Use of an Air-Coupled Ultrasound Technique to Assess the Mechanical Properties of White Salted Noodle Dough and its Potential Capability in Prediction of Cooked Noodle Texture

by
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Abstract

In this study, an innovative technique—air-coupled ultrasound—was used to measure the mechanical properties of white salted noodles, in a fast, non-destructive, non-contact way. The ultrasound technique was sensitive to the changes brought about by dough moisture content, work input (either from the mixing or sheeting process), as well as the changes in noodle properties with time. In addition, the cooked noodle texture was assessed by conventional methods: an instrumental method and a trained sensory panel. Noodles were less firm with increased water content, and with prolonged storage time (24 hours). Noodles made with CWRW (Canada Western Red Winter) flour had a comparable firmness as noodles made from high protein content flour (Canada Western Red Spring). Overall, the cooked noodle texture was highly correlated with the dough properties measured with the ultrasound technique. Therefore, this research suggests that air-coupled ultrasound has a promising capability for the prediction of noodle quality.

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1. Introduction

Noodles, as a staple food in Asian countries (Huang & Morrison, 1988), have been in existence for thousands of years. The popularity of noodles nowadays has spread all over the world and noodles are widely accessible in different regions. According to the World Instant Noodle Association (2017), in 2016 alone, a total of 97.5 billion servings of instant noodles have been consumed worldwide, not to mention other types of noodles consumed. Wheat, as one of the key ingredients in noodles, has gradually shifted its role from bread making to noodle processing. Canada, as one of the leading wheat production countries, exported 17.7 million tonnes of wheat in 2014-15 and approximately half of Canada's wheat export was shipped to Asian countries (CGC, 2017). Of the wheat exported, 20-50 % is used for Asian noodle production (Hou, 2001; Fu, 2008).

Even though western culture considers pasta as one type of noodle, attention should be paid in defining noodles. White salted noodles differ from pasta primarily in the raw material and the processing types (Fu, 2008). In general, pasta is made with durum semolina by an extrusion process, while white salted noodles are commonly made with common wheat flour by a sheeting process. Based on the types of salt used in the formulation, noodles are classified as white salted noodles or yellow alkaline noodles. In addition to sodium chloride, kansui (an alkaline salt mixture of sodium carbonate, potassium carbonate and sodium phosphate) is used to make yellow alkaline noodles (Fu, 2008). As indicated by the name, both noodles have very distinct characteristics in color, texture, flavor and method of cooking (Hou, 2001). This study focuses on white salted noodles.

White salted noodles are made with simple ingredients, wheat flour, water and salt, but they are also very diverse, as evidenced by the wide varieties of noodles with different shapes, sizes, flavor and texture. It should be noted that there is a lack of standard methods in noodle processing; thus the processing conditions vary from one study to another (Fu, 2008). In general, noodle manufacturing starts with mixing flour, water and salt into dough crumbs in a mixer and then the formed dough crumbs pass through one or two pairs of rollers which rotate inwards to form an initial dough sheet by compression. By folding the two sheets (the compounding process), a second sheeting pass helps to smooth out the surfaces. The sheeting process is repeated 4-6 times with successive reduction in the roll gap until a smooth, elastic, and extensible dough sheet is obtained. After sheeting, dough sheets are subject to cutting to noodle strands of different width (Hou, 2001). Noodle strands can be fresh, or further processed by operations such as drying, steaming, freezing, frying or a combination (Fu, 2008) to improve the shelf-life and flavor characteristics.

Texture is one of the most important quality attributes of noodles. It is strongly affected by variation in the composition, such as the protein content of the flour (Oh et al., 1985a; Park et al., 2003), protein quality (Huang & Morrison, 1988; Liu et al, 2003; Park et al., 2003; Diep et al., 2014; Gulia & Khatkar, 2015), starch properties (Moss, 1980; Oda et al., 1980; Lee et al., 1987; Crosbie et al., 1991; Konik et al., 1992; Baik et al., 1994), as well as the water addition levels (Hatcher et al., 1999; Park & Baik, 2002). More importantly, the typical hard-bite noodle texture is strongly associated with the gluten network developed through processing, mainly by the mixing and sheeting operations (Hatcher, 2001; Hou, 2001; Fu, 2008). However, little is known about how the work input through processing contributes to the development of the gluten network in noodle dough and its relationship to the resultant final quality.

To ensure consistent noodle quality, cooked noodle texture is commonly assessed by sensory evaluation (Oh et al., 1983; Pipatsattayanuwong, 1998; Noda et al., 2001) and instrumental methods (Oh et al., 1983; Ross, 2006; Pronyk et al., 2008; Mudgil et al., 2016). However, an objective method to monitor the consistency of noodle dough is still lacking. Noodle dough assessment still relies on noodle operators (Park & Baik, 2002). Based on how the dough feels in the hand, experienced personnel have to adjust the roll settings frequently in response to changes in the properties of the incoming dough, which not only slows down the production run, but also leads to inconsistent product quality (Ouellette et al., 1996). As such, an in-depth understanding of dough properties during processing is required so that an objective, on-line process monitoring tool can be developed for an automated production line.

As a fundamental rheological tool, ultrasound techniques have shown a great capability in assessment of the rheological properties of noodle dough made with different wheat cultivars (Diep et al., 2014), with addition of crosslinking enzymes (Bellido & Hatcher, 2011) and beta-glucan (Hatcher et al., 2014), and with different work input (Salimi-Khorshidi, 2016). Moreover, Diep et al. (2014) showed that the rheological properties measured with ultrasound were highly correlated with the cooked noodle texture measured with a texture analyzer, which indicated that the texture of noodles may be predicted through measurements of dough properties. However, previous ultrasound methods required good contact between ultrasound transducer and the noodle sample (elimination of the air gap), thus making them difficult to be incorporated on a production line.

In this study, an innovative method—air-coupled ultrasound —is applied (Kerhervé, 2018). It is attractive to the food industry because of its non-contact and non-destructive nature (Scanlon & Page, 2015). Therefore, the objectives of this study are:

1) to establish the relationship between rheological properties of sheeted noodle dough measured by an air-coupled ultrasound technique and the cooked noodle texture;
2) to compare noodles made with two different flours, two water addition levels, and prepared by mixing at different speeds and sheeting to different extents, and aging for different times;

2. Literature Review

2.0 Noodle Ingredients and Functionality

Ingredients play a critical role in determining noodle quality. The significance of flour components on the quality of noodles is well recognized. Therefore, this section will focus on the functionality of each ingredient in the noodle, namely, flour, water and salt, and their impact on the final product quality.

2.0.1 Noodle Flour

2.0.1.1 Wheat Class

Protein content is one of the most important factors in wheat quality and varies due to differences in the genotype and environmental conditions (Neuman et al., 1987). In general, hard wheat contains a higher amount of protein than soft wheat (Carson & Edwards, 2009). Wheat flour from different regions has been studied for making oriental noodles, including from Korea, China, Australia, Canada and the United States (Hatcher & Kruger, 1993; Crosbie et al., 1999; Park et al., 2003; Lu et al., 2009). Protein is considered one of the most important flour quality attributes in determination of noodle texture (Oh et al., 1985a; Moss et al., 1987; Park et al., 2003). Each type of noodle has a specific texture characteristic, thus the requirements for the protein and/or flour are different. Hou (2001) indicated that Japanese udon noodles require soft wheat flour with protein content in the range of 8.0-9.5 %, while other types of white salted noodles with a harder bite and elastic texture generally require flour with 10.0-13.0 % protein.

2.0.1.2 Wheat Flour Composition

2.0.1.2.1 Protein

Gluten, unique to wheat, is formed once hydrated. Gliadin and glutenin, the most important components of gluten, shape the viscoelastic behavior of the wheat flour dough (Khatkar et al., 2013). Gliadins, once hydrated, behave as a viscous liquid and make the dough extensible. On the other hand, glutenins contribute to the elastic property of the dough (Shewry et al., 2002; Khatkar et al., 2013). The balance of gliadin / glutenin is important in the noodle sheeting process (Hatcher, 2001). Protein that is neither too strong nor too weak is desirable in the sheeting process. It is difficult to control the final thickness of noodle sheets made with a very strong protein as it tends to spring back to a greater extent (Hou, 2001). On the other hand, noodle dough with a very weak protein cannot withstand the high-strain sheeting operation (Hatcher, 2001).

Gluten strength can be measured by empirical tests, such as farinograph, mixograph, extensograph, and alveograph. These tests measure dough's resistance to mechanical deformation, such as mixing, stretching, and bubble blowing, and provide information on dough's extensibility and elasticity (Khatkar et al., 2013). They are generally used to measure the gluten strength in bread dough to predict its baking quality. Due to the difference in the amount of water addition (28-36% in noodle dough vs 58-64% in bread dough) (Oh et al., 1986; Hou, 2001; Park & Baik, 2002), the dough strength measured with these empirical tests provides little information on the final quality of noodles. But some correlations have been found. Miskelly and Moss (1985) reported that firmer and more elastic texture in noodles corresponded to dough with higher extensograph maximum resistance values. Crosbie et al. (1999) showed the hardness of noodles positively correlated with dough stability measured by the farinograph. Yun et al. (1997) found the softness of Japanese white salted noodles measured with a texture analyzer positively correlated to the mixing time measured with the mixograph.

The protein content was reported to positively correlate to the firmness of cooked noodle (Oh et al., 1985a). Presumably the protein quality in the research was acceptable, since the quality of the protein is essential to noodle quality as well as the amount of protein. Huang and Morrison (1988) compared forty Chinese wheats to eight British wheats and found that the flour with a higher protein content failed to produce a high-quality noodle; rather, the cutting stress of cooked noodles was positively correlated to the SDS sedimentation value, which was an indicator of protein quality. A number of other studies also confirmed that the SDS sedimentation value was highly and positivity correlated to the firmness of noodles (Liu et al., 2003; Park et al., 2003; Gulia & Khatkar, 2015).

A number of studies have identified specific gluten fractions that are responsible for the hard bite noodle texture. Hu et al. (2007), Park et al. (2003), and Gulia & Khatkar (2015) examined the effect of gluten fractions on the final texture of noodles and reported that the firmness of noodles was strongly associated with the glutenin component. The effect of adding gliadin into the dough was also investigated as per Khatkar et al. (2013), in which they found that addition of gliadin significantly reduced the dough strength (as measured by a shortened dough development time), and the thermal stability (measured with thermal gravimetric analysis and differential scanning calorimetry). In addition, a more open dough matrix structure was also observed with gliadins using SEM (Scanning Electron Microscopy).

2.0.1.2.2 Starch

Starch is the major component of wheat flour and is composed of two types of molecules: amylose and amylopectin. Amylose is a linear chain of D-glucopyranose units linked by α-1,4 linkages and amylopectin is highly branched in structure with α-1,4 and α-1,6 linkages (Lineback et al., 1988). The ratio of amylose to amylopectin characterizes the starch's pasting properties (Miskelly & Moss, 1985). A flour with high-swelling starch is desirable in white salted noodles (Fu, 2008), as it has a high paste viscosity and resistance against breakdown of viscosity (Moss, 1980; Oda et al., 1980; Lee et al., 1987; Crosbie, 1991; Konik et al., 1992; Baik et al., 1994), low gelatinization temperature (Oh et al., 1985a; Endo et al., 1988) and high swelling power (Crosbie, 1991; McCormick et al., 1991). Fu (2008) reported that a minimum in flour peak viscosity of 700 BU is desirable in Japanese udon noodles and Korean noodles.

It was reported that the texture differences between Japanese udon and Chinese salted noodles were mainly due to the difference in the starch (Oda et al., 1980; Toyokawa et al., 1989ab; Konik et al., 1992). As the amylose content had a negative correlation with amylograph peak viscosity as well as eating quality (Oda et al.,1980), udon noodles usually use flour with a low amylose content (partial waxy wheat flour, 22-24 % amylose content) to obtain a softer and more elastic texture, which was probably attributable to the high swelling power of starch (Crosbie, 1991).

Wang and Seib (1996), and Ross et al. (1997) proposed a working mechanism of starch during noodle cooking. Raw noodle structure was considered to have a 3-D continuous gluten network with starch granules "glued" together. Upon cooking, starch gelatinization occurs where starch takes up water and swells, and amylose gradually leaches out in the boiling water. This corresponded with the scanning electron microscopy observation of Dexter et al. (1979), in which they observed open areas attributed probably to the starch leaching out, but the openings were connected by gluten fibrils in cooked noodles. This indicated that noodles with a good texture should have less open areas and the gluten fibrils should be strong enough to maintain the integrity of the noodle.

2.0.2 Water

2.0.2.1 Functionality, Specifications

Water is an important ingredient in noodle processing and can have tremendous variations in the pH level, mineral content or hardness. Hard water with an abundance of minerals seems to tighten the structure by reducing the flexibility of polymer chains, thus slowing down water penetration during mixing (Fu, 2008). On the other hand, soft water can make the dough very sticky. Therefore, water with medium to low hardness is desirable (Fu, 2008). The quality of the water used for the cooking process is also essential. Hou (2001) stated that high salt content and high pH could break down the noodle surface, so it was recommended that the pH of boiling water should be adjusted with lactic acid to a pH of 5.5 - 6.0.

2.0.2.2 Optimal Water Addition Level

Water plays an essential role in noodle processing. It directly affects sheetability of noodle dough (Edwards et al., 1996; Fu, 2008). The optimal water addition level for noodles has a broad range and was reported to be between 28 and 36 % based on the flour weight (Hou et al., 1998).

Dough made with inadequate water is very stiff, and requires more work input to roll, as the stiffness of noodle dough is inversely related to water addition level (Edwards et al., 1996). On the other hand, excessive water makes the dough very sticky.

The water addition level is strongly affected by the water absorption capability of the flour, such as particle sizes, starch damage (Hatcher et al., 2002), and protein content and quality (Park & Baik, 2002). Based on handling properties of noodle dough by experienced personnel, Park and Baik (2002) found that optimal water addition level for 34 wheat flours with different protein content and quality had an inverse correlation to protein content and SDS sedimentation volume (an indicator of protein quality).

It should be noted that an objective and reliable method to obtain the so called "optimal" water addition level in noodle is still lacking; thus determination of the optimal water level still relies on experienced personnel by assessment of handling properties (Park & Baik, 2002). A few methods were proposed such as mixograph (Oh et al., 1986) and farinograph (Seib et al., 2000), but with little success. These methods provided an estimate of the optimal water level, but have limited uses in the food industry (Hou, 2001) as the optimal water addition level found was to be 4-8 % higher than the one determined from the handling properties of the dough (Oh et al., 1986). It has been reported that the water addition level should not deviate more than 2 % from the optimal level to ensure consistent handling properties (Oh et al., 1985b). In this regard, further research on establishing the optimal water content for noodles is needed.

Water brings out significant physiochemical changes when mixed with flour. Gluten is formed once proteins are hydrated. However, as water is a limiting factor in noodle dough, full gluten development is not achieved in noodle dough, as evidenced by the observation with SEM (Scanning Electron Microscopy) (Dexter et al., 1979; Ye et al., 2009; Liu et al., 2015). Even though it is generally accepted that the elasticity of gluten is attributable to the glutenin chains linked with disulfide bonds, non-covalent bonds are also important, such as hydrogen bonds, hydrophobic interactions and electrostatic interactions (Belton, 1999; Don et al., 2003; Lefebvre et al., 2003; Kontogiorgos & Goff, 2006; Kontogiorgos, 2011). As suggested by the loop and train mechanism proposed by Belton et al. (1994, 1995), the degree of hydration in the system affects the secondary structure of protein and thus its functionality. Dry proteins are disordered and become more structured when hydrated. At low water content, the protein-protein interaction via hydrogen bonds predominates to form a β-sheet structure (train region). However, with the increase of water, some but not all interchain hydrogen bonds break and the interaction between glutamine and water is favored to form a β-turn structure (loop region). In noodle dough, FTIR spectroscopy was used to examine the secondary structure of protein by Li et al. (2017), in which the β-sheet structure was found to dominate in the noodle dough made at 38 % water addition level, and the ratio of β-sheet to β-turn structures was modified with further processing (such as resting, sheeting and cooking). These outcomes imply that the water in the system may have an important role in shaping the structure of protein, thus affecting the overall elasticity of the gluten matrix in noodle dough.

Cooked noodle texture is greatly affected by the water addition level. Hatcher et al. (1999) reported that noodles with increased water content had a slower recovery, less resistance to compression. Park and Baik (2002) also showed cooked noodles had reduced hardness with an increase of water addition.

2.0.3 Salt

Salt not only adds flavour to noodles but more importantly, it changes the dough's development properties (Hou, 2001; Fu, 2008). Dexter et al. (1979) examined the structure changes of Japanese noodle dough by use of Scanning Electron Microscopy and discovered that the addition of 2 % salt resulted in a smoother and more uniform surface than the unsalted one. But a higher addition level of salt (5 and 10 %) was not desirable, as the salt seemed to compete with protein for the water in the dough; thus less water was available to hydrate the protein.

2.1 Key Noodle Processing Steps

From ingredients to finished product, noodle processing starts with mixing all the ingredients into dough crumbs, which is then followed by repeated sheeting operations, and then cutting the dough sheet into strands. This section will focus on the basic principles related to mixing, sheeting, cooking and aging which are relevant to noodle texture.

2.1.1 Mixing

Noodle processing starts with mixing all the ingredients in a mixer, which helps evenly distribute all the ingredients and hydrate flour particles. A variety of mixers are commercially available, including vertical, horizontal, one-shaft, double-shaft, continuous high speed and vacuum mixers (Fu, 2008; Hatcher, 2001).

The mixing speed and time in noodle studies vary from one to another. The speed of mixing affects the hydration rates and the development of gluten. High-speed mixing hydrates flour more efficiently than a low-speed mixer, while a super low-speed mixer operated at < 10 rpm produced a dough similar to a hand-made one (Fu, 2008). The mixing time depends on the flour quality, the formulation of noodles as well as the efficiency of the mixer. Water absorption can vary due to mixer types and conditions (Oh et al., 1985b; Liu et al., 2015).

Dough crumbs of various sizes are formed after mixing. The dough crumb sizes can be affected by the physical and chemical properties of the flour, the type of mixer and mixing speed and mixing time. In general, flour with large particle sizes requires a longer time for water to penetrate from outside to the inside, and the flour with high protein and/or high level of starch damage tends to have large crumbs and uneven hydration (Hou et al., 1998).

It is commonly believed that gluten has minimal development at the mixing stage as water is a limiting factor (Fu, 2008). A few studies have focused on the mixing action of the noodle dough with reduced pressure levels (Solah et al., 2007; Li et al., 2012; Jiang et al., 2014; Liu et al., 2015) and showed that vacuum mixing improved noodle quality, either the appearance or the texture. To further understand the mechanism, Liu et al. (2015) examined the glutenin macropolymers (GMP) and structure changes during mixing and found that glutenin macropolymer content was significantly reduced during the initial mixing stage, an outcome which agreed with the results of Ong et al. (2010).

2.1.2 Sheeting

2.1.2.1 Principle and Types of Different Sheeters

Sheeting is commonly used for bread, pastry and other bakery products, and more importantly, it is widely used for making most Asian noodles (Fu, 2008). The sheeting process involves two rotating inward rolls, where the dough is compressed to form a dough sheet. By changing the gap size between the rolls, the dough sheet gradually reduces in thickness and the dough length increases (Levine & Boehmer, 1997; Kempf et al., 2005). Commercial noodle stands have reduction rolls with a diameter of 240 mm to 120 mm, and some other types (waved rolls) are also commercially available (Hatcher, 2001).

2.1.2.2 Sheeting Variables and Work Input

Noodle sheeting utilizes various processing conditions based on the noodle type, operator, and finished product quality (Hatcher, 2001). Noodle sheeting varies with the number of lamination and reduction passes, gap settings, resting period and sheeting speeds (Hou, 2001). In general, the initial noodle sheet is rough and requires one or more laminations and 3-5 reductions so that smooth dough with a uniform and continuous dough structure can be obtained (Fu, 2008). A rapid reduction in thickness would create too much stress on the roll stand, and also damage the noodle sheet. Therefore, Oh et al. (1985b) suggested that roll gap reductions of 30 % increment with a slow roll speed is desirable in noodle processing.

Sheeting is believed to be an energy-efficient process when compared to mixing in the context of bread dough processing, and the energy consumption of sheeting is only about 15-20%

that required for mixing (Kempf et al., 2005). In terms of noodle dough, which utilizes much less water than bread dough, the energy consumption during sheeting should be higher in comparison to bread making. Use of calibrated force or pressure transducers has been reported to capture the energy / work input utilized during the sheeting process (Kilborn & Preston, 1982; Edwards et al. 1996; Hatcher et al., 1999; 2002). Edwards et al. (1996) reported that the addition of salt significantly increased dough strength, thus increasing work input. Hatcher et al. (1999) studied how work input was affected by water addition levels. They found an inverse relationship between water addition and the work input, that is, softer dough with higher water content requires less work input.

2.1.2.3 Sheeting and Product Quality

Sheeting has long been associated with development of a smooth and uniform gluten matrix which determines the characteristic texture of noodles. Dexter et al. (1979) studied the noodle dough during the sheeting process via scanning electron microscopy and found that noodle dough microstructure was progressively modified by repeated sheeting passages. A full gluten development was not found; rather, the noodle dough became less porous, and more continuous with starch granules firmly attached to gluten after repeated sheeting. Oh et al. (1985b) studied the processing variables (roll speed, and thickness reduction rate) and the quality of dry noodles. It was found that the cooked noodle surface was firmer with a decrease of roll speed and an increase in the gap size reduction rate. It was not clear whether gluten was developed to a greater extent with longer contact time between the rolls (lower speed) or because of a higher pressure (sharp decrease in dough thickness). But surprisingly, they also found that noodles with fewer sheeting steps were firmer than the ones with more sheeting passes. The mechanisms behind this were not fully understood. The speed and gap size reduction rate are both related to time, so it would be interesting to find out if time has a greater impact on noodle quality rather than the mechanical work input.

Other than protein alignment, sheeting also helps exclude air bubbles from the dough and change the bubble distribution in the dough, an outcome which was more evident in bread dough (Stenvert et al., 1979; Pyler, 1988; Jha et al., 2017), as bread dough contains significantly more air bubbles than noodle dough (Elmehdi et al., 2007). The changes in air bubbles in the dough affect its baking quality (Koksel & Scanlon, 2012). It has been found that bread tends to have a finer texture when the dough is sheeted or molded (Sutton et al., 2003). Regarding the air bubble changes in noodle dough, Guillermic et al. (2018) examined the bubble changes by use of X-ray tomography and found that lamination (compounding) entrapped air bubbles within the dough sheet and they became smaller in size but more homogenous with an increase in the number of lamination steps. The bubbles were located in the middle of the dough sheet and were aligned in the sheeting direction.

2.1.3 Cooking

2.1.3.1 Cooking Time and Texture

It is well known that cooking time is critical for controlling noodle texture (Park & Baik, 2004); therefore, it is important to cook the noodle for an optimal amount of time. To determine the optimal cooking time, the noodles, after cooking for a certain time, are normally squeezed in between a pair of glass plates. Noodles are optimally cooked when the white core disappears (Oh et al., 1983). In addition to the observation of the core, sensory assessment is another way to determine the optimal cooking condition (Park & Baik, 2004). Both testing methods rely on human perception and could lead to variable results from person to person. As Park and Baik (2004) pointed out, judgments on the white core are mainly focused on the degree of water imbibition in the noodle, and thus neglect the change in other constituents in the noodle, such as starch and protein.

Cooking time was reported to positively correlate to the protein content. Oh et al. (1985a) and Park and Baik (2004) reported that noodles made from soft wheat flour (lower in protein) required a shorter cooking time than hard wheat flour. The difference in cooking time may be a result of protein but might be also due to noodle dimension differences. In both studies, raw noodles with a higher protein content were thicker than the low protein one; thus it would take longer time for water and heat to penetrate into the core of noodles. Jang et al. (2016) fortified noodles with maltodextrin and studied how the maltodextrin changed the rheological and thermal conductivity properties of the noodles as well as their microstructure. A significant reduction in cooking time was found for noodles fortified with maltodextrin compared to the control, due to increased thermal conductivity. It was also observed by use of SEM that noodles with maltodextrin were more porous (a honey-comb like structure) than the control, which provided more channels for heat and water to penetrate into the core. Therefore, the cooking time was significantly shortened.

2.1.3.2 Cooking Process

Noodle cooking is a complex process. A series of physio-chemical changes occur in the cooking process. Dexter et al. (1979), Sekine and Harada (1990) and Kojima et al. (2001) studied the noodle boiling process by use of Scanning Electron Microscope or Nuclear Magnetic

Resonance (NMR). In the early stage of the cooking process, the noodle surface absorbed water quickly, and the core absorbed water as well, but at a slower rate, thus a clear difference between the core and the surface was observed. On the surface, starch gelatinized rapidly, and amylose leached out, creating small openings in the noodle strand. The openings became larger in diameter upon further cooking. The core showed less changes compared to the surface. Good quality noodles kept their integrity and exhibited less breakdown at the surface after cooking for the same amount of time.

2.1.4 Aging

Visually, noodles tend to darken and develop black specs over time, which is strongly associated with the enzyme, polyphenol oxidase, inherent in the flour (Hatcher & Kruger, 1993; Kruger et al., 1994; Baik et al., 1995; Hatcher et al., 2004; 2009). The spontaneous change occurring over time refers to aging.

Other physical changes of noodles have also been reported. Miki et al. (1988) found the density of noodle increased remarkably within 2 hours of resting. The cooked noodle which was rested for 4 hours had a much higher relaxation time (1.4 fold) compared to the one with no resting. Miki et al. (1988) suggested that air bubble exclusion was responsible for the increase of the density and the resultant compact structure was the reason for the change in relaxation time.

Endo et al. (1984) and Li et al. (2014) studied the effect of aging through imaging tools such as SEM and MRI. Endo et al. (1984) discovered the cooked noodle structure was strongly modified with aging time. After cooking, more pores filled with water were observed inside the aged noodles compared to the fresh one. By use of MRI, Li et al. (2014) reported a significant difference in water distribution in the noodle upon aging. Water was uniformly distributed in fresh noodles and gradually migrated to the surface upon aging, which might disrupt the original structure of the gluten network, thus contributing to the deterioration of noodle quality.

The change in gluten has also been reported. Ong et al. (2010) found that glutenin macropolymer (GMP) content was significantly decreased in the active processing steps (mixing, compounding and sheeting) but increased after the dough was rested for 24 hours. The gel strength measured with a rheometer showed a significant difference depending on the noodle type. After resting, the strength of the gel extracted from salted noodles significantly decreased, but this trend was not found for alkaline noodles.

2.2 Noodle Texture Assessment Methods

2.2.1 Low Intensity Ultrasound

2.2.1.1 Introduction

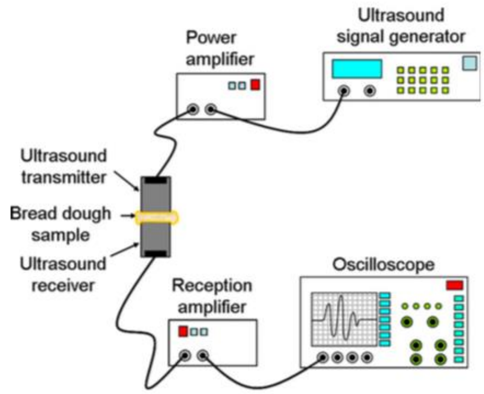
Ultrasound is a pressure wave with a frequency that is beyond the human hearing limit (~16 kHz) (Povey & McClements, 1988). Ultrasound is widely used by animals, such as bats and dolphins, to find prey; it was not discovered until the late 19th century and has a broad range of applications ever since, for example in submarine detection and disease diagnosis (Coupland, 2004) among various other fields. The application of ultrasound depends on the intensity and frequency of the sound waves. For non-destructive measurements and process and quality monitoring purposes, only low-intensity ultrasound at intensities below 1 W/cm^2 is used (Awad et al., 2012). Low intensity ultrasound does not modify the physical and chemical properties, thus making it a non-destructive method. Ultrasonic techniques are also fast, reliable and easy to be incorporated into production lines (McClements & Gunasekaran, 1997; Povey & Mason, 1998).

Longitudinal and transverse are the most common displacement modes of sound waves (Coupland, 2004). The displacement of the particles can move in parallel to the direction in which the sound wave travels in the case of a longitudinal wave, or it could be perpendicular to the direction of sound wave propagation if a transverse wave propagates. Transverse waves can be used to measure the shear properties of materials (Kulmyrzaev & McClements, 2000; Létang et al., 2001; Leroy et al., 2010) as in classic rheometry, but at much higher frequencies. Longitudinal waves are used to measure the compressional properties of materials. For materials with a high damping property (Lionetto et al., 2005), such as dough (Alava et al., 2007; Diep et al., 2014), longitudinal waves are preferred over shear waves as shear waves tend to be attenuated rapidly in soft solids and do not propagate in air or water.

2.2.1.2 Sound signal generation and reception

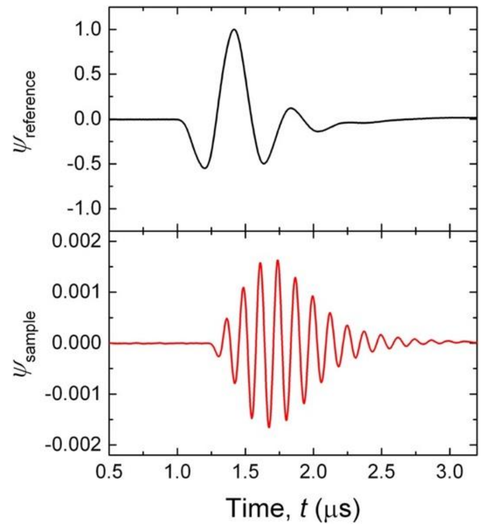
A typical ultrasound setup includes a pulse generator and receiver, transducers, an oscilloscope and a computer as shown in Figure 2.1.

Figure 2.1: An ultrasound set-up with transmission mode for a bread dough sample. Source: García-Álvarez et al., 2011 (Used with permission).



A transducer is responsible for the generation and reception of sound waves. The active element in a transducer, such as commonly used piezoelectric crystals, creates oscillations when it is subject to an electric pulse from a pulse generator. Subjected to an oscillating electric signal, a piezoelectric element deforms in a specific fashion and therefore generates an acoustic wave (Coupland, 2014; Scanlon & Page, 2015) and vice versa. Other types of transducers are also commercially available, such as capacitive transducers (Kerhervé, 2018). Capacitive transducers have no piezoelectric elements but consist of two electrodes separated by air, one of them being free to move. By changing the voltage between the two electrodes, the distance between them changes, and the motion of the free electrode generates a sound wave in air (Kerhervé, 2018). The transmitting and receiving efficiency is much improved compared to traditional piezoelectric transducers (Schindel et al., 1996), which makes non-contact measurement possible. The signal from the receiving transducer is usually amplified with a signal amplifier, and can then be visualized and recorded with an oscilloscope and a computer. An example of a reference signal and a signal after it is transmitted through a dough sample is shown in Figure 2.2.

Figure 2.2: An example of a reference signal and after it is transmitted through a material as a function of time. The y-axis represents amplitude. Source: Scanlon & Page, 2015 (Used with permission).



Reflection and transmission are commonly used techniques. In the case of reflection, sound waves are emitted from the transducer to the surface of the medium and reflected back and received by the same transducer. It is suitable for materials with a strong attenuation of sound waves (Kulmyrzaev & McClements, 2000). In a transmission set-up, wave signals are sent from one transducer through a sample and received by the second transducer on the other side of the sample. It is the most commonly used, especially for a low attenuating medium (Coupland, 2014; Scanlon & Page, 2015).

2.2.1.3 Wave analyses

No matter how complex waveforms are, they can be described as a sum of sinusoidal waves varying in frequency (f), amplitude (A) and phase (ϕ):

$$y(x,t) = A\sin(\omega t - kx + \phi) \tag{2.1}$$

where y is the displacement at position (x) and time (t), and A is the amplitude, ω is the angular frequency (rad/s) which measures the number of cycles per unit time ($\omega = 2\pi f$) and k

is the wavenumber ($k = 2\pi/\lambda$, λ is the wavelength which is the distance between two successive peaks or troughs), and ϕ is the phase shift which is a measure of the position at a specific time on a waveform relative to a reference point and expressed in the unit of radians or degrees (Povey, 1997; Koksel et al., 2016).

2.2.1.4 Material characterization tool

Materials can be characterized based on how fast the sound waves propagate and how much energy losses occur. Similar to light, a sound wave can be reflected, absorbed, or scattered depending on the properties of the medium or its impedance (Povey, 1997). Impedance (Z) is a characteristic of a material and is defined as: $Z = \rho\omega/k$ where ρ is density (kg/m^3). The transmission (t_c) and reflection (r_c) coefficients determine how much of the wave amplitude is transmitted into a medium or reflected back, and they are defined via the equations :

$$r_c = \frac{Z_1 - Z_2}{Z_1 + Z_2} \tag{2.2}$$

$$t_c = \frac{2Z_1}{Z_1 + Z_2} \tag{2.3}$$

where the subscript 1 and 2 refer to medium 1 and medium 2.

Ultrasound velocity and attenuation coefficient are the most important properties obtained from ultrasonic measurements. The velocity (c) can be determined via $c = \lambda f$ or by measurement of the amount of time (t) required for a wave to travel a known distance (x) $(c = \frac{x}{t})$. In a dispersive material, wave velocity is frequency dependent. Measurements of the velocity of each component of the pulse at a specific frequency (known as the phase velocity) are more accurate for describing the wave propagation (Page et al., 1996; Cobus et al., 2007). In order to calculate the phase velocity, the fast Fourier transform technique is used to convert wave signals from the time domain to the frequency domain, where the difference in the phase of the transmitted signal relative to the input signal is used to calculate phase velocity (v) as follows:

$$v = \frac{\omega d}{\Delta \phi} \tag{2.4}$$

where ω is the angular frequency, d is the thickness of the material tested, and $\Delta\phi$ is the phase difference between transmitted signal and the input signal (Cobus et al., 2007).

The exponential decay of the initial amplitude (A_0) through a travel distance (x) allows determination of the attenuation coefficient (α) per unit travel distance, which is a measure of energy loss due to scattering or absorption of sound waves (Scanlon & Page, 2015) and is defined by: $A = A_0 e^{-\alpha x/2}$. Absorption could be due to losses of thermal energy as well as to molecular relaxation processes (McClements, 1991; Povey, 1997). Scattering is most likely to occur in a non-homogenous medium or a composite material (McClements, 1991).

The phase velocity (v) of the longitudinal waves is related to a longitudinal modulus (M) and the density of the medium (ρ) via the equation:

$$v = \sqrt{\frac{M}{\rho}} \tag{2.5}$$

In a dispersive medium, both phase velocity and attenuation coefficient contribute to the complex modulus of a material and are thus providing information on its mechanical properties. The elastic modulus of a material with viscoelastic properties has two parts, an imaginary part (loss modulus, M'') and a real part (storage modulus, M') which can be calculated via:

$$M' = \rho v^2 \frac{\left[1 - \left(\frac{\alpha v}{2\omega}\right)^2\right]}{\left[1 + \left(\frac{\alpha v}{2\omega}\right)^2\right]^2} \tag{2.6}$$

$$M'' = \frac{2\rho v^2 \left(\frac{\alpha v}{2\omega}\right)}{\left[1 + \left(\frac{\alpha v}{2\omega}\right)^2\right]^2} \tag{2.7}$$

The storage modulus is attributable to the elastic character of a viscoelastic material. The loss modulus is related to viscosity (Bohlin & Carlson, 1980). The ratio of M'' to M' gives the tan δ value ($\tan\delta = \frac{M''}{M'}$) (Diep et al., 2014; Scanlon & Page, 2015).

2.2.1.5 Ultrasound and mechanical properties of noodles / dough

Ultrasound techniques operated at different frequencies reveal different information about materials such as dough. With low-frequency, ultrasound measures properties at large length scales, whereas high-frequency ultrasound is important for studying structural changes at small length scale (Scanlon & Page, 2015). Wheat flour dough is a highly attenuating/damping material, and even more so at higher frequencies, so the frequency range of 50 kHz - 1 MHz is commonly used (Povey, 1989). At low frequencies, the use of ultrasound techniques to study dough properties has focused on discrimination of flour type and strength (Alava et al., 2007; García-Álvarez et al., 2011), ingredient impact (Kidmose et al., 2001; Alava et al., 2007; Mehta et al., 2009) and mixing effects (Létang et al., 2001; Ross et al., 2004).

As for noodles, the ultrasound technique has been used to differentiate noodles made from various flours and other ingredients (Bellido & Hatcher, 2010; Diep et al., 2014; Hatcher et al., 2014). Bellido & Hatcher (2010) investigated the effect of the crosslinking enzyme transglutaminase on the structure and mechanical properties of yellow alkaline noodle dough at 40 kHz. At the same frequency, Diep et al. (2014) studied the mechanical properties of alkaline noodles made with nine varieties of wheat flours and successfully discriminated flours within the same class. Salimi-Khorshidi (2016) examined yellow alkaline noodle dough made with varying work input by manipulating the lamination steps during the sheeting process and measuring dough properties with ultrasound at 1.4 MHz; he found that the phase velocity of the dough laminated 10 times was significantly reduced and the attenuation coefficient increased compared to one laminated 3 times. Partially this was due to more lamination steps entrapping a greater amount of air bubbles as revealed by X-ray tomography (Guillermic et al., 2018).

Both longitudinal waves (Lee et al., 1992; Létang et al., 2001; Alava et al., 2007; Diep, 2014) and shear waves (Létang et al., 2001) operated over a range of wide frequencies have been used to examine the effect of water on the machanical properties of dough. A general trend has been found, which is that sound velocity decreases and the attenuation coefficent increases with an increase of water addition in the dough (Létang et al., 2001; Alava et al., 2007; Diep, 2014). In addition, Létang et al. (2001) measured dough with water absorption levels between 49-58 % and found that both the velocity and attenuation coefficient had a linear relationship with the water content except at a critical water content of 53%. This water content corresponded well with the fairnograph result, and it might imply excessive free water created a separate aqueous phase and coexisted with the gluten phase. One question that can be posed: what is going to happen when there is not enough water in the dough matrix, such as in noodles?

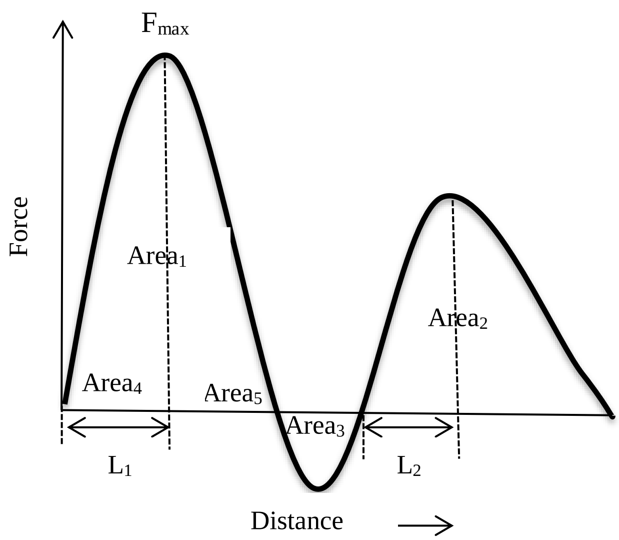
2.2.2 Texture Analyzer

Different from sensory evaluation, instrumental methods provide objective information related to the mechanical properties of tested samples with a lower cost, and in a timely manner (Ross, 2006); thus, cooked noodle texture is commonly tested with instruments such as the texture analyzer. The instruments measure the resistance of tested sample under deformation to imitate the biting and chewing action between incisors or molars in a sensory test. By following the same ideas with pasta evaluation (Cole, 1991), noodle texture assessment commonly uses compression tests, cutting tests, and texture profile analysis (TPA) (Ross, 2006). As there is a lack of an international standard for noodle preparation, cooking, and testing, various set-ups and procedures have been applied in noodle research, as summarized by Ross (2006).

A compression test for noodle texture assessment uses a probe with a rectangular contact surface or sharp cutting blade and is based on the method of Oh et al. (1983), so that three strands of noodles are typically aligned side by side and then cut crosswise by a 1mm flat blade. A force deformation curve is generated, from which the maximum cutting force (the peak force) and work (area under the force-distance curve) can be obtained. Both parameters correlate well with the sensory term “firmness” (Oh et al., 1983). A compression-recovery study done by Oh et al. (1983) was the basis to capture the elastic characteristics of noodles. In the study, a flat probe with a contact surface of 3.5×5.5 mm was used to compress three strands of noodles crosswise till reaching a fixed compression force. However, the reason to choose the specific compression force was not stated in the research and it is uncertain if it would be suitable for noodles with different dimensions or made with different materials. Choosing three noodles instead of one is to accommodate variances from sample to sample, but it could potentially average out the subtle differences in noodles and make the test less sensitive to noodle texture (Cole, 1991). Moreover, sample preparation requires extra care as a false contact surface area may occur if samples are overlapping or not aligned properly.

A number of noodle studies used TPA to measure the texture of cooked noodles, such as Baik et al. (1994), Epstein et al. (2002), Guo et al. (2003), Lu et al. (2008), Pronyk et al. (2008), Hou et al. (2013), Liu et al. (2015), Mudgil et al. (2016). TPA is a two-cycle compression test where a flat probe is used to compress the noodles to a certain strain (commonly between 70-75 %) and after the first compression is completed, a second compression is applied on the same noodle sample (Ross, 2006). TPA allows acquiring different parameters in a single test. A typical TPA curve is displayed in Figure 2.3. A number of parameters derived from the force-displacement curve, such as hardness, springiness, cohesiveness, adhesiveness, chewiness and resilience, are shown in Figure 2.3. It should be noted that a standard method for performing this test is not established yet (Pipatsattayanuwong, 1998); therefore, studies use different crosshead speeds and strain levels.

Figure 2.3: Texture profile analysis curve from Epstein et al. (2002) with modifications and derived parameters.



$$\text{Hardness} = F_{max}$$

$$\text{Cohesiveness} = \frac{Area_2}{Area_1}$$

$$\text{Springiness} = \frac{L_2}{L_1}$$

$$\text{Gumminess} = F_{max} \times \frac{Area_2}{Area_1}$$

$$\text{Chewiness} = \left(F_{max} \times \frac{Area_2}{Area_1}\right) \times \frac{L_2}{L_1}$$

$$\text{Adhesiveness} = Area_3$$

$$\text{Resilience} = \frac{Area_5}{Area_4}$$

Among all the texture attributes, surface firmness/hardness, overall hardness, and elasticity are the three main characteristics scientists are interested in (Ross, 2006). Surface firmness draws extra attention as noodles show different moisture distribution from the surface to the core during cooking (Sekine & Harada, 1990; Kojima et al., 2001); surface firmness/hardness is a good way to capture texture differences caused by various formulations and processing regimes (Oh et al., 1985ab; Rho et al., 1989; Kruger et al., 1994; Hatcher et al., 1999). Oh et al. (1985a) introduced the term surface firmness. By plotting the initial contact to the point where 60 $gf.cm^{-2}$ (5.9 kPa) of stress was applied in a compression test, the slope on the force-time curve obtained was taken to be an indicator of the surface firmness of the noodle. It is uncertain if the chosen stress level is appropriate for noodle samples with various dimensions. The mechanical parameters measured by a texture analyzer correlated well with the sensory term of firmness (Ross, 2006). Both involve compression of food samples either by molar teeth or a cutting blade. In terms of the elastic component of noodles, the descriptors used for instrumental analysis and sensory analysis are not necessarily correlated. In order to measure the elasticity of food samples, the sample has to be compressed within the linear range (approximately 6% strain for cooked noodles) (Miki & Yamano, 1991). But on the other hand, mouthfeel of elasticity involves large strain deformation to even exceed the rupture point during chewing.

To ensure good measurements on noodle texture, attention should be paid in standardizing the noodle processing and testing conditions (Ross, 2006), such as the thickness of the noodles, and the resting time. Oh et al. (1983) sheeted noodle dough to different thicknesses and found the measured maximum cutting stress significantly increased with an increase in noodle thickness. The resting time after cooking can also affect the texture measurements. According to Ross (2006), a holding time of 15 minutes after cooking significantly reduced the springiness and resilience. Oh et al. (1983) also found the maximum cutting stress significantly decreased for the first 10 minutes after cooking and gradually leveled off after 20 minutes standing.

2.2.3 Sensory Evaluation

Sensory evaluation is a scientific method to measure the human response to food objects. It uses all human senses, sight, smell, taste, touch, and hearing. And the responses are measurable and analyzable (Stone & Sidel, 2004). Sensory evaluation is widely used in the food industry, and helps in new food product development, quality control and other functions (Noda et al., 2001; Guo et al., 2003; Park & Baik, 2004; Yanaka et al., 2007).

Depending on the purposes of a study, sensory testing can be categorized into three types: difference test, affective test and descriptive test (Stone & Sidel, 2004). As the name indicates, a difference test is simply a method to detect if any difference exists between/among samples. An affective test evaluates how consumers like or dislike the tested product, and commonly uses a 9-point hedonic scale. The drawback of these methods is that they cannot reveal much information on specific characteristics of the product. On the other hand, descriptive testing is generally applied when the aim is to evaluate the degree of changes of specific characteristics of a food object. It provides both qualitative and quantitative information (Stone & Sidel, 2004).

The texture profile is one descriptive test used for texture evaluation. It was developed by a group at the General Foods Technical Center in the early 1960s by applying the same principle as flavor profiling (Brandt et al., 1963; Szczesniak, 1975). Brandt and co-workers (1963) defined a texture profile as “the sensory analysis of the texture complex of a food in terms of its mechanical, geometrical, fat and moisture characteristics, the degree of each present and the order in which they appear from first bite through complete mastication.” As the definition implies, texture profile captures mechanical properties, geometrical characteristics, and other characteristics associated with the moisture and fat content of food objects through the whole mastication process; therefore, it provides valuable information about food characteristics beyond what the instruments can detect.

2.2.3.1 Trained Sensory Panel

Descriptive sensory analysis or sensory profiling is a method to discriminate product differences by use of a group of sensory assessors. It measures an assessor’s perception in response to stimuli regardless of personal preference; therefore, the sensory panel functions as an analytical instrument. Typically, panelists are recruited based on their ability in discriminating product differences. Regarding the number of panelists, as few as 3-5 panelists are adequate depending on how well the panelists perform and the complexity of the products. Extra care is required for sensory design, including defining the quality attributes, selecting suitable panelists, delivering adequate training, conducting standardized cooking procedures and maintaining fixed sample size (Lawless & Heymann, 2010).

2.2.3.2 Noodle Texture Lexicon and Assessment Method

Both consumer testing (Toyokawa et al., 1989b; Guo et al., 2003; Ye et al., 2009) and trained panels (Oh et al., 1983; Ross et al., 1997; Pipatsattayanuwong, 1998; Crosbie et al., 1999;

Noda et al., 2001; Park & Baik, 2004) have been used to assess noodle texture by use of different scale methods, such as structured or unstructured lines, and a weighted scoring system.

Based on texture profiling, Pipatsattayanuwong (1998) developed a lexicon specific to Asian noodles, and, in total, 17 descriptors / lexicons were developed to capture the textural properties of noodles from the first chew, to chew down and to expectoration. All the lexicons were grouped into three components which accounted for 54 % of the variation in texture of noodles tested by use of principal component analysis (PCA). One component was associated with hardness, and descriptors such as "cohesiveness", "denseness", "starch between teeth", and "toothpull" were used, and one component was related to springiness and integrity of the noodles, and one component was related to smoothness of noodles, such as microroughness (smoothness of noodle surface), starch matrix (perceived chalkiness) and greasy mouthfeel. Other researchers reported that surface texture, firmness and elasticity were the most important sensory attributes in noodles (Oh et al., 1983; Ross et al., 1997; Noda et al., 2001).

3. Materials and Methods

3.0 Flour

Noodles were made from flours of two wheat classes. A composite of varieties of wheat was chosen from CWRS (Canada Western Red Spring) and CWRW (Canada Western Red Winter) wheat. Both were chosen due to their wide availability and suitability for Asian noodle processing. Both were milled at Canadian International Grains Institute, Winnipeg, at an extraction rate of 75.5 % and 78.3 %, respectively. The resultant flour was subjected to physical and chemical testing based on approved methods. The protein content was measured by using a combustion nitrogen analysis (CNA) as in Williams et al. (1998). Other tests include falling number (AACCI Method 56-81.03), moisture content (AACCI method 44-15.02), and ash (AACCI method 08-01.01).

Flour/ gluten strength is one of the most important determining factors in noodle quality (Park et al., 2003; Gulia & Khatkar, 2015); therefore, gluten strengths were determined using a Brabender Fairinograph (AACC Approved Method 54-21.02), Extensograph (AACCI method 54-10.01), and Alveogram (AACCI Method 54-30.02).

Starch damage was assessed with AACC approved method 76-33.01 and the pasting profile was examined with Newport Rapid Visco Analyzer (Newport Scientific, Sydney, Australia) and expressed as RVU (rapid visco units).

3.1 Noodle Formulation

Noodles were formulated to simulate industry practice. White salted noodles are commonly formulated with 1-3 % of table salt (Fu, 2007), and it was reported that 2 % of salt not only helps strengthen the dough but also helps to develop dough with a smoother and uniform appearance (Hou, 2001), therefore, 2 % salt was chosen for this study. We chose 32 % and 36 % to cover a range of water contents that industry uses (Hou, 2001). Taking into account the inherent difference in the moisture content in the flour, the mass of each ingredient was balanced to replicate industry practice (CIGI, 2017). The detailed formulation was based on 14 % moisture content in the flour as shown in Table 3.1.

Table 3.1: Experimental formulations of noodle doughs

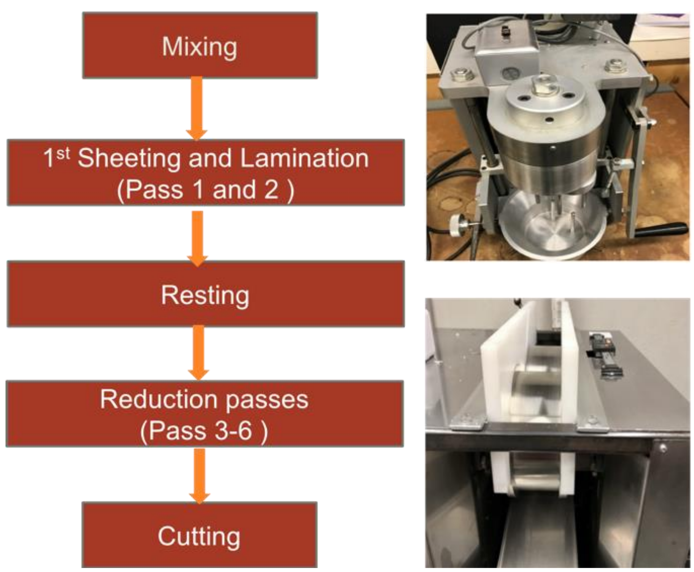
Ingredient	CWRS_32	CWRS_36	CWRW_32	CWRW_36
Flour (g)	99.65	99.65	99.19	99.19
Water (g)	32.35	36.35	32.41	36.41
Salt (g)	1.99	1.99	1.98	1.98
Total	133.99	137.99	133.59	137.59

3.2 Noodle Processing

We were aiming to process noodles to simulate commerical noodle production (Hou, 2001; Fu, 2008). However, we were also aware that researchers use various process conditions in mixing and sheeting process as shown in the Literature Review chapter. Apparently, this is caused by a lack of a standardized method. Not so apparent is that there is a lack of knowledge on how noodle quality is affected by the mixing and sheeting processes. This lack of knowledge justifies the purpose of this study.

Figure 3.1 displays the processing steps used in this study. All ingredients were combined in a pin mixer (National MFG. Co., Lincoln, USA) and mixed at either 121 rpm or 60 rpm for 3 minutes to form crumbs. The mixing speeds were chosen to represent the wide range of mixing conditions used in the literature (121 rpm used in this study represented the high-speed mixing, and 60 rpm represented the low-speed mixing condition). After mixing, the crumbs were fed into a custom-built noodle machine as described by Pronyk et al. (2008). The noodle machine was equipped with a 186 W DC gear motor and a pair of rotating stainless steel rolls, 180 mm in diameter and 75 mm in width. After mixing, a handful of dough crumbs was fed into the noodle machine, compressed between the rolls and formed into a dough sheet. The initial gap was set at 2.6 mm. After the first sheeting pass, the dough sheet was folded in two and passed through the same gap, a process called lamination or compounding. After the lamination process, the dough sheet was wrapped with cling wrap, placed in a plastic bag and rested for 30 minutes in an environmental chamber (Memmert HPP 750 IPP plus, Buchenbach, Germany) at 22 °C and 85 % Relative Humidity.

Figure 3.1: Noodle processing equipment and steps



After resting, the thickness of the dough sheet was successively reduced in increments of 30% in four reduction passes as in Oh et al. (1985b). The reduction rate used corresponded to the one used in the food industry, typically in the range of 15-33 % as reported by Hatcher (2001) and Nagao (1996). Table 3.2 shows the gap settings used for this study. After the final pass, the thickness of noodle sheet was between 1.4 and 1.6 mm. As the properties of dough evolve continuously with time, as seen in bread dough (Létang et al., 1999), the time for each processing step and measurement was carefully controlled. After Pass 2 and Pass 6 the noodle sheet was cut with a customized cutter (7.5 × 8.5 cm) for density and acoustic measurements and only a fresh sheet after Pass 6 from the same production run was further cut into 5 mm wide strands with a manual noodle cutter for cooked noodle texture analysis.

Table 3.2: Roll gap settings for noodle processing

Pass #	Gap size (mm)
1	2.6
2	2.6
3	1.8
4	1.3
5	0.9
6	0.6

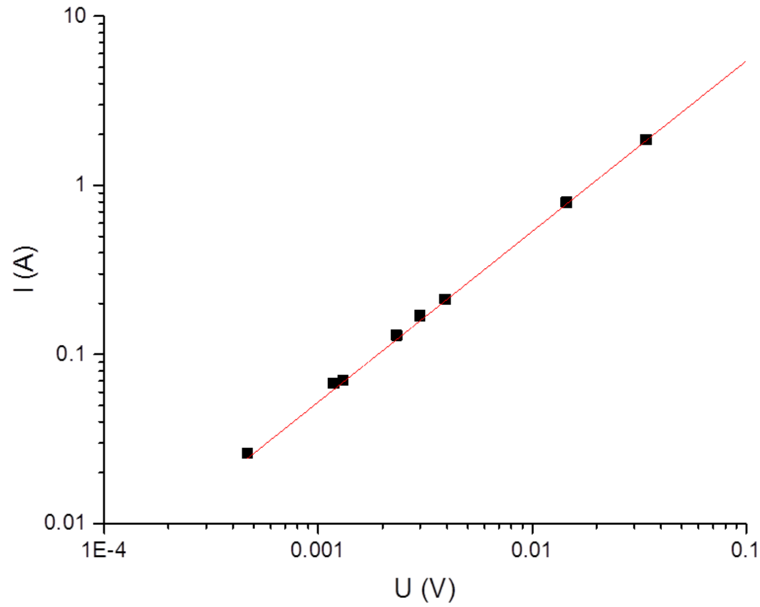
3.3 Work Input During Sheeting

The power consumption during the sheeting process was captured by using a 2105 Wide Range Power Analyzer (Valhalla Scientific, San Diego, USA) and a multi-meter (Agilent 34401A). The power analyzer was connected in series with the noodle machine so that the current delivered to the noodle machine passed straight through it in series. The power analyzer displays both true power and either current or voltage on its front panel displays, but does not have outputs for transferring this information directly to a computer. To overcome this limitation, the digital multi-meter was used to measure the voltage across the internal shunt resistance of the power analyzer, with this voltage being sent to a computer so that the current was the same through each component and was measured every 2 seconds. The current, I, was obtained from the voltage U shown on the multi-meter via:

$$I = \frac{U}{R} \tag{3.1}$$

where R is the internal shunt resistance of the power analyzer and was obtained through calibration by connecting different devices that draw varying power levels to the output terminals of the power analyzer. These calibration data are plotted in Figure 3.2, and yielded R^{-1} = 54.752 (Ω^{-1}). The apparent power was calculated as: $P_{app}=V\times I$, with V being the mains voltage (120 V); thus $P_{app}=V\times\frac{U}{R}=120\times 54.7527753\times U$. The P_{app} was calculated in a MATLAB program (Math Works, Natick) and plotted against time. The average of the readings from the power meter before feeding the dough sample between the sheeting rolls was taken as the baseline. The apparent power consumption for dough sheeting with the rolls running during sheeting of the dough was calculated by subtracting the baseline power. The apparent power was converted to true power using the power factor for the sheeting machine, which was determined during test sheeting trials by comparing the true power readings (in Watts) displayed on the power meter to the measured apparent power (in VA). For the range of currents drawn by the noodle machine while sheeting noodles, the average power factor was found to be approximately 0.12, so the true power $P \approx 0.12 \times P_{app}$. By integration of the power readings over time, the total work input was obtained by summing the product of power P_i for each 2 second interval, Δt_i, and Δt_i = 2 s, i.e., Work$=\sum_i P_i \times \Delta t_i$. The weight of the dough was measured separately; by dividing the total work by the weight of the dough, work input per unit mass of dough was obtained and expressed as J/g of dough.

Figure 3.2: The relationship of voltage (U) measured by a multi-meter and the corresponding current (I) displayed on the power meter, plotted on a log scale. The slope represented the inverse of resistance (R^{-1}), and R^{-1}= I/ U= 54.752 (Ω^{-1}).



3.4 Raw Noodle Density

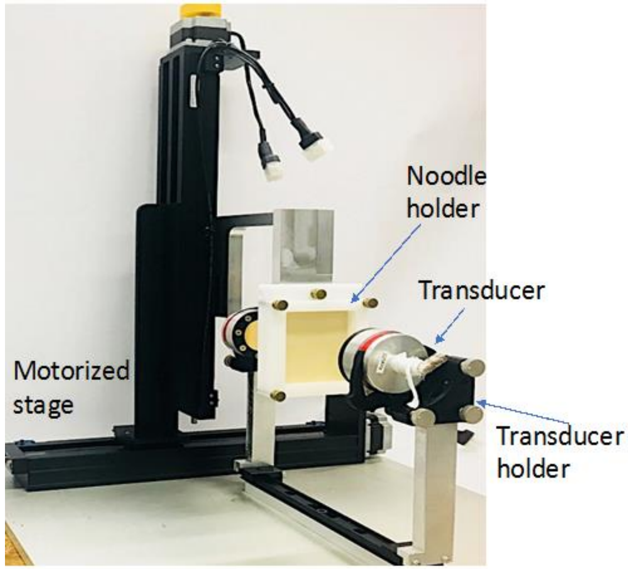
A water displacement method was used for density measurement of raw noodles according to Bellido and Hatcher (2010). Noodles subjected to various amounts of work input and aging time were examined. For each treatment, three dough pieces (approximately 0.5-1 g) were cut using a sharp blade after the lamination process (Pass 2), and after the sheeting process (Pass 6). Two pieces were cut from the sides and one from the center of a dough sheet. Noodle dough sheets aged for 24 hours were also analyzed for density measurements.

3.5 Acoustic Measurements on Raw Dough Sheets

Traditional piezoelectric transducers are commonly used for immersion or contact measurement, but if they are coupled with air, the large impedance mismatch at the boundary reduces the transmitting and receiving efficiency (Schindel et al., 1996). Therefore, we used two capacitive transducers (central frequency of 225 kHz) from VN Instruments Ltd (Brockville, Canada) for this study.

Transducers were placed parallel to each other, 15.5 cm apart, as shown in Figure 3.3. One transducer sent signals through the air gaps and the noodle while the other transducer acted as a receiver. At the beginning of each day of experiments, the two transducers were aligned and centered to maximize the signal. To do so, a reference plastic plate was used to replace the noodle holder. Instead of transmission mode, the reflection mode was used in this case. Alignment was checked for one transducer holder at a time by gently adjusting the screws on the transducer holder until the reflected signal reached a maximum in amplitude. Parallelism was achieved when the reflected signal was maximum.

Figure 3.3: Ultrasonic measurement set-up



A sample (8.5 cm × 7.5 cm) was excised from the noodle sheet and held by a clamp specially designed by Andrew Pankevi in the Faculty of Science Mechanical Shop to avoid sagging and deformation of the dough sheet. The noodle dough holder was fixed on a motorized stage controlled with MATLAB (Math Works, Natick). Prior to experiments, the holder was centered to ensure that the signal would travel only through the noodle dough piece. To prevent the noodle sample from drying out, experiments were performed in an environmental chamber (Memmert HPP IPP plus, Buchenbach, Germany) at 22 °C and 85 % Relative Humidity. Opening the environmental chamber door caused the humidity level to drop significantly, so the noodle holder was customized for easier attachment to the transducer holder to minimize the time spent with the door open. Also, the acoustic measurements were not started until the humidity recovered to 85 %. It took approximately 3 minutes for humidity recovery.

For each sample, 25 static acquisitions were taken. Using the motorized stage, a sample was moved out of the transducer axis and a reference signal was acquired through air. The thickness of the noodle was measured with a digital caliper (Mitutoyo, Kawasaki, Japan) after acquisition was completed and four measurements were taken for each sample.

To analyze sound waves, raw waves were filtered with the SIA-7 data analysis system from VN Instruments and the signal was transformed into the frequency domain via the Fast Fourier Transformation technique. Data analysis was carried out by a program developed in-house using MATLAB. This is a brief overview of the analyzing method; Kerhervé (2018) has provided more detailed information from a physics perspective.

In this study, sound waves propagated in a multi-phase system where the noodle dough sample was sandwiched between air. Due to the acoustic impedance mismatch between air and the dough, not all the waves generated by the transducer were transmitted into the dough. Impedance is defined as: $Z = \rho\omega/k$ where ρ is density (kg/m^3) and ω is angular frequency (rad/s) and k is the wave number (rad/m). The transmission (t_c) and reflection (r_c) coefficients define how much sound waves are transmitted or reflected via the equation :

$$t_c = \frac{2Z}{Z + Z_a} \tag{3.2}$$

$$r_c = \frac{Z - Z_a}{Z + Z_a} \tag{3.3}$$

where Z is the impedance of the noodle, and Z_a is the impedance of air.

Any complex wave can be expressed as a sinusodial wave varying in amplitude, phase and frequencies (Povey, 1997). Through experiment, the amplitude of transmitted waves and phase shift were obtained. The absolute value of total transmission (T) in amplitude leads to the calculation of the attenuation coefficient (α), where d is the thickness of the noodle.

$$|T| = \left|\frac{4Z_a Z}{(Z_a + Z)^2}\right| \exp\left(-\frac{\alpha}{2} d\right) \quad (3.4)$$

$$\alpha = -\frac{2}{d} \ln\left(|T| \left|\frac{(Z_a + Z)^2}{4Z_a Z}\right|\right) \quad (3.5)$$

The phase velocity v_p was calculated from the difference in the phase of the transmitted signal relative to the reference signal as shown below:

$$\phi = \gamma + \left(\frac{1}{v_p} - \frac{1}{v_a}\right) \omega d \quad (3.6)$$

$$V_p = \frac{v_a}{1 + (\phi - \gamma) \frac{v_a}{\omega d}} \quad (3.7)$$

where ϕ is the phase of waves propagating through the noodle sample and γ is the phase of the reference signal (air in this case), and v_a is the velocity of sound in air, which was measured as 347 m/s in the environmental chamber with the fan on as shown by Kerhervé (2018).

$$Z = \rho \frac{\omega}{k} = \frac{\rho v_p}{1 + i \, {}^{\alpha v_p}/_{2\omega}} \quad (3.8)$$

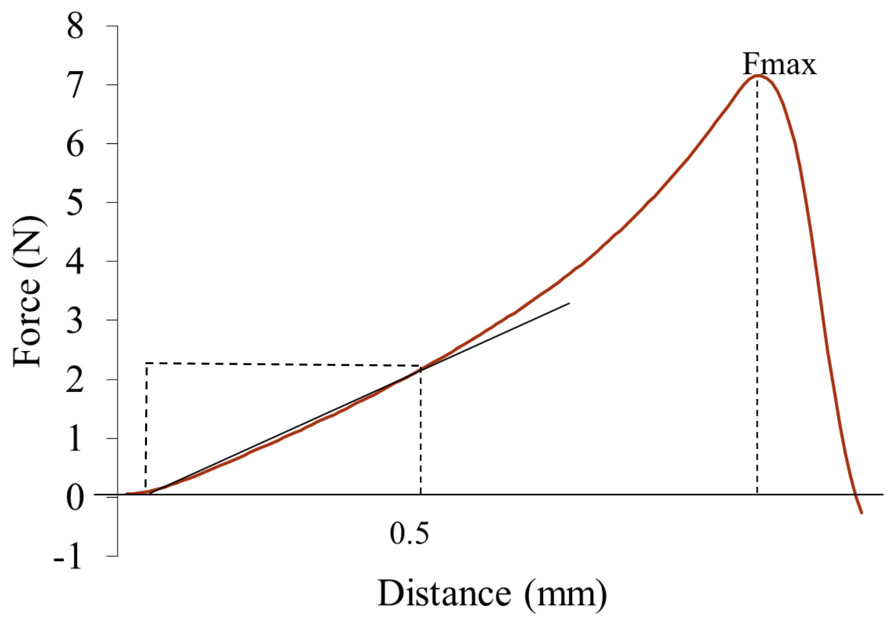
Phase velocity and attenuation coefficient were calculated via an iteration process in a data analysis program developed in-house by Sébastein Kerhervé using MATLAB. In addition, with the measured noodle density, the complex longitudinal modulus was calculated (Elmehdi et al., 2004).

3.6 Instrumental Texture Analysis on Cooked Noodles

The texture of cooked noodles was tested with a TA-XT2i Plus instrument (Texture Technologies, Scarsdale) with the setup described by Oh et al. (1983) with some modifications. Instrumental testing was carried out on fresh noodles (2 hours after processing) and aged noodles (26 hours). The noodle sheet was cut into 5-mm-wide and 8.5-cm-long strands after its final sheeting pass by use of a manual noodle cutter (brand name unknown). Noodle strands were cooked in a beaker with 350 mL of boiling tap water with water to noodle weight ratio greater than 10 (Fu, 2007) on a hot plate and three noodle strands were taken out after 2, 6 and 10 minutes of cooking and immediately immersed in another beaker with 350 mL of tap water (15-20 °C) to stop the cooking process. After 30 seconds, noodles were cooled down to 21-23 °C and taken out for texture measurement. One noodle strand was placed on the sample holder and excess water was gently dabbed with a fingertip. The noodle strand was compressed crosswise with a flat blade probe TA-47A (5 mm × 50 mm) at 1 mm /s to 80 % of the noodle's thickness. The width of the noodle was measured at three random locations away from the damage zone with a digital caliper after the compression test. The thickness of the cooked noodle strand was determined from the force-displacement curve, dividing by 0.8, the distance the probe traveled from its first point of contact with the noodle until its reversal at 80 % of the thickness.

From the force-displacement curve, the initial slope, work, the peak stress, and the resiliency were obtained. The initial slope, representing the surface firmness, was measured according to Oh et al. (1985a) with modifications, in which they captured the linear portion of the compression curve by calculating the slope (from the first point where the probe contacted with a noodle sample to a point where 60 $gfcm^{-2}$ of stress was applied). To cover the wide linear range of the compression curve, we measured the gradient from the surface where the texture analyzer detected 5 g of force to a depth of 0.5 mm, appoximately 30 % strain as shown in Figure 3.4. Work was calculated as the area under the force-displacement curve, and it was normalized by dividing the initial contact surface area of the noodle samples as conducted by Oh et al. (1983). The peak stress was calculated as the peak force divided by the initial contact surface area of the noodle. Resiliency was defined as the ratio of recoverable energy after the compression stress was removed and calculated as the unloading area under the force-displacement curve divided by the loading area as described by Epstein et al. (2004).

Figure 3.4: An example of the force-displacement curve for a cooked noodle showing determination of peak force and initial slope.



3.7 Cooked Noodle Texture Evaluated by a Trained Sensory Panel

A trained sensory panel was used to evaluate the characteristics of cooked noodles by use of descriptive texture profiling (Janto et al., 1998; Szczesniak, 2002). A total of 13 students and staff from the Food and Human Nutritional Sciences Department and the Physics and Astronomy Department were recruited, 3 male and 10 female participants. The majority of them originated from Asian countries and were very familiar with noodles. A variety of reference samples as shown in Table 3.3 were carefully chosen to represent a wide range of textural characteristics to train the panelists.

Table 3.3: Samples used for sensory training

Noodle samples		Cooking time	Surface firmness	Overall hardness	Elasticity
Catelli Fettuccine		10 mins	7-8	6-7	1-2
A-Sha Dry Mandarin noodle		4 mins	6	6	5
Round Udon noodles		2.5 mins	2-3	5-6	8-9
Ottogi Wheat Noodle Wild round		6.5 mins	5-6	4	3-4
Asian style noodle		7 mins	5-6	5-6	NA

Panelists were first trained on the sequence of tasting according to van Vliet et al. (2009): "ingestion by the lips, biting by the front (incisor) teeth, chewing of hard foods by the molars, wetting with saliva and enzymatic breakdown, deformation of semi-solid foods between the tongue and hard palate, manipulation of the food into a bolus by the tongue and swallowing". Second, the sensory descriptors were defined according to Oh et al. (1983) and discussion ensued until all the panelists fully understood the meanings of the descriptors. Specific to cooked noodles, perception on the first bite, and the overall chewing experience were the focus.

To help panelists understand the complex textural properties of noodles, attributes of noodles were evaluated separately, and 3 attributes were chosen: surface firmness, overall hardness and elasticity (Oh et al., 1983). Surface firmness was a panelist's assessment of the force required to bite through the noodle strand by use of incisor teeth (Janto et al., 1998). If the noodle breaks with a minimum of force, it indicates the noodle is soft; on the other hand, if the same amount of force is used but the noodle does not split into two, it indicates the noodle is firm. Overall hardness was defined similarly to surface firmness, but instead of using front teeth, overall hardness evaluates the amount of force needed to completely bite through the sample with molars (Janto et al., 1998). Elasticity was the word used to describe the capacity of the noodle to return to its original shape after removal of the force (Janto et al., 1998). Panelists were asked to sense the spring-back of the noodle while slowly releasing the noodle sample after one bite. If the sample was mushy and stuck on the teeth after one bite, this represented a non-elastic sample. On the other hand, an elastic sample returned to its original thickness once released from the molars and required a few more bites to break it down. Once panelists fully understood the descriptors, they were instructed to taste reference samples with different textural properties, one sample at a time and rate on an 8-9 intensity scale.

After training, a mock sensory panel was carried out to test the panelists' capability to discriminate samples. The samples were manipulated by cooking for a different amount of time or formulating with a different flour, thus the cooked noodle texture varied. Panelists who failed to detect the difference in firmness due to cooking time were rejected. Nine participants were selected for formal sensory evaluation based on their performance in the mock sensory. In total, each selected panelist went through two one-hour training sessions, one mock sensory session and four formal sensory sessions. Panelists evaluated 16 samples in four sessions, 2 sessions per day. To prevent palate fatigue, each panelist was allowed a 15-minute break before starting the second session. Panelists were instructed to taste one reference sample at the beginning of each session.

Each panelist sat in an individual booth and received a tray with four sample cups, one reference sample cup, one water cup, one spill cup, one napkin, one ballot and one pencil. Sample cups were labeled with a 3-digit number as shown in Table 3.4 and the order of testing for each panelist was randomized to avoid psychological biases. Time was critically controlled, and all the panelists were asked to be punctual as noodles have the best texture right after boiling and gradually lose favourable texture over time (Miki et al., 1996). Therefore, all the tests were completed within 15 minutes of cooking. Panelists were instructed to taste the reference sample first. To avoid palate fatigue, panelists were not allowed to taste the reference sample repeatedly.

Table 3.4: Sensory testing samples and codes

	Session 1	Sample Code	Session 2	Sample Code
Day 1	CWRW_32_HM_24h	199	CWRW_32_LM_24h	289
	CWRS_32_LM_24h	219	CWRW_36_HM_24h	337
	CWRS_36_LM	484	CWRS_36_HM	764
	CWRS_32_HM	670	CWRW_36_LM	894
Day 2	CWRW_32_HM	216	CWRW_32_LM	404
	CWRS_32_LM	280	CWRW_36_HM	475
	CWRS_36_LM_24h	425	CWRS_36_HM_24h	564
	CWRS_32_HM_24h	552	CWRW_36_LM_24h	901

HM: high speed mixing, LM: low speed mixing

3.8 Statistical Analysis

Data analysis used a mixed model analysis of variance for treatment in SAS 9.4 (SAS Institute Inc., Cary). The LSD (Least Significant Difference) method was used to compare sample means. The significance level was set at 0.05. Sensory panel analysis used XLSTAT software.

4. Results and Discussion

4.0 Flour Strength and Characteristics

CWRS is the largest class of wheat grown in western Canada (CGC, 2017), with 3 milling grades available. CWRW is a hard winter wheat class, with protein level normally 2 % less than CWRS. Both flours used for this experiment were milled from a composite collection of varieties of wheat. Both had very similar values in moisture content and starch damage. Even though flour extracted at a lower rate (as low as 40 %) is preferred in noodle making for better colour and appearance (Hatcher & Kruger, 1993), the ash contents of both flours used in this study were still lower than 0.55 which is the first-grade noodle flour required by China (Hatcher, 2001). However, even though CWRW was milled at a higher extraction rate (78.3 %), the ash content was still 0.04 % lower than that of the CWRS flour as shown in Table 4.1. It was not clear what the responsible mechanism was for this difference.

Protein is considered as one of the most important factors in determination of noodle texture (Huang & Morrison, 1988; Hou, 2001; Fu, 2008). In this study, No. 2 CWRS flour had 13.4 % protein and No.1 CWRW flour contained 12.1 % protein based on 14 % moisture basis. With the difference in protein content, one may assume noodles made with CWRS would have a better texture than CWRW noodles (Oh et al., 1985a). Huang and Morrison (1988) and Diep et al. (2014) have pointed out that it is not just the protein quantity, but rather the protein quality that was more critical in noodle quality.

Other than protein, starch pasting property has been associated with noodle texture (Crosbie, 1991; Baik et al., 1994; Huang & Lai, 2010). However, as displayed in Table 4.2, both flours function similarly in the pasting profile tested by a Rapid Visco Analyzer. It was interesting to note that CWRW had a significantly higher value in Falling number, 116 seconds longer than CWRS. Even though the falling number of both flours was high enough, the difference indicated both flours may have a different enzymatic activity, such as alpha-amylase activity.

Table 4.1: Wheat flour testing results.

Flour (14% moisture basis)	CWRS	CWRW
Protein content, %	13.4	12.1
Falling number, s	382	498
Ash content, %	0.51	0.47
Starch damage, UCD[1]	23.6	25.8
Moisture, %	13.7	13.3

[1]UCD: arbitrary unit

Table 4.2: Pasting profile of flours with Rapid Visco Analyzer.

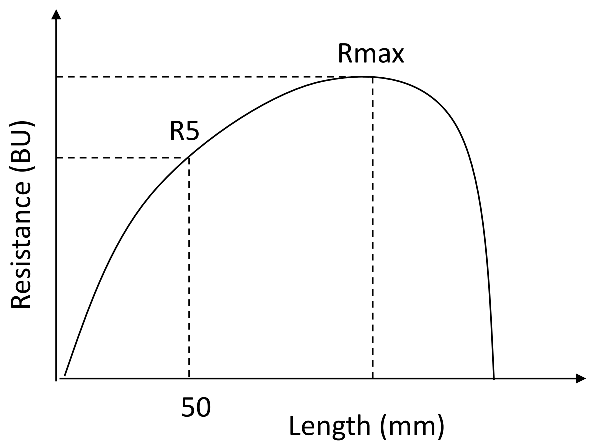
	CWRS	CWRW
Peak viscosity, RVU[1]	206	202
Hot paste viscosity, RVU	121	112
Breakdown, RVU	85	90
Final viscosity, RVU	202	199
Setback, RVU	81	88
Peak time, min	6.2	6.13

[1] Rapid visco unit

Further examination with empirical tests provided more practical information about gluten strength which is essential to final product quality. A farinogram measures the resistance of dough during mixing and is expressed with Brabender Units (BU), an arbitrary unit. Farinograph absorption measures the amount of water to reach the required consistency, commonly 500 BU for bread. As shown in Table 4.3, CWRS had higher water absorption (65.4 %) than CWRW (60.2 %). The higher water absorption in CWRS corresponded to the greater amount of protein in the flour (Navickis et al., 1982).

The extensogram commonly uses the water absorption from the farinogram to make the dough so that the dough's resistance to stretching is examined (Sudha et al., 2007). The test is conducted for the dough after resting for 45 minutes and repeated at 135 minutes as well. From the extensogram (as shown in *Figure 4.1*), the y-axis represents resistance in BU and x-axis represents the dough extension length. From the graph, Rmax (maximum height / resistance in BU), R5 (height of the curve at 5 cm after start of the test), A (area under the curve), and E (extensibility in mm) were obtained (Bangur et al., 1997; CGC, 2016).

Figure 4.1: An example of the extensogram and derived parameters.



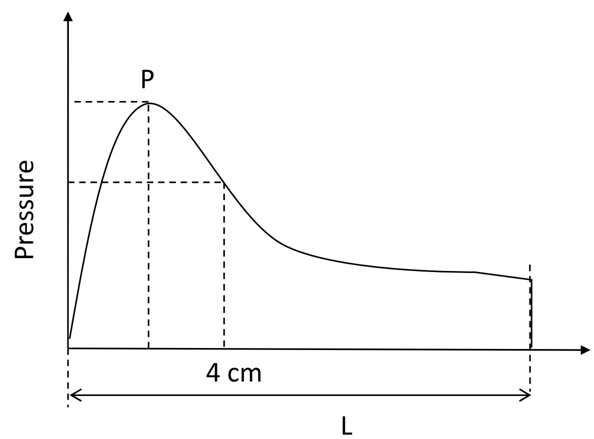
According to the quality data from Canadian Grain Commission (2016), the average Rmax of No. 2 CWRS flour dough (from western prairie at extraction rate of 74 %) was 406 BU in 2016 and 512 BU in 2015. Rmax value of CWRS flour used in this study was slightly lower than the reported value, partially this could be due to the slightly higher extraction rate used. The extensogram result in Table 4.3 showed that CWRW had a higher value in all parameters compared to CWRS doughs, except in E. This indicated that CWRW was more resistant to extension and less extensible than CWRS.

Table 4.3: Empirical testing (farinogram, extensogram and alveogram) results for dough made from CWRS and CWRW flours.

Farinogram						
Flour	Absorption (%)	Dough Development time (min)		Stability (min)	Mixing tolerance index (BU)	
CWRS	65.4	5.8		12	24	
CWRW	60.2	5.4		8.4	38	
Extensogram (45 min)						
	Rmax (BU)	R5 (BU)	E (mm)	A (cm^2)	Rmax/E	
CWRS	363	204	230	111	1.6	
CWRW	424	234	224	125	1.9	
Extensogram (135 min)						
	Rmax (BU)	R5 (BU)	E (mm)	A (cm^2)	Rmax/E	
CWRS	398	234	216	113	1.8	
CWRW	426	249	206	114	2.1	
Alveogram						
	P (height×1.1) (mm)	L (mm)	G (mm)	W (×10e-4) (J)	P/L	Ie, %
CWRS	99	108	23.1	349	0.92	58.3
CWRW	82	159	28.1	413	0.52	62.9

The alveogram is a bubble blowing test, as shown in Figure 4.2, P is the maximum over pressure needed to blow the dough bubble, and L (the length of the curve) measures the dough's extensibility, W (the area under the curve) represents the amount of work needed to inflate the dough bubble, G is the index of swelling in mm, and Ie is the elasticity index in % (pressure at 4 cm from the start of the test divided by the maximum pressure). As shown in Table 4.3, CWRW had a much higher value of L and W. This suggested that CWRW was more extensible than CWRS but required more work to inflate the dough bubble, indicating CWRW possessed a stronger protein (Bettge et al., 1989).

Figure 4.2: An example of the alveogram curve and derived parameters.



4.1 Noodle Work Input and Thickness

All the noodle sheets, regardless of the different treatments, had a final thickness between 1.4 and 1.6 mm as shown in Table 4.4. Statistically, no significant differences in thickness were found for noodle dough sheets made with the different treatments.

Table 4.4: The final thickness of fresh and aged (24 hours after processing) noodle dough sheets made with CWRS or CWRW at 32 or 36 % water addition and mixed at low speed (LS) or high speed (HS) ± standard deviation.

	Pass 6 (mm)	**Pass 6_24h (mm)**
CWRS_32_LS	1.47 ± 0.03	1.50 ± 0.05
CWRS_32_HS	1.51 ± 0.05	1.49 ± 0.05
CWRW_32_LS	1.47 ± 0.07	1.45 ± 0.04
CWRW_32_HS	1.45 ± 0.09	1.44 ± 0.08
CWRS_36_LS	1.44 ± 0.06	1.40 ± 0.03
CWRS_36_HS	1.44 ± 0.05	1.42 ± 0.05
CWRW_36_LS	1.44 ± 0.09	1.40 ± 0.13
CWRW_36_HS	1.43 ± 0.01	1.41 ± 0.03

Mechanical work plays a significant role in noodle processing and it is strongly associated with gluten network development (Hou, 2001; Fu, 2008). Figure 4.3 displays the accumulated work input during the noodle sheeting process measured with a power meter. The initial sheeting and compounding (Pass 1 and 2) accounted for half of the total work input. Noodles with different treatments had a total work input between 13 and 17 Joules per gram of dough. Even though there were no significant differences for each pass with different treatments except at Pass 3 (Figure 4.4), the noodle dough made with different water content required different amounts of energy input. As more water was added to the noodle dough, less work input is required. This agreed with the findings from Edwards et al. (1996).

Figure 4.3: Accumulated work input for CWRS and CWRW noodle dough during sheeting process. Error bars represent ± standard deviation.

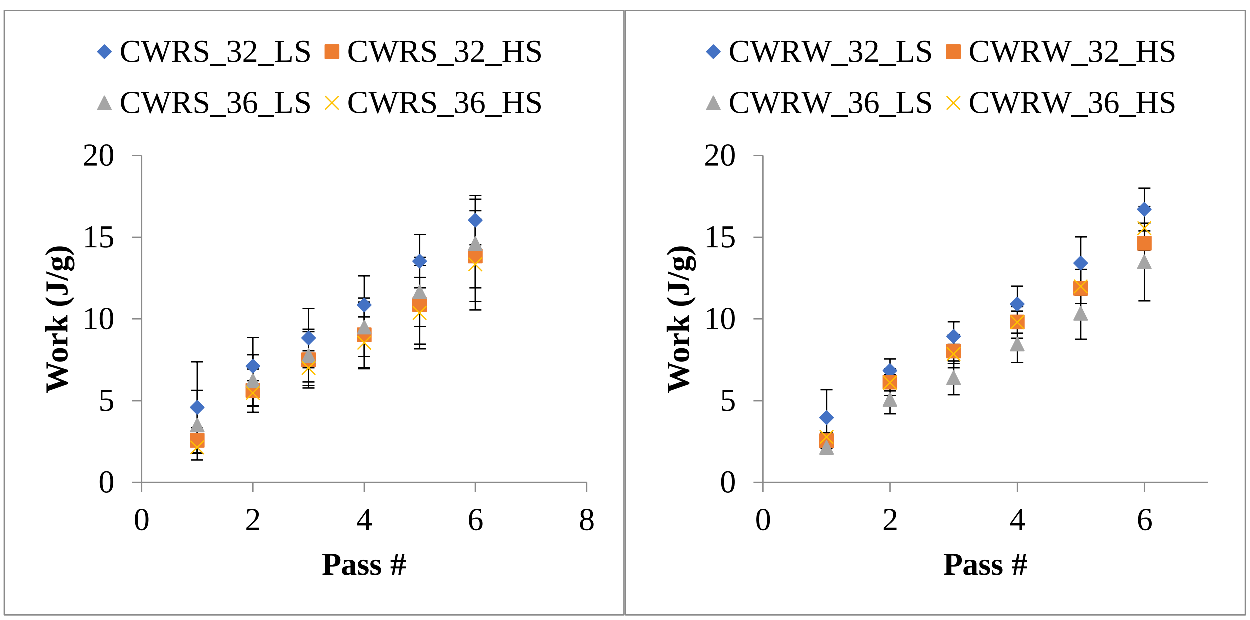
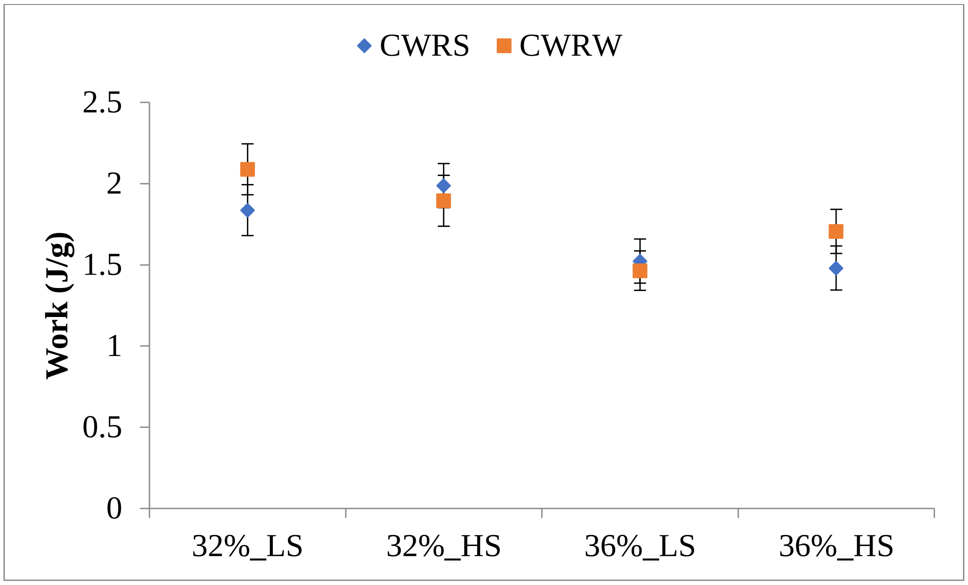


Figure 4.4: The work input per gram of noodle dough made with CWRS and CWRW during sheeting Pass 3.



4.2 Noodle Density

Figure 4.5 shows the density changes of noodle dough in response to different treatments and the statistical analysis is shown in Table 4.5 for a comparison of process effects, and in Table 4.6 for comparing the effect of aging. As a characteristic of a material, density changes with the modification of the composition or structure (Elmehdi et al., 2007). The effect of water addition was consistent for all the treatments, both in fresh and aged noodle dough. As 4 % more water was incorporated into the noodle dough, the density was significantly ($P<0.0001$) reduced (by 10 kg/m^3 on average over all the treatments). This agreed with the findings from Miki et al. (1988), and is probably due to the "diluting" effect from water as the density of water is lower than that of the wheat flour (Diep, 2014).

Figure 4.5: Density of fresh (after Pass 2 and Pass 6) and aged noodle dough (Pass 6_24h) made with CWRS and CWRW at 32 and 36 % water and mixed at a high speed (HS) or low speed (LS). Error bars represent ± standard deviation.

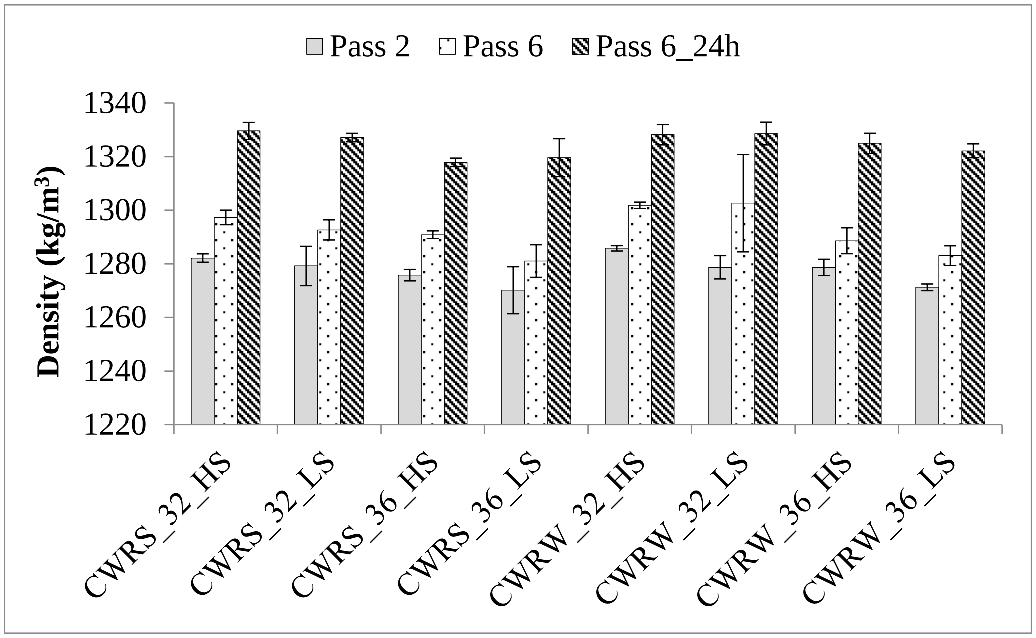


Table 4.5: Statistical analysis (F value and P value) of density of noodle dough made with CWRS and CWRW flours at 32 and 36 % of water and mixed at a high or low speed and sheeted after Pass 2 and Pass 6. The highlighted effects were significant as P<0.05.

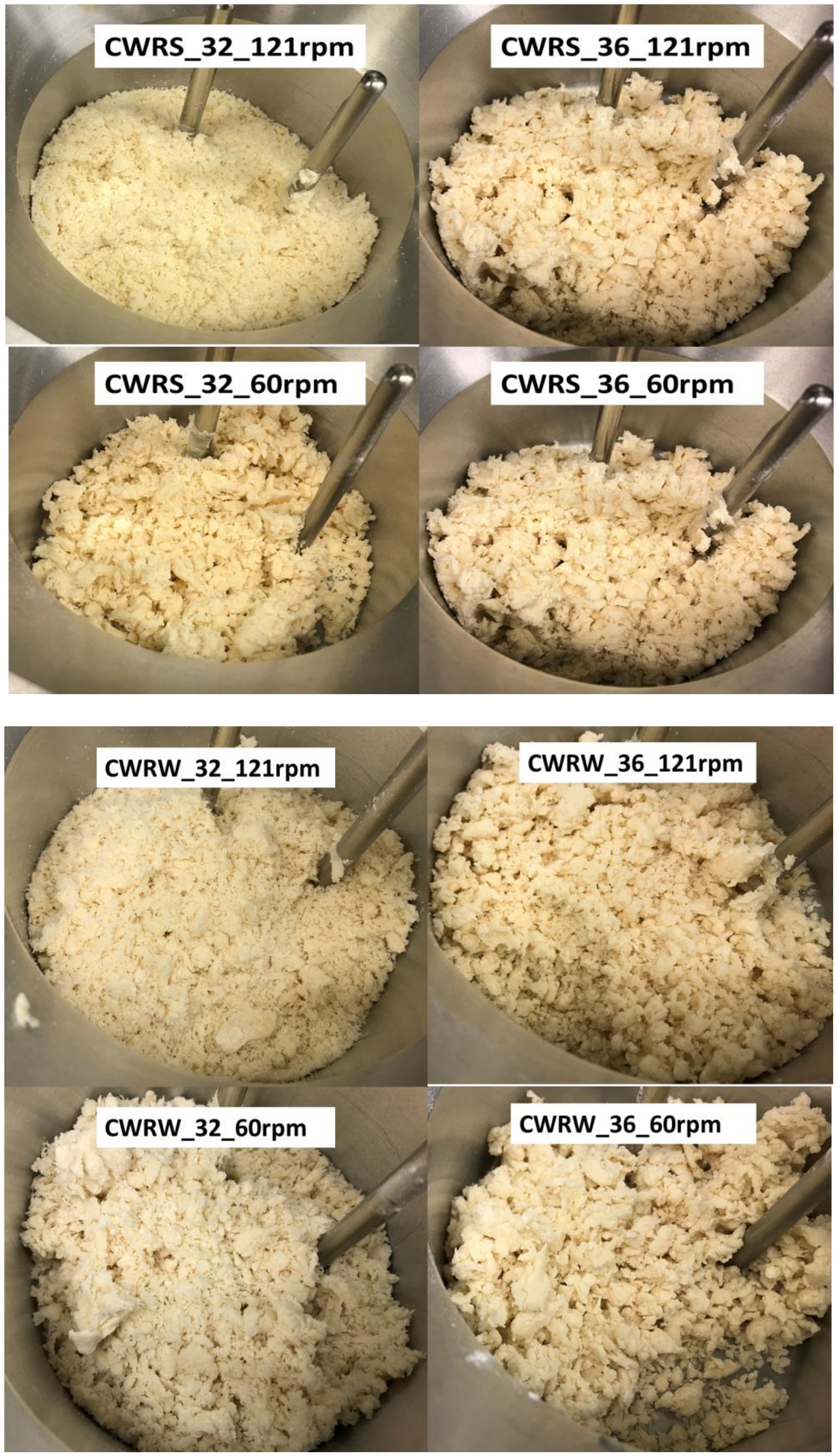
Effect	F Value	P > F
Pass	67.97	<.0001
Flour	2.29	0.1401
Pass*Flour	0.26	0.6136
Water	32.9	<.0001
Pass*Water	2.19	0.1487
Flour*Water	0.97	0.3309
Pass*Flour*Water	1.22	0.2768
Mixing	3.69	0.0636
Pass*Mixing	0.26	0.6112
Flour*Mixing	0.66	0.4235
Pass*Flour*Mixing	0.75	0.3942
Water*Mixing	4.45	0.0428
Pass*Water*Mixing	0.71	0.4073
Flour*Water*Mixing	1.34	0.2549
Pass*Flour*Water*Mixing	0	0.9933

Table 4.6: Statistical analysis (F value and P value) of density of sheeted noodle dough made with CWRS and CWRW flours at 32 and 36 % water and mixed at a high or low speed and aged for 0 or 24 hours. The highlighted effects were significant as P<0.05.

Effect	F Value	P > F
Aging	355.1	<.0001
Flour	2.68	0.112
Aging*Flour	0.18	0.6757
Water	34.2	<.0001
Aging*Water	2.23	0.1454
Flour*Water	0.08	0.7808
Aging *Flour*Water	3.42	0.0739
Mixing	0.24	0.6294
Aging*Mixing	0.89	0.3518
Flour*Mixing	0.29	0.5927
Aging*Flour*Mixing	0.35	0.5566
Water*Mixing	3.54	0.0693
Aging*Water*Mixing	1.25	0.2715
Flour*Water*Mixing	0.25	0.622
Aging*Flour*Water*Mixing	0.45	0.5059

As the noodle sheet was subject to more work input from Pass 2 to Pass 6, density significantly increased (by 25 kg/m^3 on average over all treatments). This disagrees with the work from Miki et al. (1988), in which no changes in density were found during the sheeting process. The discrepancy could be due to different equipment and sheeting processes used in the two studies. Environmental conditions might be another reason. Based on our preliminary trials, noodles require as high as 95 % relative humidity to prevent dehydration. Even though the dough was wrapped as soon as it was sheeted, losing moisture was inevitable. Despite any moisture loss effect, the density increase could be attributed to the removal of air bubbles through repeated sheeting, and the structure changes caused by the alignment of the gluten network (Hou, 2001; Fu, 2008). The density of the noodle dough sheet was also different under the two mixing conditions, which was dependent on the water content (significant interaction between water and mixing, $P<0.05$). Visually, there was a difference in crumb sizes as displayed in Figure 4.6.

Figure 4.6: Noodle dough crumbs made with CWRS and CWRW flour after mixing for 3 minutes at 121 rpm or 60 rpm.



In general, larger crumb sizes were observed for the dough made with higher water content and mixed at a low speed than the counterpart. The dough is composed of two parts, an incompressible dough matrix and highly compressible air bubbles (Scanlon & Page, 2015). Provided the mass is the same, air bubble volume changes will lead to changes in density according to $\rho = m/V$ (m: mass V: volume). Dough density changes, due to air inclusion, have been confirmed by Miki et al. (1988), in which the density of noodle dough mixed in a mixer significantly decreased with an increase of mixing time. The mixing-induced density change seemed to be dependent on the energy input level, as no changes of density were observed for the hand mixed dough with mixing time (Miki et al., 1988). In this study, denser dough was obtained by mixing at a higher speed and the mixing effect on dough properties was more evident after Pass 6, except the one made with CWRW flour at 32 % water content.

It was interesting to note that after aging for 24 hours dough density significantly ($P < 0.0001$, Table 4.6) increased from 1290 to 1325 kg/m^3 on average. This agrees with Miki et al. (1988), where they found that density dramatically increased after resting of the noodle dough sheet, likely due to a de-aeration process. It seemed that gas escaped from the air bubbles during resting. To fully understand the evolution of air bubbles over time, the research team from the Department of Food and Human Nutritional Sciences and the Department of Physics and Astronomy, University of Manitoba, is currently investigating the air bubble changes in noodle dough by use of X-ray tomography. More in-depth knowledge on air bubble evolution will be gained.

4.3 Ultrasonic Results on Raw Noodle Dough Sheets

To further understand the impact of composition, work input and aging on the rheological properties of noodle doughs during sheeting, this study analyzed dough properties using an air-coupled ultrasound technique. As the strain imposed by ultrasound is very low, the linear relationship between stress and strain holds true, thus allowing us to investigate the native mechanical properties of the dough (Povey & McClements, 1988; Scanlon & Page, 2015).

The phase velocity and attenuation coefficient characterize the acoustic properties of dough obtained from the ultrasound measurements. It is known that the molecular bonds of a material affect the speed of sound waves propagating, and the attenuation coefficient measures the loss of energy due to scattering and absorption (Povey & McClements, 1988). Wheat flour dough used in this study is a highly attenuating/damping material (Povey, 1989), and even more so at high frequencies, therefore, the low frequency ranging between 210 and 250 kHz was chosen. Furthermore, air-coupled ultrasonic measurements are more difficult at higher frequencies due to higher attenuation in air. Bellido and Hatcher (2010; 2011) and Diep et al. (2014) measured the properties of alkaline noodle dough in contact mode at the low frequency of 40 kHz. At low frequencies, the ultrasound technique reveals information on the dough properties as affected by dough matrix changes associated with formulation and processing conditions as well as due to changes in air bubbles (Scanlon & Page, 2015).

The following sections will start with an overview of the acoustic results and more detailed discussion on the effect of flour, water, work input and aging will be followed after.

Figure 4.7 and Figure 4.8 illustrate the acoustic properties of noodles made with different treatments. Fresh noodle dough properties use the scale on the left-hand side, while the aged dough scale is on the right-hand side. The following sections will start with an overview of the acoustic results and more detailed discussion on the effect of flour, water, work input and aging will be followed after.

Figure 4.7: Phase velocity of fresh noodle dough during the sheeting process (after Pass 2 and Pass 6) and after aging for 24 hours (Pass 6_24 h). Error bars represent ± standard deviation. Samples with the same letter subscripts are not significantly different at P=0.05 (Pass 2 and Pass 6 only).

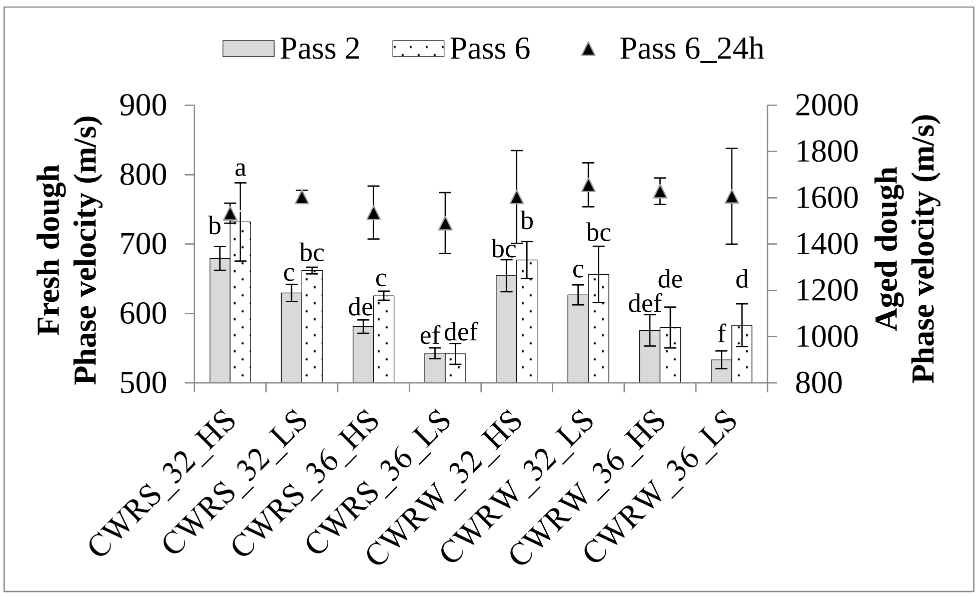
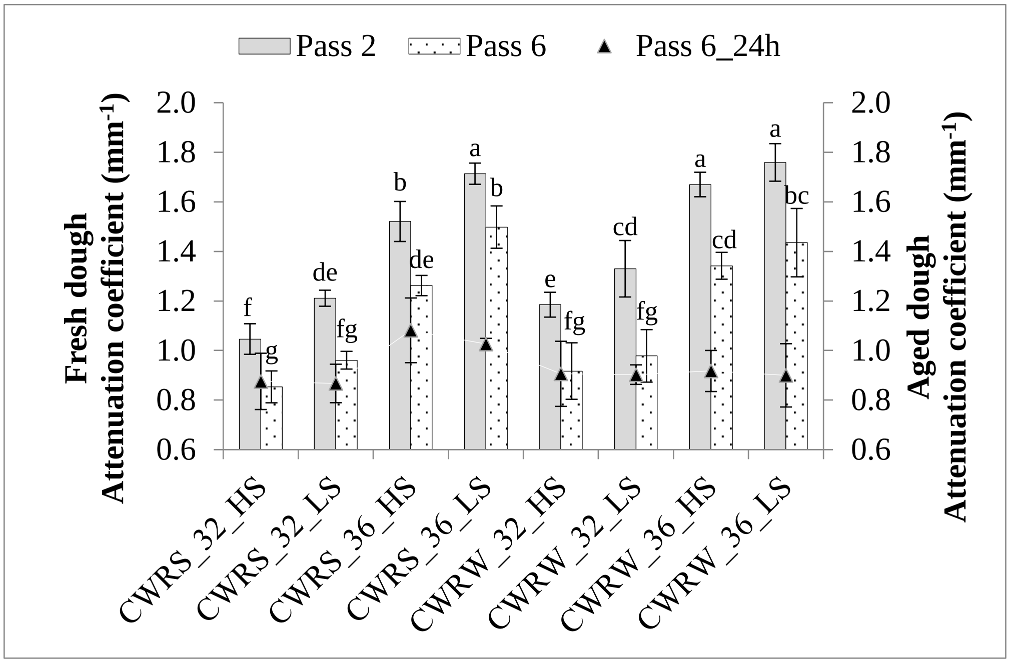


Figure 4.8: Attenuation coefficients of fresh noodle dough during the sheeting process (after Pass 2 and Pass 6) and after aging for 24 hours (Pass 6_24 h). Error bars represent ± standard deviation. Samples with the same letter subscripts are not significantly different at P=0.05.



Fresh noodle dough with different treatments had phase velocity in the range of 540-740 m/s and attenuation coefficient in the range of 0.8-1.8 (per mm distance traveled in the dough). Despite the fact that phase velocity and attenuation coefficient of dough are frequency dependent (Cobus et al., 2007), for yellow alkaline noodle dough at 40 kHz, Diep et al. (2014) measured phase velocities that ranged from 449 to 508 m/s and attenuation coefficients in the range of 0.448-0.587 (per mm distance traveled in the dough), which was slightly lower compared to this study, probably due to their use of lower frequencies. Salimi-Khorshidi (2016) also measured the properties of yellow alkaline noodle dough at 1.4 MHz. The phase velocity was in the similar range but he had a higher attenuation coefficient, which was likely due to the effects of a higher frequency (Cobus et al., 2007).

Compared to the fresh noodle dough, the attenuation coefficient of aged noodle dough ranged from 0.87 to 1.08 mm^{-1}. The phase velocity ranged from 1491 to 1656 m/s. It should be noted that even though the error bars of aged noodle dough were similar in height as those of the fresh noodle dough, but they are of much larger in magnitude for velocity, due to the scale differences.

Dough is a viscoelastic material and can be viewed as consisting of a Hookean solid-like elasticity and a non-Newtonian fluid-like viscosity (Faubion & Hoseney, 1990). With the measurement of density, the longitudinal moduli can be obtained from velocity and attenuation coefficient measurements. They are shown in Table 4.7, Table 4.8 and Table 4.9. The longitudinal moduli (storage modulus M', loss modulus M'') and the damping factor, tan δ, allow one to understand how the dough's rheological properties change with each treatment. The statistical analysis of these parameters measured on fresh noodle dough is shown in Table 4.10.

Table 4.7: The mean values and standard deviations of the longitudinal loss modulus (M'') of raw noodle dough made from CWRS and CWRW flours at 32 and 36 % water addition and mixed at a high or low speed.

	M''(MPa)		
	Pass 2	Pass 6	Pass 6_24h
CWRS_32_HS	318 ± 36	319 ± 59	3078 ± 469
CWRS_32_LS	291 ± 10	272 ± 11	3333 ± 47
CWRW_32_HS	321 ± 26	279 ± 16	3439 ± 806
CWRW_32_LS	313 ± 4	271 ± 22	3752 ± 478
CWRS_36_HS	285 ± 25	304 ± 14	3378 ± 436
CWRS_36_LS	269 ± 23	239 ± 20	3170 ± 558
CWRW_36_HS	279 ± 14	239 ± 6	3160 ± 608
CWRW_36_LS	253 ± 7	272 ± 21	3854 ± 913

Table 4.8: The mean values and standard deviations of the longitudinal storage modulus (M') of raw noodle dough made from CWRS and CWRW flours at 32 and 36 % water addition and mixed at a high or low speed.

	M'(MPa)		
	Pass 2	Pass 6	Pass 6_24h
CWRS_32_HS	592 ± 29	705 ± 122	3091 ± 237
CWRS_32_LS	507 ± 18	566 ± 7	3418 ± 122
CWRW_32_HS	551 ± 39	597 ± 46	3450 ± 875
CWRW_32_LS	503 ± 24	562 ± 68	3653 ± 423
CWRS_36_HS	431 ± 15	503 ± 10	3122 ± 459
CWRS_36_LS	377 ± 11	386 ± 22	3118 ± 520
CWRW_36_HS	424 ± 35	434 ± 43	3518 ± 259
CWRW_36_LS	362 ± 17	436 ± 48	3747 ± 860

Table 4.9: The mean values and standard deviations of tan δ of raw noodle dough made from CWRS and CWRW at 32 and 36 % water addition and mixed at a high or low speed.

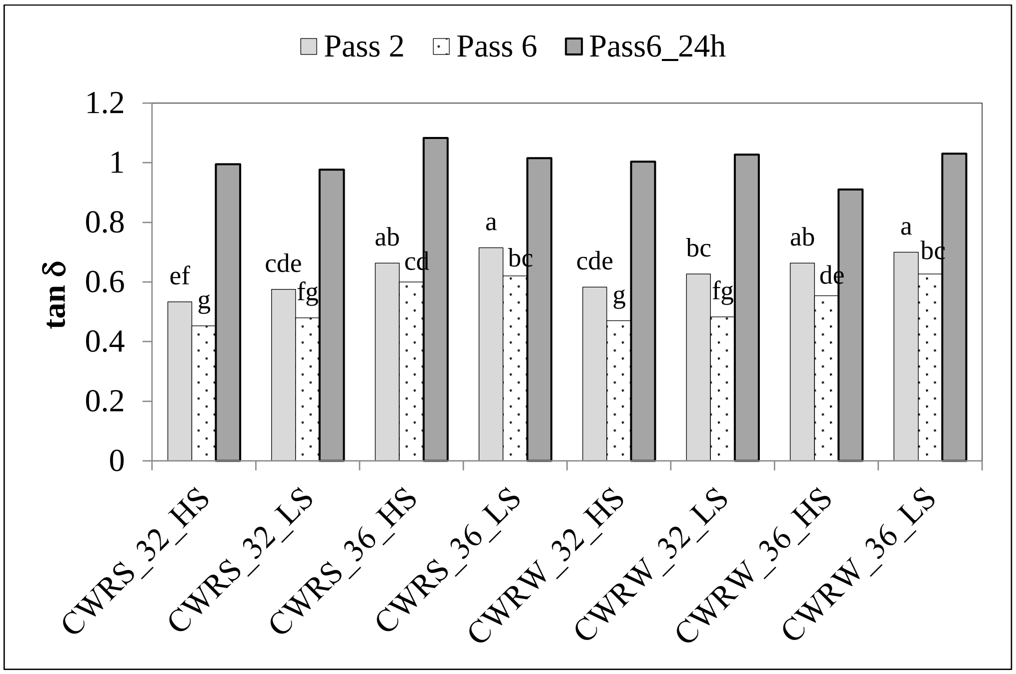
	tan δ		
	Pass 2	Pass 6	Pass 6_24h
CWRS_32_HS	0.54 ± 0.04	0.45 ± 0.03	0.99 ± 0.08
CWRS_32_LS	0.57 ± 0.01	0.48 ± 0.02	0.98 ± 0.05
CWRW_32_HS	0.58 ± 0.02	0.47 ± 0.04	1.00 ± 0.03
CWRW_32_LS	0.62 ± 0.04	0.48 ± 0.02	1.03 ± 0.02
CWRS_36_HS	0.66 ± 0.04	0.60 ± 0.03	1.08 ± 0.02
CWRS_36_LS	0.71 ± 0.04	0.62 ± 0.03	1.02 ± 0.06
CWRW_36_HS	0.66 ± 0.08	0.55 ± 0.04	0.91 ± 0.23
CWRW_36_LS	0.70 ± 0.01	0.63 ± 0.03	1.03 ± 0.05

Table 4.10: Statistical analysis (P value) of phase velocity, attenuation coefficient, M'', M' and tan δ of raw fresh noodle dough. The effects highlighted were statistically significant at P=0.05.

Effect	Phase velocity	Attenuation coefficient	M'',	M'	tan δ
Pass	0.0002	<.0001	0.0166	<.0001	<.0001
Flour	0.0467	0.0112	0.207	0.0535	0.4228
Pass*Flour	0.6361	0.0963	0.1689	0.5313	0.1988
Water	<.0001	<.0001	<.0001	<.0001	<.0001
Pass*Water	0.5368	0.595	0.1977	0.2585	0.2605
Flour*Water	0.287	0.3425	0.4888	0.2485	0.0359
Pass*Flour*Water	0.4952	0.8532	0.2886	0.483	0.497
Mixing	<.0001	<.0001	0.0048	<.0001	0.0005
Pass*Mixing	0.8761	0.4883	0.8753	0.6927	0.6064
Flour*Mixing	0.0135	0.0585	0.0114	0.0161	0.7569
Pass*Flour*Mixing	0.05	0.8758	0.0238	0.0552	0.497
Water*Mixing	0.7903	0.3282	0.7763	0.4452	0.497
Pass*Water*Mixing	0.7479	0.4192	0.5795	0.6736	0.5233
Flour*Water*Mixing	0.95	0.22	0.5881	0.7668	0.5233
Pass*Flour*Water*Mixing	0.2933	0.8972	0.1093	0.5397	0.3152

M" and M' for the fresh noodle dough measured in this study were in the range of 239-320 MPa, and 361-705 MPa, respectively. After the dough aged for 24 hours, M" ranged from 3078 to 3752 MPa and M'ranged from 3091 to 3747 MPa. The tan δ of noodles with different treatments in Figure 4.9 shows that the tan δ values of the fresh noodle dough were in the range of 0.47 to 0.72, and the aged ones ranging from 0.91 to 1.08. The moduli obtained from this study were in a similar range to those of Diep (2014) and Bellido and Hatcher (2010), where alkaline noodle dough was assessed by use of a contact ultrasound technique at 40 kHz.

Figure 4.9: The damping factor (tan δ) of noodle dough made with different treatments. Treatments with the same letter are not significantly different at P=0.05.



4.3.1 The Effect of Flour

Discrimination of flour effects on dough properties by use of ultrasound has been reported by many researchers (Létang et al., 2001; Alava et al., 2007; García-Álvarez et al., 2011; Diep et al., 2014). However, characterizing flour properties by use of non-contact ultrasound technique is innovative and shows great advantage for on-line application.

As shown in Table 4.10, the noodle dough made with two flours significantly ($P<0.05$) differed in phase velocity and attenuation coefficient. Overall, the dough made with CWRS flour had slightly higher phase velocity and lower attenuation coefficient than the one made with CWRW, which agrees with Diep et al. (2014), and is probably due to the higher protein content in the CWRS flour. However, no significant difference in the longitudinal moduli of the noodle dough made with the two different flours was found, which indicated protein quantity did not have a significant impact on the viscoelasticity of noodle dough, rather the protein quality may be more relevant. Even though CWRW flour contained less protein, it possessed greater gluten strength than CWRS as shown in the empirical tests, which explained the capability of CWRW flour to make noodle dough with a similar viscoelasticity to the CWRS flour.

4.3.2 The Effect of Water

With dough, one should never neglect the importance of water. Noodle dough with different water contents showed significant differences in all the acoustic parameters as shown in the statistical analysis (Table 4.10). The phase velocity, M' and M'' were significantly reduced as water addition increased from 32 % to 36% while the attenuation coefficient significantly increased. Values for tan δ were only increased for the dough made with CWRS flour, not for the one with CWRW. This agrees with the work of Alava et al. (2007), in which ultrasonic velocity decreased and attenuation coefficient increased as the amount of water increased from 40 % to 60 % in bread dough. Measurements of dough with water absorption levels between 49 % and 58 % by use of longitudinal waves at 5 MHz also confirmed the plasticizing effect of water (Létang et al., 2001). Specific to noodle studies, Diep (2014) compared the ultrasonic properties of alkaline noodle dough made with 34 % and 37 % water addition levels at 40 kHz. Despite the fact that the phase velocity and attenuation coefficient are frequency dependent, the same trend was also found: dough with a higher water content had a lower phase velocity and a higher attenuation coefficient than the counterparts.

Edwards et al. (1996) and Yu and Ngadi (2006) measured the elastic shear modulus of noodle dough with a rheometer and found that the elastic modulus decreased with the increase of water addition level, which was independent of flour class and noodle types. Even though there are fundamental differences between the ultrasound method and fundamental rheology method (Scanlon & Page, 2015), the effect of water in the dough was evident from both methods.

4.3.3 The Effect of Mixing and Sheeting

As shown in Table 4.10, mixing had a significant impact on the acoustic properties. Dough mixed at a higher speed had a significantly higher phase velocity, M', and M'', and lower attenuation coefficient and tan δ value compared to the dough mixed at low speed. It indicated that dough prepared by mixing at high speed was more elastic and less attenuating to sound waves.

The sheeting process is critical in noodle processing, and it is believed to be responsible for gluten network development (Fu, 2008). From acoustic measurements, as more work was put into dough from pass 2 to pass 6, the phase velocity and M' of noodle dough sheet significantly increased, and the attenuation coefficient, M'' and tan δ were significantly reduced, which indicated that the noodle dough became more elastic after the final sheeting pass. This corresponded to the increase of density from pass 2 to pass 6, likely due to changes in the air bubbles. As revealed by X-ray tomography, air bubbles aligned along the sheeting direction

(Guillermic et al., 2018), which indicated a more structured dough matrix formed after repeated sheeting passes.

The changes associated with gluten might be another reason for the observed changes in acoustic properties. It is well known that glutenin is closely related to dough's elasticity (Wall, 1979; Shewry et al., 2002). Similar to bread dough, polymers are entangled in the noodle dough mixture, and mechanical energy is needed to unfold the gluten molecules. As a result of the stretching force, a significant reduction of glutenin macropolymer (GMP) content and sulfhydryl (SH) group in noodle dough after mixing has been reported (Ong et al., 2010; Liu et al., 2015). The sheeting process allows the glutenin polymers in the noodle dough to repolymerize; thus disulfide bonds significantly increased in noodle dough after resting and sheeting processes (Li et al., 2017), which indicated more crosslinks in the noodle dough. The resultant dough with a more tightly-bound structure allows sound waves to travel faster through the noodle dough sheet. The ultrasound technique used in this study elucidated the changes in the mechanical properties of the noodle dough during the mixing and sheeting processes, which makes it a valid tool in processing control during noodle production.

4.3.4 The Effect of Aging

Long before this study, researchers had noticed age-related phenomena in noodles, including noodle sheets darkening over time or in the appearance of black specs, which was strongly associated with the enzyme, polyphenol oxidase (Hatcher & Kruger, 1993; Kruger et al., 1994; Baik et al., 1995; Hatcher et al., 2004; 2009). In this study, the effect of aging was evident by use of the ultrasonic technique.

For all the treatments used in this study, the phase velocity, M'', $M'$and tan δ significantly increased (shown in Table 4.7, Table 4.8, and Table 4.9), even doubled for noodle dough aged for 24 hours, while the attenuation coefficient was significantly reduced (Figure 4.8), and the degree of change was more evident for noodles made with CWRW. Overall, noodle dough was less elastic after aging for 24 hours, as indicated by the increased tan δ. The changes in acoustic properties corresponded to the increase of density, likely due to the decrease in the air volume fraction and increase of bubble sizes (unpublished results) as well as the structural changes in protein. Li et al. (2017) investigated the deterioration process of fresh noodles upon aging and found both microbial and physicochemical changes occurred during aging. As noodle is a high-moisture product, spoilage by microorganisms is common. As a result of spoilage, Li et al. (2017) reported protein in the noodle dough partially depolymerized during aging, evidenced by the significant increase in free amino acids content. Changes in GMP were also reported. Ong et al. (2010) also investigated the role of GMP in the noodle processing steps and as well as after aging for 24 hours. They extracted more GMP from noodle dough sheets which were aged for 24 hours compared to the fresh dough, but gel strength measured by a rheometer was significantly reduced, which indicated the mechanical properties of raw noodle dough were modified by the changes in its gluten structure.

In addition, water re-distribution also occurred during storage of fresh noodles according to Li et al. (2017), in a study in which they monitored the water distribution in the fresh noodle over time via NMR and MRI. It was observed that water was uniformly distributed in the fresh noodle, but migrated to the surface of noodles upon aging, which weakened the original gluten network.

The evolution of air bubbles over time in the noodle dough may also contribute to the overall changes in the mechanical properties of noodle dough. Based on preliminary analysis of the noodle dough sheet by use of X-ray tomography (unpublished results), the air bubble size distribution was significantly modified upon aging, thus affecting the acoustic signature of the noodle dough.

4.4 Instrumental Texture of Cooked Noodles

Noodles may have various optimal cooking times due to differences in the formulation, processing conditions, as well as different thickness and width. However, there is not an objective standard method for determination of optimal cooking time (Park & Baik, 2004). To determine the optimal cooking time, the cooked noodles are normally squeezed in between a pair of glass plates. Noodles are optimally cooked when the white core disappears (Oh et al., 1983). Park and Baik (2004) pointed out this squeezing test relied on human perception of the degree of water imbibition in the noodle, which could lead to variable results from person to person. Thus, this study was interested in how the noodles behaved in response to a fixed cooking time and how the texture changed from raw to overcooked conditions. In this study, both fresh and 24-hour aged noodles from the same production run were compared as well. The cooking process started 2 hours after manufacture or after 24 hours' storage. Three cooking times were chosen, 2, 6 and 10 minutes. The white core of noodles was visible after cooking for 2 minutes for all the noodle samples, indicating that the noodles were undercooked at 2 minutes. The white core of noodles gradually disappeared after 6 minutes' cooking, which indicated noodles were optimally cooked. Noodles were intentionally cooked for an extended time (10 minutes in total), which represented overcooked noodles.

4.4.1 Cooked Noodle Thickness Expansion

Noodle weight before and after cooking is commonly measured in the industry to calculate the noodle cooking gain/yield (%), but it was not measured in this study due to experimental difficulties. In addition, the measurement does not take into consideration of components lost in the cooking water, such as salt and starch. The weight gain of noodles is not truly representing the total yield. Rather, the changes in noodle expansion is closely related to the texture perceived in the mouth (Nagao, 1996). Therefore, cooked noodle thickness was obtained from the force-displacement curve. The thickness expansion was defined as the percentage increase in cooked noodle thickness compared to raw dough thickness. As it is mostly influenced by cooking time, the thickness expansion was grouped based on aging time and cooking time (2, 6 and 10 minutes) and the mean value is displayed in Table 4.11, with the statistical analysis shown in Table 4.12.

Table 4.11: The mean value and standard deviations of thickness expansion (%) of fresh and aged noodles cooked for 2, 6, and 10 minutes.

	Fresh (%)			Aged (%)		
	2min	6min	10min	2min	6min	10min
CWRS_32_HS	20 ± 3	31 ± 4	43 ± 4	16 ± 5	27 ± 3	35 ± 6
CWRS_32_LS	22 ± 2	32 ± 2	44 ± 3	17 ± 1	29 ± 1	37 ± 2
CWRS_36_HS	10 ± 1	19 ± 4	34 ± 3	10 ± 3	18 ± 4	30 ± 3
CWRS_36_LS	16 ± 2	28 ± 3	40 ± 8	12 ± 9	22 ± 9	32 ± 9
CWRW_32_HS	19 ± 5	32 ± 11	47 ± 10	22 ± 9	33 ± 8	43 ± 8
CWRW_32_LS	19 ± 5	30 ± 8	42 ± 11	20 ± 2	32 ± 3	41 ± 3
CWRW_36_HS	19 ± 4	32 ± 7	45 ± 8	17 ± 3	29 ± 3	40 ± 4
CWRW_36_LS	15 ± 9	23 ± 7	36 ± 8	12 ± 7	22 ± 9	34 ± 9

Table 4.12: Statistical analysis (P value) of thickness expansion for fresh noodle (2h) and aged noodle (24h) cooked for 2 min, 6 min and 10 min. Other effect analyses were not significant, thus are not shown.

Effect	2h-2min	24h-2min	2h-6min	24h-6min	2h-10min	24h-10min
Flour	0.2907	0.0042	0.2686	0.001	0.2512	0.0002
Water	<.0001	<.0001	0.0002	<.0001	0.003	0.0011
Flour*Mixing	0.0087	0.0126	0.0012	0.0096	0.0037	0.0428

It was interesting to note that fresh noodles made with two different flours had no significant difference in expansion, but significant difference was found after aging. Noodles made with CWRW had more expansion (4.1-5.8 % overall) than noodles made with CWRS, which was consistent for the three cooking times. It seemed that the aged noodle had a reduced water absorption and holding capability, which was probably associated with the weakened gluten network induced by water redistribution, and enzymatic activities from microorganisms or the inherent enzymes in the flour (Li et al., 2017). Considering a series of microbiological and physio-chemical reactions could occur during the aging time, other possible causes cannot be ruled out either, such as the changes in starch properties (Miskelly & Moss, 1985; Ross et al., 1997; Maningat & Seib, 2010; Li et al., 2017) and starch related enzymatic activity (Crosbie, 1991).

Water addition level had a significant impact on the expansion of cooked noodles. As the water content in noodles increased from 32 % to 36 %, the thickness of noodles after cooking expanded 5-7.5% less overall, and this trend was consistent for all the cooking times for both fresh and aged noodles. This agrees with Hatcher et al. (1999), in which a significant reduction in the cooked noodle thickness was reported as the water addition level increased from 28 % to 34 %. This outcome was probably due to the reduced concentration of protein and starch in the dough system, which allowed heat and water penetration more rapidly during cooking (Hatcher et al., 1999; Gulia & Khatkar, 2013).

It was also noted that there was a significant interaction between flour and mixing effects. Noodles made with CWRS seemed to have more expansion when the dough was mixed at a low speed. On the other hand, noodles made with CWRW expanded more when the dough was mixed at a high speed. It was uncertain what the causes are, but this could be attributed to the stronger protein in CWRW which allowed the dough to withstand the high shear mixing operation (Bekes et al., 1994).

4.4.2 Textural Properties of Noodle Surface

During the noodle boiling process, the noodle surface absorbed water quickly, and the core absorbed water as well but at a slower rate. The difference in water distribution between the core and the surface has been well reported by the use of Scanning Electron Microscopy (SEM) and Nuclear Magnetic Resonance (NMR) techniques (Dexter et al., 1979; Sekine & Harada, 1990; Kojima et al., 2001). Noodles with such a gradient in water require different amount of mechanical force to break it down to pieces, thus affecting the perception of texture in the mouth. Good quality noodles should have less degradation at the surface while the core of the noodle is cooked. Therefore, the initial slope from the force-displacement curve was calculated to reflect the changes in texture from the noodle surface to the core (Oh et al., 1985a). Table 4.13 shows the statistical analysis of the initial slope of the cooked noodles and Figure 4.10 displays the initial slope of noodles cooked for different lengths of time.

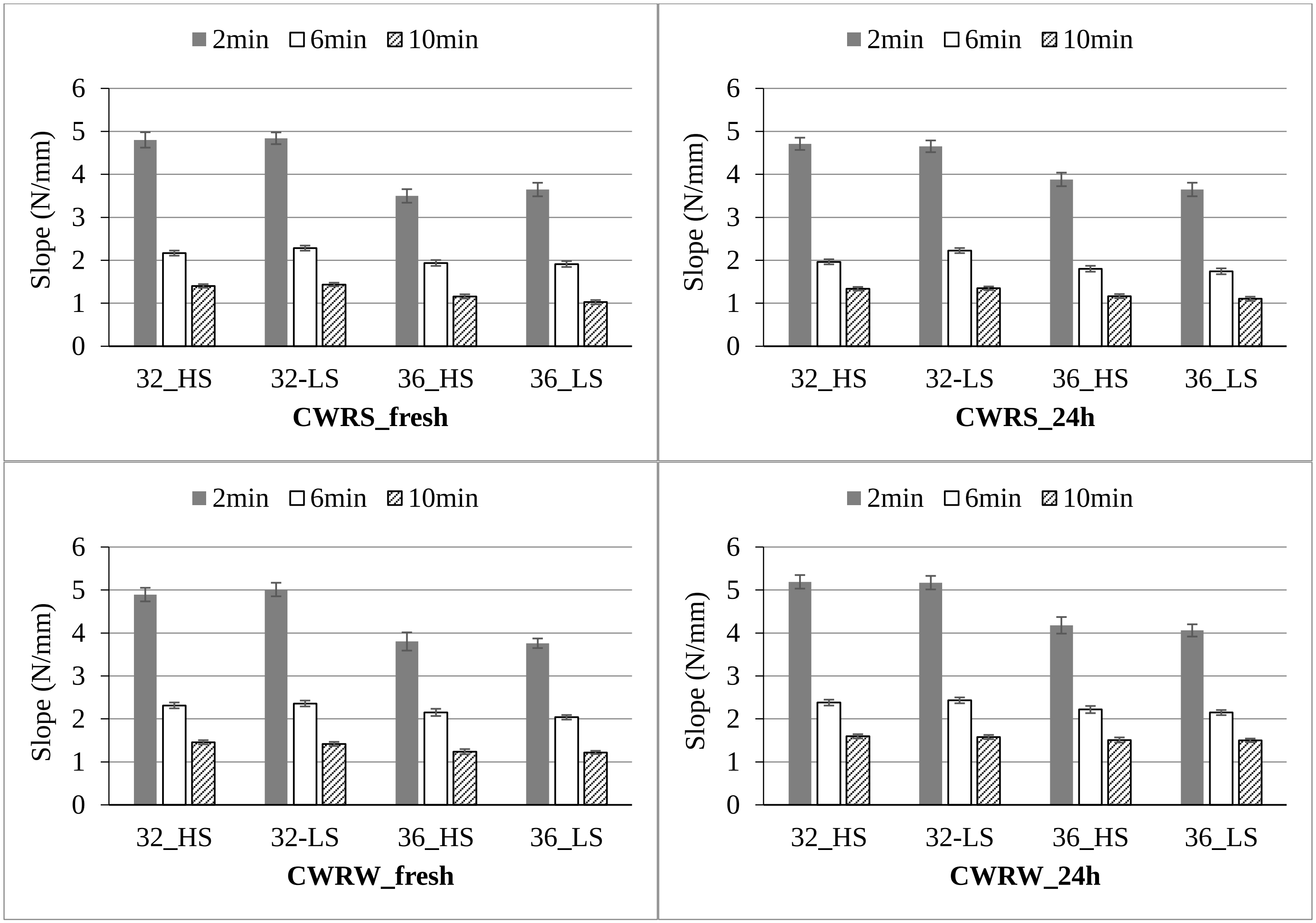
Table 4.13: Statistical analysis (P value) of initial slope of noodles cooked for different lengths of time. The significant effects are highlighted as P<0.05.

Effect	2 min P > F	6 min P > F	10 min P > F
Aging	0.0532	0.3567	<.0001
Flour	0.0003	<.0001	<.0001
Aging*Flour	0.1094	0.0013	<.0001
Water	<.0001	<.0001	<.0001
Aging*Water	0.1675	0.9795	0.0114
Flour*Water	0.8318	0.2433	0.001
Aging*Flour*Water	0.4845	0.7613	0.9304
Mixing	0.7929	0.442	0.2227
Aging*Mixing	0.2761	0.5459	0.6709
Flour*Mixing	0.9454	0.1557	0.7247
Aging*Flour*Mixing	0.6763	0.8207	0.9235
Water*Mixing	0.6095	0.0063	0.271
Aging*Water*Mixing	0.7209	0.5882	0.6688
Flour*Water*Mixing	0.7608	0.5031	0.1638
Aging*Flour*Water*Mixing	0.5878	0.4224	0.5725

The surface firmness of noodles has been shown to be greatly affected by the properties of protein (Hu et al., 2006), starch (Miskelly & Moss, 1985; Ross et al., 1997; Maningat & Seib, 2010) and processing conditions (Oh et al., 1985b). In this study, the initial slope continuously decreased with the increase of cooking time for all the noodle samples, which agreed with Oh et al. (1985a). Noodles made with different flours and water contents were significantly different in surface texture as assessed by their initial slope. Noodles made with CWRW had a significantly higher slope than those made with CWRS, which was consistent for all three cooking times, indicating that noodles made with CWRW had firmer surface texture than their CWRS counterparts. The initial slope was significantly reduced with the increase of water addition level from 32 % to 36 %, which agreed with Rho et al. (1989) and Oh et al. (1985a). The interaction of flour and aging indicated that noodles made with different flours varied in surface texture after aging for 24 hours. The aged noodle made with CWRW had a significantly higher slope than the fresh one, and the one made with CWRS had no change or a significant lower slope, which was more pronounced for noodles cooked for 6 and 10 minutes.

By comparing noodles made with different wheat cultivars, Oh et al. (1985a) reported that noodle dough made with a higher protein content flour did not enhance the surface firmness of noodles, rather, the gluten strength and the gluten network development in the dough was deemed to be more relevant (Dexter et al., 1979; Oh et al., 1985a). The initial slope was used to indicate the noodle surface as per Oh et al. (1985a), but more precisely, it measured the texture change from the surface to the core. With a fixed degree of work input, gluten was developed more in the soft wheat flour dough compared to the hard wheat flour dough, thus the resultant noodle tended to have a stronger core which could effectively prevent excessive disruption of the noodle (Oh et al., 1985a). In this study, noodle dough made with CWRW contained stronger gluten inherent to the flour, and the dough also exhibited a slightly higher density, and a lower tan δ, which indicated a well-developed gluten network which allowed the noodles to be less susceptible to disruption during the cooking process, thus retaining better firmness.

Figure 4.10: The initial slope of force-displacement curves for fresh and 24-hour aged noodles cooked for 2min, 6min or 10min. Error bars represent ± standard error.



4.4.3 Work and Peak Stress of Noodles

Work and peak stress are two parameters commonly used to evaluate the overall firmness of noodles (Oh et al., 1983; Edwards et al., 1993; Hatcher et al., 2009). Figure 4.11 displays the work, which is the area under the compression curve normalized by dividing the work by the initial surface contact area, as defined in Oh et al. (1983). The more work required in the compression test, the harder the cooked noodle texture. This held true for the peak stress (shown in Figure 4.12) as well. The peak stress is measured as the peak force per unit contact surface area.

All the values for normalized work and the peak stress were reduced as the cooking time increased. Statistical analysis is shown in Table 4.14 and the data in yellow highlights significance levels lower than 0.05. Even though there were significant interactions between the effects of aging, flour, water and mixing, the single effect of flour, water and aging were also significant, and consistently so for all the cooking times. No significant difference in the normalized work and the peak stress was found for dough mixed differently.

Figure 4.11: The normalized work required for compression of cooked fresh and aged noodles made with CWRS and CWRW flours processed with different water content and mixer speed, and cooked for 2, 6, or 10 min. Error bars represent ± standard error.

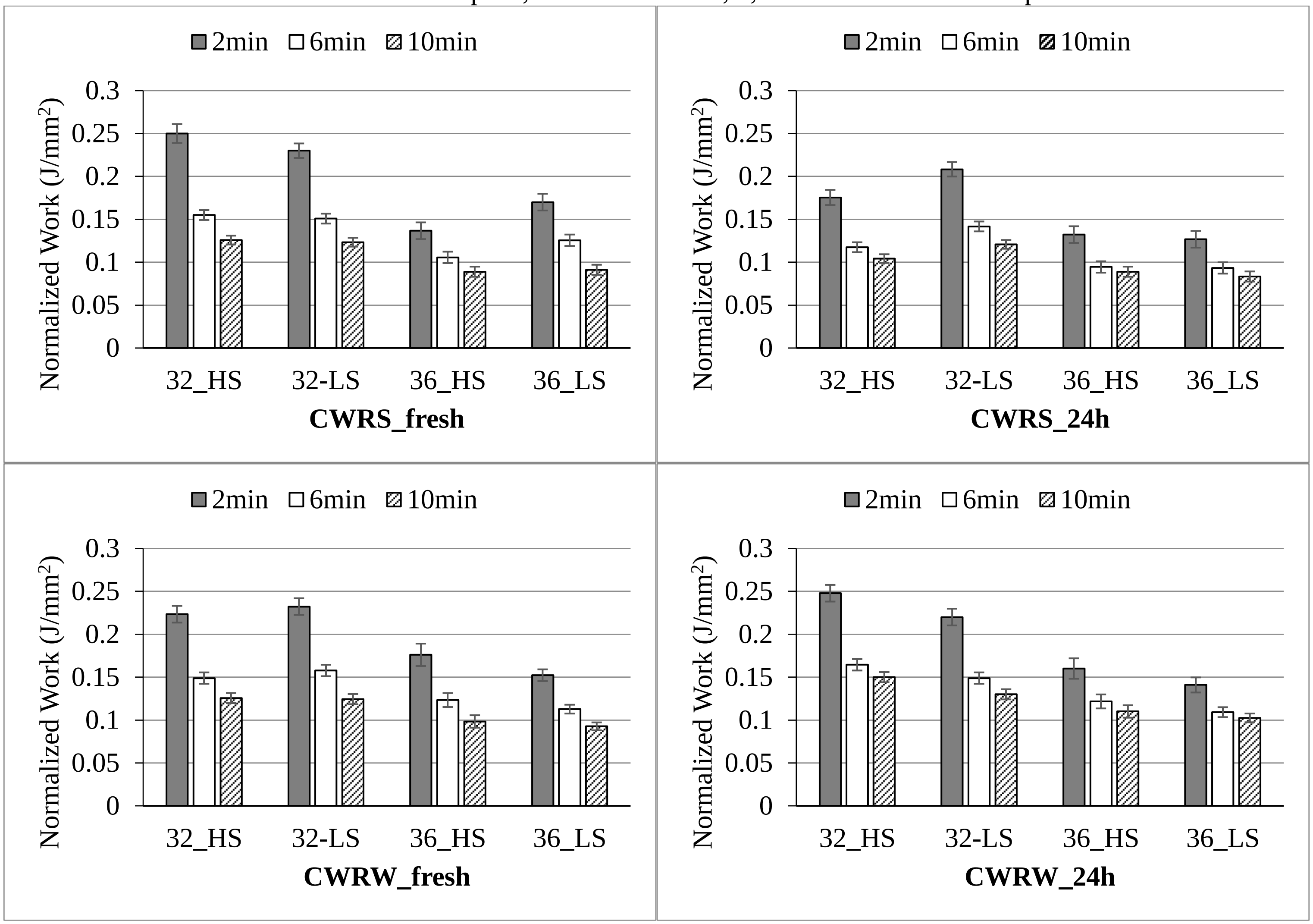


Figure 4.12: The peak stress required for compression of cooked fresh and aged noodles made with CWRS and CWRW flours processed with different water content and mixer speed, and cooked for 2, 6, or 10 min. Error bars represent ± standard error.

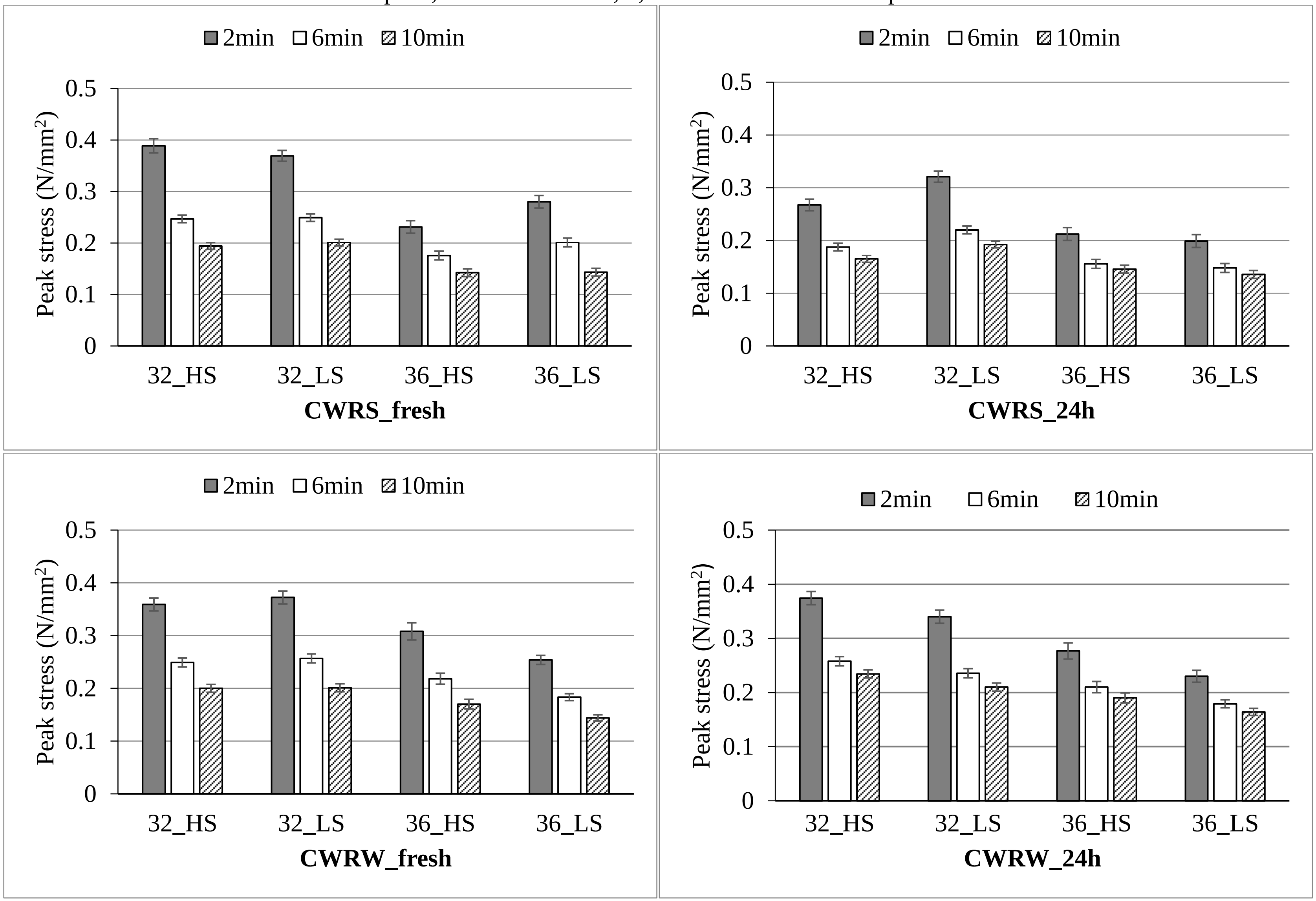


Table 4.14: The P value of normalized work and peak stress of noodles cooked for 2, 6 and 10 mins. The highlighted effect was significant at P=0.05.

	Normalized work			Peak stress		
Effects	2 min	6 min	10 min	2 min	6 min	10 min
Aging	<.0001	0.0009	0.4003	<.0001	<.0001	0.1614
Flour	0.0021	0.0001	<.0001	<.0001	<.0001	<.0001
Aging*Flour	0.0013	0.0006	0.0004	<.0001	<.0001	<.0001
Water	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001
Aging*Water	0.8207	0.7449	0.7341	0.5273	0.6589	0.313
Flour*Water	0.9183	0.7871	0.8445	0.3434	0.6469	0.7753
Aging*Flour*Water	0.0264	0.5617	0.2848	0.029	0.6469	0.2218
Mixing	0.5912	0.7289	0.3136	0.2892	0.41	0.0932
Aging*Mixing	0.647	0.4661	0.6878	0.5472	0.3822	0.5965
Flour*Mixing	0.01	0.0093	0.0536	0.0001	0.0001	0.0009
Aging*Flour*Mixing	0.2429	0.201	0.1681	0.2995	0.5	0.2363
Water*Mixing	0.8171	0.5005	0.6808	0.1128	0.041	0.0166
Aging*Water*Mixing	0.2005	0.3052	0.6703	0.1053	0.3822	0.8334
Flour*Water*Mixing	0.323	0.556	0.2742	0.1006	0.3063	0.6227
Aging*Flour*Water*Mixing	0.0009	0.0065	0.0597	0.0002	0.0039	0.0527

It was interesting to note that noodles made with CWRW showed a greater work and peak stress than those made with CWRS, thus they were firmer than their CWRS counterparts. Upon aging, the noodles made with CWRS had significantly reduced work and peak stress, but this was less pronounced for noodles made with CWRW flour. This is probably due to the different gluten strength in the noodle dough (Baik et al., 1994). In this study, even though CWRS flour contained more protein, the CWRW dough exhibited greater gluten strength as indicated by its extensogram Rmax, even after aging for 135 minutes. Miskelly and Moss (1985) and Gulia and Khatkar (2013) have reported that the flour dough with a higher Rmax or Rmax/E led to noodles with a firmer texture.

As the water addition level increased from 32 to 36 %, the cooked noodles had significantly reduced amounts of work needed for the compression test, and the peak stress showed the same trend. Therefore, noodles made with 36 % water addition had a softer texture than those made at

32 %. This agrees with Hatcher et al. (1999) and Park and Baik (2002), in which they reported that noodles with increased water addition had less resistance to compression and a reduced maximum cutting stress, thus being less firm in texture.

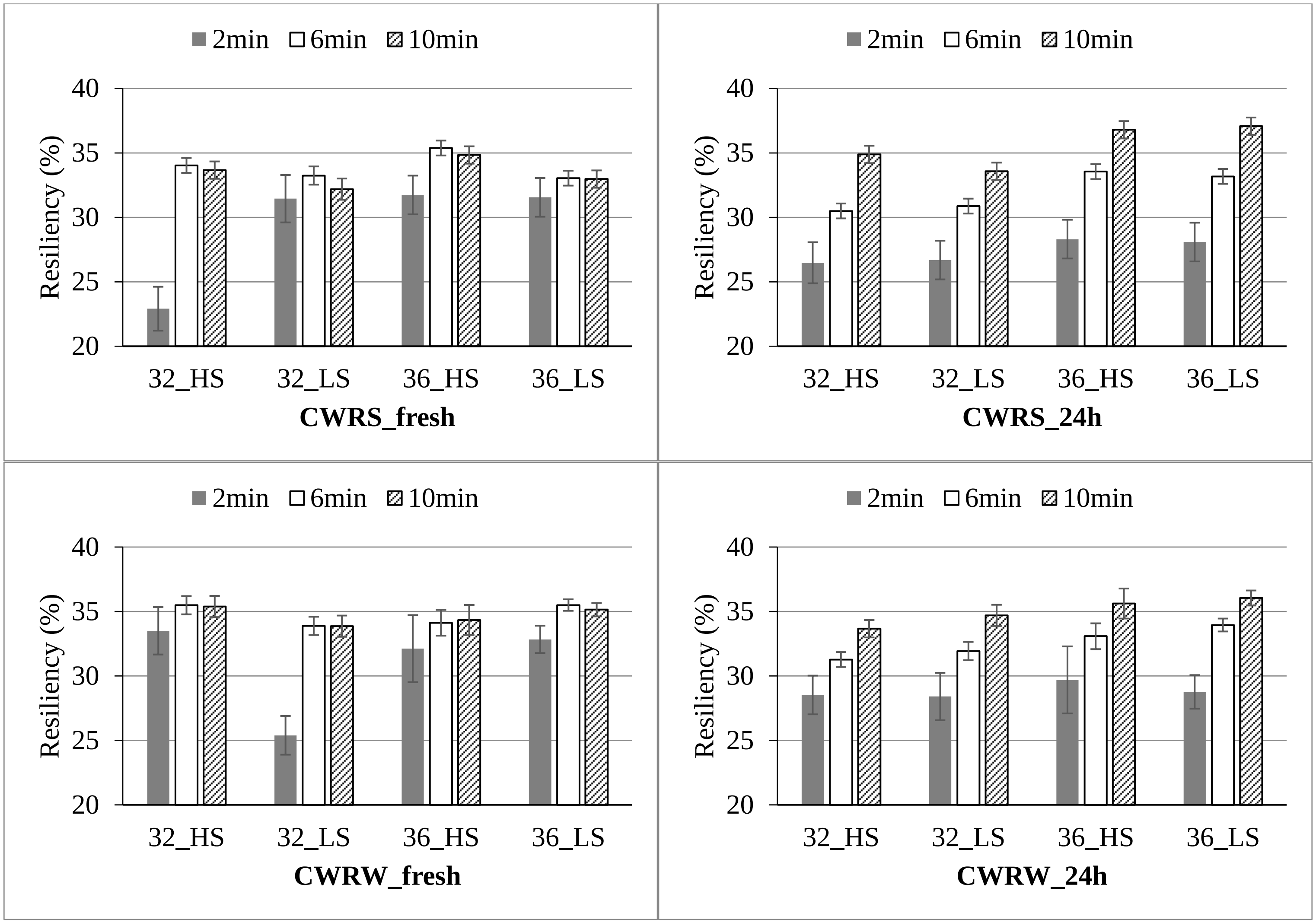
4.4.4 Resiliency of Cooked Noodles

Resiliency measures the recoverable energy and is used to evaluate the elasticity of noodles. Noodles with a higher resiliency are more elastic in texture (Epstein et al., 2002). Statistical analysis of resiliency is shown in Table 4.15 and Figure 4.13 displays the resiliency of the cooked noodles.

Table 4.15: Statistical analysis (P value) of resiliency of noodles cooked for 2, 6 or 10 minutes. The highlighted effect was significant at P=0.05.

Effect	2min	6min	10min
Aging	0.0182	<.0001	0.0018
Flour	0.0838	0.0433	0.3729
Aging*Flour	0.9559	0.6629	0.0194
Water	0.0051	0.0001	0.0006
Aging*Water	0.1412	0.0043	0.0379
Flour*Water	0.5109	0.3663	0.2216
Aging*Flour*Water	0.866	0.814	0.9016
Mixing	0.9881	0.4969	0.2438
Aging*Mixing	0.7702	0.0698	0.1496
Flour*Mixing	0.0168	0.1011	0.1029
Aging*Flour*Mixing	0.0354	0.6105	0.9694
Water*Mixing	0.8695	0.7414	0.3515
Aging*Water*Mixing	0.8447	0.4649	0.7606
Flour*Water*Mixing	0.0143	0.0423	0.8653
Aging*Flour*Water*Mixing	0.0107	0.1845	0.1172

Figure 4.13: Resiliency of fresh and aged noodles made from CWRS and CWRW flour and processed with different water content and mixer speed, and cooked for 2, 6, or 10min. Error bars represent ± standard error.



Overall, a general trend was found from the effect of water and aging. As shown in Figure 4.13, the resiliency of noodles was significantly reduced after aging, which was consistent for all the three cooking times, and it seemed that noodles made with 36 % water were less affected compared to 32 % water addition level. As the water addition level increased from 32 % to 36 %, a general increase of resiliency of noodles was observed.

The flour effect was only significant when the noodles were cooked for 6 minutes. Noodles made with CWRW had a comparable resiliency to those made with CWRS. This was probably attributed to the greater gluten strength in CWRW as measured by the empirical tests. A high correlation between protein quality measured with SDS sedimentation value and noodle elasticity has been reported by Morris and Huang (1985) and Park et al. (2003).

It was interesting to note that fresh noodles and aged noodles showed different trends with the increase of cooking time. Fresh noodles seemed to reach maximum resiliency after cooking for 6 minutes and no further increase was observed. For the aged noodles, a continuous increase even after cooking for 10 minutes was found. It is uncertain what the underlying causes are, but it may indicate that the hydration rate of the noodles changed during aging. It should be noted there were significant interactions among water, flour, and mixing, indicating the resiliency of cooked noodles was dependent on the specific composition and mixing condition, thus no definitive conclusion can be drawn from the resiliency test.

4.5 Sensory Evaluation of Cooked Noodle Texture

Instruments such as the Texture Analyzer are widely used by industry as it is a cheaper, faster, more convenient and reproducible method to assess noodle texture (Ross, 2006; Hatcher & Anderson, 2007). However, since texture is a sensory attribute (Szczesniak, 2002), capturing the human perception of foods in the mouth is still un-replaceable. Therefore, I conducted sensory evaluation of noodle texture. Instead of using a number of non-trained consumer panels, a trained panel was used since a trained panel is more reliable and can provide valuable information on specific texture characteristics (Janto et al., 1998).

The descriptive panel evaluated three attributes: surface firmness, overall hardness and elasticity as per Oh et al. (1983). From the instrumental method, no significant difference was found in cooked noodle texture when samples were mixed differently; therefore, mixing was used as a block effect (session effect) rather than a fixed effect for panel analysis (Romana et al., 2002). The boxplot for each sensory attribute is shown in Figure 4.14 to Figure 4.16. For each attribute, the ratings were arranged from low to high value, and each boxplot displays the minimum, 1st quartile, mean (labeled as cross), median (the line in the box or not shown if overlap with another line), 3rd quartile, and maximum of the ratings as well as potential outliers. In general, the panel was able to sense differences in samples. To test if there were true differences between treatments and how reproducible their assessment, each individual attribute was analyzed by use of the MIXED Procedure in SAS as shown in Table 4.16.

Figure 4.14: Boxplot of surface firmness of cooked noodles made with different treatments.

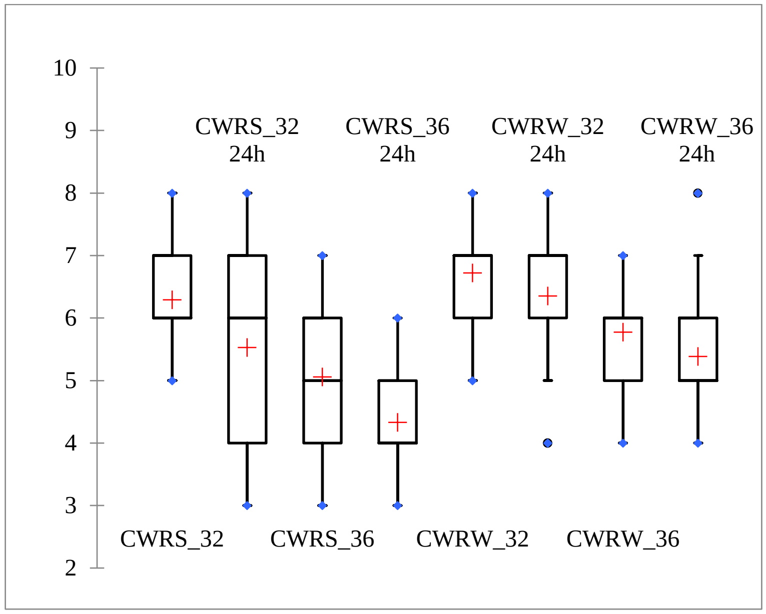


Figure 4.15: Boxplot of overall hardness of cooked noodles made with different treatments.

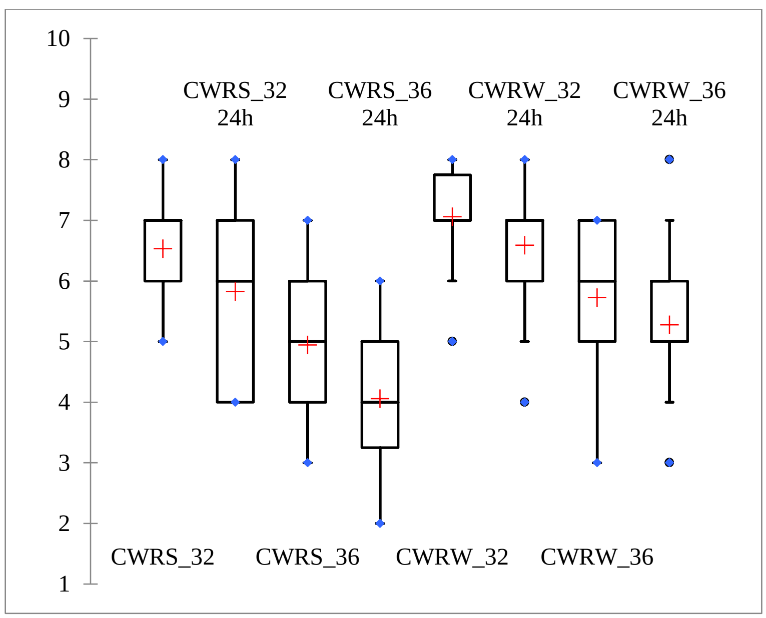


Figure 4.16: Boxplot of elasticity of cooked noodles made with different treatments.

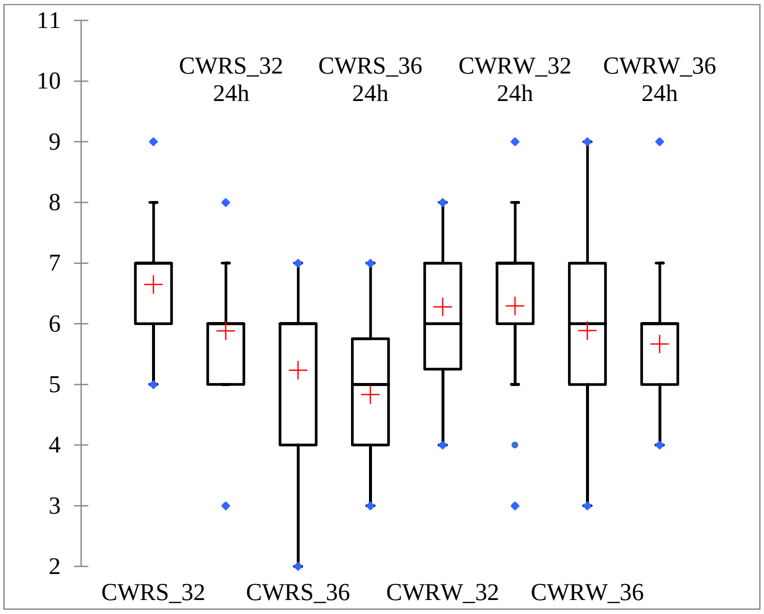


Table 4.16: Type III Sum of squares analysis (F value and P value) of surface firmness, overall hardness and elasticity. Significant (P<0.05) effects are highlighted.

	Surface firmness		Overall hardness		Elasticity	
Source	F	P > F	F	P > F	F	P > F
Products	7.796	0.005	7.612	0.012	4.154	0.018
Assessors	11.379	0.001	45.381	0.046	18.399	< 0.0001
Sessions	0.280	0.615	0.021	0.891	0.070	0.806
Products*Assessors	1.187	0.267	0.837	0.743	1.542	0.058
Products*Sessions	2.088	0.061	2.820	0.014	1.494	0.190
Assessors*Sessions	1.088	0.386	0.462	0.877	0.659	0.724

The products effect (samples made with different treatments) were significant at P<0.05 for all three sensory attributes evaluated. This was consistent for all the sessions. However, in sensory evaluation, panelists may use different scales for the same sensory property. It is important to remove the scale difference and find out whether the difference in ratings truly reflects the difference in samples; this can be achieved by use of PCA (principal component analysis). PCA is a statistical procedure which transforms original data into two un-correlated dimensions (or principal components). It is a linear transformation based on the correlations among variables, and generates factor loadings (blue dots shown in Figure 4.17), which represent the correlations to the principal components, and factor scores which represents each panelist's rating in the new dimension (shown in red dots). PCA helps to analyze if the panel reached a consensus (Luciano & Naes, 2009). As shown in Figure 4.17, the panel was in good agreement for the surface firmness and overall hardness assessments of noodle texture. All the panelists were close to each other except Panelist 6, indicating a good agreement on the ratings, and there was a true difference in the texture of cooked noodles. For the elasticity of noodles, the majority of the panel members were in agreement, but it was noted that Panelist 3 and 6 were different from the rest of the panel as shown in Figure 4.18. Their ratings were more correlated with the 2nd principal component rather than 1st, which indicated that these two panelists may have very different interpretation of elasticity, and thus failed to differentiate samples from one to another. Therefore, the ratings from Panelist 3 and 6 were removed for elasticity assessment.

Figure 4.17: PCA plot of surface firmness (left) and overall hardness (right) ratings of cooked noodles. Red dots represented each panelist's rating and blue dots represented the variable loadings.

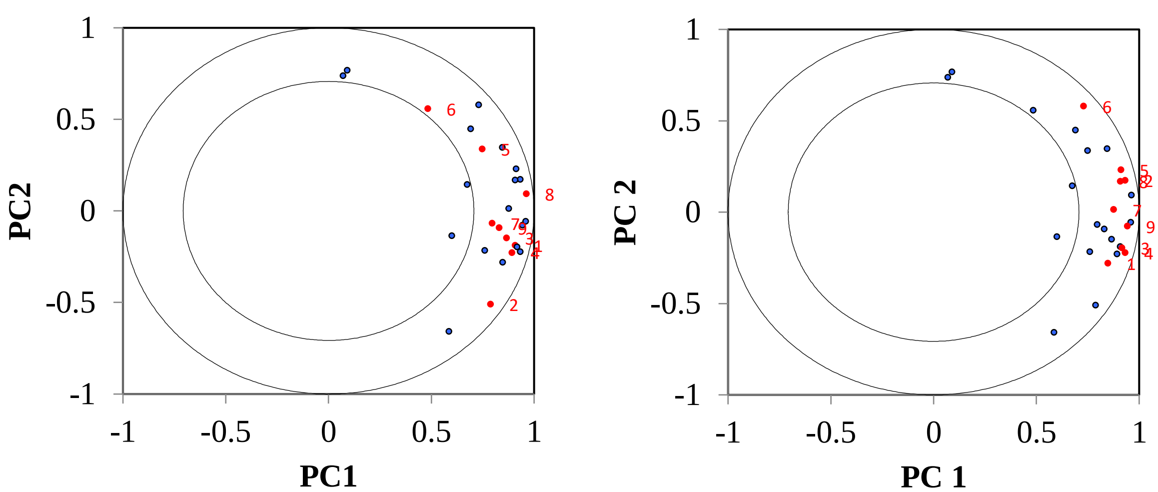
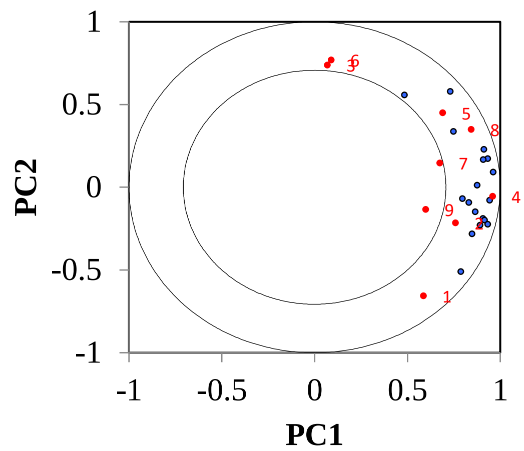
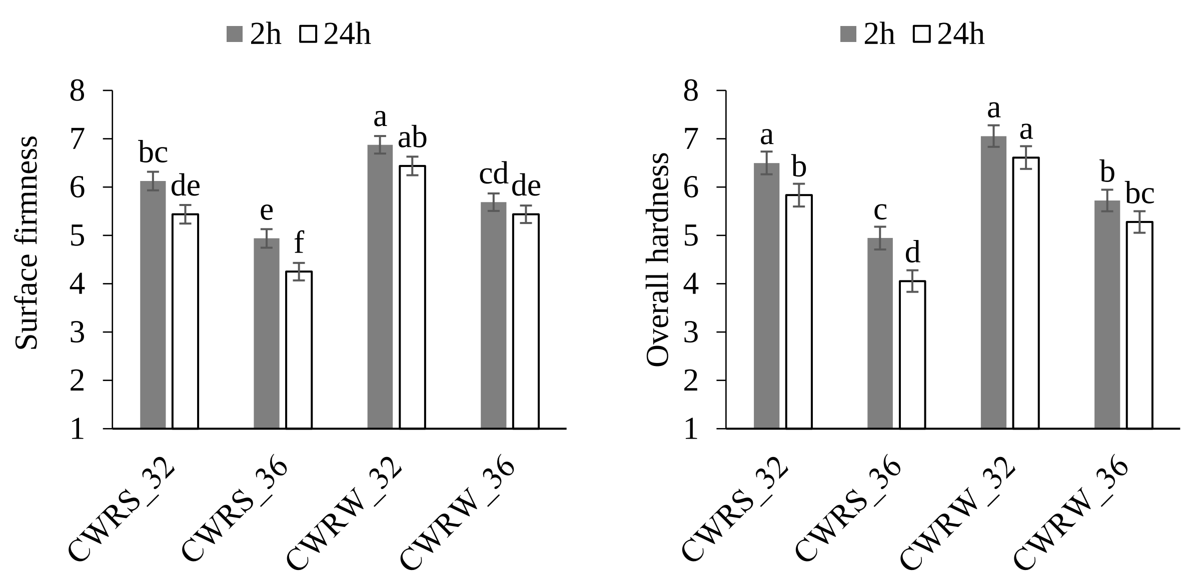


Figure 4.18: PCA plot of elasticity of cooked noodles, red dots represented each panelist's rating and blue dots represented the variable loadings.



The LSD (Least Significance Difference) method was used to compare sample means at a significance level of 0.05. As shown in Figure 4.19, both the surface firmness and overall hardness followed the same trend.

Figure 4.19: Surface firmness, overall hardness evaluated by the sensory panel for cooked noodles (fresh and aged) made with CWRS and CWRW at 32 % and 36 % water additions. Only samples labeled with different letters are significantly different.



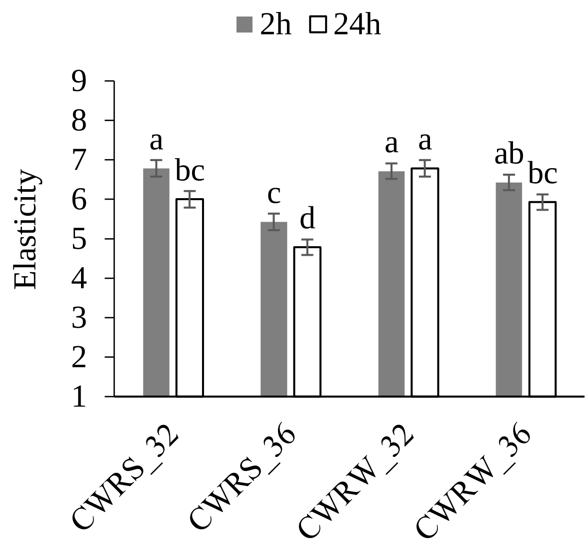
In a comparison of the fresh noodles made with two flour types, the firmness rating of noodles made with CWRW was significantly greater than their CWRS counterpart. This was probably due to the difference in gluten strength as suggested by Oh et al. (1985a). In this study, CWRW had lower protein content, but the strength of gluten was greater than CWRS as measured by empirical tests. A number of studies on the structure of noodles by use of SEM have been reported (Dexter, 1979; Oh et al., 1985a; Sekine & Harada, 1990). During noodle boiling, small openings or voids on the noodle surface were observed, which provided channels to allow more efficient water and heat penetration. The small openings could be created by the leaching out of the amylose (Wang & Seib, 1996; Ross et al., 1997) or exist as part of the noodle structure (Jang et al., 2016; Guillermic et al., 2017). Noodles with a uniform, strong and continuous gluten network would function as a good barrier so that an excessive amount of water would not enter into the core of the noodle; thus the noodle would retain better integrity and texture. The texture differences due to the gluten network development have been readily discerned by trained sensory panelists as per Pipatsattayanuwong (1998), in which different types of noodles were studied. Taiwanese noodle (white salted noodle) showed the highest score in springiness, and smoothness with the best integrity due to a uniform gluten development which did not occur in a matrix with a different pH level (alkaline noodle) or different ingredients (rice noodle).

The firmness rating was significantly reduced as the water content increased from 32 % to 36 %, independent of flour types, and aging time, which corresponded to the texture result measured by a texture analyzer (Hatcher et al., 1999).

The sensory panelists found that noodles became less firm after aging for 24 hours, and it was more pronounced for the noodle made with CWRS flour. No significant changes were detected in the noodles made with CWRW flour. Ong et al. (2010) investigated the aging effect on GMP content and gel strength extracted from noodle dough. A significant increase of the GMP content in the noodle dough after aging for 24 hours was reported, but the gel strength of the extracted GMP measured with a rheometer was significantly reduced, which might explain the detrimental effect of aging on the noodle texture. The air bubbles in the noodles may also contribute to the texture change. Based on preliminary results (not published), the aged noodle may have fewer but bigger air bubbles after aging, thus forming a noodle with a porous structure, similar to the one found in noodles fortified with maltodextrin (Jang et al., 2016), which could facilitate water and heat penetration into the core more rapidly, so that the texture would be less firm. The research team at the University of Manitoba is undertaking the investigation of air bubbles in raw and cooked noodles by use of X-ray tomography, which will advance the knowledge of air bubbles in noodles.

In terms of elasticity (shown in Figure 4.20), noodles made with CWRS were inversely affected by the water addition levels and became less elastic in texture when the water addition in the noodle dough increased from 32 % to 36 %. This agreed with the instrumental measurement done by Hatcher et al. (1999), in which they examined the water addition effect on the textural properties of noodles and reported that the resistance to compression and the recovery measured by a texture analyzer were significantly reduced as the water addition increased. In this study, it was also noted that the elasticity of noodles made with CWRW was less affected by the change of water content. Similar to surface firmness and overall hardness, aged noodles made with CWRS had significantly reduced elasticity compared to the fresh ones, but not for those made with CWRW. This indicated that the noodles made with CWRW had less degradation in quality.

Figure 4.20: Elasticity evaluated by the sensory panel for cooked noodles (fresh and aged) made with CWRS and CWRW at 32 % and 36 % water additions. Only samples labeled with different letters are significantly different.



4.6 Correlations among Ultrasonic, Sensory and Instrumental Methods

Noodles made with different treatments had distinct texture characteristics and they were evidently detected by the sensory panelists. In addition, the conventionally used instrumental method also quantified the difference in cooked noodle texture under the large-strain compression test. The final texture of cooked noodles is derived from the dough, where the interaction of ingredients (flour, water and salt) occurred, through a series of the processing steps, mainly mixing and repeated sheeting processes (Fu, 2008). The ultrasound technique used in this study is able to probe the dough's mechanical properties in a timely, non-destructive manner. Understanding the connection of the raw dough to the final quality (texture) would help the prediction capability of the ultrasound technique. Table 4.17 and Table 4.18 display the correlations of parameters between the fresh noodle dough and cooked noodle texture measured by either the compression technique or the sensory panel. The correlations were analyzed based on the three cooking times (2 min, 6 min and 10 min), and aging time (fresh vs aged). Only significant correlations with P value less than 0.05 are shown.

As noodles were cooked for 6 minutes (shown in Table 4.17), density, phase velocity, M', and tan δ significantly correlated to most of the texture parameters measured with a texture analyzer, such as the peak stress, with R values ranging between 0.64 and 0.82. A similar result was also found by Diep et al. (2014), in which they studied the raw yellow alkaline noodle dough with ultrasound at 40 kHz: a significant correlation between the phase velocity value and the maximum cutting stress of cooked noodles measured by a texture analyzer was also found, with R=0.72. In addition, in this study, raw noodle dough parameters were significantly (P<0.01) correlated to all the sensory attributes as well, with R ranging from 0.36 to 0.63.

Table 4.17: The correlation coefficient (R) between the raw noodle dough parameters and the various texture measurements (instrumental and sensory panel) for noodles cooked for 6 minutes.

	Density	Phase velocity	Attenuation coefficient	M'	M''	tan δ
Slope		0.37**		0.43**		−0.47***
Work	0.52***	0.48***		0.51**		−0.62***
Peak stress	0.64***	0.67***		0.69***		−0.82***
Thickness expansion		0.42**		0.38***		−0.67***
Resiliency			-0.45**			
Surface firmness	0.46***	0.58***		0.53***		−0.60***
Overall hardness	0.55***	0.63***		0.58***	0.36**	−0.56***
Elasticity	0.52***	0.50***		0.39**		−0.44**

* Significant at P<0.05, ** at P <0.01, *** at P<0.001

After noodles were cooked for 2 and 10 minutes (Table 4.18), the instrumental noodle texture parameters had moderate to strong correlations to its dough properties with R ranging from 0.42 to 0.92.

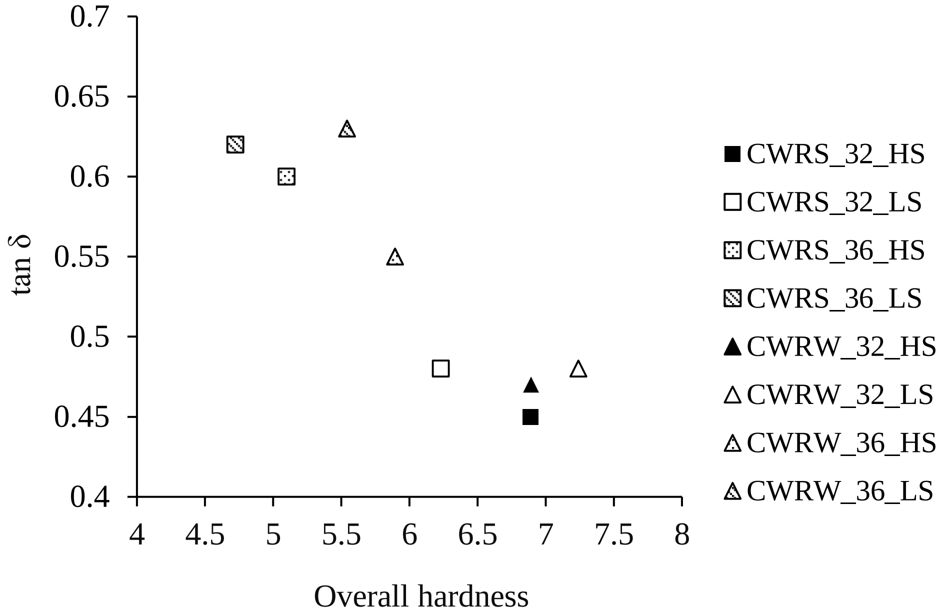
Table 4.18: The correlation coefficient (R) between the raw noodle dough parameters and the measurements with an instrumental method for noodles cooked for 2 or 10 minutes.

	2min		10min		
	Density	tan δ	Density	Phase velocity	tan δ
Slope	0.56**	−0.61***	0.80***	0.65***	−0.76***
Work	0.53**	−0.53**	0.77***	0.59**	−0.79***
Peak stress	0.45*	−0.45*	0.76***	0.74***	−0.92***
Thickness expansion		−0.52*	0.42*		−0.59**

* Significant at P<0.05, ** at P <0.01, *** at P<0.001

Among all the correlations for the fresh noodles, tan δ negatively correlated with cooked noodle parameters measured either instrumentally or by sensory, regardless of cooking time. An example plot of tan δ value and overall hardness assessed by sensory panelists is shown in Figure 4.21, where noodles with an overall hardness rating higher than 6 had a tan δ value lower than 0.48, and the less firm noodles (shown at the left corner) had tan δ values higher than 0.55. As the tan δ value can be viewed as an indicator of structure (Létang et al., 2001), noodle dough with a more organized structure (lower tan δ values) tended to have a firmer texture.

Figure 4.21: Scatterplot of the mean tan δ value of raw noodle dough and the cooked noodle hardness ratings assessed by the sensory panel.



For the aged noodles, significant correlations were also found as shown in Table 4.19. Density and the phase velocity had strong but negative correlations with the peak stress and work with R ranging from −0.5 to −0.75. The negative correlations (as opposed to positive correlations for fresh noodles) indicated the rheological properties of noodles were modified with time as a result of physio-chemical changes of gluten components as well as the water distribution (Li et al., 2017).

Table 4.19: The correlation coefficient (R) between the raw noodle dough parameters and the various texture measurements (instrumental and sensory panel) for aged noodles cooked for 2, 6 or 10 minutes.

	Density			Phase velocity		M''	M'
	2min	6min	10min	2min	10min	10min	10min
Slope						0.44*	0.64**
Work	−0.68***	−0.73***	−0.56**	−0.65***	−0.50*		
Peak stress	−0.75***	−0.68***	−0.68***	−0.71***	−0.53**		
Resiliency		0.77***	−0.63**				
Thickness expansion		−0.58**	0.52*		0.52*		
Surface firmness			−0.43*		−0.46*		

* Significant at P<0.05, ** at P <0.01, *** at P<0.001

5. Conclusions

This study applied an air-coupled ultrasound technique to assess the fundamental rheological properties of raw white salted noodle dough. It monitored the real time changes of dough properties in a non-destructive, non-contact way. As a small-strain technique, the ultrasound technique revealed the linear viscoelastic nature of noodle dough, which was strongly affected by dough moisture content, work input (either from the mixing or sheeting process), as well as changes in noodle properties with time. This study elucidated the role of the air-coupled ultrasound technique as a valid quality control tool. Previous ultrasonic studies have focused on the mechanical properties of dough, but the connection to the final product quality had not been investigated. Therefore, in this study, an instrumental method as well as a trained sensory panel were used to detect the texture changes of cooked noodles. Overall, the mechanical properties of raw noodle dough measured by the ultrasound technique and the cooked noodle texture parameters were highly correlated. My research therefore suggests that air-coupled ultrasound has a promising capability for the prediction of noodle quality.

The elasticity of raw noodle dough was strongly correlated with the cooked noodle texture. Cooked noodle texture was inversely affected by the water addition level. Noodle dough became less elastic (increased tan δ value) with the increase of water content from 32 % to 36 %, and the degree of impact was specific to flour types. The resultant noodle after cooking was softer with the increase of moisture content, which was detected by both the instrument method and the trained sensory panel. Noodle dough made with the red winter wheat (CWRW) used in this study was more robust to changes in moisture content compared to a hard red spring wheat (CWRS).

Work input is critical for noodle dough development. Mixing the dough at different speeds affects the elasticity of raw noodle dough, but had a minimal impact on the cooked noodle texture. The noodle dough mixed at high speed was slightly more elastic, probably due to the stronger mechanical force which broke the gluten polymer chains (Skerritt et al., 1999) so that more sulfhydryl groups would be available for disulfide bond linking. The gluten network was more developed through the repeated sheeting process and this was manifest as a significant increase in the phase velocity and reductions in the attenuation coefficient and tan δ when dough from Pass 2 was compared to that from the final sheeting pass.

The rheological properties of raw noodle dough as well as the cooked noodle texture were greatly impacted by noodle dough aging time. Noodle dough after aging had a very distinct acoustic signature compared to fresh noodle sheets, which was evidenced by a dramatic increase in phase velocity, density, M', M'', tan δ and a decrease in the attenuation coefficient. A significant reduction in firmness and elasticity examined by both instrumental analysis and the sensory panelists was also found. These measured changes were probably due to the structural changes of glutenin as well as water distribution in the dough. The flours used in this study showed differences in noodle texture after aging for 24 hours, with less degradation in textural quality found for noodles made with CWRW. Understanding mechanisms affecting the time-dependent nature of noodles would help researchers better define experimental protocols to reduce experimental errors in their studies. More importantly, from a manufacturing perspective, understanding the aging properties of noodles would help breeders, flour millers and noodle processors to select the appropriate flour which would maintain consistency and less degradation in noodle quality over time.

In this study, CWRW flour, which had a lower protein content but greater gluten strength, produced noodles with a comparable firmness and elasticity as the one (CWRS) with a higher protein content, even after aging for 24 hours. It indicated the importance of protein quality in determination of final texture.

6. Future work

The ultrasound technique used in this study demonstrated a great sensitivity to noodle composition and processing conditions and revealed the corresponding rheology changes. The acoustic signature in noodle dough is affected by the dough matrix as well as by the dough's air bubbles, but in this study it was not possible to use the air-coupled ultrasound technique to discriminate the effect of air bubbles from the dough matrix properties. Therefore, a further study with contact measurement at a wider frequency range would be useful to differentiate bubble effects from dough matrix effects.

This study focused on white salted noodles, and yellow alkaline noodles are another type of noodles widely consumed. By use of different salts in the formulation, yellow alkaline noodles have a very distinct quality characteristic. A similar study should be carried out on yellow alkaline noodles to understand key quality determinants, which will help understand how the gluten network forms and is modified over time in an environment with a different pH level.

This study has clearly showed the effect of aging on dough properties. Noodle discoloration over time is commonly seen and is strongly associated with the activity of polyphenol oxidase. But the connection between the rheological properties of noodle dough and the visual observation is unknown. Therefore, it would be insightful to investigate how the color and rheological properties of noodles are affected by the aging time and storage condition, which would enhance the prediction capability of the ultrasound technique.

Noodles made with CWRW flour used in this study showed a very comparable quality as the noodle made with high protein flour (CWRS) and it was less affected by water addition level and aging time. In noodle dough, full development of gluten is not achieved, and water plays an important role in the texture, which may be associated with its function in shaping and maintaining the dough's molecular structure (secondary structure of protein) via hydrogen bonds. An in-depth research is needed to understand the secondary structural changes of proteins in noodle dough, and identify the specific traits in the flour which determine excellent noodle making properties.

The sheeting process is a widely used operation in the food industry. It appeals to industry as it is energy efficient and versatile, and has inspired new innovations to meet ever changing consumer demand. Fortification of wheat noodles with healthier ingredients (such as pulses, buckwheat), and manipulation of the sheeting process, such as a "sandwich" style lamination, to process whole wheat noodles, are contemporary trends. In order to enhance the health benefits of noodles without compromising the quality attributes, air-coupled ultrasound technique can be used to help optimize the formulation and processing conditions.

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8. Appendices

Appendix 1: Research Ethics Approval Certificate

UNIVERSITY OF MANITOBA

Research Ethics and Compliance

Human Ethics
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PROTOCOL APPROVAL

TO: **Huiqin (Mia) Wang** (Advisor: [redacted])
Principal Investigator

FROM: [redacted] Chair
Joint-Faculty Research Ethics Board (JFREB) [redacted]

Re: **Protocol J2017:004 (HS20449)**
"Evaluation of texture of white salted noodles made with varying formulation and processing conditions"

Effective: March 1, 2017 **Expiry:** March 1, 2018

Joint-Faculty Research Ethics Board (JFREB) has reviewed and approved the above research. JFREB is constituted and operates in accordance with the current *Tri-Council Policy Statement: Ethical Conduct for Research Involving Humans.*

This approval is subject to the following conditions:

1. Approval is granted only for the research and purposes described in the application.
2. Any modification to the research must be submitted to JFREB for approval before implementation.
3. Any deviations to the research or adverse events must be submitted to JFREB as soon as possible.
4. This approval is valid for one year only and a Renewal Request must be submitted and approved by the above expiry date.
5. A Study Closure form must be submitted to JFREB when the research is complete or terminated.
6. The University of Manitoba may request to review research documentation from this project to demonstrate compliance with this approved protocol and the University of Manitoba *Ethics of Research Involving Humans.*

Funded Protocols:
- **Please mail/e-mail a copy of this Approval, identifying the related UM Project Number, to the Research Grants Officer in ORS.**

Research Ethics and Compliance is a part of the Office of the Vice-President (Research and International)
umanitoba.ca/research

Appendix 2: Participants Consent Form

University of Manitoba | Faculty of Agricultural and Food Sciences

Consent Form

Project Title: Evaluation of texture of white salted noodles made with varying formulations and processing conditions

Principal Investigator: [redacted]
Contact information: [redacted]
Research Supervisor: [redacted]
Contact information: [redacted]

This consent form, a copy of which will be left with you for your records and reference, is only part of the process of informed consent. It should give you the basic idea of what the research is about and what your participation will involve. If you would like more detail about something mentioned here, or information not included here, you should feel free to ask. Please take the time to read this carefully and to understand any accompanying information.

I consent to my participation in the sensory study which is designed to compare the texture differences of sixteen white salted noodles made with varying formulations and processing conditions and cooking time. This project is generously funded by NSERC (Natural Sciences and Engineering Research Council of Canada). I understand that I will be **participating in a 45-60 minutes' training session** where I will learn the sensory testing procedure and familiarize with the tested texture attributes. I understand that I may or may not be selected for the formal sensory panel based on my performance in the **mock sensory**. Once I am selected, I will **participate in four sessions (16 samples in one day)**. I will be assigned four samples in each session which will take approximately 15 minutes to complete the tasks. The tentative schedule is outlined as shown below.

	Activity	Time	Location	What to expect
Day 1	Training session	10:30—11:10am	TBD	• Overview of project objectives, scheduling, and tasks • Overview of Consent form • Learn the testing procedures and requirement • Familiar with texture attributes with reference samples
Day 1	Mock sensory	11:15-11:30am	TBD	• Evaluate 2 samples • Test panelists' capability in discrimination of samples
Day 2	Formal sensory session 1	10:00-10:15am	221 Ellis Building	• 4 samples for evaluation
Day 2	Formal sensory session 2	10:30-10:45am	221 Ellis Building	• 4 samples for evaluation
Day 2	Formal sensory session 3	2:30-2:45pm	221 Ellis Building	• 4 samples for evaluation
Day 2	Formal sensory session 4	3:00-3:15pm	221 Ellis Building	• 4 samples for evaluation,

Potential risks and benefits

I also understand there is a potential risk for people who are allergic or sensitive to wheat products as all the noodles will be made from wheat flour. As far as I know, I don't have any wheat product allergies or sensitivities. If I am feeling not well physically during or after the sensory test, I will report to the researcher. The researcher will take me for medical treatment if necessary, either the campus clinic or Victoria Hospital based on the situation.

By participating in this study, I understand that I will learn a new sensory testing technique which is used extensively in the food industry. By participating the training session, I will learn the sensory procedures and lexicon associated with noodles. The knowledge I gain from this study can be easily transferred to another food product.

Information debriefing and dissemination

As soon as the data analysis is finished (approximately in June 2017), I understand that I will receive a summary of results via email if I am willing to, and a hard copy of the summary report is also available upon request.

The sensory result from this trained panel will be included in the researcher's thesis and oral presentations and the results will be expressed as the mean and standard deviation of all the samples and no individual data will be shown.

Compensation

All the participants will receive a $15 Bookstore gift card from University of Manitoba after the training session. I understand if I am selected and participate in the formal sensory test, I will receive an additional $20 Bookstore gift card.

Anonymity and confidentiality

I understand that the data collected in this study include my initials and will be kept confidential and stored in a locked drawer in the researcher's office. Only the primary researcher and her advisor have access to the data collected. I understand that each participant will be assigned a code for data analysis so that my data will not be directly associated with my initials. And the code is securely stored in the researcher's laptop encrypted. All the data sheets collected will be kept until the research is published or five years after the test (May 2022), whichever comes first, and will be securely destroyed at that point.

Right to withdraw

I also understand that I can refuse to participate in any sessions, and I can choose not to taste any samples, without reasons or consequence. If I want to withdraw from this study after the sensory test is finished, I can contact the researcher via email as shown above so that all the data I generated will be deleted electronically or destroyed if it is on paper. I understand that my rights to withdraw apply until May 2022, when the research is published. After this date, I will not be able to withdraw from this study.

Questions or concerns

I understand that I may take any other complaints or concerns I may have to [redacted] or [redacted] via the email as shown above or the Human Ethics Coordinator at [redacted] or via email ([redacted]).

Your signature on this form indicates that you have understood to your satisfaction the information regarding participation in the research project and agree to participate as a subject. In no way does this waive your legal rights nor release the researchers, sponsors, or

involved institutions from their legal and professional responsibilities. You are free to withdraw from the study at any time, and /or refrain from answering any questions you prefer to omit, without prejudice or consequence. Your continued participation should be as informed as your initial consent, so you should feel free to ask for clarification or new information throughout your participation.

The University of Manitoba may look at your research records to see that the research is being done in a safe and proper way.

This research has been approved by the Joint-Faculty Research Ethics Board at the University of Manitoba. A copy of this consent form has been given to you to keep for your records and reference.

Participant's Signature: _________________ Date: _________________

Would you like to receive a summary of results (1-3 pages) in June 2017? Y / N

Would you like to receive it via email? If Yes, please provide your email blow.

Participant's email: ________________________

Appendix 3: Sensory Ballot Form

Sensory Evaluation---- White Salted Noodles

Initials_______ Date________

Please write down your initials and the date. Read the instruction carefully before you start.

Instructions:

Start with your reference sample first and followed by the other samples. Rate one sample at a time by following the order written on the ballot form. Rinse with water between samples and feel free to use the spill cup if needed.

Place one noodle strand between your front teeth with your fork and after your first bite, rate the surface firmness. And then place the sample into your mouth and chew with your molars and rate overall hardness and elasticity. The rating in bold on each scale represents the reference point. Please restrict the use of reference sample repeatedly to avoid palate fatigue.

Surface firmness: Rate the amount of force required to bite through the noodle strands by use of front teeth.

1	2	3	4	5	**6**	7	8
Extremely soft	Very soft	Moderately soft	Slightly soft	Slightly firm	**Moderately firm**	Very firm	Extremely firm

Overall hardness: Rate the force required to bite completely through samples placed between molars.

1	2	3	4	5	**6**	7	8
Extremely soft	Very soft	Moderately soft	Slightly soft	Slightly hard	**Moderately hard**	Very hard	Extremely hard

Elasticity: Rate the degree to which the noodle strands recover their original shape after deformation by the molars.

1	2	3	4	**5**	6	7	8	9
Not elastic		Slightly elastic		**Moderately elastic**		Very elastic		Extremely elastic

Sample #	1	2	3	4
Surface firmness				
Overall hardness				
Elasticity				

Comments: ____