.7	-3.9
40%, 300 rpm	0.1	-2.2
Particle Size	**A - B**	
Estimate (%)	-19.7*	

[a] 93-145 μm fraction had 100% dispersibility.
M = moisture (%), S = screw speed (rpm), T = zone 5 temperature (°C).
Standard deviation measured between powders produced from repetition of extrusion.
A = jet milled fraction, B = <93 μm fraction.
* Significant at $p<0.05$.

Table 4.25. Stability and Statistical Relationships of Extruded and Milled Defatted Soy Flour Powders

	Particle Size		
Extrusion Conditions M/S/T	93-145 μm	<93 μm	≈15 μm (Jet Milled)
	Stability (%)		
30/300/120	29.8±1.1	54.3±0.4	78.1±0.0
30/200/120	33.2±2.3	56.7±0.5	74.8±2.3
40/200/120	37.5±1.8	55.6±1.3	80.0±1.7
40/300/120	35.1±4.7	57.9±2.2	77.9±2.1
30/300/145	30.4±1.8	53.7±1.3	77.7±1.6
30/200/145	30.2±1.6	53.3±1.1	79.3±0.5
40/200/145	29.3±0.7	54.8±0.6	81.1±1.2
40/300/145	29.5±0.4	55.5±0.1	81.1±0.4
Raw Defatted Soy Flour = 74.6%			
	Particle Size		
	93-145 μm	<93 μm	≈15 μm (Jet Milled)
	F value		
M	7.94*	6.98*	12.41*
S	4.31	0.25	0.02
T	35.17*	10.76*	8.38*
M*S	0.11	5.19	1.85
M*T	17.54*	0.17	0
S*T	5.45	0.30	0.89
M*S*T	0.14	3.84	5.96*
	Least Squares Means		
M: 30% - 40%	**Estimate of Difference (%)**		
200 rpm, 120°C	-4.3	1.1	-5.2
200 rpm, 145°C	0.9	-1.5	-1.8
300 rpm, 120°C	-5.2	-3.6	0.3
300 rpm, 145°C	1.0	-1.9	-3.4
S: 200 rpm - 300 rpm			
30%, 120°C	3.5	2.4	-3.3
30%, 145°C	-0.2	-0.4	1.6
40%, 120°C	2.5	-2.3	2.2
40%, 145°C	-0.2	-0.8	0.0
T: 120°C - 145°C			
30%, 200 rpm	3.0	3.4	-4.5
30%, 300 rpm	-0.7	0.7	0.4
40%, 200 rpm	8.2*	0.8	-1.1
40%, 300 rpm	5.5	2.4	-3.2
Particle Size	**C - B**	**C - A**	**B - A**
Estimate (%)	23.5*	46.9*	23.4*

M = moisture (%), S = screw speed (rpm), T = zone 5 temperature (°C).
Standard deviation measured between powders produced from repetition of extrusion.
A = 93-145 μm particle size, B = <93μm particle size, C = ≈15 μm (jet milled).
* Significant at $p<0.05$.

Table 4.26. Stability and Statistical Relationships of Extruded and Milled Defatted Soy Flour + Lecithin Powders

	Particle Size		
Extrusion Conditions M/S/T	93-145 μm	<93 μm	≈15 μm (Jet Milled)
	Stability (%)		
30/300/120	35.1±2.5	60.2±2.6	85.6±0.3
30/200/120	38.6±1.3	62.5±3.3	84.0±1.1
40/200/120	39.8±1.1	61.4±1.0	86.5±3.5
40/300/120	37.8±0.8	61.3±1.1	87.2±1.2
30/300/145	32.3±0.8	58.4±2.3	84.9±2.1
30/200/145	32.6±1.1	58.0±0.9	84.0±1.6
40/200/145	33.5±0.8	58.7±0.3	88.3±1.3
40/300/145	32.2±0.8	57.4±1.7	88.0±1.1
Raw Defatted Soy Flour + Lecithin = 73.4%			
	Particle Size		
	93-145 μm	<93 μm	≈15 μm (Jet Milled)
	F value		
M	6.41*	0.01	12.31*
S	14.84*	2.77	0.82
T	129.73*	41.46*	0.32
M*S	0.05	0.07	0.43
M*T	2.91	0.02	1.05
S*T	4.61	0.59	0.23
M*S*T	1.89	3.86	0.01
	Least Squares Means		
M: 30% - 40%	**Estimate of Difference (%)**		
200 rpm, 120°C	-1.2	1.1	-2.5
200 rpm, 145°C	-0.9	-0.8	-4.3
300 rpm, 120°C	-2.7	-1.2	-1.6
300 rpm, 145°C	0.2	1.0	-3.1
S: 200 rpm - 300 rpm			
30%, 120°C	3.5	2.4	-1.6
30%, 145°C	0.3	-0.4	-1.0
40%, 120°C	2.0	0.1	-0.7
40%, 145°C	1.3	1.3	0.3
T: 120°C - 145°C			
30%, 200 rpm	6.0*	4.6*	0.1
30%, 300 rpm	0.4	1.8	0.7
40%, 200 rpm	6.3*	2.7	-1.8
40%, 300 rpm	5.6*	3.9	-0.9
Particle Size	**C - B**	**C - A**	**B - A**
Estimate (%)	26.3*	50.8*	24.5*

M = moisture (%), S = screw speed (rpm), T = zone 5 temperature (°C).
Standard deviation measured between powders produced from repetition of extrusion.
A = 93-145 μm particle size, B = <93μm particle size, C = ≈15 μm (jet milled).
* Significant at $p<0.05$.

Table 4.27. Stability and Statistical Relationships of Extruded and Milled Blend of Defatted Soy Flour with Full Fat Soy Flakes (S-Blend) Powders

Extrusion Conditions M/S/T	Stability (%)
30/300/120	57.5±0.3
30/200/120	57.8±1.1
40/200/120	57.7±0.9
40/300/120	57.5±1.1
30/300/145	55.8±0.4
30/200/145	55.9±1.6
40/200/145	56.6±2.1
40/300/145	56.3±1.1
	Raw S-Blend = 75.3%
	F value
M	0.20
S	0.13
T	6.34*
M*S	0
M*T	0.34
S*T	0
M*S*T	0
	Least Squares Means
M: 30% - 40%	**Estimate of Difference (%)**
200 rpm, 120°C	0.1
200 rpm, 145°C	-0.7
300 rpm, 120°C	0.1
300 rpm, 145°C	-0.6
S: 200 rpm - 300 rpm	
30%, 120°C	0.3
30%, 145°C	0.2
40%, 120°C	0.2
40%, 145°C	0.3
T: 120°C - 145°C	
30%, 200 rpm	1.9
30%, 300 rpm	1.8
40%, 200 rpm	1.1
40%, 300 rpm	1.2

M = moisture (%), S = screw speed (rpm), T = zone 5 temperature (°C).
Standard deviation measured between powders produced from repetition of extrusion.
* Significant at $p<0.05$.

4.3. Blends of Wheat and Soy Powders for Instant Drinks

Combining the different wheat and soy powders with different functional properties produced blends with a range of instant properties (Tables 4.28-4.30). In general, dispersibility was better with WFL-soy blends than with WF-soy blends. Dispersibility was poorest in blends that contained SFL powder. The differences in stability were not great among the various samples. However, formulations containing the S-Blend powders were poorest.

Suspensions with ranges in viscosity were produced and blends with WFL generally had lower viscosities than blends with WF. By choosing the right extrusion conditions and degree of milling, powders with improved viscosity, dispersibility, and stability can be produced.

The combining of wheat and soy flours prior to extrusion may be more convenient, however, separate extrusion allows for better control of the product characteristics. Particle size requirements for acceptable instant properties are also different for the two extruded materials. Instant wheat flour powders are much more difficult to disperse and should be of relatively larger particle sizes for acceptable dispersibility characteristics. Soy powders, on the other hand, need to be ground to a fine powder to improve the final product mouthfeel. An additional consideration is that blends which contain approximately 14 g of soy powder per serving have enough soy protein to meet the Food and Drug Administration criteria for a health claim regarding lowering the risk of heart disease - - 6.25 g of soy protein per serving (FDA, 1999).

Table 4.28. Dispersibility of 50:50 Blends of Wheat and Soy Powders

	Dispersibility (%)			
	WF 25/300/120[a]	WF 35/200/120	WFL 25/300/120	WFL 35/200/120
SF 30/300/120	70.6	89.4	90.1	95.3
SFL 30/300/120	58.5	86.9	84.5	88.3
S-Blend 30/300/120	74.5	100	99.8	100

[a] moisture (%), screw speed (rpm), zone 5 temperature (°C).
WF = wheat flour, WFL = wheat flour + lecithin, SF = defatted soy flour, SFL = defatted soy flour + lecithin, S-Blend = blend of defatted soy flour with full fat soy flakes.

Table 4.29. Stability of 50:50 Blends of Wheat and Soy Powders

	Stability (%)			
	WF 25/300/120 [a]	**WF 35/200/120**	**WFL 25/300/120**	**WFL 35/200/120**
SF 30/300/120	76.1	68.9	70.2	66.5
SFL 30/300/120	73.4	71.0	71.6	67.4
S-Blend 30/300/120	64.8	60.5	59.2	54.5

[a] moisture (%), screw speed (rpm), zone 5 temperature (°C).
WF = wheat flour, WFL = wheat flour + lecithin, SF = defatted soy flour, SFL = defatted soy flour + lecithin, S-Blend = blend of defatted soy flour with full fat soy flakes.

Table 4.30. Cold Viscosity of 50:50 Blends of Wheat and Soy Powders

	Cold Viscosity (RVU)			
	WF 25/300/120[a]	**WF 35/200/120**	**WFL 25/300/120**	**WFL 35/200/120**
SF 30/300/120	12	7	7	6
SFL 30/300/120	11	8	6	4
S-Blend 30/300/120	15	12	5	4

[a] moisture (%), screw speed (rpm), zone 5 temperature (°C).
WF = wheat flour, WFL = wheat flour + lecithin, SF = defatted soy flour, SFL = defatted soy flour + lecithin, S-Blend = blend of defatted soy flour with full fat soy flakes.
Viscosity measured in Rapid Visco Units (RVU).

V Conclusions

Through the control of extrusion conditions and particle size during milling, instant wheat powders with different properties can be produced. Depending on the desired product, water absorption, solubility and viscosity can be adjusted. The specific mechanical energy provides a measure of the starch transformations taking place during extrusion and is correlated with final product characteristics. The addition of lecithin provides another means to modify instant wheat powders, especially as it relates to the improvement of dispersibility.

These results can be applied to the case of instant powders for beverages where dispersibility and viscosity are important. Extrusion of wheat flour with lecithin would be best suited because viscosity can be controlled while still producing a powder with good dispersibility. Control of particle size during milling is also important to viscosity, dispersibility, and stability to sedimentation.

Although extrusion cooking of soy inactivated trypsin inhibitors, the changes in extrusion conditions in this study were not able to create soy powders with a range of functional properties as has been done with wheat flour. Therefore extrusion of defatted soy flours may not be as practical or economical as toasting during the desolventizing process in the production of defatted soy flours. However, the extrusion of full-fat soy flours has been shown previously to be an efficient means of processing and may be practical for blends of full and defatted soy.

The milling of soy flours is crucial to the dispersibility and stability of the instant powders produced. To improve stability so that soy powders could be used in products such as beverage mixes, a very fine powder is needed. However, dispersibility can

become a problem with fine powders, as was the case with the ≈15 μm (jet milled) soy powders. The addition of lecithin to the defatted soy flour prior to extrusion did not improve dispersibility.

VI Suggestions for Further Research

One area for further investigation regarding instant wheat powders is the relationship between starch modifications and dispersibility. Of interest is the poor dispersibility of wheat powders found for samples with high water solubility. Another related area of study is the rate of hydration of the powders. Better control of particle size, such as the removal of very fine particles from the WF <93 μm particle size fraction, may also be important. The role of lecithin is another area to investigate as other lipids aside from lecithin may improve dispersibility. Formulations of lecithin with different hydrophilic-lipophilic balances, blended with wheat or soy may work better. Sensory studies would identify which particle sizes are best suited for products such as gruels or beverages. They are also necessary to determine if milling of the soy was able to adequately reduce its graininess. Sensory studies would also be valuable to relate dispersibility and stability values to end product qualities.

Appendix I

Moisture Content of Extruded and Milled Powders

Appendix Ia. Moisture Content of Extruded and Milled Wheat Flour Powders

		Moisture (%)		
		Particle Size (µm)		
Treatment	**Rep**	**145-249**	**93-145**	**<93**
25/300/120	1	7.1	6.9	6.3
	2	4.3	4.3	3.6
25/200/120	1	6.4	6.1	5.6
	2	5.0	5.0	4.9
35/200/120	1	4.9	4.8	4.7
	2	5.7	5.4	5.0
35/300/120	1	4.9	4.9	4.8
	2	5.6	5.5	5.2
25/300/145	1	5.0	5.3	4.7
	2	3.9	4.3	3.8
25/200/145	1	6.1	6.1	5.8
	2	4.4	4.3	4.4
35/200/145	1	4.5	4.7	4.4
	2	4.3	4.1	3.6
35/300/145	1	3.8	3.8	3.6
	2	6.0	6.0	5.6
Raw Wheat Flour = 13.2% moisture				

Appendix Ib. Moisture Content of Extruded and Milled Wheat Flour + Lecithin Powders

		Moisture (%)		
		Particle Size (μm)		
Treatment	**Rep**	**145-249**	**93-145**	**<93**
25/300/120	1	6.0	5.6	5.5
	2	5.6	5.9	5.8
25/200/120	1	5.8	5.6	5.8
	2	5.5	5.6	5.8
35/200/120	1	6.1	5.9	6.0
	2	5.7	5.4	5.0
35/300/120	1	6.5	6.7	6.3
	2	6.0	6.2	6.1
25/300/145	1	5.6	5.6	5.7
	2	5.3	5.2	5.6
25/200/145	1	5.8	5.8	6.2
	2	5.6	5.8	5.5
35/200/145	1	5.8	5.8	5.2
	2	6.0	5.9	6.1
35/300/145	1	5.6	5.6	5.2
	2	5.9	5.8	5.4
Raw Wheat Flour + Lecithin = 12.8% moisture				

Appendix Ic. Moisture Content of Extruded and Milled Defatted Soy Flour Powders

		Moisture (%)		
		Particle Size (μm)		
Treatment	**Rep**	**93-145**	**<93**	**Jet Milled**
30/300/120	1	6.6	6.6	5.3
	2	5.7	5.9	5.3
30/200/120	1	7.0	7.0	6.1
	2	5.7	5.5	5.0
40/200/120	1	6.7	6.5	5.3
	2	5.6	6.0	5.0
40/300/120	1	7.8	7.2	5.7
	2	6.1	6.1	5.1
30/300/145	1	7.2	6.9	5.9
	2	6.7	6.1	5.6
30/200/145	1	7.1	7.2	5.5
	2	6.1	5.8	5.7
40/200/145	1	6.2	6.3	5.2
	2	6.3	6.4	6.2
40/300/145	1	6.5	6.6	5.3
	2	6.2	6.6	6.2
Raw Defatted Soy Flour = 6.0% moisture				

Appendix Id. Moisture Content of Extruded and Milled Soy Flour + Lecithin Powders

		Moisture (%)		
		Particle Size (μm)		
Treatment	**Rep**	**93-145**	**<93**	**Jet Milled**
30/300/120	1	7.6	7.5	7.0
	2	5.6	5.6	5.7
30/200/120	1	7.1	7.0	6.3
	2	5.6	5.6	5.6
40/200/120	1	5.7	5.8	6.0
	2	5.9	5.7	5.7
40/300/120	1	7.1	7.0	6.1
	2	5.7	5.7	5.5
30/300/145	1	8.0	8.0	6.8
	2	5.9	6.0	6.0
30/200/145	1	7.5	7.3	6.2
	2	6.2	6.1	5.9
40/200/145	1	7.7	7.5	6.5
	2	6.4	6.1	6.0
40/300/145	1	6.9	6.6	6.4
	2	6.9	6.7	6.1
Raw Defatted Soy Flour + Lecithin = 6.0% moisture				

Appendix Ie. Moisture Content of Extruded and Milled Blend of Defatted Soy Flour with Full Fat Soy Flakes (S-Blend) Powders

Treatment	Rep	Moisture (%)
30/300/120	1	6.5
	2	6.4
30/200/120	1	6.7
	2	6.1
40/200/120	1	6.5
	2	6.1
40/300/120	1	6.6
	2	6.3
30/300/145	1	6.9
	2	6.3
30/200/145	1	6.9
	2	6.6
40/200/145	1	7.3
	2	6.4
40/300/145	1	6.8
	2	6.1
Raw S-Blend = 9.3% moisture		

Appendix II

Torque, Die Pressure, and Specific Mechanical Energy (SME) During Extrusion

Appendix IIa. Torque, Die Pressure, and Specific Mechanical Energy (SME) During Extrusion of Wheat Flour

Extrusion Conditions M/S/T	Feed Rate (kg/hr)	Torque (%)	Die Pressure (PSI)	SME (Wh/kg)
25/300/120	2.4	38±1	375±64	190±7
25/200/120	2.4	44±1	545±21	144±1
35/200/120	2.8	27±3	160±71	78±8
35/300/120	2.8	27±0	115±50	118±1
25/300/145	2.4	35±1	210±57	173±3
25/200/145	2.4	36±0	300±14	120±1
35/200/145	2.8	29±2	150±42	83±1
35/300/145	2.8	28±1	80±28	118±3

M = moisture (%), S = screw speed (rpm), T = zone 5 temperature (°C).
Standard deviation measured between powders produced from repetition of extrusion.

Appendix IIb. Torque, Die Pressure, and Specific Mechanical Energy (SME) During Extrusion of Wheat Flour + Lecithin

Extrusion Conditions M/S/T	Feed Rate (kg/hr)	Torque (%)	Die Pressure (PSI)	SME (Wh/kg)
25/300/120	2.4	33±1	350±28	165±7
25/200/120	2.4	40±1	535±7	133±5
35/200/120	2.8	26±0	210±28	75±1
35/300/120	2.8	26±1	170±28	112±5
25/300/145	2.4	30±0	215±7	150±0
25/200/145	2.4	31±0	310±14	104±1
35/200/145	2.8	24±0	150±0	70±0
35/300/145	2.8	24±1	100±0	102±3

M = moisture (%), S = screw speed (rpm), T = zone 5 temperature (°C).
Standard deviation measured between powders produced from repetition of extrusion.

Appendix IIc. Torque, Die Pressure, and Specific Mechanical Energy (SME) During Extrusion of Defatted Soy Flour

Extrusion Conditions M/S/T	Feed Rate (kg/hr)	Torque (%)	Die Pressure (PSI)	SME (Wh/kg)
30/300/120	2.6	78±4	805±78	362±16
30/200/120	2.6	82±5	750±71	253±16
40/200/120	3.0	55±4	470±14	146±11
40/300/120	3.0	47±3	425±35	188±11
30/300/145	2.6	70±6	625±21	324±30
30/200/145	2.6	72±12	665±78	238±37
40/200/145	3.0	45±3	375±21	120±8
40/300/145	3.0	41±1	330±28	164±6

M = moisture (%), S = screw speed (rpm), T = zone 5 temperature (°C).
Standard deviation measured between powders produced from repetition of extrusion.

Appendix IId. Torque, Die Pressure, and Specific Mechanical Energy (SME) During Extrusion of Defatted Soy Flour + Lecithin

Extrusion Conditions M/S/T	Feed Rate (kg/hr)	Torque (%)	Die Pressure (PSI)	SME (Wh/kg)
30/300/120	2.6	49±2	615±21	227±10
30/200/120	2.6	54±2	590±42	167±6
40/200/120	3.0	40±5	330±85	106±13
40/300/120	3.0	39±6	415±148	156±23
30/300/145	2.6	42±1	475±21	168±6
30/200/145	2.6	44±1	415±7	137±4
40/200/145	3.0	37±3	280±28	99±8
40/300/145	3.0	32±1	260±0	152±3

M = moisture (%), S = screw speed (rpm), T = zone 5 temperature (°C).
Standard deviation measured between powders produced from repetition of extrusion.

Appendix IIe. Torque, Die Pressure, and Specific Mechanical Energy (SME) During Extrusion of Blend of Defatted Soy Flour with Full Fat Soy Flakes (S-Blend)

Extrusion Conditions M/S/T	Feed Rate (kg/hr)	Torque (%)	Die Pressure (PSI)	SME (Wh/kg)
30/300/120	2.6	27±0	205±7	126±0
30/200/120	2.6	29±1	180±14	89±2
40/200/120	3.0	27±4	140±28	71±9
40/300/120	3.0	23±1	135±21	93±4
30/300/145	2.6	25±1	145±35	115±3
30/200/145	2.6	27±2	140±14	84±6
40/200/145	3.0	26±6	115±50	69±2
40/300/145	3.0	25±1	140±28	98±3

M = moisture (%), S = screw speed (rpm), T = zone 5 temperature (°C).
Standard deviation measured between powders produced from repetition of extrusion.

Appendix III

Rapid Visco Analyzer Analysis of Extruded and Milled Powders

Appendix IIIa. Rapid Visco Analyzer Analysis of Extruded and Milled Wheat Flour Powders

Treatment	Particle Size Fraction (μm)	Cold Viscosity (RVU)	Hot Paste Viscosity (RVU)	Hold (RVU)	Breakdown (RVU)	Final Viscosity (RVU)	Setback (RVU)	Peak Time (min)	Cold Peak Area (RVUxmin)
25/300/120	145-249	108±5	126±1	14±1	113±1	54±7	40±6	2.7±0.2	121±6
	93-145	110±17	102±12	12±2	90±14	53±3	41±1	2.1±0.2	192±30
	<93	54±4	47±2	12±2	35±4	53±7	41±5	2.2±0.2	99±6
25/200/120	145-249	121±10	147±9	20±7	128±16	59±4	39±11	12.9±14.1	134±14
	93-145	172±0	148±4	19±6	130±10	60±9	42±15	2.1±0.0	282±5
	<93	66±6	55±2	16±1	38±1	59±20	43±21	2.2±0.0	119±6
35/200/120	145-249	148±7	261±1	22±0	239±1	93±13	71±13	5.1±0.1	155±9
	93-145	208±3	210±4	21±2	189±1	89±8	68±9	2.3±0	331±0
	<93	143±11	139±3	20±1	119±4	85±11	65±12	4.5±3.4	261±20
35/300/120	145-249	153±2	210±16	17±1	193±17	68±11	50±10	4.2±0.2	161±10
	93-145	196±79	195±79	16±0	179±79	67±13	52±13	2.1±0.0	320±116
	<93	133±17	121±8	15±1	105±8	62±10	46±9	2.1±0.0	239±25
25/300/145	145-249	135±20	152±30	13±2	142±23	56±2	43±2	2.9±0.1	156±23
	93-145	161±3	151±2	15±4	136±6	57±3	42±2	2.1±0.0	284±0
	<93	94±2	84±5	10±2	71±3	52±3	42±2	2.1±0.1	168±2
25/200/145	145-249	152±29	180±31	23±0	157±31	65±19	42±19	3.1±0.2	180±47
	93-145	230±25	213±19	22±1	191±20	63±16	41±18	2.1±0.0	388±44
	<93	111±2	97±7	19±0	78±7	57±14	38±14	2.1±0.0	201±4
35/200/145	145-249	213±23	251±21	20±6	231±15	81±1	61±7	3.2±0.1	244±31
	93-145	244±37	243±36	18±2	226±39	76±5	58±8	2.1±0.0	405±58
	<93	156±2	1401±7	17±2	124±5	70±4	53±7	2.1±0.0	282±4
35/300/145	145-249	206±9	234±6	13±3	221±3	52±1	39±4	3.1±0.0	240±15
	93-145	218±36	213±33	13±2	200±32	51±1	38±3	2.1±0.0	375±63
	<93	132±28	121±22	12±1	110±21	47±1	35±2	2.1±0.0	239±46
Raw WF		3	227	119	108	431	312	8	7

Viscosity measured in Rapid Visco Units (RVU).
Standard deviation measured between powders produced from repetition of extrusion.

Appendix IIIb. Rapid Visco Analyzer Analysis of Extruded and Milled Wheat Flour + Lecithin Powders

Treatment	Particle Size Fraction (μm)	Cold Viscosity (RVU)	Hot Paste Viscosity (RVU)	Hold (RVU)	Breakdown (RVU)	Final Viscosity (RVU)	Setback (RVU)	Peak Time (min)	Cold Peak Area (RVUxmin)
25/300/120	145-249	136±8	225±6	13±2	212±3	46±1	33±1	4.4±0.0	131±6
	93-145	241±8	242±8	14±1	228±9	46±0	32±1	2.3±0.1	380±11
	<93	106±3	106±4	12±0	94±4	37±1	26±1	2.1±0.0	197±5
25/200/120	145-249	128±6	238±16	16±2	221±14	60±7	43±6	4.9±0.5	129±11
	93-145	239±0	244±1	16±2	228±3	58±6	42±4	2.5±0.0	362±0
	<93	118±19	123±9	17±4	106±5	49±3	32±1	4.3±3.2	217±36
35/200/120	145-249	71±1	342±48	24±2	318±46	91±0	67±2	6.6±0.0	74±5
	93-145	160±12	353±22	24±1	328±21	94±5	70±6	6.5±0.0	255±32
	<93	52±4	179±1	21±0	158±0	70±6	49±6	6.7±0.0	99±9
35/300/120	145-249	90±1	306±1	18± 2	288±1	67±6	48±4	6.5±0.0	93±4
	93-145	168±11	281±4	18±2	263±7	66±5	48±3	6.5±0.0	263±17
	<93	62±6	151±1	16±2	135±1	52±5	37±3	6.8±0.0	117±12
25/300/145	145-249	127±6	228±15	14±2	214±13	54±4	40±2	4.9±0.1	126±3
	93-145	235±3	237±6	13±2	224±4	53±3	40±1	2.4±0.1	356±20
	<93	101±1	103±4	11±2	92±1	41±3	30±1	4.2±3.1	185±4
25/200/145	145-249	122±6	288±16	20±3	268±12	82±8	62±5	5.7±0.2	118±5
	93-145	233±21	258±18	19±4	239±14	79±8	60±4	4.9±0.4	328±25
	<93	85±9	122±12	14±4	108±8	52±5	38±1	6.4±0.0	151±18
35/200/145	145-249	207±2	314±19	24±5	290±14	92±18	68±7	4.3±0.0	203±12
	93-145	216±8	221±5	21±3	200±7	83±9	63±5	2.5±0.2	320±23
	<93	117±27	145±6	15±2	130±8	52±0	37±1	6.7±0.1	215±50
35/300/145	145-249	177±11	260±4	17±1	243±3	58±5	41±3	4.7±0.9	176±18
	93-145	167±5	169±8	16±1	153±8	57±1	43±2	2.1±0	272±4
	<93	121±16	137±7	12±0	125±6	42±4	30±3	6.7±0.1	221±29
Raw WFL		4	213	115	99	393	279	8	9

Viscosity measured in Rapid Visco Units (RVU).
Standard deviation measured between powders produced from repetition of extrusion.

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