

**The Use of Low Intensity Ultrasound to Investigate the Effect of Mixing
Time and Ingredients on the Mechanical Properties of Bread Dough.**

Keyur Mehta

A Thesis
Submitted to the Faculty of Graduate Studies in Partial Fulfillment of the
Requirements for the Degree of

MASTER OF SCIENCE

Department of Food Science
University of Manitoba
Winnipeg, Manitoba

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by

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A Thesis/Practicum submitted to the Faculty of Graduate Studies of The University of

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GENERAL ABSTRACT

Mixing is the vital stage of breadmaking as it transforms a mixture of flour, water, salt and other ingredients (bread improvers) into a viscoelastic dough for breadmaking. The nucleation of gas cells in the dough also occurs during dough mixing. The matrix and the gas cells in dough affect the mechanical properties of dough which in turn affects the final product quality. There are many conventional methods available to investigate the properties of the dough as a whole, but studies to demonstrate the contribution of the gas cells to the mechanical properties of dough are few. The use of ultrasonic techniques in assessing the quality of food products has great potential in this regard.

The aim of the thesis research was to use low intensity ultrasound (at 50 kHz) as a tool to investigate the effects of mixing time and bread improvers (shortening and surfactant) on the mechanical properties of dough. This approach is based on measuring the velocity and the attenuation coefficient of the longitudinal waves as they propagate through the dough sample, giving information on the mechanical properties of dough. To accomplish our aim, we have performed three separate sets of experiments. In first set of experiments, the doughs were prepared using CWRS wheat flour (good breadmaking flour) and shortening as a bread improver. The mixing time, head space pressure of the mixing bowl during

dough mixing and level of shortening in the dough were the variables used to control the amount of air occluded in the dough. In the second set of experiments, SWS wheat flour (poor breadmaking flour) and surfactant as the bread improver were used to prepare the doughs. The mixing time, head space pressure of the mixing bowl during dough mixing and level of surfactant in the dough were the variables used to control the amount of air occluded in the dough. To relate the first and the second set of experiments, the third set of experiments comprised of using CWRS flour along with different levels of surfactant to prepare the doughs.

By relating the ultrasonic velocity and attenuation coefficient results to the void fraction (calculated from the dough density and the matrix density), the effects of voids on the elastic properties of the dough were revealed. For the first set of experiments (for doughs prepared from CWRS flour and shortening as a bread improver), based on the capabilities of the mixer and vacuum pump to create vacuum in the headspace of the mixer during dough mixing, a void fraction (ϕ) approximately ranging from $0.003 < \phi < 0.14$ was achieved. For lower void fractions ($0.003 < \phi < 0.005$), with an increase in ϕ the attenuation coefficient increased from 600 to 1100 m^{-1} for the control doughs. But in contrast to this the ultrasonic velocity dramatically decreased from 3000 to 167 ms^{-1} . At higher ϕ values the increase in attenuation coefficient and decrease in ultrasonic velocity (from 165 to 105 ms^{-1}) was less rapid. The effects of void fraction on the

ultrasonic parameters (ultrasonic velocity and attenuation coefficient) were similar when additional bread improver (shortening) was added to the control doughs (0 % shortening) except a decrease in ultrasonic velocity and an increase in attenuation coefficient was observed.

For the second set of experiments (doughs prepared from SWS flour and surfactant) the effect of gas cells on ultrasonic parameters (ultrasonic velocity and attenuation coefficient) were similar to those observed in the first set of experiments. But addition of surfactant to the dough formula (0.5, 1, 2 % w/w) increased the velocity (160 ms^{-1} for control dough and 200 ms^{-1} for doughs having 2% surfactant for 1 min mixed doughs), while the attenuation coefficient decreased (2100 m^{-1} for control dough and 1500 m^{-1} for doughs having 2% surfactant for 1 min mixed doughs) for doughs when compared to the control doughs (doughs prepared from SWS flour with 0% surfactant). For doughs prepared with CWRS flour and surfactant (third set of experiments), the results were similar to those of the second set of experiments. An increase in velocity and decrease in attenuation coefficient when compared with control doughs (doughs having 0% surfactant) was observed with addition of surfactant to the dough formula.

The results presented in this thesis demonstrate the potential for using ultrasound as a non-destructive and accurate tool in the baking industry for studying the effects of voids and changes in the dough matrix due to ingredients on the mechanical properties of dough. Further research on

the effects of other breadmaking ingredients on the ultrasonic parameters is recommended due to the potential of the use of ultrasound as an on-line quality control tool in the baking industry.

1. GENERAL INTRODUCTION

Wheat is one of the most important cereal grains worldwide in terms of production and utilization. Wheat flour has the unique ability to form viscoelastic dough when mixed with water (Hoseney, 1985, pp 205). This unique ability has been exploited in production of an enormous variety of bread and other baked products.

Dough mixing is the initial stage in the breadmaking process and is widely considered to be the most critical step in the transformation of a mixture of flour, water and other added ingredients into bread (Hoseney, 1985, pp 206). During dough mixing, mechanical energy is imparted to the dough which helps to transform a hydrated mass of dough into the fully developed viscoelastic structure of dough. It is the unique ability of wheat proteins, especially the gluten proteins, which get hydrated to form a film like structure during mixing, that gives the dough a viscoelastic nature for producing aerated bread. Each variety of wheat flour has to be mixed to an optimum mixing time depending on the water absorption (derived from farinograph) and the additional ingredients added. Doughs that are optimally developed possess optimum dough handling characteristics for further processing so that an optimum quality product can be obtained (Hoseney, 1985, pp 213).

Gas cell nucleation during dough mixing is also one of the most vital aspects considered in breadmaking, since bubble characteristics

establish a relationship between processing conditions and product properties. The gas cell structure created in the bread dough during mixing has a direct effect on the gas cell structure in the baked loaf (Baker and Mize, 1941; Cauvain *et al.*, 1999; Cauvain, 2000). The gas cells are present in a considerable number in the dough and the final product. If there are not enough gas cells then the grain will be very coarse with only a few large cells. Usually gas cells represent approximately 70% or more of the loaf volume in the bread. Campbell *et al.* (1998) pointed out that breadmaking could be viewed as a series of aeration processes, as during dough mixing the gas cells are nucleated in the dough and during fermentation (proofing) these gas cells are filled with the carbon dioxide produced.

Although the gas cells are important for the final baked product quality, having an appropriate size and number of gas cells is also essential for the product to have optimal characteristics. If an excessive amount of gas cells is incorporated in the dough a poor quality baked product results (Williams, 1975). Applying a partial vacuum to the mixing bowl during dough mixing is beneficial, because it reduces the amount of air entrained (number of bubbles per unit volume of the dough). The small bubbles expand under reduced pressure and thus get sub-divided into more bubbles. The bubbles remain discrete and do not coalesce for a longer period of time of proofing and baking and thus produce a finer texture in the baked loaf.

Applying rheological concepts to understand the behaviour of dough will directly help to identify the relationship among the flour composition, additional ingredients added, process parameters and characteristics of the final baked product.

Additional types of ingredients added to the bread dough formulation improve the dough handling characteristics, eating quality and shelf-life (Stauffer, 1983). Shortening is one of the essential ingredients added in preparation of baked products. Shortening improves crumb texture and extends the shelf-life of the bread. The changes in dough properties found after addition of shortening have been mainly attributed to adsorption of fat crystals on the surface of bubbles by a process which involves the fusion of the crystal-water interface with the air-water interface (Brooker, 1996). Due to this adsorption, the shortening provides a continuous supply of melted fat to seal off the leaks in the expanding dough film and thus improves the gas retention as the temperature of the dough increases. Addition of shortening to the bread dough formulation improves the loaf volume, and provides uniformity of crumb structure with thin cell walls (Brooker, 1996). Previous findings by researchers have shown that addition of shortening affects the viscoelastic properties of dough. For example, O'Brien *et al.* (2000) showed that shortening reduces the elasticity of dough.

Increasing consumer awareness of the adverse health effects of consuming high calorie food products has motivated food processors to modify the formulation of food products. Replacing a part or the whole amount of shortening or fats with a surfactant is one such achievement, especially in the baking industry (Kamel and Hoover, 1992). The use of surfactants not only reduces the calories of the food but also improves the shelf life of the product and the dough handling characteristics. The formation of a molecular complex through interaction of surfactant with wheat flour proteins is one of the major reasons that the rheological properties of the dough are affected (Tu and Tsen, 1978; Stauffer, 1990; Azizi and Rao, 2004).

In every phase of breadmaking, the dough undergoes many types of deformations due to application of force or load (Bushuk, 1985). During dough mixing, the dough undergoes extreme deformations beyond the rupture limits. During fermentation the deformation is smaller. During sheeting, punching and shaping, the deformations are intermediate, and during baking the dough undergoes more deformations. Dough is considered to be a composite material having both viscous and elastic properties (Bloksma, 1990). The intermolecular reactions between gluten proteins and non-protein constituents contribute significantly to the rheological properties of dough (Bushuk, 1985). Empirical testing methods of dough mixing, for example by the farinograph or mixograph, have been performed since the early days of

cereal science. More recently, fundamental testing methods using dynamic oscillatory rheometry have been applied to the dough, although the relevance of these small deformation tests to bread doughs is periodically questioned (Muller, 1975; Dobraszczyk and Morgenstern, 2003). As in a dynamic food processing environment, a food processor needs a rapid technique that can precisely evaluate the problem so that corrective action can be taken. In the baking industry, characterizing the structure and the rheology of dough are the most important elements that affect processing operations. Ultrasound has the capability as a technique to interpret these elements based on the ultrasonic parameters measured (velocity of sound passing through the sample and decrease in amplitude of the signal when passed through the dough sample (attenuation)). As gas cells in dough are an important constituent in baked products, affecting the rheology and consumer acceptance, characterizing the gas cells is also an important issue. Ultrasound can be used as a reliable analytical tool for identifying the presence of air bubbles (gas cells) in the food system (Elmehdi *et al.*, 2004; Létang *et al.*, 2001). When the ultrasonic waves encounter the gas cells their energy is attenuated and/or scattered. Because it is non-destructive in nature, ultrasound is used in wide application in studies of food materials. Low intensity ultrasound can be used for determining food composition, structure, flow rate, physical state and molecular properties of opaque materials.

In summary, the purpose of this thesis research was to examine the effect of processing and ingredients on the mechanical properties of bread dough using low intensity ultrasound (at a low frequency, 50 kHz). The goal of the thesis is also to promote ultrasound as an in-line tool for quality control during breadmaking. The specific goals are as follows:

- To understand the overall picture of the dough mixing process (i.e., from the undermixed doughs to optimally mixed doughs to overmixed doughs)
- To study the effect of change in headspace pressure of the mixing bowl during dough mixing process on the mechanical properties of dough.
- To understand the effects of additional ingredients added to the bread formulations (shortening, surfactant) on the mechanical properties of dough.
- To study the effects of different varieties of flour on the ultrasonic parameters.

2. LITERATURE REVIEW

2.1. Wheat production

Wheat is one of the most important cereal grains worldwide, in terms of production and utilization. Due to the underlying genetic diversity of wheat, it is adaptable to a wide variety of soil and climatic conditions. The number and diversity of products that can be made from wheat are remarkable. These include breads, cakes, cookies, pasta, biscuits, crackers, pretzels, doughnuts, muffins, gruels and breakfast cereals primarily (Hoseney and Rogers, 1990). In addition, each of the above products could be sub-divided into different forms (e.g., many types of breads and pastas).

Wheat commerce has important economic consequences for countries with a significant net surplus production. The difference in wheat production and consumption in a given country has a significant effect on the pattern of world trade. In year 2005, the European Union alone produced 22% of total wheat produced in world (135 million metric tons), Canada produced 26 million metric tons of wheat, which is 5% of the total world wheat production. Wheat flour consumption in Canada was about 67 kg/year per person (Ministry of Industry, 2005). Countries like Canada, Australia, and the U.S.A are the major wheat exporters.

2.2. Wheat kernel- structure and composition

The wheat kernel is essentially composed of three histological sections: the germ, the endosperm, and the bran, each having a characteristic chemical composition. The germ (2.4 -3.6% w/w of the kernel) comprises the embryonic axis and the scutellum. The endosperm (81-83% w/w of the kernel) includes the starchy endosperm and the aleurone layer, and the bran (14.7-15% w/w of the kernel) is composed of multi-layered bran tissues such as epidermis, hypodermis, cross cells, tube cells and seed coat (Morris *et al.*, 1945; Kent and Evers, 1969; Pomeranz, 1988; Hosney, 1994).

Wheat flour has the unique ability to form viscoelastic dough when mixed with water and this ability is exploited to produce an enormous variety of baked products, one of which is bread. Although the wheat kernel owes its functionality to its main components, wheat proteins appears to be the most important component contributing towards a good quality end-product. In spite of the research that has been conducted characterizing these proteins for the last 90 years, a full understanding has not been achieved. This lack of knowledge has been generally attributed to the complexity of the composition and physical properties of wheat proteins (Lasztity, 1984; Eliasson and Larsson, 1993).

From the perspective of seed functionality in the wheat endosperm tissue, proteins can be classified into two general groups: storage proteins and non-storage proteins, representing 80 and 20% of the total protein content

respectively (Simmonds and Orth, 1973; Kasarda *et al.*, 1976; Shewry and Mifflin, 1985; Pomeranz, 1987). The storage proteins function as a nitrogen store for developing the embryo upon germination. They can be classified into two groups of protein: gliadins and glutenins (Bushuk, 1993). Storage proteins of wheat, when mixed with water, form a cohesive mass called gluten. Gluten is fundamental to the baking quality of wheat flour because of its viscoelastic properties (Bailey, 1941).

Gliadins form a heterogeneous group of polypeptides (about 40% of flour protein) with molecular weights varying from approximately 30 kDa to 75 kDa (Shewry and Tatham, 1997). Gliadins are small structures and are considered to be the proteins that confer viscous flow and contribute to the extensibility and stickiness of doughs (MacRitchie, 1984; Bushuk and MacRitchie, 1989). Glutenin constitutes the most important protein fraction for creating a continuous protein network in dough (Khan and Bushuk, 1979; Graveland *et al.*, 1982). This network may result from the H-bonding potential arising from the large number of glutamine side chains and/or the potential hydrophobic interactions between the many non-polar amino acids present in glutenin (Bushuk, 1985).

The non-storage proteins are mainly comprised of metabolically active enzymes which have as their substrates various endosperm storage components (e.g., starch and storage protein) or structural components (e.g., cell walls). Non-storage proteins are mainly monomeric, i.e., single chain polypeptides, of relatively low molecular weight (< 30 kDa) (Porceddu *et al.*,

1983; Shewry and Mifflin, 1985). Albumins and globulins are classified as non-storage proteins based on their solubility properties (Bushuk, 1993). Albumins are water soluble (Ewart, 1969), while globulins are soluble in dilute salt solutions (example, 0.5 M NaCl). Mullen and Smith (1965) and Smith and Mullen (1965) described the effects of mixing of flour proteins using poor and good breadmaking flours. They found that the amount of salt soluble properties (albumins and globulins) extracted from the two flours was similar and had little relationship to mixing characteristics. The salt-insoluble fraction contained 90% of the total protein in the flours and was the fraction that was responsible for major differences in the mixing properties of the flours. Tanaka and Bushuk (1973) also found that salt soluble proteins were not related to the baking quality of flour.

2.3. Wheat Products

Wheat is one of the most important cereal crop in the world and ubiquitous in North American culture. Wheat has been called the 'staff of life' for hundreds of years because of its excellent nutrition, storability and versatility. Different wheat varieties are optimal for the many different types of end-products. All wheat varieties on a world-wide basis can be broadly classified into four categories based on the amount of protein and kernel hardness (Pylar, 1982, pp 341), as shown in Table 2.1

Table 2.1 Broad Categories of Wheat Types

Type	Kernel texture
Common wheat of high protein content	Hard
Common wheat of intermediate protein content	Intermediate
Common wheat of low protein content	Soft
Durum wheat	Very hard

All types of baked goods, noodles and pasta can be manufactured from these types of wheats. Each type of bakery product requires a different type of wheat flour. All kind of breads, and like products, such as rolls, bagels, pizza crust, frozen dough etc, are manufactured from hard texture higher protein content wheat flours (Eliasson and Larsson, 1993). Cookies, crackers, pretzels and cakes are made from soft wheat flour.

2.4. Dough Composition

The basic formula for bread dough is flour, water, yeast and salt. Other ingredients that are typically found in the formula are: yeast food, sugar, fat, milk products, surfactants, mould inhibitors, and flour improvers such as oxidants and various enzymes (Hoseney, 1985; Matz, 1992).

Wheat flour is one of the key ingredient to produce baked goods today (Hoseney, 1985, pp11). Wheat flour proteins have a unique property to yield a continuous extensible matrix upon wetting and mixing. The components of flour are carbohydrates, proteins, lipids, minerals and vitamins. Carbohydrates, which include starches, sugar and both water soluble and insoluble polysaccharides, are the most abundant component. Proteins are the next most important component and can be classified as: albumin, globulins, gliadins and glutenins (Hoseney, 1985, pp 72). Gluten is formed by the gliadins and glutenins (MacRitchie 1987; Dackevitch and Autran, 1989; Khatkar *et al.*, 1995). The glutenins of wheat flour are the most important group of proteins for baking quality. Lipids are present in flour (1.5 % flour basis), but more are generally required (4-5 % flour basis) to improve the loaf volume (by some 15 to 20 %) (Smith and Johansson, 2004). Finally, there are other important components which are present in minute amounts including minerals and vitamins. Added water plays a key role in dough formation, and represents nearly 40% of the total dough mass. Water acts as a plasticizer and a solvent for many biochemical reactions that take place during dough development by

mixing and fermentation. Therefore, even relatively minor amounts of active ingredients dissolved in water may exert an effect on dough characteristics and bread quality. Yeast converts fermentable carbohydrates to carbon dioxide and ethanol (Hoseney, 1985, pp 223). This function brings about an increase in the volume of the dough mass, which will ultimately result in an aerated or leavened loaf of bread. Common table salt (sodium chloride) is typically used at a level of 1.5-2.5% flour basis (Hoseney, 1985, pp 205). It adds flavour to bread and improves the cohesiveness of dough.

Apart from the basic ingredients, bread dough formulations include other ingredients which facilitate easier handling of the dough. Some form of sweetener is used in most North American white bread (4-8% flour basis) (Hoseney, 1985, pp 245). Other than imparting sweetness, sweeteners also improve the toasting quality and enhance crust colour. Initially the yeast metabolizes the sugar provided by the sweeteners added in the bread dough formulation, after which the sugars available from the degradation of starch in flour are metabolized. Shortening, whether liquid or solid shortening (of vegetable or animal origin), provides lubrication and aeration to dough systems. It improves the tenderness, uniformity of crumb and shelf life of bread by reducing the firming rate (Hoseney, 1985, pp 213). To achieve the maximum potential out of a given flour, particularly in terms of loaf volume, small amount of oxidizing agents (e.g., ascorbic acid) are added. Milk solids are added to bread dough formula for increasing the nutritional benefits, improving the crust and crumb colour, and improving bread flavour. They are

also used to increase the water absorption of doughs. Many types of surfactants are also used in breadmaking, including sodium and calcium stearoyl-2-lactylate (SSL and CSL), succinylated monoglycerides and sodium stearyl fumarate. Surfactants improve the loaf volume and crumb grain of bread. The ability to complex with gluten, via hydrophobic interactions, makes surfactants very useful in breadmaking. Tu and Tsen (1978) and Azizi and Rao (2004) showed that surfactants form glutenin-surfactant complexes during dough mixing which enhance dough stability.

2.5. Importance of dough mixing

Mixing is a key step during the production of dough-based products. The mixing step allows for the flour, water, and other ingredients to be assimilated, thereby forming a coherent mass. Mechanical energy is applied to the dough during mixing which allows conformational arrangements of gluten proteins (MacRitchie, 1985). The gluten proteins are transformed into a network of small elastic fibrils, which gradually form a film or sheet-like structure in which starch granules are embedded (Bernardin and Kasarda, 1973). During mixing, gluten layers incorporate air bubbles which affect the quality of the final product.

2.5.1. Hydration and formation of the continuous protein matrix. At a macroscopic level, the processes of dough mixing can include three stages: hydration, dough development and overmixing (Hoseney, 1985; MacRitchie, 1986). In hydration, the flour absorbs water and a cohesive mass begins to be formed. In this stage, there is an excess amount of water in the system and the dough is quite fluid, showing relatively little resistance to extension. Upon more work input, the dough forms a cohesive mass with minimum mobility and maximum consistency. At this point, the dough has well defined viscoelastic properties and has attained its optimal or peak development. Upon further mixing, dough consistency decreases and it becomes wet and sticky. In an

overmixed condition, dough usually produces a deleterious effect on the ultimate quality of bread (Hoseney, 1985; MacRitchie, 1986).

At a molecular level, the time required to mix a dough to optimum development (at a given mixing intensity), is related to the properties of the polymeric protein, and, in particular, the insoluble or the largest molecules present (Ewart, 1968; Graveland *et al.*, 1985). It has been postulated that two opposing processes occur during mixing; the gradual transformation of hydrated proteins into a continuous film, and the breakdown of this film (Paredes-Lopez and Bushuk, 1982). The disaggregation of flour proteins appears to be necessary before film formation can occur (Mecham *et al.*, 1965; Graveland *et al.*, 1994). There are several molecular forces involved in the complex reactions occurring between flour constituents, particularly the gluten proteins during dough mixing. The most important covalent bond involved in dough mixing reactions is the disulphide bond, providing stability to dough structure and participating in interchange reactions with sulphhydryl groups between protein molecules (Bloksma, 1975; Schroeder and Hoseney, 1978). Mecham *et al.* (1962) showed that the sulphhydryl groups are involved in the production of a continuous gluten network. Noncovalent forces are also important in dough mixing. Hydrogen bonds can significantly contribute to elasticity and viscosity and thereby facilitate dough development when stabilized by covalent cross-links (-SS- bonds) (Bushuk and Kawka, 1990). Hydrophobic interactions also contribute considerably to the dough structure. A large fraction of amino acid side groups possess a hydrophobic nature. A

series of hydrophobic interactions between two polypeptides chains can exert a strong effect on the dough properties (Bushuk and Kawka, 1990; Tolstoguzov, 1997).

2.5.2. Incorporation of air. For porous food products like bread, the incorporation of air during mixing is an essential step and it plays an important role in the quality of the final product (Lee *et al.*, 2004). Baker and Mize (1946) established the fact that air bubbles were incorporated into doughs during the mixing stage and that these bubbles form nucleation sites for the carbon dioxide produced by yeast during proofing. The importance and role of gluten proteins on gas retention has been extensively studied (Hoseney, 1984; Gan *et al.*, 1995). During dough mixing, the protein (gliadins and glutenins) structure is altered, thus developing the gluten structure. During further mixing of the dough to optimum mixing time the gluten structure is stretched, forming a continuous network (Peighambardoust *et al.*, 2006). As gluten layers are being sheared and folded by the mixer blades air gets trapped within these layers.

The amount of air and the bubble size distribution incorporated during dough mixing critically affects baked loaf structure, texture and appearance. Campbell *et al.* (1998) explained that during dough mixing four aeration processes take place (entrainment of air, disentrainment, bubble break-up, and bubble compression). The air content of bread dough during mixing depends on a balance between entrainment and disentrainment of air. The incorporation

of air bubbles within the system can be altered by changing the viscosity of dough, the speed of the mixer and the concentration and types of surface-active agents added in the dough formulation (MacRitchie, 1976).

Gas cells present in the bread dough are spherical in shape and have diameters ranging from 10 to 100 μm (Carlson and Bohlin, 1978; Junge et al., 1981; Pomeranz et al., 1984). The number of gas cells per unit volume by the end of mixing is 10^{11} to 10^{14} / m^3 (Bloksma, 1990).

2.6. Dough Rheology

2.6.1. Importance of dough rheology. Rheology is the science devoted to the study of the deformation and flow of matter (Steffe, 1996). Rheological properties of a system are expressed in terms of force, deformation and time (Mohsenin, 1986). Stress is a measure of the internal forces extant in a material when external forces are applied, and it is independent of the size and shape of the specimen (Eqn. (2.1)):

$$\sigma = \frac{F}{A} \dots\dots\dots (2.1)$$

where σ is stress (N/m^2), F is the force applied (N), and A is the area of the face of the specimen to which the force is applied (m^2).

Strain is a measure of the deformation of the material, characterized by the displacement between its particles normalized according to the specimen's original size or shape (Eqn. (2.2)):

$$\varepsilon = \frac{\Delta l}{L} \dots\dots\dots (2.2)$$

where ε is strain, Δl is the change in length of the specimen (m), and L is the original length of the specimen (m). When the stress is applied to an elastic material it deforms, and when the stress is removed the material recovers to its original dimensions (Mohsenin, 1986; Menjivar, 1990). When the stress is applied to a viscous material it deforms, but it never regains its original

dimensions on removal on stress (Mohsenin, 1986). This is due to irreversible deformation of the material, which for a viscous material is time dependent.

Viscosity of a material refers to its resistance of flow as indicated by the ratio of shear stress to shear rate in the fluid. The relevance of rheology lies in its applications for both industry and cereal science. Rheological measurements have traditionally been used to give some indication of the probable baking quality of dough (MacRitchie, 1992; Khatkar *et al.*, 1995). Rheological properties of materials depend on the structural arrangement of constituents and forces between them. The fundamental rheological properties of wheat flour doughs are important in determining both the handling properties of dough during processing and the quality of the finished product. Dough rheology can be assessed by either empirical or fundamental rheological instruments (Rha and Pradipasena, 1986; Menjivar, 1990; Eliasson and Larsson, 1993; Cuq *et al.*, 1998; Dobraszczyk and Morgenstern, 2003).

2.6.2. Empirical rheology. Traditional dough testing instruments include instruments such as the Brabender Farinograph, Mixograph, Penetrometer, the Instron for texture profile analysis, and the Brabender Extensograph (Baltsavias *et al.*, 1997; Khatkar *et al.*, 1996; Kieffer *et al.*, 1998). Although empirical instruments have the advantages of imitating the breadmaking process (being very useful for practical quality control), are relatively inexpensive, fast, and rugged, they have the limitation that they do not define the rheological properties of doughs in fundamental units (Bushuk, 1985;

Menjivar, 1990). As the results from these instruments are given in arbitrary units, researchers started using basic rheometrical instruments with well defined geometrics providing results in absolute physical units rather than in arbitrary units (Bushuk, 1985; Menjivar, 1990). However, empirical rheology is still more widely used compared to the fundamental tests. Commonly, rheological properties are categorized according to the magnitude of the imposed strain as either low or high strain. Moreover, different instruments have been designed in order to analyze the material at low or high frequencies.

The mixograph determines resistance to mixing as a function of time, as well as estimating optimal mixing time (for optimum bread loaf characteristics), and the farinograph also determines resistance to mixing in order to assess optimal water absorption. Mixograph curves represent the torque (%) exerted by the dough on the blades or pins of these laboratory mixers as a function of time (min) of the test. Mixograms show a maximum torque after a specific period of mixing (peak time), which indicates the time when the dough has the strongest properties and this can be used as an indicator of flour quality (i.e., its optimal development has been reached) (MacRitchie, 1997). Several mixograph studies have been conducted over the years with the aim of studying the effects of various factors (mixing time, water absorption, type of cultivars, headspace pressure during mixing, and addition of various bread improvers) (Tschoegl *et al.*, 1970; Bloksma, 1990; Van Vliet *et al.*, 1992; Dobraszczyk and Roberts, 1994; Janssen *et al.*, 1996; Kokelaar *et al.*, 1996; Uthayakumaran *et al.*, 2002).

The extensigraph and the alveograph determine dough's resistance to extension and so measure flour strength; the former instrument subjects the dough to uniaxial extension, while the latter applies a biaxial extension (Weipert, 1992; Hoseney, 1994; MacRitchie, 1999).

2.6.3. Fundamental rheology. Fundamental rheology includes different types of tests, which are mentioned as follows (Cumming and Tung, 1975; Eliasson and Larsson, 1993; Gras *et al.*, 2001):

- Viscosity measurements that relate shear rate and shear stress
- Stress- relaxation measurements consist in the application of a strain while measuring the resultant stress.
- Dynamic measurements, where a small amplitude stress or strain is applied in an oscillatory manner.
- Characterizing the bulk behavior of materials from surface rheology measurements.
- Creep measurements that consist in the sudden application of a stress, which is kept constant while measuring the resultant strain as a function of time.

Many fundamental large strain rheological methods, such as stress relaxation (Bohlin, 1980; Safari-Ardi and Phan-Thein, 1998) and creep have shown potential in predicting the baking quality of different flours, but they are not appropriate for online process control methods.

Two parameters that are obtained from fundamental small strain rheological tests are used to characterize the properties of flour doughs: the shear moduli, G' (elastic or storage modulus) and G'' (viscous or loss modulus) (Dreese *et al.*, 1988; Weipert, 1990). G' is related to the elasticity of the material which gives indication of the solid-like characteristics of the material, while G'' is related to viscosity which gives an indication of liquid like characteristics of the material (Bohlin and Carlson, 1980; Zhao *et al.*, 1999) as given by Eqn (2.3;2.4).

$$G' = \left(\frac{\sigma_0}{\gamma_0} \right) * \cos \delta \quad \dots\dots\dots (2.3)$$

where σ_0 is the stress amplitude (Pa), γ_0 is the strain amplitude, δ is the loss angle.

$$G'' = \left(\frac{\sigma_0}{\gamma_0} \right) * \sin \delta = \omega \eta' \quad \dots\dots\dots (2.4)$$

where ω is the oscillatory frequency (rad/s), and η' is the dynamic viscosity. A function that involves both moduli is called the loss tangent and is defined as the ratio between the two shear moduli.

$$\tan \delta = \left(\frac{G''}{G'} \right) \quad \dots\dots\dots (2.5)$$

The loss tangent, $\tan \delta$ defines the relative contributions of the viscous (G'') and elastic (G') characteristics of the material as shown in Eqn. (2.5).

When the material behaves more like a solid i.e., when the deformation within the linear range is essentially elastic and recoverable, the elastic character (G') exceeds the viscous character (G'') and $\tan \delta < 1$. On the other hand, when the material behaves more liquid like, $\tan \delta$ is greater than 1 (Khatkar, 2004).

The oscillatory shear test at low strain provides researchers with rheological information that can be related to the native structure of the material. The deformation is kept sufficiently small that the instrument stretches but does not disrupt bonds and entanglements within the sample being tested, thus providing information on the native undisturbed structure of the material (Baltsavias et al., 1997; Gras et al., 2001). In the low frequency range ($0.01 < f < 100$ Hz), tests can be performed in stress or strain controlled rheometers, while for measurements in the high frequency range, wave propagation methods such as ultrasound can be used (Létang et al., 1999).

There is considerable literature regarding oscillatory tests on wheat flour doughs. Bohlin and Carlson (1980) and Khatkar (2004) showed the effect of mixing time on the rheological properties of doughs. They showed that the rheological changes during mixing are strongly dependent on wheat cultivar. For weaker doughs the G' and G'' values reduce with the increase of mixing time and for stronger doughs the shear moduli are lower and increase post optimum mixing time. Danno and Hosney (1982) and Dreese *et al.* (1988) showed the effect of various processing and ingredient changes on the rheological properties of dough. Weipert (1990) has identified the problem of linearity when measuring the rheological properties of dough, and for

reproducibility and consistency of results oscillatory tests should be performed in the linear viscoelastic regime. It has been noted that doughs show linear viscoelastic behaviour at strain levels less than 1%. At strains greater than this limit the storage modulus and loss modulus decrease (Létang *et al.*, 1999).

2.7. Process factors that affect dough properties

Process parameters like dough mixing duration and headspace pressure have a significant effect on the final quality of baked products (Sai Manohar and Haridas Rao, 1997; Kilborn and Tipples, 1972; Mani Lindborg *et al.*, 1997; Wooding *et al.*, 1999). The effect of mixing conditions (changing the mixing time or mechanical energy input) induces great changes in mechanical properties of wheat flour doughs. Baker and Mize (1941; 1946) showed that by changing headspace pressure in the mixer during dough mixing the amount of air entrained in the dough will affect the fineness of the baked loaf texture.

2.7.1. Mixing time. Mixing time of dough is an important process parameter as it has an important influence on product quality. It is considered the most critical operation in dough processing, since undermixing or overmixing has profound effects on final product quality (Aamodt *et al.*, 2003; Basaram and Gocmen, 2003). Doughs that are undermixed will have poorly hydrated starch and proteins which cannot interact in the dough during fermentation (Hoseney, 1986, pp 216). On the other hand overmixing leads to the formation of wet sticky dough which poses problems during handling. When it is optimally mixed, the dough is not sticky, is easy to handle and possesses appropriate viscoelastic properties for producing products of good quality after baking.

The change in rheological properties of dough as a function of mixing time can be investigated using a mixograph (Hoseney, 1993). The apparatus

measures the dough resistance (measured in arbitrary units) as a function of mixing time. A typical mixing curve is shown in Figure 2.1 in which the resistance increases with mixing until a peak is reached, and then it starts to decrease. Hydration occurs at the molecular level (Bloksma, 1990), and is a slow process that is accelerated by mixing and is also related to the speed of the mixer. As the level of free water in the system decreases, the dough feels drier, resistance to extension increases. The peak point is the “mixing time” of the flour. It is also called the point of minimum mobility (Bushuk and Tsen, 1968). Continued mixing beyond this time will result in an increase in dough mobility and extensibility, and a breakdown of the viscoelastic properties of the dough that impairs its ability to retain gas (Kilborn and Tipples, 1972). The aeration and rheological properties of dough at the end of mixing have a direct effect on the gas cell structure in the baked loaf (Mazur *et al.*, 1981; Campbell and Mougeot, 1999; Kuchel *et al.*, 2006).

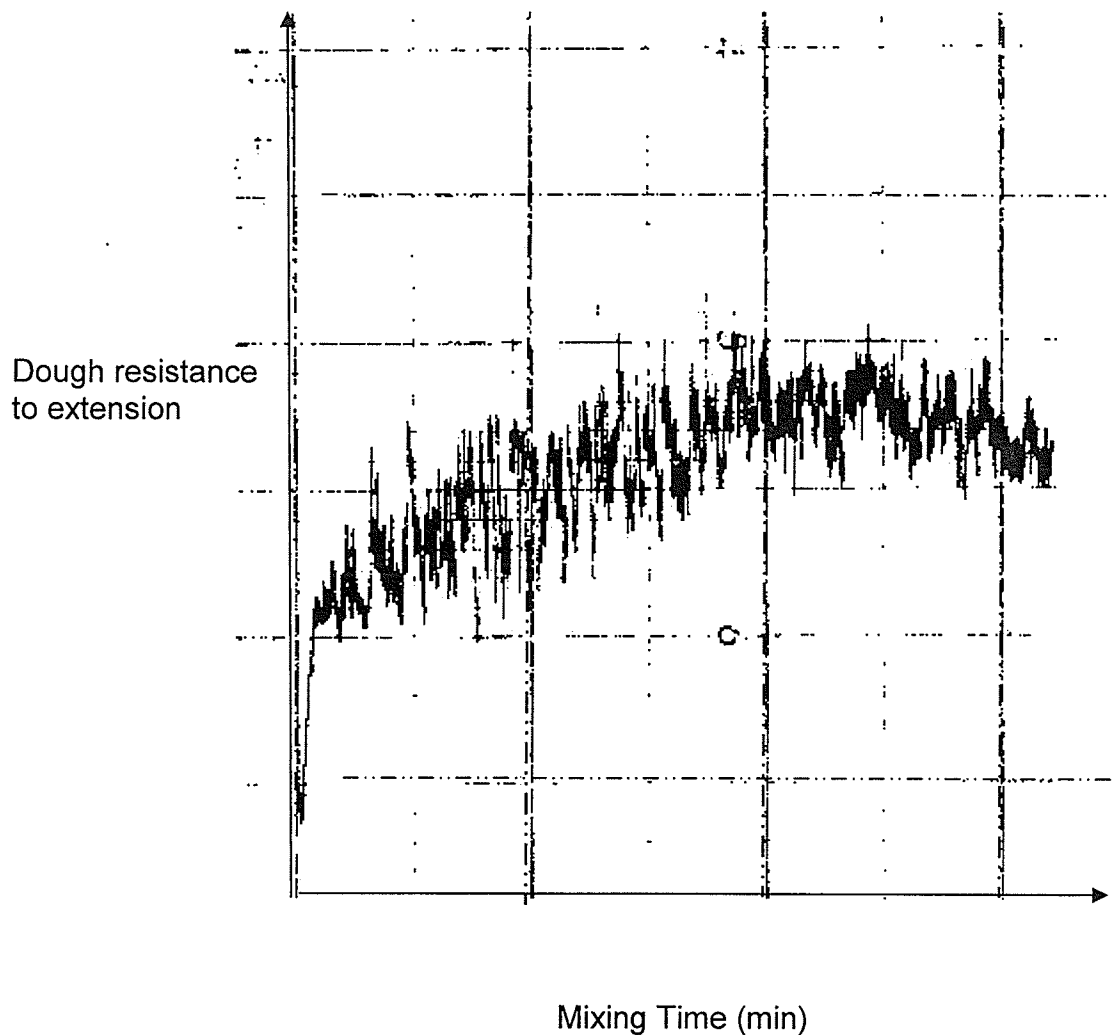


Figure 2.1 Typical mixing curve obtained when dough was prepared in GRL-200 mixer (200 g handling capacity) using CWRS flour (100 g) having 61% water absorption. The graph shows the relationships between the resistance of the mixer pins as a function of mixing time (min). Each square on the horizontal scale represents a minute. Each square on the vertical scale represents dough resistance to extension in arbitrary units (Scanned from one of the mixing curves).

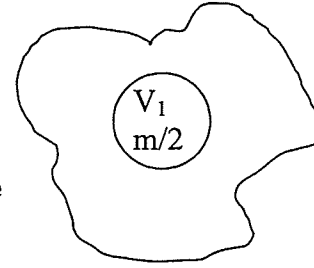
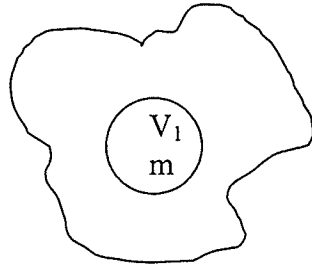
A review of the literature indicates that many studies of the influence of mixing time on rheological properties of dough have been performed (Dreese *et al.*, 1988; Amemiya and Menjivar, 1992; Macche-Rezzoug *et al.*, 1998). Amemiya and Menjivar (1992) explained that with the increase in mixing time G' values decreased for doughs developed from poor breadmaking flours and the doughs behaved similar to doughs having higher moisture contents, whereas Bohlin and Carlson (1980) and Navickis (1989) found increasing G' with increasing mixing time for doughs developed from good breadmaking flours. Based on the literature provided, no general conclusion can be derived because the effect of overmixing depends strongly on the type of flour used. The mixing time of wheat flour is affected by the environmental conditions (soil, temperature, availability of nitrogen etc) that the wheat is grown in and the protein content of flour (Khatkar, 2004).

2.7.2. Headspace pressure. Despite the importance of bubbles in the dough, Williams (1975) found that excessive incorporation of air resulted in poor structure of the baked loaf. Applying a partial vacuum during dough mixing rectified the problem. Baker and Mize (1937; 1941) found that the fineness of the baked loaf can be improved by applying a vacuum to the mixing bowl during dough mixing. During mixing, the gas cells are introduced into the dough by shearing and folding of dough by mixer blades. In addition, the air bubbles are subdivided to produce gas cells of small size (Baker and Mize, 1937; 1941). Baker and Mize (1941) showed that when the dough is mixed

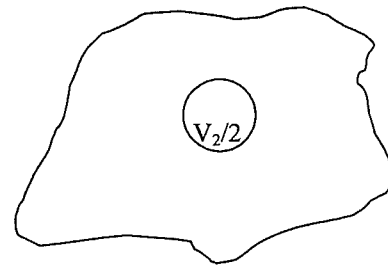
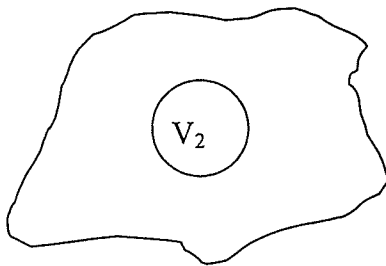
under vacuum, the air cells can be substantially eliminated. Their results showed that for doughs mixed under reduced pressure, the number of air cells per unit volume in a baked loaf is much less than for a loaf when made from a dough mixed at atmospheric pressure. The density of the dough mixed under reduced pressure was found to be higher than that of the dough mixed under ambient pressure. Campbell (1991) and Campbell *et al.* (1998) explained that mixing the dough under reduced pressure reduces the number of air cells. Their observation suggests that mixing under reduced pressure produces fewer bubbles per unit volume in the dough but the size distribution of the bubbles remains the same. The mechanism by which they explained their observation is illustrated in Figure 2.2.

Mixed at Atmospheric Pressure

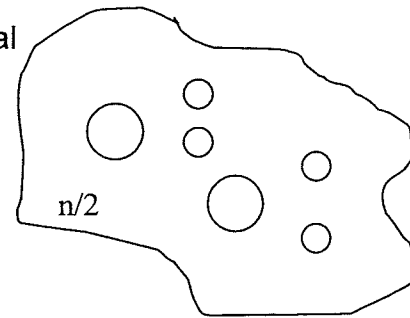
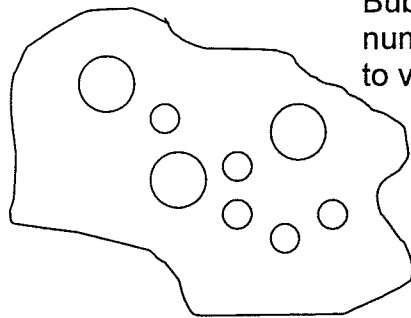
Mixed at 1/2 Atmospheric Pressure



(a)
Bubbles of equal volume V_1 enter the doughs. Mass of the gas is proportional to mixing pressure



(b)
Bubbles are compressed; volume is proportional to mass



(c)
Bubbles break up; number is proportional to volume

(d)
Mixing ends, dough relaxes, bubbles expand slightly

(d)
Mixing ends, pressure is increased to atmospheric; bubbles shrink slightly. Dough relaxes; bubbles expand slightly.

Figure 2. 2 Illustration of the difference between mixing at atmospheric and under reduced pressure (Campbell *et al.*, 1998).

Four major aeration processes have been identified during mixing (Campbell, *et al.*, 1998): entrainment of air, disentrainment of air, bubble compression and bubble break-up. Extra compression is experienced by the air bubbles due to the viscoelastic nature of dough (Folger and Goddard, 1970). In step (a) two primary bubbles of equal volume enter the doughs which are being mixed at atmospheric pressure and at half atmospheric pressure. Based on the ideal gas law ($PV = nRt$), the mass of the gas in the bubble in the dough mixed at half atmospheric pressure is half of that mixed at atmospheric pressure (Campbell *et al.*, 1998). In step (b) the bubbles experience compression due to stress in the dough and the volume of the gas bubble is approximately proportional to the mass of the gas contained. Upon further mixing in step (c) both primary bubbles break up giving the same size distribution of small bubbles. The doughs mixed at atmospheric pressure have twice as many gas bubbles as doughs mixed at half atmospheric pressure. At the end of mixing step (d), the final pressure is atmospheric pressure, so that the bubbles in the dough mixed at half atmospheric pressure case shrink. However this, shrinkage does not occur immediately, due to the viscoelastic properties of the dough. At the same time the bubbles should expand as the compressive strain that developed during mixing relaxes. This expansion should also occur in the dough mixed at atmospheric pressure. This mechanism explains why mixing at reduced pressure produces fewer bubbles, but with a similar distribution of sizes, compared to mixing at atmospheric pressure.

2.8. Ingredient factors that affect dough properties

2.8.1. Flour type. Wheat flours from various classes and cultivars of wheat display great diversity in their functional properties. The variations in functional properties of a wheat cultivar are attributed largely to its gluten quality and quantity (MacRitchie, 1992). Within a cultivar, the breadmaking quality increases linearly with the increase in the protein content, but for a given protein content it largely depends on the gluten protein quality (Khatkar *et al.*, 1995).

Flour type strongly affects the baked loaf quality. Doughs from strong flours incorporate less air during mixing than doughs from weak flours and give larger loaf volumes, finer crumb structure, or both (Baker and Mize, 1946; Chamberlain *et al.*, 1970; He and Hosney, 1990; Campbell *et al.*, 1993; Hayman *et al.*, 1998). Optimum mixing time required by each flour is different and is genetically controlled (Autio *et al.*, 2001). Differences in hydrophobic interactions between proteins differentiate flours having good and poor bread making quality. Chung and Pomeranz (1979) showed that the glutenin from poor quality flour is less hydrophobic than that from good quality flour, whereas gliadins from good quality flour are more hydrophobic than those from a weaker one. Hydrogen bonds contribute to the structure of dough (Bushuk, 1993). Tkachuk and Hlynka (1968) showed that hydrogen bonding significantly contributed to the dough mixing properties as a result of conducting studies where heavy water (D₂O) was incorporated in the doughs. Deuterium bonds

are considerably stronger than hydrogen bonds and adding D₂O resulted in stronger doughs. Despite the low level of ionizable residues in gluten proteins, ionic bonds play an important part in dough structure. This observation can be inferred from the effect that salt and pH have on dough properties (Maher Galal *et al.*, 1978)

Changes in the rheological properties of dough during mixing are different for different varieties of wheat flour. Khatkar (2004) showed that the modulus values for weak breadmaking flours were higher than those for strong breadmaking flours when the doughs were undermixed. With the increase in mixing time the trend in values of the modulus reversed. This behaviour might be because during undermixing the weak flour having lower water absorption results in drier doughs in comparison with stronger flours having high water absorption values. Rao *et al.* (2000) also showed that at all frequencies storage and loss modulus values for strong bread making flours were consistently higher than those of poor bread making flours.

The mixing action develops the viscoelastic properties of gluten and changes the gluten protein composition (Skerritt *et al.*, 1999). Most rheological studies indicate that changes occur within the polymeric protein fraction during mixing and resting of dough, determining the quality characteristics of wheat products (Weegels *et al.*, 1996). A change in rheological properties of dough caused by structural changes in gluten protein during mixing has been studied (Attenburrow *et al.*, 1990; Larsson *et al.*, 2000; Dobraszczyk and Morgenstern,

2003; Grasberger *et al.*, 2003).

2.8.2 Bread improvers. Various types of chemical and biochemical agents are used in bakery products to improve dough handling characteristics, eating quality and shelf life (Stauffer, 1983; Fitchett and Frazier, 1987). They are mainly grouped into five categories: shortenings, surfactants (e.g., SSL), oxidants (e.g., bromates), reductants (e.g., l-cysteine), and mixing time reducers (e.g., proteases). The rheological properties of the dough change differently as the amount and kind of ingredients (dough conditioners) changes (Danno and Hosney, 1982).

2.8.2.1 Shortening. In North America, bread is usually made with 2-4% shortening (Bloksma and Bushuk, 1988). Shortening agents in the form of lards, compound shortenings, hydrogenated oils, butter, and other edible fats and oils, have a marked effect upon bread characteristics (Bohn and Bailey, 1936).

The use of shortening in baked products initiates a number of changes in the internal as well as the external characteristics of the finished product. It is an essential ingredient as bread containing fat in the formula stays soft and more palatable for a longer period of time. Shortening tenderizes or shortens the texture of the breads or cakes (Smith and Johansson, 2004). Bread exhibits an optimal textural quality immediately after removal from the oven. Bread then loses its desirable qualities progressively after baking because of

staling (Hoseney, 1994, pp 178). Bread firms, the crust toughens, flavor decreases, and there is a decrease in soluble starch with increasing time after baking. These deleterious effects are mainly a result of recrystallization of amylopectin. Added shortening decreases the development of firmness during staling (Rogers *et al.*, 1988). The interaction of shortening with native lipids is a critical factor in retarding the firmness in the bread.

Addition of shortening to bread dough formulations leads to improved loaf volume and finer, more uniform crumb structure with thin cells walls (Brooker, 1996). The presence of shortening in bread doughs might cause (i) lowered permeability of crumb cells to steam or carbon dioxide; (ii) delay in the increase in viscosity associated with the starch gelatinization; and (iii) delayed protein denaturation (Baker and Mize, 1941; Baldwin *et al.*, 1963; Tamstorf *et al.*, 1986; Slade and Levine, 1995). Brooker (1996) explained the role of fat crystals in the stabilization of air bubbles in bread doughs. He showed that during mixing, fat crystals become coated with an interfacial layer of adsorbed protein (crystal-water interface). Fats adsorb to the surface of bubbles by a process which involves the fusion of the crystal-water interface with the air-water interface. Baker and Mize (1942) and Baldwin *et al.* (1963) hypothesized that solid fat provides a reservoir of crystals that melt in the dough as the temperature rises, thus providing a continuous supply of melted fat to seal off leaks in the expanding dough film and thus improve gas retention. Studies conducted by Junge and Hoseney (1981) have shown that doughs containing shortening continue to expand during baking for longer time than doughs

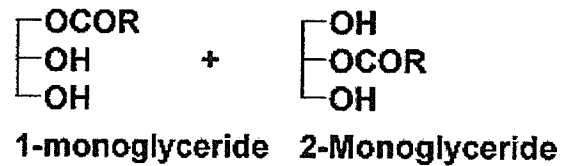
without added shortening. Therefore, the final baked volume of baked goods is bigger. Slade *et al.* (1989) have postulated that the increased bake loaf volume with added shortening is due to lipid plasticization of gluten, which extends gluten's period of thermoplasticity early in the baking process, prior to thermosetting of the water-plasticized gluten network at the end of baking. Shortening with higher solids content engendered by hydrogenation of oils was commercially introduced into the breadmaking process in 1910 (Baldwin *et al.*, 1963). Baker and Mize (1942) demonstrated that shortening with low solids content exerted a deleterious effect on bread quality. They suggested that solid fats, when present in sufficient quantity, improved the gas retention of the doughs by plugging voids in cell walls. Baldwin *et al.* (1963; 1965) observed changes occurring in dough structure while dough was being baked under a microscope. They confirmed that shortening having 10-12% crystalline fat is beneficial as gluten films are better defined and the gas cells rarely combine or coalesce. The size of fat crystals had a dramatic effect on the loaf volume. For doughs mixed at atmospheric pressure small β' crystals (1 to 5 μm) were able to incorporate air so well because these smaller crystals could arrange themselves around the interface of small bubbles more easily than the larger β polymorph (25 to 150 μm) (Berger *et al.*, 1979; Mahdi *et al.*, 1981).

The effect of shortening on the rheological properties of dough during mixing is well explained by many researchers (MacRitchie, 1983; Manley, 1983; Bushuk, 1986). During mixing the incorporation of fat at molecular level will exert a plasticizing effect on the viscoelastic properties of the dough.

Plasticizer also dilutes the polymer concentration per unit volume. Fu *et al.* (1997) showed that with the addition of 5% fat to the dough there was reduction in G' values by an order of magnitude. The results of decreasing G' and an increase in phase angle with addition of shortening to the doughs were confirmed by O'Brien *et al.* (2000).

2.8.2.2 Surfactants. An increase in consumer demand for low caloric light products (based on nutritional and health concerns) has encouraged food manufacturers to produce food items with less or no fat in it (Kamel and Hoover, 1992). Therefore to meet consumer demands, food processors started using surfactants as ingredients in place of fats for manufacturing food products (especially baked goods) (Stauffer, 1999). Surfactants are amphiphilic substances, as their chemical structure possesses both hydrophilic and lipophilic properties. The ratio of hydrophilic domains to lipophilic domains (HLB) of a surfactant molecule mostly determines its behavior in emulsification. The use of surfactants in breadmaking is well established, so that nearly all bread products in North America contain one or more surfactants (Krog, 1981). Surfactants such as diacetyl tartrate esters of monoglyceride (DATEM), distilled monoglycerides (DMG) and sodium stearoyl-2-lactylate (SSL) are most commonly added in formulations to improve the physical and textural properties of bread (Tramstorf *et al.*, 1986). In North America, bread is usually made with 0.375 - 0.5% surfactant (Kamel, 1992).

To understand the effect of adding surfactant in breadmaking formula on the mechanical properties of bread dough, distilled monoglycerides were used for this thesis research. The molecular structure of distilled monoglycerides is as bellow:



Surfactants used in bakery products are generally divided into dough strengtheners and crumb softeners (Knightly, 1981; Progieter, 1992). The crumb-softening effect of surfactants is closely related to their effect as starch-complexing agents (Knightly, 1973). Krog and Jensen (1970) and Lagendijk and Pennings (1970) found that surfactants also reduce the level of firmness and firming rate of bread crumb. Surfactants form a complex with amylose rather than amylopectin. Complexed amylose is less flexible and thus has less ability to interact with other amylose or amylopectin molecules. Thus retrogradation of the starch would be reduced, leading to a reduced rate of firming (Lord, 1950; Leach *et al.*, 1959 and Gray and Schoch, 1962).

As a dough-bread system is heated above a certain temperature and starch granules swell, the viscosity of the dough may increase, restrict its expansion, and eventually the crumb structure sets. Interaction among various components also relates to crumb firming, which occurs over time. Fatty compounds like monoglycerides can reduce the swelling and solubility of starch (Lord, 1950; Leach *et al.*, 1959; Gray and Schoch, 1962). These

compounds also reduce the level of firmness and firming rate of bread crumb (Krog and Jensen, 1970; Lagendijk and Pennings, 1970).

Certain surfactants improve the grain of bread by creating many small cells during the mixing process that give the bread a fine grain (Junge *et al.*, 1981). Knightly (1988) noted that surfactants improve gas retention and proofing rate. Many mechanisms have been proposed explaining the effects of surfactants on loaf fineness and volume. Surfactants alter the distributions of gluten protein fraction (Kovacs *et al.*, 1992). Altering the gluten protein fraction distribution depends on the polarity of the surfactants (Kovacs and Vamos-Kardos, 1993). Inoue *et al.* (1995) found that unsaturated monoglycerides (glyceryl monooleate and monoelaidate) bound more rapidly to the gluten fraction than monostearate did. Surfactants also modify the mixing properties of doughs to obtain higher or later arriving dough development time consistency peaks and increased tolerance to mixing time and rate (Tu and Tsen, 1978; Tsen and Weber, 1981; Knightly, 1981; Stampfli *et al.*, 1996). During dough mixing, surfactants form ordered lipid-water structures together with flour lipids (Silva, 1993). As a result, by lowering the surface tension at interfaces, they reduce the thermodynamic driving force for bubble coalescence (Gan *et al.*, 1995). Junge *et al.* (1981) showed that surfactants lower the surface tension at the interface of air bubbles which aids bubble breakup. This facilitates obtaining a fine crumb structure in baked products. Because surfactants interact with gluten proteins they can change the rheological properties of dough. Aggregation of gluten proteins increases when

surfactants like DATEM are added, which in turn changes the dough's rheological properties (Stauffer, 1990). The lipophilic tail of surfactant binds to the gluten protein hydrophobic patches, incorporating negative charge into the complex, moving the net charge closer to zero and promoting hydrophilic aggregation of gluten protein (Stauffer, 1990). Eliasson and Larsson (1993) found an increase in modulus (G) when lecithins were added to doughs. Shiau (2004) also found that with an increase in concentration of SSL from 0.5 to 1.5 % the G' and G'' values increased. But for surfactants like sucrose fatty acid ester 160, monoglycerides (MG) and lecithin had opposite effects. Comparatively, G' and G'' values decreased with the increase in the concentration. Eliasson (1986) showed that MG and lecithin depressed the G' and G'' values for wheat flour doughs. Berland and Launay (1995) also found that lecithin had a softening effect on dough. The lower value for the ratio of hydrophilic domains to lipophilic domains (HLB) is considered to be responsible for the softening effects.

2.9. Ultrasound: Importance and application to dough rheology

Although conventional rheological techniques can characterize the rheological properties of food products, there is a need to develop new rapid techniques that can perform precise evaluations (Létang *et al.*, 2001). In addition, in order to be successful, food processors must be able to rapidly respond to problems affecting the quality of the product during processing.

Applications of ultrasonics can be divided into two main categories as high and low intensity ultrasonics. Low intensity ultrasonics has gained widespread acceptance as both an analytical tool and a process monitoring technique in the food industry (Self *et al.*, 1992). Monitoring applications can be employed in quality assurance, process control and non-destructive inspection (Lambert, 1982; Lister, 1984; Singh *et al.*, 1990; Fairley, 1992; Povey, 1997). Low amplitude ultrasonic waves can be used for determining food composition, structure, flow rate, physical state, and molecular properties of optically opaque materials (Dogan *et al.*, 2005). Due to its non-destructive nature, ultrasound has found wide application in studies of food, mainly in online process analysis (Blitz, 1963; Samari, 1994; McClements, 1997; Létang *et al.*, 2001; Dogan *et al.*, 2005; D'Amico *et al.*, 2006; Stojanovic and Silva, 2006; Zdunek and Bednarczyk, 2006). The velocity of propagation of the sound (ultrasonic velocity) and how quickly the sound is absorbed (attenuation coefficient) are the two ultrasonic parameters that have been used to characterize structural, compositional and physical properties of food systems

(Samari, 1994; McClements, 1997; Elmehdi *et al.*, 2004). Ultrasonic velocity is the measurement of the distance traveled by the ultrasonic wave per unit time through the sample, and it is related to the wavelength and the frequency of the wave ($v=\lambda f$). There are two kinds of velocity measurements that can be made: longitudinal velocity measurements (v_L), obtained from compression waves, and shear velocity measurements (v_s), obtained from shear waves. The velocity at which the ultrasound waves travel through a material depends on the density (ρ) and the elastic moduli of the material, including the bulk modulus (K) and shear modulus (G) (Povey, 1998).

A longitudinal wave propagates in both a liquid and a solid. In a liquid, this velocity depends on the bulk modulus, whereas in a solid it is associated with both the bulk and the shear modulus (Povey, 1998). Sound can propagate through a solid material faster than through a liquid material because solid materials resist shearing. Although a shear wave can propagate through most solid materials, it is often highly attenuated.

For an elastic solid medium (Eqn 2.6; 2.7)

$$v_L = \left(\frac{K + \frac{4G}{3}}{\rho} \right)^{\frac{1}{2}} \dots\dots\dots (2.6)$$

$$v_s = \left(\frac{G}{\rho} \right)^{\frac{1}{2}} \dots\dots\dots (2.7)$$

While for a fluid medium (Eqn 2.8)

$$v_L = \left(\frac{K}{\rho} \right)^{\frac{1}{2}} \dots\dots\dots(2.8)$$

The attenuation coefficient indicates how rapidly the amplitude of a wave decreases as it travels through a material, as the result of either absorption of the ultrasonic energy, or the scattering of the beam by heterogeneities in the sample. The attenuation coefficient is related to the change in amplitude of the signal by Eqn (2.9):

$$A = A_0 e^{\left(\frac{-\alpha x}{2} \right)} \dots\dots\dots (2.9)$$

where A is the signal amplitude at a thickness x (V), A₀ is the signal amplitude at the surface of the dough sample (V), α is the attenuation coefficient (mm⁻¹), x is the thickness of dough sample (mm) (Samari, 1994; McClements, 1997).

Dough is a viscoelastic material and therefore has both an elastic component (a storage component) and a viscous component (a loss component). Therefore it is important to define and present equations that can be used to obtain both the elastic and viscous component of the material from fundamental ultrasound measurements, as shown in Eqn.(2.10; 2.11) (Elmehdi, 2001).

$$\beta' = \frac{\rho v^2 (1 - (\alpha^2 v^2 / 4\omega^2))}{(1 + (\alpha^2 v^2 / 4\omega^2))} \dots\dots\dots (2.10)$$

$$\beta'' = \frac{\rho v^3 \alpha / \omega}{(1 + (\alpha^2 v^2 / 4\omega^2))} \dots\dots\dots (2.11)$$

where β' is the elastic or storage component of the longitudinal modulus, β'' is the viscous or loss component of the longitudinal modulus obtained from fundamental compression wave ultrasound measurements, and ω is the angular frequency.

The values of moduli obtained from ultrasound and rheological measurements can differ by several orders of magnitude. Kudryashov *et al.* (2001) compared the rheological parameters of milk gels by high frequency ultrasonic techniques and low frequency dynamic rheology and observed a difference in absolute values of storage modulus values by nearly four orders of magnitude. Regardless of the difference in values, there are examples from the literature where ultrasound has been used to measure the textural properties of foods, for example, elastic modulus of cooked carrots (Nielsen and Martens, 1997), elastic modulus of biscuits (Povey and Harden, 1981), and deformability of cheese (Benedito *et al.*, 2000).

Ultrasound has been used as a method for examining dough rheology including characterizing the effects of fermentation and mixing time on the rheological properties of wheat flour doughs (Létang *et al.*, 2001; Elmehdi *et*

al., 2004; Lee *et al.*, 2004; Ross *et al.*, 2004). Both the ultrasonic velocity and attenuation coefficient of the dough have been proven to be adequate for the characterization of dough systems. Elmehdi *et al.* (2003) studied the effect of fermentation on wheat flour doughs. They found that fermentation leads to structural changes in protein and bigger gas cells that are observed through a decrease of ultrasonic velocity and an increase of the attenuation coefficient. Létang *et al.* (2001) and Ross *et al.* (2004) assessed the effects of mixing time on the dough by ultrasound. Their work showed that differences in dough development lead to differences in ultrasonic velocity and attenuation coefficient, and thus ultrasound can be used for the prediction of dough development. The results explained the molecular changes in the dough system as the mixing process proceeded; particularly emphasizing the presence of free and bound water. Kidmose *et al.* (2001) used ultrasound to evaluate rheological properties of dough from different wheat varieties. However, they did not find any distinct correlation between ultrasonic and rheological characteristics. Salazar *et al.* (2002) studied the effect of various flour varieties, water content in the dough and work input on the rheological properties of dough using ultrasound. They showed that ultrasonic parameters are sensitive to flour characteristics. They also found that with the increase in work input, velocity decreased and attenuation increased for various types of bread making flours.

The Use of Low Intensity Ultrasound to Investigate the Effect of Mixing Time and Vegetable Shortening on the Mechanical Properties of Bread Dough.

3. ABSTRACT

Mixing is a critical stage in breadmaking since it controls gluten development and gas cell nucleation in dough. Gas cells are important since they affect both the rheology of the dough and the quality of the final product. One tool capable of probing the effect of mixing on dough properties in a non-destructive manner is low-intensity ultrasound. The objective of this study was to use ultrasound to examine gas cell entrainment as a function of mixing time in doughs prepared with different levels of shortening. Doughs were made from red spring wheat flour with various amounts of shortening (0, 2, 4, 8 % w/w). The doughs were mixed at atmospheric pressure or under vacuum (0.04 atm) for various times. Ultrasonic velocity and attenuation (at 50 kHz) were measured in the doughs, as was dough density (from specific gravity measurements). As mixing time increased at atmospheric pressure, velocity and density decreased while attenuation increased. For example, in control doughs, velocity decreased from 165 to 105 ms⁻¹ and density from 1200 to 1050 kgm⁻³, while attenuation increased from 1800 to 2700 m⁻¹. Superimposed on the overall decrease in velocity was a discernible peak in velocity at optimum mixing time. Similar trends were observed for doughs prepared with shortening, but velocities and densities at a given mixing time were progressively lower as shortening levels increased. In doughs mixed

under vacuum, little variation in velocity and density was observed with mixing time. However, changes in attenuation coefficient (from 600 to 1540 m^{-1}) suggested that ultrasound was sensitive to the changes in the properties of the dough matrix during dough development. This study showed the potential of ultrasound for probing the effect of mixing times and ingredients on dough properties, and thus the possibility of on-line ultrasonic quality control in the baking industry.

3.1. Introduction

Mixing is a most critical stage in breadmaking and it performs three important functions: (i) blending of ingredients into a macroscopically homogenous mass, (ii) developing the polymers in the dough so that it has a viscoelastic nature with good gas retaining properties, and (iii) incorporating air that acts as nuclei for gas bubbles that grow during dough fermentation. The gas bubble structure created in bread dough during mixing has a direct effect on the gas cell structure in the baked loaf (Baker and Mize, 1941). Different types of ingredients are frequently included in bread formulations to improve the nutrition, sensory properties and shelf life of the bread (Hoseney, 1986, pp 234). These ingredients affect the rheology of the dough during mixing and the bread making performance of the dough during processing.

Shortening is an ingredient used in bakery products to improve loaf volume and to obtain a bread crumb with a fine and uniform gas cell structure, composed of thin gas cell walls (Baker and Mize, 1942). Therefore, in almost all baked products, oils and fats are important added ingredients. In an examination of the role of shortening in the stabilization of air nuclei in the dough, Baker and Mize (1941), Baldwin *et al.* (1963) and Brooker (1996) showed that fat crystals are redistributed during mixing, becoming preferentially adsorbed at the dough matrix-air nucleus interface and are able to stabilize a large number of small air bubbles by adsorbing to their surface. It is therefore useful for examination of the effect of shortening on gas cell

structure in the bread, if interactions between shortening and air nuclei in the dough can be determined, preferably quantitatively.

Ultrasound is a materials' characterization technique that is based on the principle of propagating sound at high frequencies (20 kHz to over 100 MHz) into the material and using the sound propagation properties to understand the properties and structure of the material. Some examples of foods that have been analyzed with ultrasound include fruit juices, brine, oils, alcoholic drinks, fats, salad creams, meat, fish, vegetable, dairy products and wheat flour doughs (McClements, 1997; Povey, 1989; Létang *et al.*, 2001; Elmehdi *et al.*, 2004). Longitudinal ultrasonic pulses are very sensitive to the presence of compressible regions in the material, such as air nuclei in dough (Elmehdi *et al.*, 2004). It would therefore appear that ultrasound of wavelengths larger than the mean air nucleus size is able to probe interactions between shortening and air nuclei in dough systems during mixing.

In low-intensity ultrasonic determinations of material properties, (McClements, 1997; Elmehdi *et al.*, 2003; Scanlon, 2004) the velocity of propagation of the sound (velocity) and how quickly the sound is absorbed (attenuation coefficient) are the two parameters that are frequently previously used. For homogenous materials, the ultrasonic velocity is related to the density and elastic modulus, whereas for heterogeneous foods, the ultrasonic properties depend on reflections, scattering, refraction and absorption mechanisms (McClements, 1997).

Wheat flour doughs are materials whose structure and physico-chemical properties change with mixing conditions, water content and rest time (Dempster and Hlynka, 1958; Walker and Hazelton, 1996; Létang *et al.*, 2001). These changes in structure and properties are expected to be manifest as changes in the velocity and attenuation of an ultrasonic pulse traveling through a dough sample, particularly because the amount of air nuclei entrained in the dough is a function of mixing time (Baker and Mize, 1946; Campbell *et al.*, 1993). Shortening added to the dough would be expected to interact with these nuclei and lead to a change in the ultrasonic signal.

The objective of this work is to show how low frequency ultrasound (50 kHz) can be used to examine gas cell entrainment as a function of mixing time in dough prepared with various amounts of shortening.

3.2. Materials and Methods

All flour used for the experiments was milled from Canada Western Red Spring (CWRS) hard wheat grade No.2 with a flour protein content of 12.4% on the CIGI pilot mill (Winnipeg, MB). Sodium chloride was purchased as reagent grade from Fisher Scientific (Nepean, ON). Distilled water was used for making dough samples. Vegetable shortening (partially hydrogenated soyabean and palm oil) was used to assess the effect of ingredients on ultrasonic properties of the dough; it was purchased from J. M. Smucker Inc. (Toronto, ON).

3.2.1. Dough mixing under different conditions

3.2.1.1 Dough developed at atmospheric pressure. Control dough samples were prepared by mechanical development of dough using the Canadian Short Process Method (Preston *et al.*, 1982) using flour (100g), salt (2.4% fwb), and water (61% fwb, to give optimum dough handling characteristics). Doughs were also prepared using the same ingredients as control doughs, but with shortening (2, 4, or 8 % fwb) added. Ingredients were mixed at 165 rpm using a GRL-200 mixer at 30 °C. Various mixing times (2, 3, 4, 4.5, 5, 5.5, 6 and 6.7 min) were employed to obtain an overall picture of the mixing process from the hydration of flour particles through optimum dough development (10% past peak) until over-mixing had occurred. To obtain the optimum dough mixing time (or the 10 % past peak in the mixing curve), five dough samples were

mixed for both control (0% shortening) and for doughs with the three levels of shortening. The optimum mixing time was calculated by averaging the five optimum mixing times obtained from the five mixing curves. For ultrasonic analyses, duplicate mixings of dough were acquired for each treatment mixed to a particular mixing time.

3.2.1.2. Dough developed under vacuum. Headspace pressure during mixing was manipulated by drawing a vacuum using a Duo-Seal vacuum pump (Welch Scientific, Skokie, IL), which was connected to an outlet on the mixing bowl. The ingredients were mixed for 1 min at atmospheric pressure to allow flour particles to hydrate so that they would not be drawn out by the vacuum, after which the vacuum was applied for the remaining mixing time. Headspace pressure inside the mixing bowl was controlled by a pressure valve. The pressure inside the mixing bowl was measured with a digital pressure meter (ACSI Digital Pressure Meter, St. Louis, MO) positioned between the mixer bowl and the vacuum pump. The headspace pressure in the mixing bowl was 0.04 atm approximately throughout mixing (following the initial 1 min at atmospheric pressure). Duplicates were acquired for each dough mixed under vacuum for a particular mixing time.

3.2.2. Density measurements

Dough densities were measured to determine the amount of air incorporated into the dough. The density of the dough was measured using specific gravimetric bottles (25 ml capacity) with 24 mm diameter necks (Kimble Glass Inc., Vineland, NJ). A Mettler AE 160 scale (Fisher Scientific, Pittsburgh, PE) was used for all weight determinations which had the capability of weighing 0.01 g.

After mixing, the dough was placed in a covered container (Tupperware) to avoid moisture losses. Sub-samples (approximately 5 g) were cut from the dough piece for density measurements. After every density measurement the gravimetric bottle was dried and cleaned, filled with distilled water and weighed again. The sub-sample of dough was weighed before being immersed in the gravimetric bottle filled with distilled water (30 °C). The displaced water was dried off the bottle before it was weighed again. The volume of the sub-sample of dough was determined by calculating the volume of the water displaced from the specific gravity bottle when the sub-sample was immersed in the bottle. Five sub-samples were analyzed from each mixed dough.

The density of the dough sub-sample (g cm^{-3}) was determined from the formula (3.1.):

$$\rho_{\text{dough}} = m_{\text{dough}} / V_{\text{dough}} \quad \dots\dots\dots (3.1.)$$

where,

ρ_{dough} is the density of the dough (g cm^{-3})

m_{dough} is the mass of the sub-sample of the dough (g)

V_{dough} is the volume of the dough (cm^3) = $\{(\text{Mass of (gravimetric bottle + water + sub-sample of the dough)} - \text{Mass of (gravimetric bottle + water)}) / \text{Density of water at } 30^{\circ}\text{C} (0.995 \text{ g cm}^{-3})\}$

3.2.3. Equipment used for ultrasonic experiments

A schematic diagram of the ultrasound set-up is given in Figure 3.1. The dough sample was sandwiched in direct contact between the two piezoelectric transducers of 50 kHz frequency (Panametrics, Edmonton, AB). Each transducer was situated in a plexi-glass sheet with one side flush with the face of the transducer. Locking nuts held the transducer in place so that when the distance between plates was set, so too was the distance between transducers. An electromagnetic (EM) pulse was sent to the generating transducer using 50 Ω BNC cables. The transmitting transducer converted the electromagnetic signal to an ultrasonic pulse which passed through the sample. The receiver transducer converts the ultrasonic signal (altered by its passage through the dough sample) back to an electromagnetic signal. The EM signal is amplified in an amplifier which is further displayed on a computer controlled oscilloscope (Tektronix TDS 420 A, Chicago, IL). Data were stored on a computer which was connected to the oscilloscope.

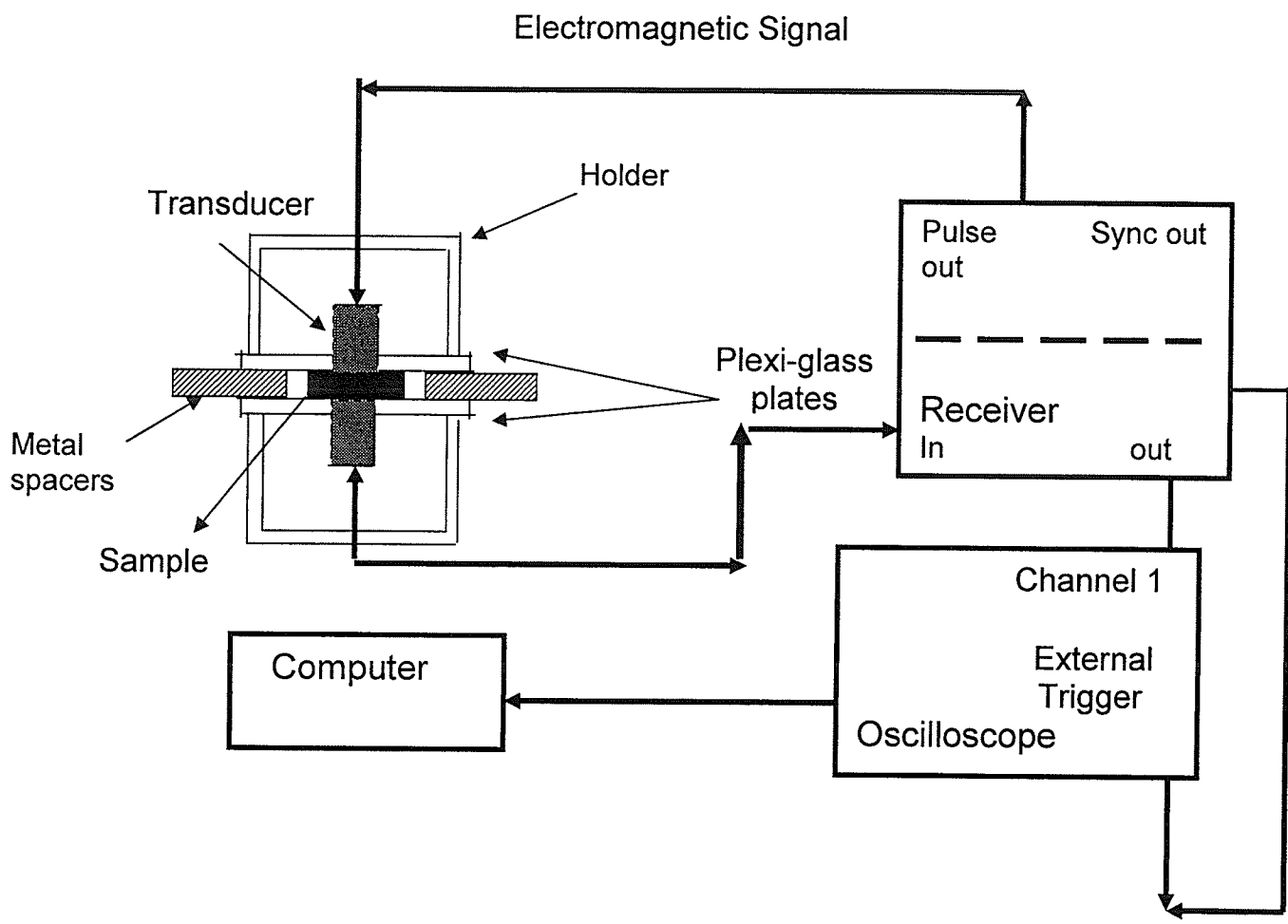


Figure 3.1 Block diagram of experimental set-up of the ultrasound experiment.

3.2.4. Ultrasound parameters

The mechanical properties of the dough were investigated by studying the behaviour of the longitudinal ultrasonic signal following its propagation through the dough sub-sample. The phase velocity of the signal and the attenuation coefficient are parameters which describe the propagation of the ultrasonic signal.

A reference signal was taken every time before testing the dough piece mixed at a particular mixing time. A thin layer of coupling agent (Ultragel II, ultrasonic couplant, Sonotech Inc., Bellingham, WA) was sandwiched between the two transducers. Sub-samples of dough were drawn from the dough piece using scissors. The dough piece was kept in the tupperware after it had been mixed until all sub-samples were removed. Sub-samples of dough were subject to minimal handling while preparing for ultrasonic experiments to avoid changing the mechanical properties of the dough sub-sample. Sub-samples drawn from the dough piece mixed at a particular mixing time were analyzed at five different thicknesses (1, 2, 3, 4, 5 mm), with duplicate sub-samples analyzed for each thickness from the same piece of dough. Metal spacers were used to accurately control the distance between the two transducers, and thus the thickness of the sub-sample of dough. The ultrasonic data consisted of signal amplitude (mV) vs. time (μs). The acquired ultrasound wave data was plotted on a time domain diagram (signal amplitude (mV) vs time (μs)) using Origin (Microcal Origin, version 7.5, Microcal software Inc.

Northampton, MA). From differences between the waveforms of the sample and reference signals, the transit time (μs) and amplitude (mV) of the pulse transmitted through the dough were determined (Figure 3.2). The transit time (Δt) for sound passing through dough of a given thickness was calculated by measuring the time difference between the first oscillation of the reference and that of the dough sample. The amplitude of each waveform representing a particular sub-sample thickness was directly measured from the height of the first oscillation.

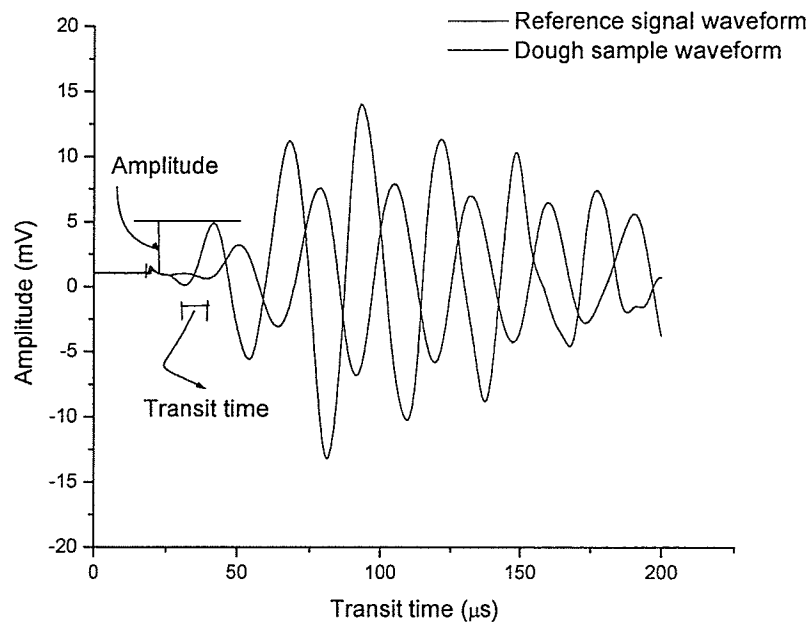


Figure 3.2 Typical ultrasonic waveforms of reference signal and the signal after passing through the control dough sample.

The values of transit time were plotted as a function of sample thickness of the dough samples (Figure 3.3). The velocity through the dough was calculated from the inverse of the slope of this graph.

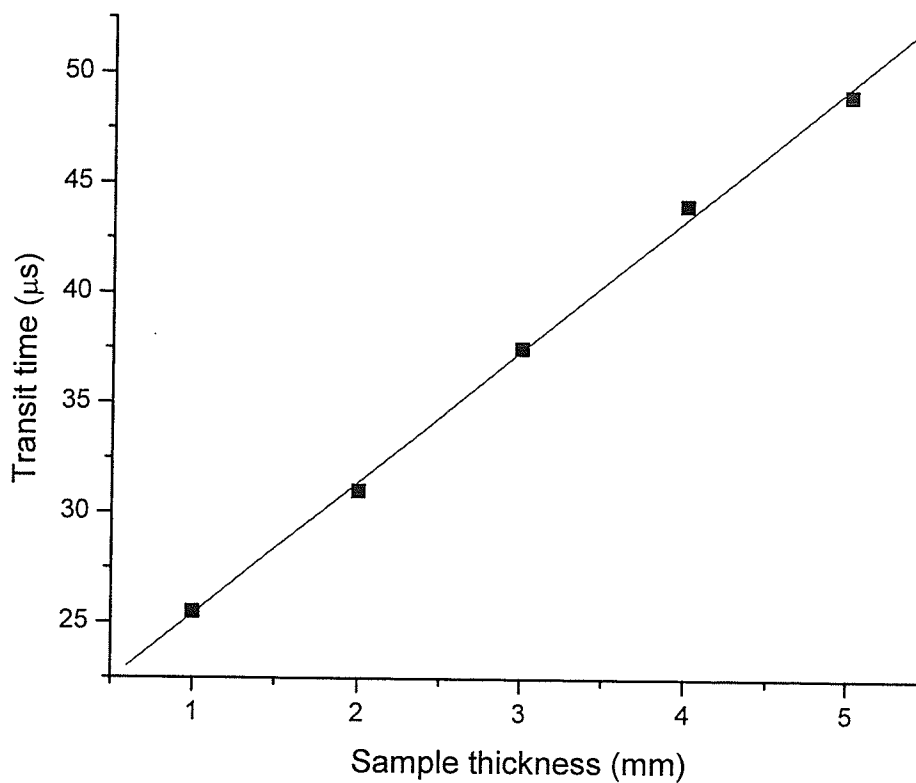


Figure 3.3 Typical graph of transit time as a function of sample thickness for control dough.

The values of amplitude were also a function of sample thickness of the dough samples. A graph of amplitude for various sample thickness was plotted

and a single exponential decay curve was fitted (Figure 3.4). The attenuation coefficient was obtained using the following equation (3.2.):

$$A = A_0 e^{(-\alpha x/2)} + B \dots\dots\dots(3.2.)$$

where,

A is the signal amplitude at a thickness x (mV)

A₀ is the signal at the surface of the dough sample (mV)

α is the attenuation coefficient (mm⁻¹)

x is the thickness of dough sample (mm)

B is the offset (mV)

Offset due to bond losses of acoustic signal at the transducer-sample bond and due to interfacial reflections were eliminated for true sample attenuation to be accurately determined. The offset value is eliminated by deducting the amplitude value at transit time=0 from the peak amplitude value of a waveform. A₀ is determined by extrapolating back the decay curve to sample thickness (x=0) and the attenuation coefficient (α) is determined from the decay curve (Eqn 3.3).

α = 2 / slope of the decay curve

$$\alpha = \frac{-2}{x \ln \frac{A - B}{A_0}} \dots\dots\dots (3.3)$$

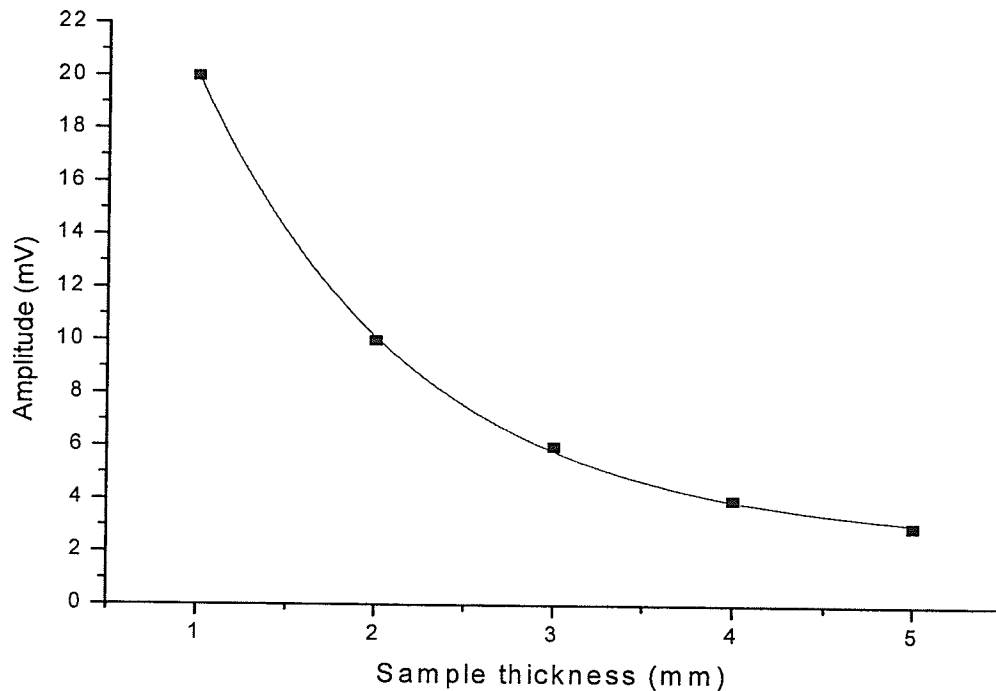


Figure 3.4 Typical graph of the amplitude as a function of sample thickness for control dough.

3.2.5. Experimental design

Because of extensive time delays that would be associated with changing the mixer configuration for vacuum and atmospheric mixing analyses, experiments were divided into two sets. The first set of experiments included the doughs mixed at atmospheric pressure and the other set included doughs mixed under vacuum (0.04 atm). Each set had 48 experiments encompassing the doughs mixed at six mixing times with different levels of shortening (0, 2, 4, or 8% w/w), and with duplicates of each mixing experiment.

A random number list for these 48 dough mixings was generated to determine the order in which the experiments were conducted.

3.2.6. Statistical analysis

Data were analysed using Statistical Analysis System software program, version 8.1 (SAS Institute, Inc., Cary, NC). Data were analyzed using analysis of variance (ANOVA) with a criterion of $P \leq 0.01$ to detect significant differences among treatments. The "P" value defines the degree of probability that the event has occurred by chance. For e.g. when the P value is less than 0.01 that means the event has occurred by a probability of less than 1 % by chance. The treatments to be analysed were:

- Effect of mixing time on density, ultrasonic velocity and attenuation coefficient of the doughs, comparing different dough mixing times.
- Effect of shortening on density, ultrasonic velocity and attenuation coefficient of the doughs, comparing different levels of shortening at the same dough mixing time.
- Effect of different headspace pressure on density, ultrasonic velocity and attenuation coefficient of doughs, comparing between doughs mixed at atmospheric pressure and under vacuum.

3.3. Results

Previous research has shown that the number of gas cells per unit volume and matrix properties of dough change when mixed for different times and under different atmospheres (Baker and Mize, 1941; Campbell *et al.*, 1998). Doughs were mixed at atmospheric pressure and under vacuum (0.04 atm) for different mixing times to evaluate the effect of altering the number of gas cells and the dough matrix on the physical properties of the dough as assessed by ultrasonic measurements.

3.3.1. Effects of shortening on dough development time

Doughs were mixed at various mixing times to obtain an overall picture of events happening in the mixing process from the hydration of flour particles through optimum dough development (10% past peak) until over-mixing had occurred. In general, the presence of shortening “weakened” the dough since shorter mixing times were required to attain optimal consistency of the dough. The addition of shortening (0, 2, 4 or 8%) to doughs significantly reduced ($p < 0.0001$) the optimum mixing times. Optimum mixing time for doughs mixed at atmospheric pressure with and without the addition of shortening is shown in Table 3.1.

Table 3.1 Effects of shortening on optimum mixing time of bread doughs.

Treatment	Optimum mixing time (min)
Control (0%)	5.61± 0.09 ^a
2%	4.91± 0.08 ^b
4%	4.43± 0.05 ^c
8%	4.1± 0.04 ^d

Mixing time values are the mean ± SD, n=5
Numbers with different superscripts are significantly differently

The results of mixing experiments for doughs with shortening are consistent with previous studies by Manohar and Rao (1999) and Singh *et al.* (2002) who noticed a similar effect of shortening on reducing the mixing times of flour doughs. It has been reported that doughs mixed under vacuum do not exhibit a peak in torque attributable to dough development (Baker and Mize, 1937). Therefore, "optimum mixing time" is not a meaningful concept for the doughs mixed under vacuum, and the doughs were mixed for the same mixing times as the doughs mixed at atmospheric pressure.

3.3.2. Effects of shortening on dough density

Incorporation of air within the dough proceeds as mixing progresses (Baker and Mize, 1946). Figure 3.5 shows the dough density as a function of mixing time for doughs prepared at atmospheric pressure with various amounts of shortening. High density values of dough were observed for under-mixed doughs indicating little entrainment of air. When resistance to mixing reaches a maximum, the rate of occlusion increases and air is incorporated into the dough more rapidly. For example, for control dough there is a decrease of 60 units in the dough density when the dough is mixed from 2 to 5.6 min (undermixing), but there is 70 units of decline when mixed beyond optimum mixing time (5.6 min) to overmixing (6.7min). These mixing experiments produced results consistent with the previous findings of Baker and Mize (1941) where a decrease in density with an increase in dough mixing time was measured. Irrespective of the amount of shortening added to the doughs, an increase in mixing time significantly reduced ($p < 0.0001$) the dough densities. The amount of shortening significantly affected ($p < 0.0001$) dough densities (see below).

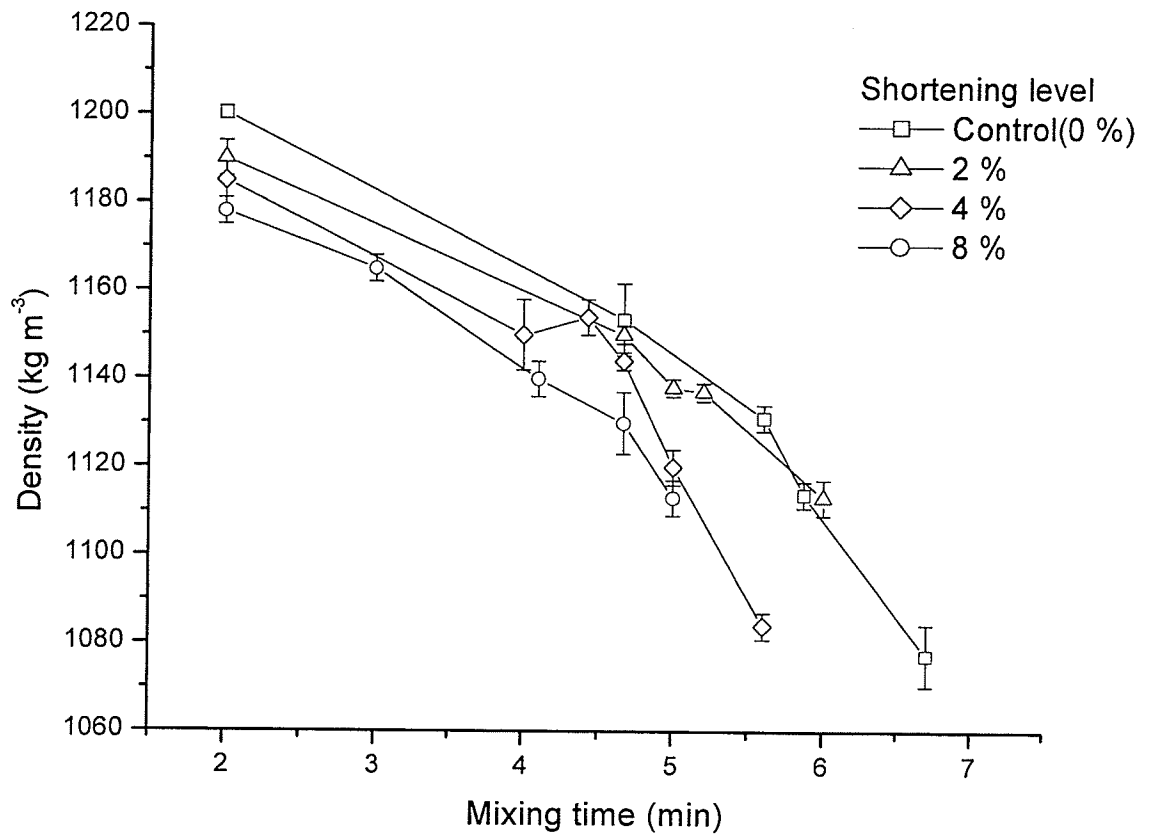


Figure 3.5 Effect of mixing time (in air) on dough density for doughs of various shortening content (% f.w.b)

Figure 3.6 shows the density of dough with various amounts of shortening as a function of mixing time for doughs prepared under vacuum (0.04 atm). Mixing of doughs under vacuum leads to substantially higher dough densities compared to doughs mixed in air irrespective of the amount of shortening in the dough. It is apparent that the gas cell nuclei were essentially eliminated in the doughs mixed under vacuum, resulting in an increase in dough density. Both mixing time and various shortening amounts had a highly

significant ($p < 0.0001$) effect on dough densities. The addition of shortening reduces the dough densities at all mixing times, and this is attributable to the density of shortening being lower ($\rho = 900 \text{ kg m}^{-3}$) than that of the dough (Brooker, 1996).

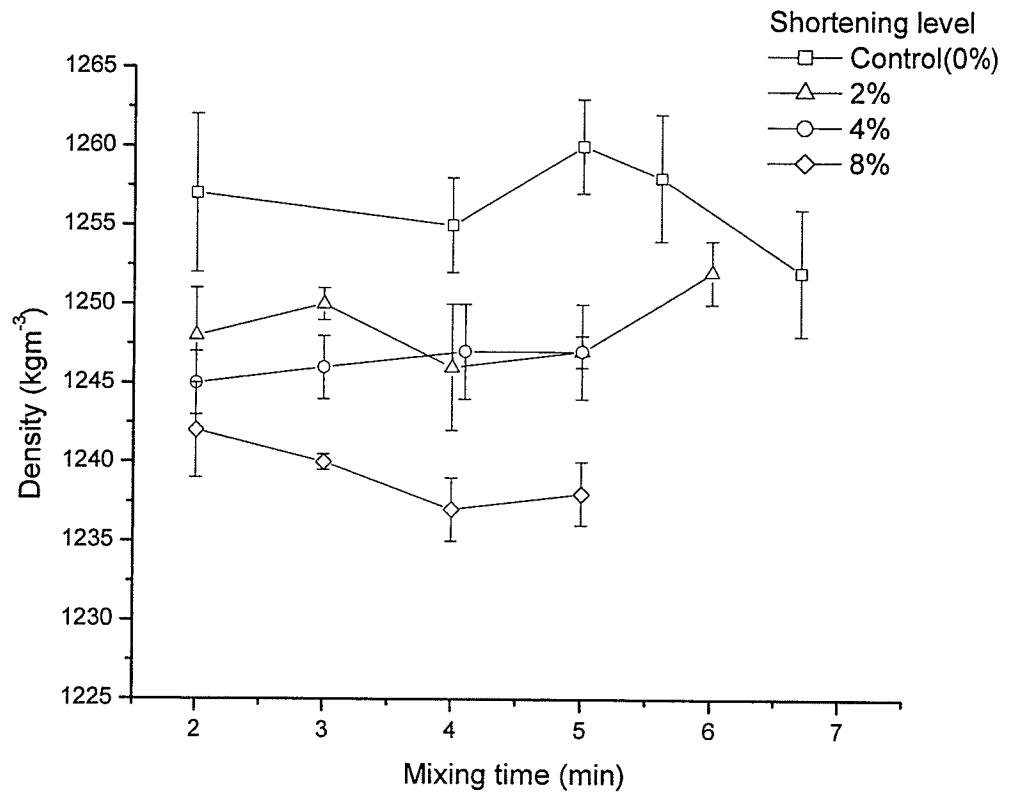


Figure 3.6 Effect of mixing time (under vacuum) on dough density for doughs of various shortening content (% f.w.b)

3.3.3. Effects of shortening on ultrasonic velocity measurements of bread dough

Since the air bubbles are much more compressible than the dough matrix, the velocity of sound in the dough is markedly affected by a small volume fraction of air bubbles (Elmehdi *et al.*, 2004). Ultrasonic velocity as a function of mixing time for doughs prepared at atmospheric pressure with various amounts of shortening is shown in Figure 3.7. For the doughs mixed in air the ultrasonic velocities tend to follow the trend of dough density versus mixing time, and so are higher for under-mixed doughs and decrease with increase in mixing time. A discernible shoulder in velocity at the optimum mixing time was observed for all doughs regardless of the amount of shortening added. This shoulder occurs at earlier times as shortening is increased, consistent with the results of Table 3.1. Ultrasonic velocities of doughs were significantly lowered ($p < 0.0001$) with increase in mixing time. These results are in agreement with those of Kidmose *et al.* (1999) and Ross *et al.* (2004) who found that there was a decrease in ultrasound velocity when the doughs were mixed past optimum mix time. Occurrence of the peak may be due to the alignment of glutenin polymers due to shear and extensional forces imposed during the mixing. This leads to dough with high strength resulting to form a peak at optimum mixing time. Addition of shortening significantly lowered ($p < 0.0001$) the velocities of sound propagating through dough.

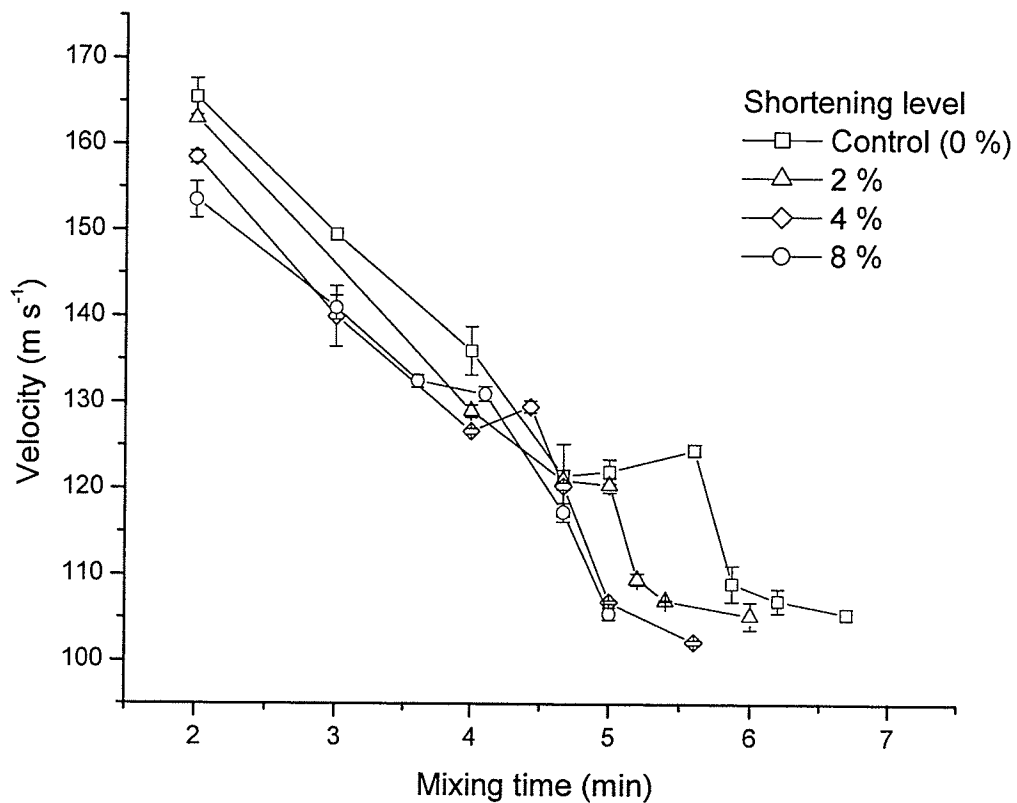


Figure 3.7 Effect of mixing time (in air) on ultrasonic velocity for doughs of various shortening content (% f.w.b).

To observe the effects of dough matrix on the ultrasonic parameters independently of the effect of the bubbles, doughs were mixed under vacuum (0.04 atm). The relationship of ultrasonic velocities and mixing time with varying amount of shortening is shown in Figure. 3.8. It was observed from the density results that the doughs mixed under vacuum have substantially fewer air bubbles in comparison to the doughs mixed in air. It can be therefore concluded that the absence of gas bubbles dramatically increased the

ultrasonic velocity. As with doughs mixed in air, increasing the dough mixing time had a significant effect ($p < 0.0005$) on ultrasonic velocities as did addition of shortening ($p < 0.0001$).

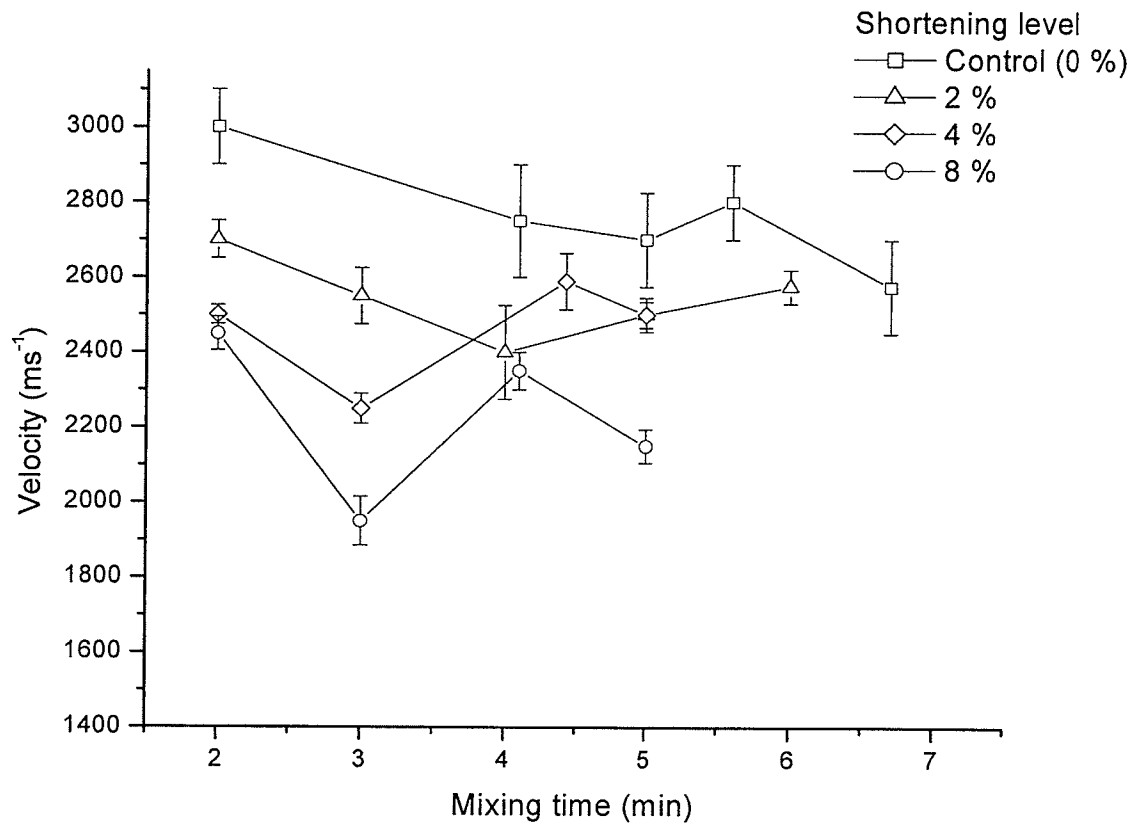


Figure 3.8 Effect of mixing time (in vacuum) on ultrasonic velocity for doughs of various shortening content (% f. w. b).

3.3.4 Effects of shortening on attenuation coefficient measurements of bread dough

Figure 3.9 shows attenuation coefficient as a function of mixing time for doughs prepared at atmospheric pressure with various amounts of shortening. The attenuation coefficient of dough mixed in air generally increased with mixing time as the amount of air trapped in the dough increases. However, the effect of bubbles on the attenuation coefficient was not as pronounced as their effect on velocity. There seemed to be a change in the rise of attenuation in the region of optimum mixing time but its position relative to optimum mixing time was not as strong as the shoulder in velocity versus mixing time. Increase in mixing time had a significant effect on the attenuation coefficients of dough mixed at atmospheric pressure ($p < 0.0001$). The results of attenuation coefficient for the doughs are consistent with previous studies by Ross *et al.* (2004) who noticed a peak in attenuation coefficient at optimum mixing time. Increasing the amounts of shortening significantly increased ($p < 0.0001$) the attenuation coefficient of the doughs.

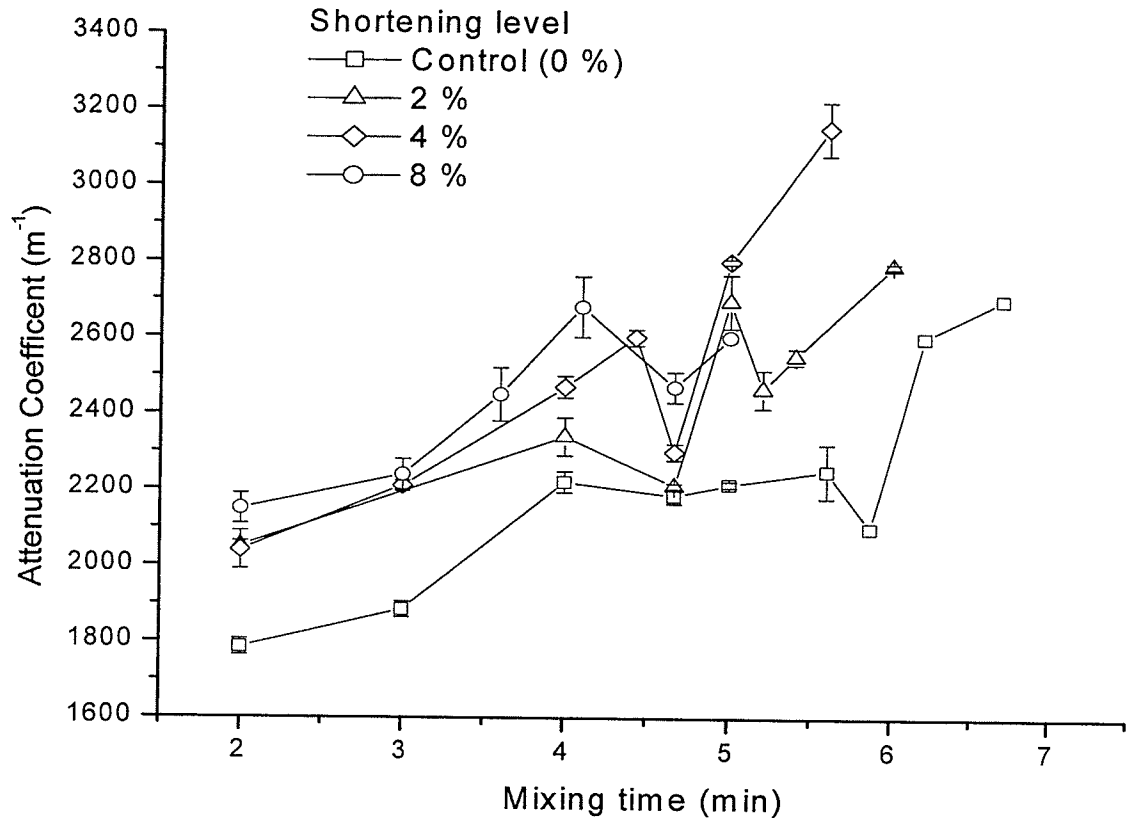


Figure 3.9 Effect of mixing time (in air) on attenuation coefficient for doughs of various shortening content (% f. w. b).

The relationship between attenuation coefficient of dough prepared under vacuum pressure and mixing time for doughs having various amounts of shortening is shown in Figure 3.10. It was observed that mixing time significantly affected ($p < 0.0001$) the attenuation coefficient of doughs. The changes in attenuation coefficient were ascribed to changes in the dough matrix since we know that the doughs mixed under vacuum (0.04 atm) had much less entrainment of air. Increase in shortening amounts also significantly increased the attenuation coefficient of doughs.

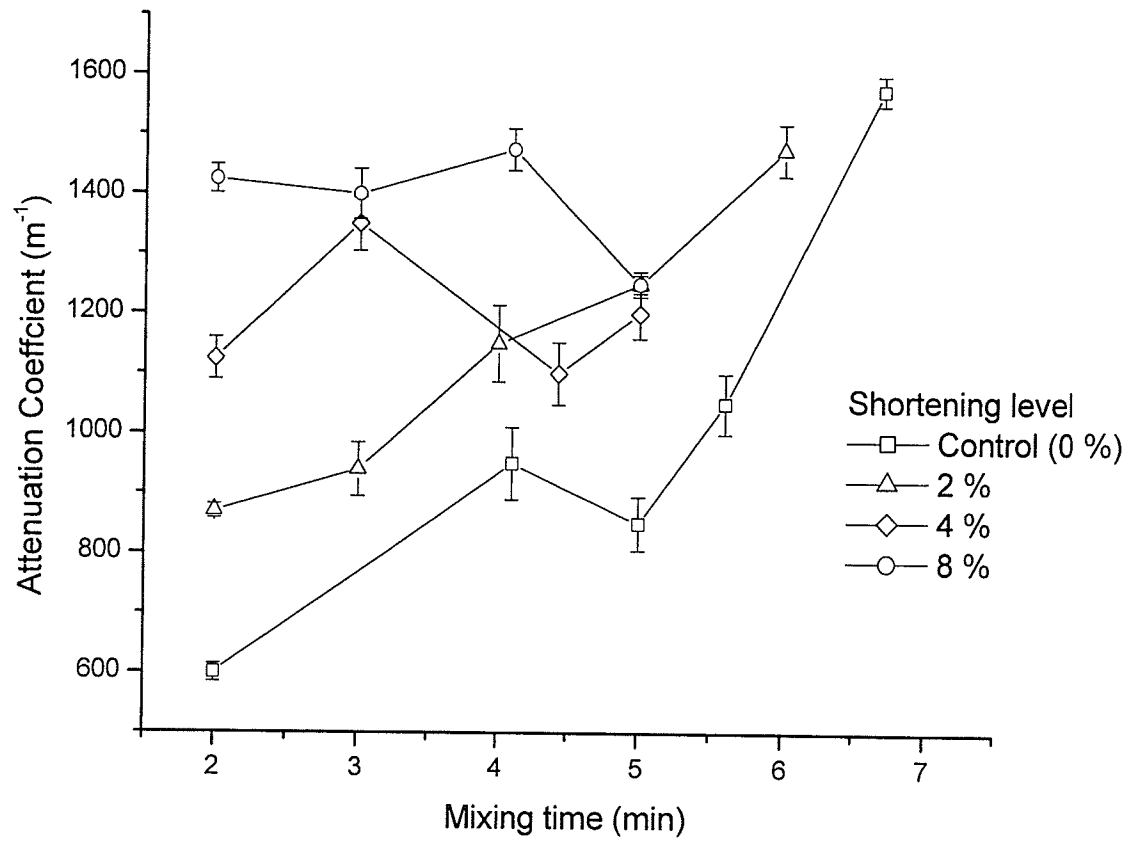


Figure 3.10. Effect of mixing time (in vacuum) on attenuation coefficient for doughs of various shortening content (% f. w. b).

3.4. Discussion

3.4.1. Density measurements

Figure 3.5 shows that the dough density reduces with the increase in mixing time when mixed at atmospheric pressure. Baker and Mize (1946) showed that with the increase in mixing time the amount of gas cells nucleated in the dough increases. During the initial mixing times (i.e., doughs that are undermixed), water hydrates the surface flour particles. Due to the abundance of free water there is less resistance to extension which can be noticed in the mixographs (Figure 2.1). The flour particles rub against each other, to the pin of the mixer and the surface of the mixer and more unhydrated flour particles are exposed to the water molecules. As the dough is underdeveloped the air in the dough escapes through the hydrated mass of the dough so that higher dough density values are apparent. As the dough mixing continues, the gluten network begins to develop so that by the time optimum mixing time is reached all the hydrated gluten proteins are transformed into a continuous film in which the starch granules are embedded. The gluten layers are sheared and folded by the mixer blades and during which the gas cells are formed resulting in reduction of dough density.

Densities of doughs prepared with shortening (2, 4, 8% fat) were lower when compared to the control doughs (0% fat). As the density of the shortening is lower ($\rho=900 \text{ kgm}^{-3}$) (Chung *et al.*, 1981), it reduces the density of doughs compared to the control. Effects of the addition of shortening on the reduction of dough density were less significant when compared to mixing time.

For example, there were 30 units reduction in the dough density when 8% of shortening was added to the control dough (0% shortening), but there were 120 units of dough density reduction when the dough was mixed from 2min (undermixed) to 6.7min (overmixed).

To convert the densities into volume fraction of bubbles in the dough, knowledge of the gas-free density of the dough is required. Figure 3.11 shows a typical graph used for determining the gas free dough density by linear extrapolation between the dough densities when mixed at atmospheric pressure and under vacuum. Campbell *et al* (1998) hypothesized linear relationship between the dough density and headspace pressure of the mixing bowl during dough mixing. The reduction in the number of gas cells per unit volume of the dough is the basis of this hypothesis which they proved by measuring the bubble size distribution using microscopy. Elmehdi (2001) also showed the same linear trend (decrease in dough density with the increase in the headspace pressure of the mixing bowl during dough mixing) in results which were consistent with those of Campbell *et al* (1998). Based on the same hypothesis, the gas free density of the dough is obtained from the intercept at $P=0$ atm.

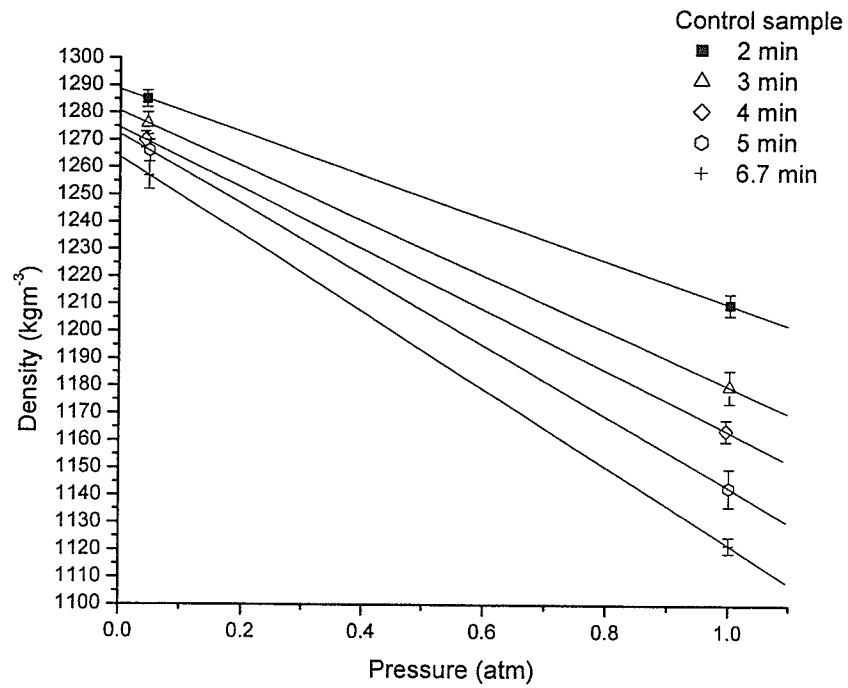


Figure 3.11 Density of control dough as a function of mixer headspace pressure (atm) for a given mixing time (min).

The relationships between the shortening level, mixing time and the gas free dough density are shown in Table 3.2. For example, the gas-free dough matrix density (ρ_m) for control dough mixed for 5 min is 1262 kgm⁻³.

Table 3.2 Effect of shortening and mixing time on gas-free dough density (kg m⁻³).

Shortening level (%)	2 min	3 min	4.1 min	4.43 min	5 min	5.6 min	6 min	6.7 min	Mean density
Control (0)	1261	1262	1262	1262	1262	1260	1263	1262	1262
2	1251	1253	1255	1255	1255	1257	1258	1255	1255
4	1249	1251	1254	1256	1257	1256	1257	1253	1254
8	1247	1244	1243	1246	1246	1246	1246	1245	1245

From Table 3.2 we can observe that the gas free dough density does not change much with the mixing time, but the addition of shortening strongly affects the gas free dough density values. Comparing the values of dough density obtained by Figure 3.6 (dough density when mixed under vacuum) and Table 3.2 (gas free dough density) there is a clear indication that shortening does not contribute superior air entrainment effects in the dough during dough mixing.

The void fraction (air content) in the dough can be determined based on the dough density and gas free dough density values as shown in equation (3.4.):

$$\phi = 1 - (\rho / \rho_m) \dots\dots\dots (3.4)$$

Here ρ is the density of dough at a given mixing time for a given headspace pressure, ρ_m is the matrix density (gas free dough density) for a dough at a particular mixing time. This relationship is used to convert the mixing time (min) to void fraction, thereby simplifying the interpretation of ultrasonic results as a function of the aeration properties of the dough.

3.4.2 Velocity measurements

Figure 3.12 shows the relationship of the ultrasonic velocity as a function of void fraction (ϕ) (calculated from Eqn. 3.4). There is a rapid decrease in velocity values with a small increase in void fraction (ϕ). The data fall into two groups: the vacuum mixed doughs have high velocities and their void fractions cover a small range. The second group, with lower velocities is for the air-mixed doughs, where the void fraction is much wider, caused by the greater entrainment of air as mixing time increases. For example, for the control doughs the velocity reduced from 3000 m/s to 167 ms⁻¹ when void fractions increased from 0.0027 < ϕ < 0.048. At higher ϕ values the decrease is less rapid, for example for control doughs the velocity reduced from 167 to 105 ms⁻¹ for void fractions in the range of 0.05 < ϕ < 0.14. Thus the velocity at this frequency (50 kHz) is extremely sensitive to the presence of gas cells in the dough especially at low ϕ . The current data on ultrasonic velocity measurements are consistent with the results reported by Elmehdi *et al.* (2004). The values for velocities of vacuum-mixed doughs are a bit higher than

those of Elmehdi *et al.* (2004), the reason attributable to this might be the better vacuum applied to the mixing bowl during mixing (resulting in lower ϕ values for vacuum mixed doughs). Another possible reason might be the decrease in moisture content of dough as the mixing pressure was reduced further than that attained by Elmehdi *et al.* (2004). Moisture changes will affect the velocity by stiffening the dough matrix. This effect was confirmed by Elmehdi *et al.* (2004) who noticed that greater moisture losses occurred when doughs were mixed at lower headspace pressure. The loss ranged from 3.2% for doughs mixed at atmospheric pressure to 6.7% when mixed at 10 cm of Hg. Addition of shortening decreased the ultrasonic velocity when compared to the control doughs (0% shortening). The pattern of decrease in ultrasonic velocity remained consistent even with the addition of shortening to the dough during mixing. As from Table 3.2 it is clear that addition of shortening changes the gas free dough density (or the dough matrix density), the changes in the ultrasonic velocities may be due to changes in the properties of the dough matrix.

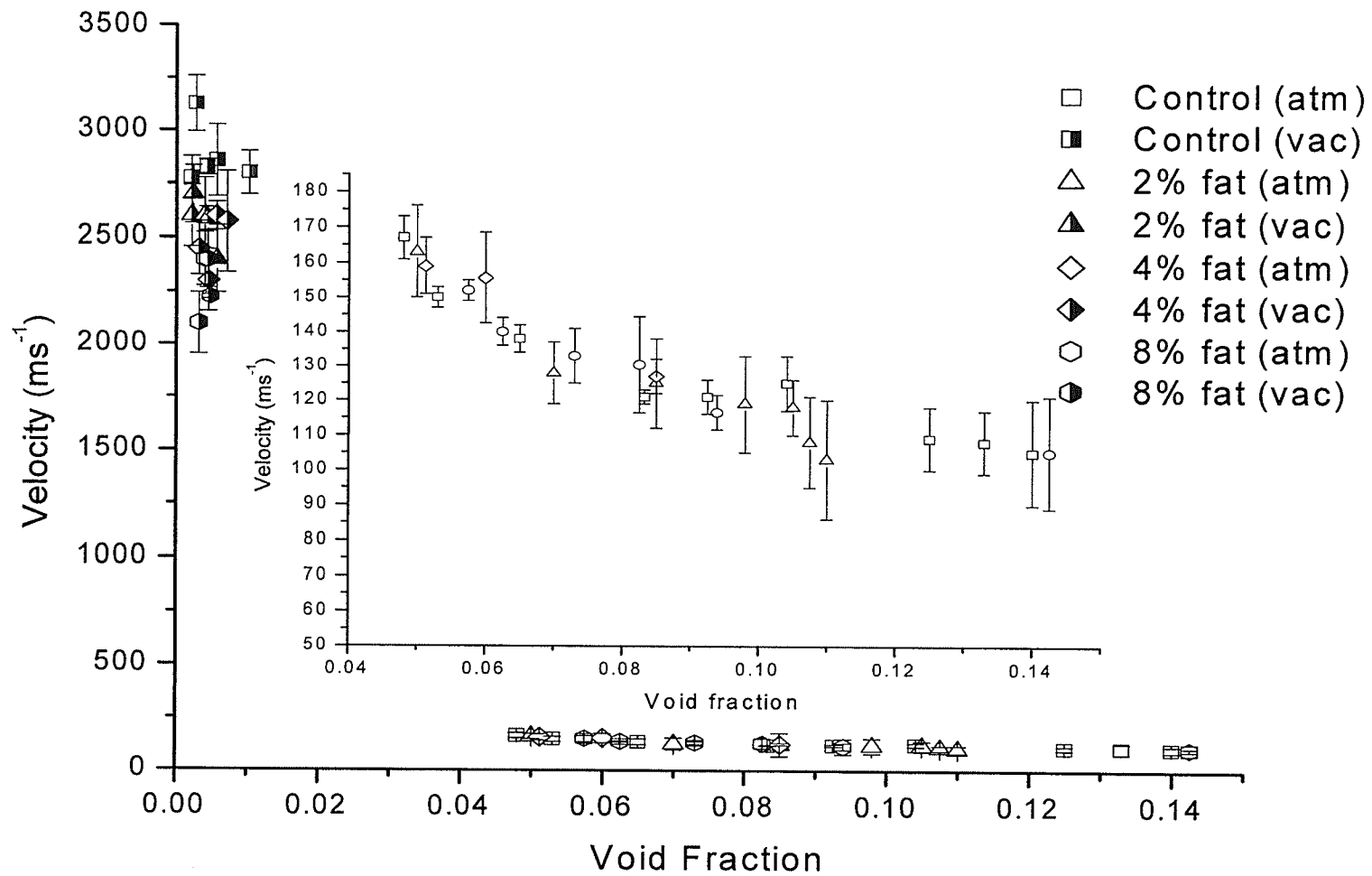


Figure 3.12 Ultrasonic velocity in dough as function of void fraction (ϕ), for doughs prepared with different amounts of shortening. Inset expands velocity scale for doughs mixed at atmospheric pressure.

3.4.3 Attenuation coefficient

Figure 3.13 shows the relationship of attenuation coefficient as a function of the void fraction (ϕ). It is clear that the attenuation coefficient increases with the amount of gas trapped in the dough, and that the bubbles or gas cells make a significant contribution to α for $\phi > 0$. Doughs mixed at reduced pressure have fewer gas cells and either absorb less acoustic energy or there is less scattering of the ultrasonic signal, resulting in low attenuation coefficient values. Elmehdi *et al* (2004) noted that the values of the attenuation coefficient at $\phi = 0$ is the amount which the dough matrix contributes to the total attenuation coefficient. Addition of shortening to dough increases the attenuation coefficient when compared to the control doughs having no shortening. As we know from the density results that addition of shortening to the dough does not lead to superior air entrainment effects, there is a clear indication of changes in dough matrix with the addition of shortening to the dough during dough mixing. Therefore, given the curvature evident in this graph, it is possible that a series of curves could be constructed that would pass through the origin.

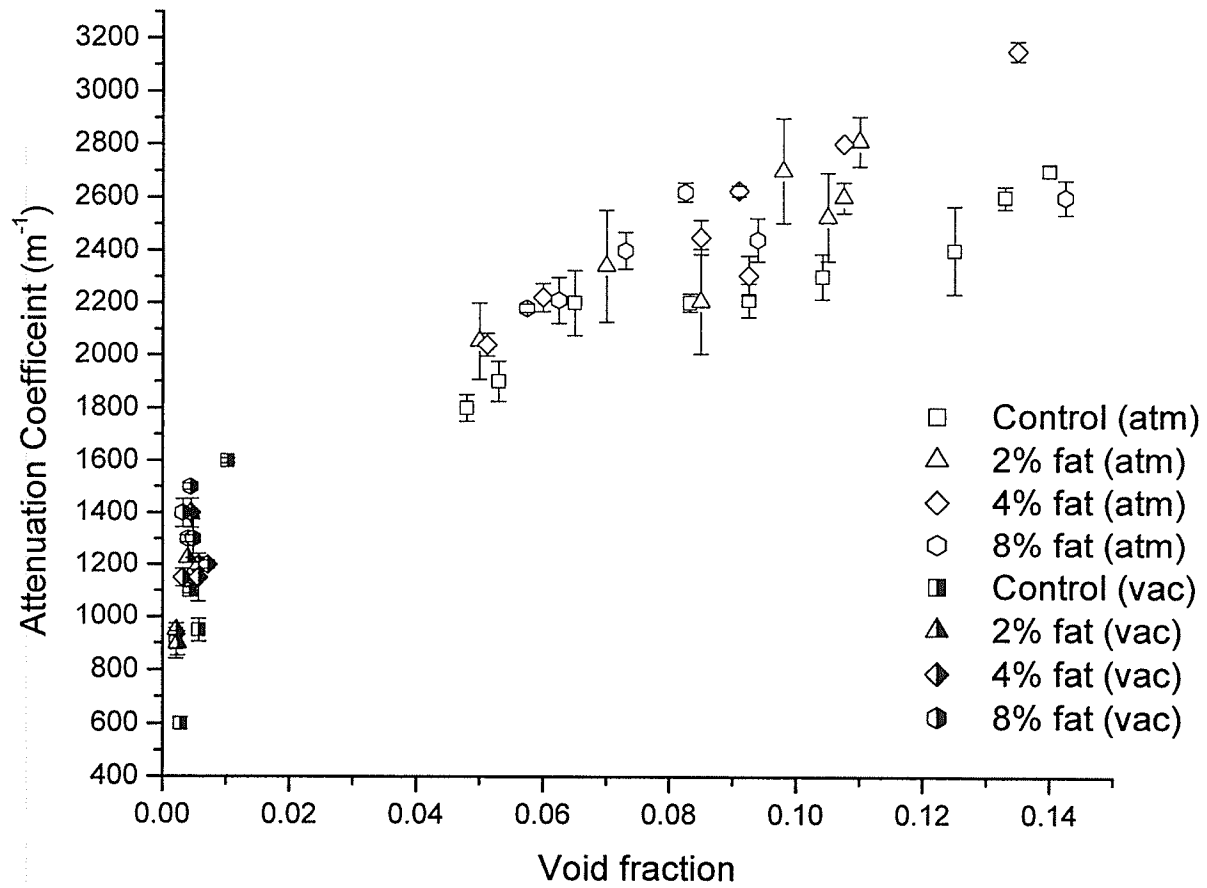


Figure 3.13 Attenuation coefficient of dough as a function of void fraction (ϕ)

From the attenuation data we know that absorption of ultrasonic energy in the dough is appreciable at this frequency (50 kHz). Therefore the modulus is complex (Elmehdi *et al.*, 2004), and both velocity and attenuation contribute to the storage and loss moduli, β' and β'' . To relate these changes in ultrasonic parameters (velocity and attenuation coefficient) more directly to the mechanical properties of dough, the longitudinal elastic modulus of the doughs was calculated from the data using Eqn. 2.10 and 2.11. Figure 3.14 is the graph of the change in longitudinal modulus (β' and β'') with void fraction (ϕ) for the control dough samples. There is a considerable increase in both moduli as ϕ is decreased, a result also seen by Elmehdi *et al.* (2004). In this case, void fraction has been manipulated by mixing time at two extremes of headspace pressure, rather than by head space pressure alone. With the increase of shortening level in the dough the values of both moduli decrease when compared to the control dough. The result for 8% shortening is shown in Figure 3.14, the results for 2 and 4% shortening are in the appendix. The change in β''/β' for control dough samples over the void fraction is shown in Figure 3.15. There is an increase in the β''/β' values with the increase in void fraction, although changes are small for doughs mixed at atmospheric pressure.

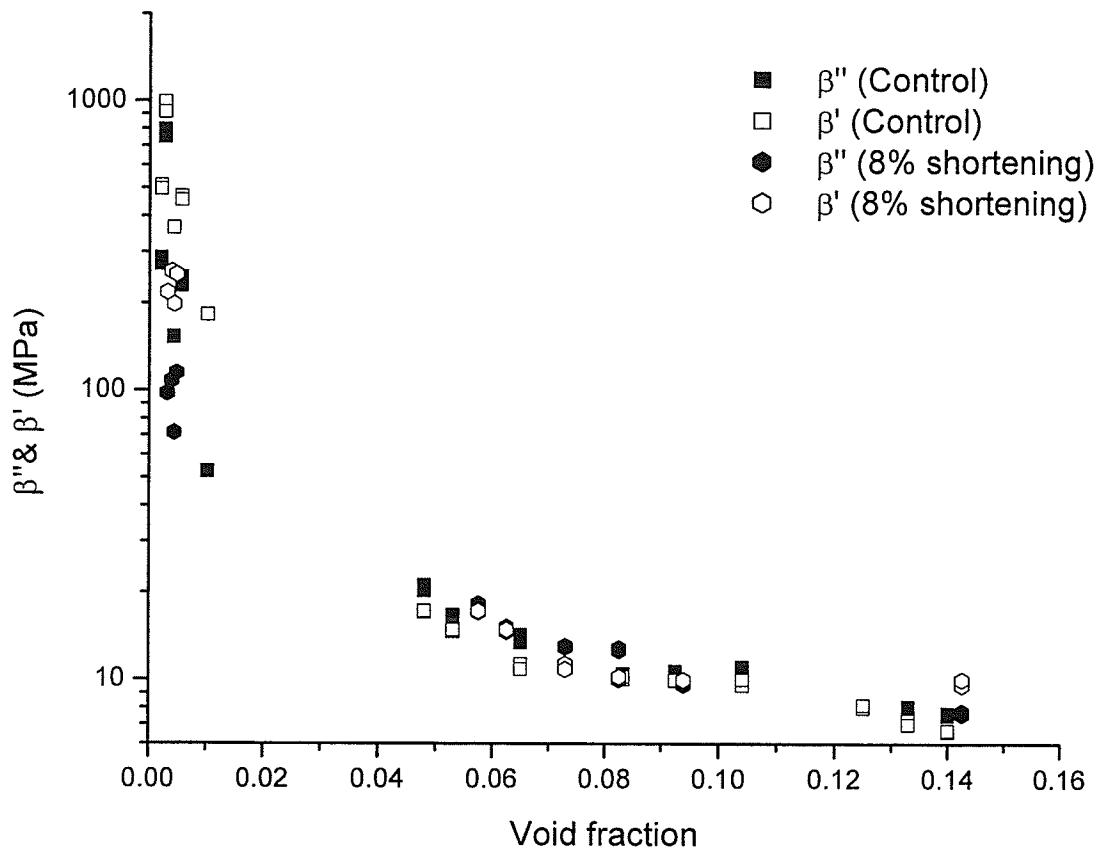


Figure 3.14 Longitudinal moduli (β'' and β') of a control dough and dough with 8% shortening as a function of void fraction.

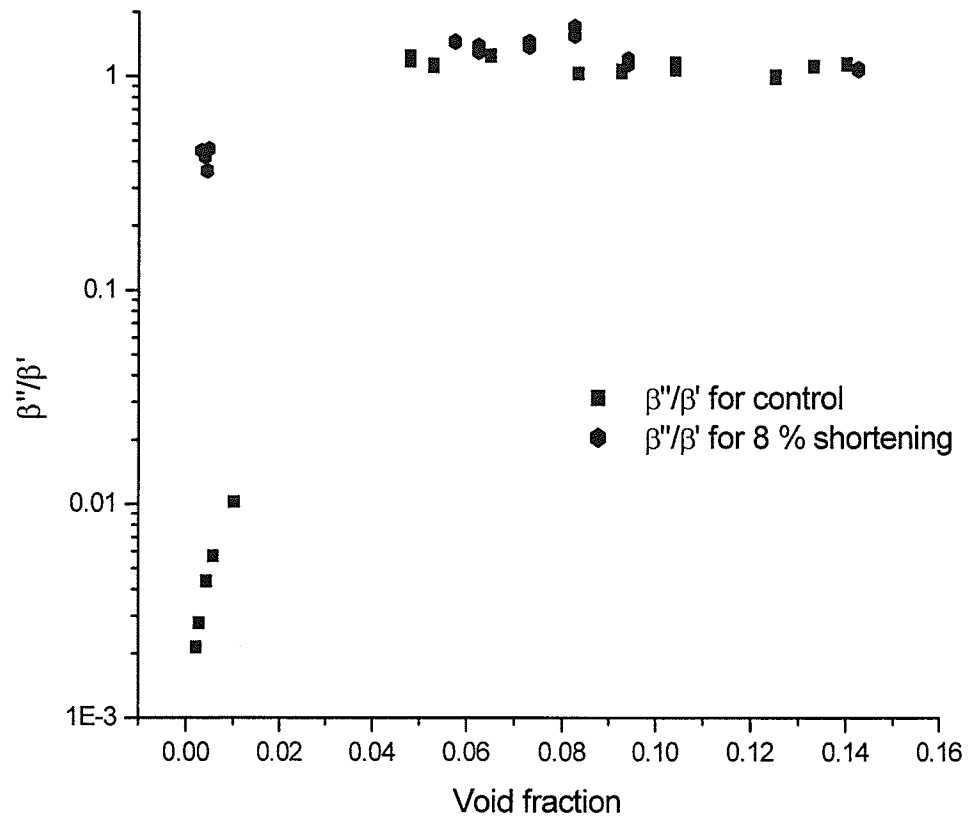


Figure 3.15 Ratio of loss and storage modulus (β''/β') for a control dough as function of void fraction.

3.5 Conclusion

The influence of mixing time and shortening on the dough density and ultrasonic parameters (velocity and attenuation coefficient) was studied. The experimental results presented in this paper demonstrate that low frequency (50 kHz) ultrasound can be successfully used to investigate the effect of mixing time and shortening on the mechanical properties of dough.

The ultrasonic parameters are very sensitive to the presence of the gas cells entrained in the dough during mixing. The void fractions (ϕ) in the dough varied with the mixing time. The ultrasonic velocity changed drastically as the amount of gas in the dough sample varied. The velocity varied by more than an order of magnitude as the void fraction varied from 0.0027-0.048. The attenuation coefficient increased with the increase in the amount of gas cells in the dough. The attenuation coefficient at $\phi=0$ can be successfully used to gain insights into the effects of the dough matrix on the dough properties.

Addition of shortening reduces the density of dough due to its lower density. From the experiments it can be clearly concluded that mixing time variation has much greater effects on the gas entrainment in the dough than that due to shortening. From the ultrasonic measurements it is shown that addition of shortening changes the dough matrix.

The density, velocity and attenuation data were used to calculate the longitudinal elastic modulus of dough, and the modulus values were

significantly higher at lower void fractions. From the data it can be concluded that increase in mixing time, which increases the void fractions in the dough, significantly reduces the modulus values. The modulus values also reduced with the addition of shortening.

The Use of Low Intensity Ultrasound to Investigate the Effect of Mixing Time and Surfactant on the Mechanical Properties of Bread Dough.

4. ABSTRACT

Mixing is a vital step in breadmaking, as it regulates the amount and distribution of gas cells in the dough. Aeration during bread dough mixing is important as it affects baked loaf structure. The amount of air and the bubble size distribution incorporated during mixing critically affects the rheology of the dough and the quality of the final product. One tool capable of probing the effect of mixing on dough properties in a non-destructive manner is low-intensity ultrasound

The aim of this study was to use ultrasound to examine gas cell entrainment in doughs prepared with different levels of surfactant as a function of mixing time. Doughs were made from Soft White Spring (SWS) and Canada Western Red Spring (CWRS) wheat flour with various amounts of surfactant (0, 0.5, 1, 2 % w/w) separately. The doughs were mixed at atmospheric pressure or under vacuum (0.04 atm) for various times. For SWS wheat flour 1, 2, 3, 4 and 5 min and CWRS wheat flour 2, 4.5 and 6.5 min were the dough mixing times used. Ultrasonic velocity and attenuation (at 50 kHz) were measured in the doughs, as was dough density.

For doughs prepared from SWS wheat flour at atmospheric pressure, the velocity and the dough density decreased with the increase in mixing time. For example, for the control dough prepared from SWS flour, the velocity decreased from 160 to 110 ms⁻¹ and the density decreased from 1215 to 1135 kgm⁻³ with the increase in mixing time. But the attenuation coefficient increased with the increase in mixing time. For example, an increase in attenuation coefficient from 2000 to 2900 m⁻¹ was noticed for the control doughs prepared from SWS flour with increase in mixing time. For doughs prepared from CWRS flour a decrease in both ultrasonic velocity and dough density and an increase in attenuation coefficient was similarly noticed. Similar trends were observed for doughs prepared with surfactant, but velocities at a given mixing time were progressively higher for doughs prepared from both types of wheat flour as the surfactant level increased. For doughs prepared from both types of wheat flours (SWS and CWRS) mixed under vacuum, little variation was observed in both the ultrasonic velocity and dough density with mixing time. An increase in attenuation coefficient suggested that ultrasound was sensitive to the changes in the properties of dough matrix during dough development.

This study showed the potential of ultrasound for probing the effect of mixing times and ingredients on dough properties, and thus the possibility of on-line ultrasonic quality control in the baking industry.

4.1. Introduction

Most baked products containing wheat flour start with a mixing of flour, water and various other ingredients to form dough. Mixing is a critical stage in breadmaking as it controls gas cell nucleation and gluten development in the dough (Hoseney, 1985). Baker and Mize (1941) established the fact that air bubbles were incorporated into doughs during the mixing stage and that these bubbles form nucleation sites for the carbon dioxide produced during proofing. To obtain the optimum baked loaf characteristics, the dough should be mixed for a specific mixing time referred to as "optimum mixing time". It is also called the point of minimum mobility, where the dough is not sticky, is easy to handle and possesses appropriate rheological properties for producing good quality baked products (Bushuk and Tsen, 1968). Doughs that are undermixed or over mixed have profound effects on final product quality (Aamodt *et al.*, 2003; Basaram and Gocmen, 2003).

Nucleation, growth and stabilization of gas cells in dough are critical components in breadmaking process, since they largely govern appearance and rheological properties of baked goods (Campbell *et al.*, 1991). During dough mixing, excessive incorporation of air in the dough results in poor structure of the baked loaf (Williams, 1975). But, this problem can be rectified by applying partial vacuum to the mixing bowl during dough mixing. Dough mixed under reduced pressure can be used to change the amount of gas cells

in the baked product (Baker and Mize, 1937; 1941; Campbell *et al.*, 1998). Elmehdi *et al.* (2004) investigated the influence of gas cells on the rheological properties of doughs when mixed under reduced pressure.

In industrial breadmaking processes, the rheological properties of dough are very important as the dough should not stick to metal surfaces, but it should show a good resistance to mechanical shock (impacts on doughs due to processing) (Azizi and Rao, 2004). Various types of dough conditioners are used in baked products to improve dough handling characteristics, eating quality and shelf life (Stauffer, 1999). Surfactants such as distilled mono-glycerides (DMG) and sodium stearyl-1-lactylate (SSL) are used as dough conditioners in bread formulations to increase bread crumb fineness, softness, and volume (Stauffer, 1999; Xu *et al.*, 1992; Collar *et al.*, 1998). Surfactants form liquid films of lamellar (thin layer) structure in the interphase between the gluten strands and the starch. They improve the ability of gluten to form a film, which retains the gas produced (Krog, 1990; Azizi and Rao, 2004). Addition of surfactants in the breadmaking formula increases the optimum dough mixing time (an increase in time to peak) (Lang *et al.*, 1992). Surfactants also increase tolerance of the dough to mixing stresses and delay staling of the crumb produced from the dough (Knightly, 1981, 1988; Stampfli, 1996; Campbell *et al.*, 2001). Research done by Junge *et al.* (1981) and Gan *et al.* (1995) showed that surfactants aid the break-up of bubbles in the mixer, resulting in more and smaller gas cells in the baked loaf. During proofing and baking, surfactants

reduce the surface tension at interfaces resulting in retardation of bubble coalescence (Gan *et al.*, 1995).

Although there are many conventional methods that can be used to characterize dough rheology, there is a need to develop new rapid techniques that can perform precise evaluations of the properties and quality of dough (Létang *et al.*, 2001). The fact that manufacturing food products is highly dynamic and competitive means that food processors must be able to respond immediately to problems affecting the quality of products during processing (McClements, 1997). Ultrasound is a promising technique that uses sound propagation properties to understand the material and structural properties of the body. Using ultrasound has many advantages including that of measuring optically opaque systems rapidly and precisely. Being sensitive to the presence of internal defects and structural flaws, such as air pockets and fractures, ultrasound can be useful to the food processor as an on-line determination tool to detect defects in food products during processing. It is a non-destructive, non-invasive technique and is available as easy-to-use commercial instruments (McClements, 1997; Létang *et al.*, 2001; Coupland, 2004; Scanlon, 2004). However ultrasound has a limitation for interpreting the properties of food samples having high attenuations (especially when gas bubbles are present (Samari, 1994; Verdier and Piau, 1997; Resa *et al.*, 2004)).

The velocity of propagation of the sound (velocity) and how rapidly the amplitude of a wave decreases as it travels through a material (attenuation coefficient) are the two ultrasonic parameters that have been used to characterize structural, compositional and physical properties of food systems (Povey, 1989; Lee *et al.*, 1992; Self *et al.*, 1992; McClements, 1997; Elmehdi *et al.*, 2004; Scanlon, 2004). For homogenous materials, ultrasonic velocity depends on the material's density and elastic modulus (Povey, 1997)), whereas for heterogeneous foods, various dissipative processes occur at the interface of the various phases within the food structure so the ultrasonic properties depend on reflections, scattering, refraction and absorption mechanisms (McClements, 1997).

Ultrasound has been successfully used for determining food composition, structure, flow rate, physical state, and molecular properties of optically opaque materials (Povey, 1989; Lee *et al.*, 1992; McClements, 1997; Elmehdi *et al.*, 2004). It has also been used to measure the textural properties of foods: elastic modulus of cooked carrots (Nielsen and Martens, 1997); elastic modulus of biscuits (Povey and Harden, 1981); deformability of cheese (Benedito *et al.*, 2000). Elmehdi *et al.* (2004) have proved that ultrasound is a very effective tool in predicting the effects of headspace pressure during dough mixing on the rheological properties of dough properties.

Due to advantages in probing the composition and structure of food systems, low-intensity ultrasound appears to be a useful technique for studying

the effects of ingredients and mixing time on the mechanical properties of dough. The objective of this work is to show how low frequency ultrasound (50 kHz) can be used to examine gas cell entrainment as a function of mixing time in dough prepared with various amounts of surfactants.

4.2. Materials and Methods

Dough samples were prepared separately from two different types of wheat flours: Soft White Spring wheat (SWS) flour having a flour protein content of 9.1% and Canada Western Red Spring (CWRS) hard wheat grade No.1 with a flour protein content of 12.4%. All wheat was milled in the Canadian International Grains Institute (CIGI) pilot mill (Winnipeg, MB). CWRS wheat flour used for the first set and the third set of experiments was obtained from a different crop year. CWRS wheat flour for the first set of experiments was milled in November 1999 and for the third set of experiments the wheat was milled in March 2004. The optimal mixing time for the latter flour was not determined as it had been for the first set of experiments, and to maintain consistency in experimental design, a fixed water content of 61% (fwb) was used for the CWRS flour in both experiments. Sodium chloride was purchased as reagent grade from Fisher Scientific (Nepean, ON). Distilled water was used for making dough samples. A bakery surfactant was used to assess the effect of ingredients on density and the ultrasonic properties of the dough; it was received from Danisco Inc. (Copenhagen, Langebrogade).

4.2.1. Dough mixing under different conditions

4.2.1.1 Dough developed at atmospheric pressure. The Canadian Short Process method (Preston et al 1982) was used for dough sample preparation for both types of flours (SWS and CWRS). The control dough formula consisted of flour (100g), salt (2.4% fwb), and water (for SWS 57% fwb and for CWRS 61% fwb, to obtain optimum dough handling characteristics). Doughs were also prepared using the same ingredients as control doughs, but with surfactant (0.5, 1, 2 % fwb) added. A GRL-200 mixer was used to prepare the doughs at a mixing speed of 165 rpm. To understand the overall picture of the dough mixing process, various mixing times were used. Doughs prepared from SWS flour were mixed for 1, 2, 3, 4, and 5 min. Doughs prepared from CWRS flour were mixed for 2.5, 4.5, and 6.5 min. Duplicate doughs were acquired for each doughs mixed at a particular mixing time.

4.2.1.2 Dough developed under vacuum. The mixing bowl was air-tight sealed by applying vacuum grease and the outlet was connected to a Duo-Seal vacuum pump (Welch Scientific, Skokie, IL) to manipulate the mixer headspace pressure. To avoid drawing flour particles out of the mixer, the ingredients were mixed for 15 sec at atmospheric pressure, after which the vacuum was applied for the remaining mixing time. A pressure valve controlled headspace pressure inside the mixing bowl. For pressure measurements

inside the mixing bowl a digital pressure meter (ACSI Digital Pressure Meter, St. Louis, MO) was installed between the mixer bowl and the vacuum pump. The headspace pressure in the mixing bowl was approximately 0.06 atm throughout mixing (following the initial 15 sec at atmospheric pressure). Duplicate doughs were acquired for each dough mixed under vacuum for a particular mixing time.

4.2.2. Density measurements

Densities of the different doughs mixed for various mixing times were measured. All density determinations were performed using a specific gravity bottle (25 ml capacity) with a 24 mm diameter neck (Kimble Glass Inc. Vineland, NJ). All weight determinations were done using a Mettler AE 160 scale (Fisher Scientific, Pittsburgh, PE) having a capability of weighing 0.01 g.

To avoid moisture losses after mixing, the dough was kept in an airtight Tupperware container. Sub-samples (approximately 5 g) were cut from the dough piece for density measurements. The gravimetric bottle was cleaned, dried, filled with distilled water and weighed every time after each density measurement. The sub-sample of dough was weighed before placing into the gravimetric bottle filled with distilled water. The bottle was weighed after drying the displaced water from the exterior. The volume of the sub-sample of dough was determined by calculating the volume of the water displaced from the

specific gravity bottle when the sub-sample was immersed in the bottle. Five sub-samples were analyzed from each mixed dough.

The density of the dough sub-sample (g cm^{-3}) was determined from the formula (4.1):

$$\rho_{\text{dough}} = m_{\text{dough}} / V_{\text{dough}} \quad \dots\dots\dots(4.1)$$

where,

ρ_{dough} is the density of the dough (g cm^{-3})

m_{dough} is the mass of the sub-sample of the dough (g)

V_{dough} is the volume of the dough (cm^3) = {(Mass of (gravimetric bottle + water + sub-sample of the dough) – Mass of (gravimetric bottle + water))/ Density of water at 30°C (0.995 g cm^{-3})}

4.2.3. Equipment used for ultrasonic experiments

A block diagram of the ultrasonic set-up apparatus is shown in Figure 1. Each piezoelectric transducer (Panametrics, Edmonton, AB) of 50 kHz frequency was fixed in a plexi-glass sheet with one side flush with the face of the transducer. Locking nuts held the transducer in place so that when the distance between plates was set, so too was the distance between transducers. The dough sample was sandwiched in direct contact between the two transducers. An electromagnetic (EM) pulse was sent to the generating

transducer using 50 Ω BNC cables. The transmitting transducer converted the electromagnetic signal to an ultrasonic pulse that passed through the sample. The receiver transducer converted the attenuated ultrasonic signal back to an electromagnetic signal. The amplified EM signals were averaged on a digitizing oscilloscope (Tektronix TDS 420 A, Chicago IL). Data was downloaded to a computer for subsequent analysis.

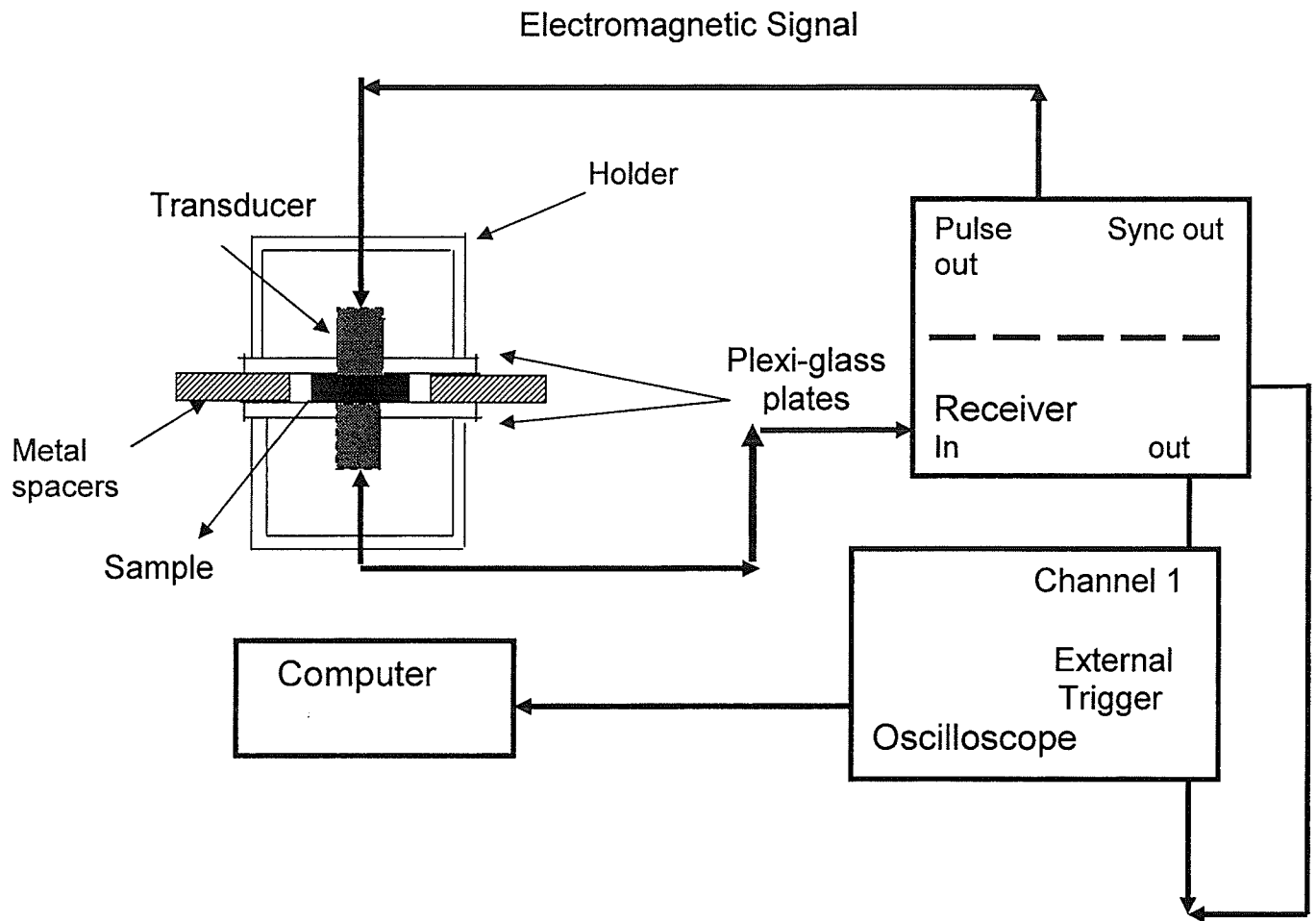


Figure 4.1 Block diagram of experimental set-up for ultrasound measurements.

4.2.4. Ultrasound parameters

Changes in the longitudinal ultrasonic signal behavior during transmission through the dough sub-sample were studied in order to determine the mechanical properties of dough. The phase velocity and the attenuation coefficient are parameters that characterize the way in which the ultrasonic signal propagates.

A reference signal was taken every time before testing the dough piece mixed at a particular mixing time. To do this, a thin coupling agent (Ultrigel II, ultrasonic couplant, Sonotech Inc., Bellingham, WA) was sandwiched between the two transducers, that were essentially touching each other. The distance between the two transducers, and thus the thickness of the sub-sample of dough, was accurately controlled using metal spacers. The ultrasonic data consisted of signal amplitude (mV) vs. time (μs). The acquired ultrasound wave data was plotted on a time domain diagram (signal amplitude (mV) vs time (μs)) using Origin (Microcal Origin, version 7.5, Microcal software Inc. Northampton, MA). From the waveform the transit time (Δt) (μs) and amplitude (mV) of the transmitted pulse were determined (Figure 4.2.). The time difference between the first oscillation of the reference and that of the dough sample was used to calculate the transit time (Δt) for sound passing through the dough sub-sample of a given thickness. The amplitude of each

waveform representing a particular sub-sample thickness was directly measured from the height of the first oscillation.

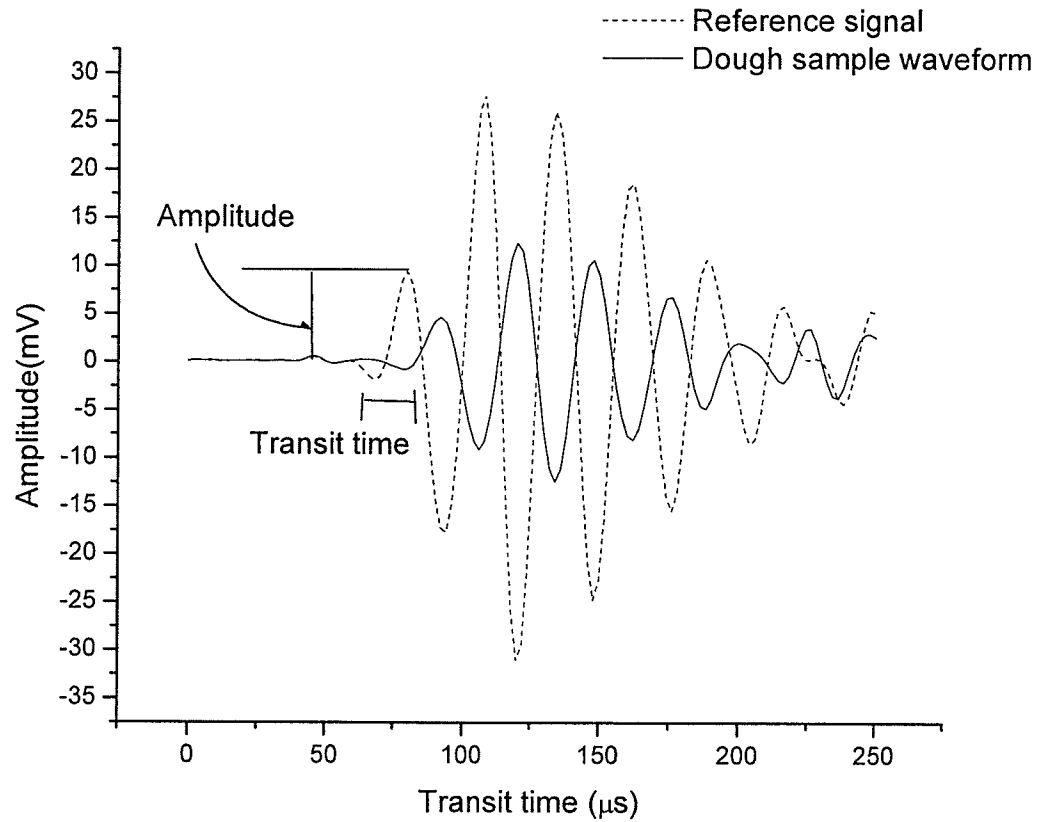


Figure 4.2 Typical ultrasonic waveforms of reference signal and the signal after passing through the control dough sample prepared from SWS flour.

The values of transit time were plotted as a function of sample thickness of the dough samples (1, 2, 3, 4 and 5 mm dough sample

thicknesses were used) (Figure 4.3). The velocity through the dough was calculated from the inverse of the slope of this graph.

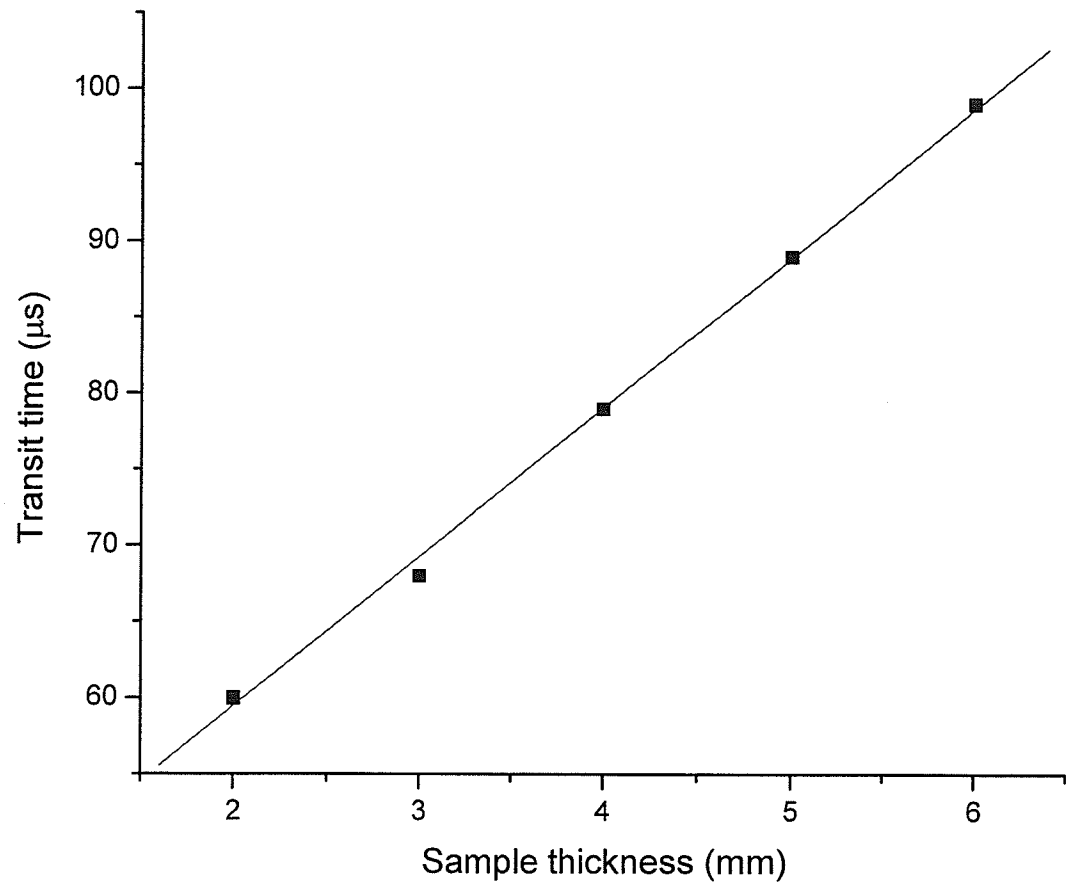


Figure 4.3 Typical graph of transit time as a function of sample thickness for a control dough prepared from SWS flour.

The values of amplitude were also a function of sample thickness of the dough samples. An exponential decay curve was fitted to a graph of amplitude for various sample thicknesses (Figure 4.4). The attenuation coefficient was obtained using the following equation:

$$A = A_0 e^{(-\alpha x/2)} + B \quad \dots\dots\dots(4.2)$$

where,

A is the signal amplitude at a thickness x (mV)

A₀ is the amplitude of the signal at the surface of the dough sample (mV)

α is the attenuation coefficient (mm⁻¹)

x is the thickness of dough sample (mm)

B is the offset (mV)

Offsets due to bond losses of the acoustic signal at the transducer-sample bond and due to interfacial reflections were eliminated in order that true sample attenuation could be accurately determined. They occur due to inaccuracy of the oscilloscope. The offset value is eliminated by deducting the amplitude value at transit time=0 from the peak amplitude value of a waveform. A₀ is determined by extrapolating back the decay curve to zero sample thickness (x=0) and the attenuation coefficient (α) is determined from the decay curve (see Eq. 3.3)

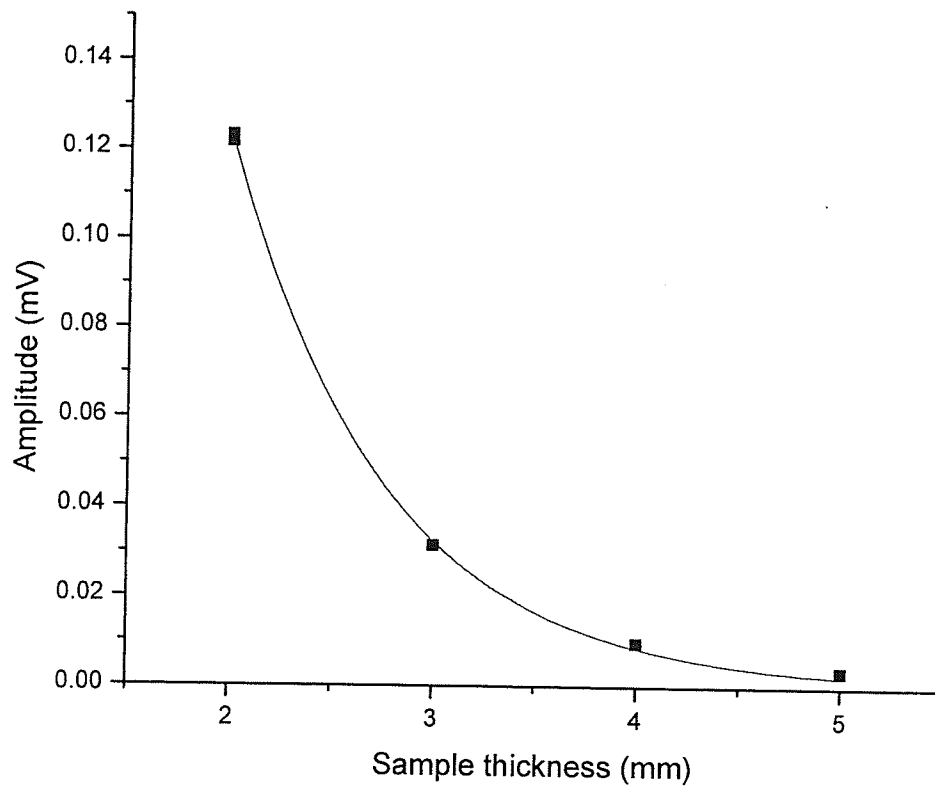


Figure 4.4 Typical graph of the amplitude as a function of sample thickness for control dough prepared from SWS flour.

4.2.4. Experimental design

Due to extensive time delays that would be associated with changing the mixer configuration for vacuum and atmospheric mixing analyses, experiments were divided into two sets. The first set of experiments included the doughs mixed at atmospheric pressure and the other set included doughs mixed under vacuum (0.06 atm). Each set had 40 experiments encompassing the doughs mixed at five mixing times with different levels of surfactants (0, 0.5, 1, or 2% w/w), and with duplicates of each mix. A random number list for these 40 numbers was generated to determine the order in which the experiments were conducted.

4.2.4. Statistical analysis

Data were analysed using Statistical Analysis System software program, version 8.1 (SAS Institute, Inc., Cary, NC). Data were analysed using analysis of variance (ANOVA) with a criterion of $P \leq 0.01$ to detect significant differences among treatments.

The treatments to be analysed were:

- Effect of mixing time on density, ultrasonic velocity and attenuation coefficient of the doughs, comparing different dough mixing times.
- Effect of surfactant on density, ultrasonic velocity and attenuation coefficient of the doughs, comparing different levels of surfactants over all dough mixing times.
- Effect of different headspace pressure on density, ultrasonic velocity and attenuation coefficient of doughs, comparing between doughs mixed at atmospheric pressure and under vacuum.

4.3. Results

4.3.1. Effects of surfactant on dough density

As dough mixing time progresses the amount of gas cell incorporation changes (Baker and Mize, 1941; Hosney, 1985). Figures 4.5 to 4.8 show the relationship of dough density as a function of mixing time for doughs prepared from SWS and CWRS flours when mixed in air and under vacuum. When doughs were mixed at atmospheric pressure with various amounts of surfactants, irrespective of the surfactant level present in the dough, the dough densities were significantly reduced ($p < 0.0001$) with increase in mixing time (Figures 4.5 to 4.7). For undermixed doughs the density values of doughs were high indicating low amounts of gas cell entrainment. Reduction in dough density with an increase in mixing duration indicated that the amount of gas entrained increases with mixing time. These current mixing experiments for the doughs are consistent with previous studies by Baker and Mize (1941) and Hosney (1985) who noticed a decrease in density with an increase in dough mixing time. Density of doughs having surfactant were lower ($p < 0.0001$) when compared to the control dough density (0% surfactant) as the density of surfactant is lower ($\rho = 940 \text{ kg m}^{-3}$) (Rao *et al.*, 1992). The trends of decrease in dough densities with the addition of surfactant to the dough were consistent

with the results of Junge *et al.* (1981) who noticed that surfactants lowered the dough density.

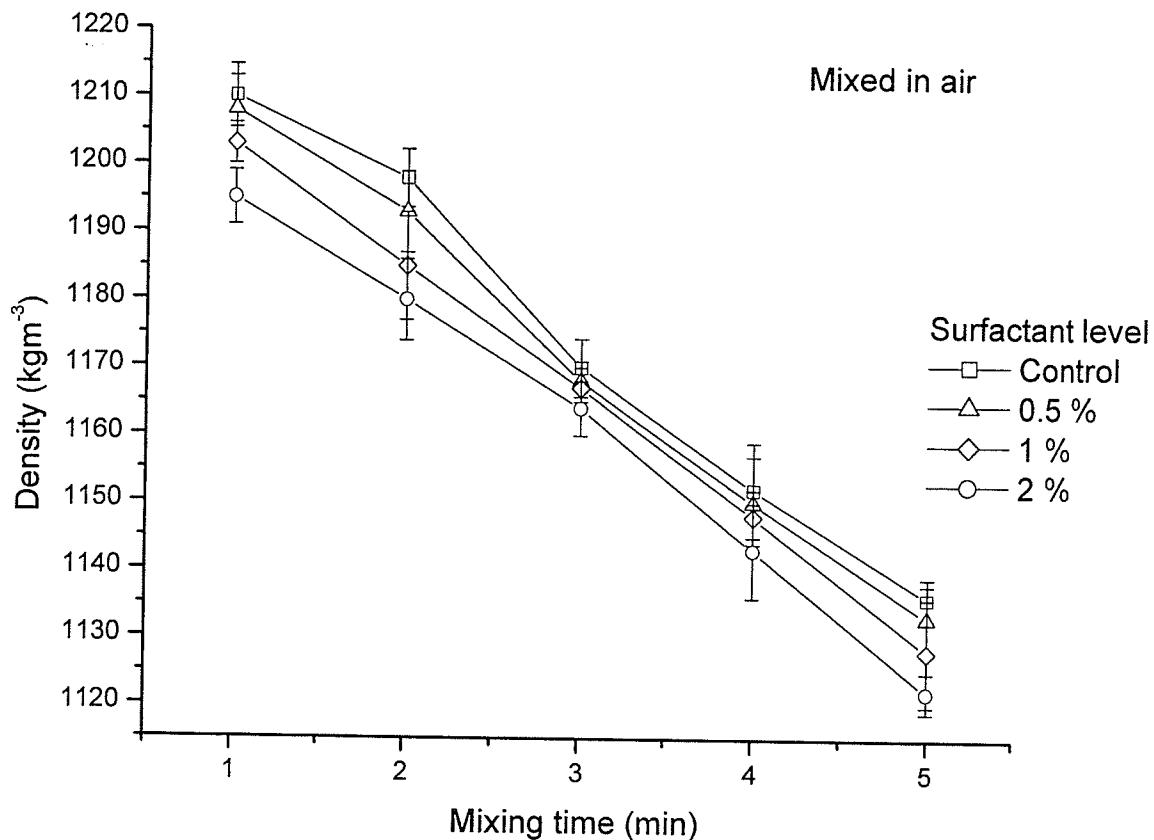


Figure 4.5 Effect of mixing time (in air) on dough density for doughs prepared from SWS flour with various amounts of surfactant (% f.w.b).

Figures 4.6 and 4.8 shows the effect of surfactant at various levels on the density of dough prepared from SWS and CWRS flour, respectively, as a function of mixing time when mixed under vacuum (0.06 atm). For both flours the density of dough when mixed under reduced pressure (0.06 atm) was

substantially higher when compared to the dough mixed at atmospheric pressure. This density difference is caused by the occlusion of fewer gas cells in the dough that has been mixed at reduced pressure. Due to difference in the headspace pressure in the mixing bowl during dough mixing (0.04 atm for control doughs prepared from CWRS wheat flour in Chapter 3 and 0.06 atm for control doughs prepared from CWRS wheat flour in Chapter 4), there were differences in the dough densities for doughs prepared for CWRS wheat flour in Chapter 3 and 4. The results of dough density are consistent with the previous findings by Baker and Mize (1937) who noticed that bread doughs mixed under reduced pressure were denser when compared to the dough mixed at atmospheric pressure. Campbell *et al.* (1998) and Elmehdi *et al.* (2004) also showed that there is an increase in dough density when mixed at reduced pressure compared to doughs prepared at atmospheric pressure. For both flours, the mixing time and surfactant had a significant ($p < 0.0001$) effect on the dough density.

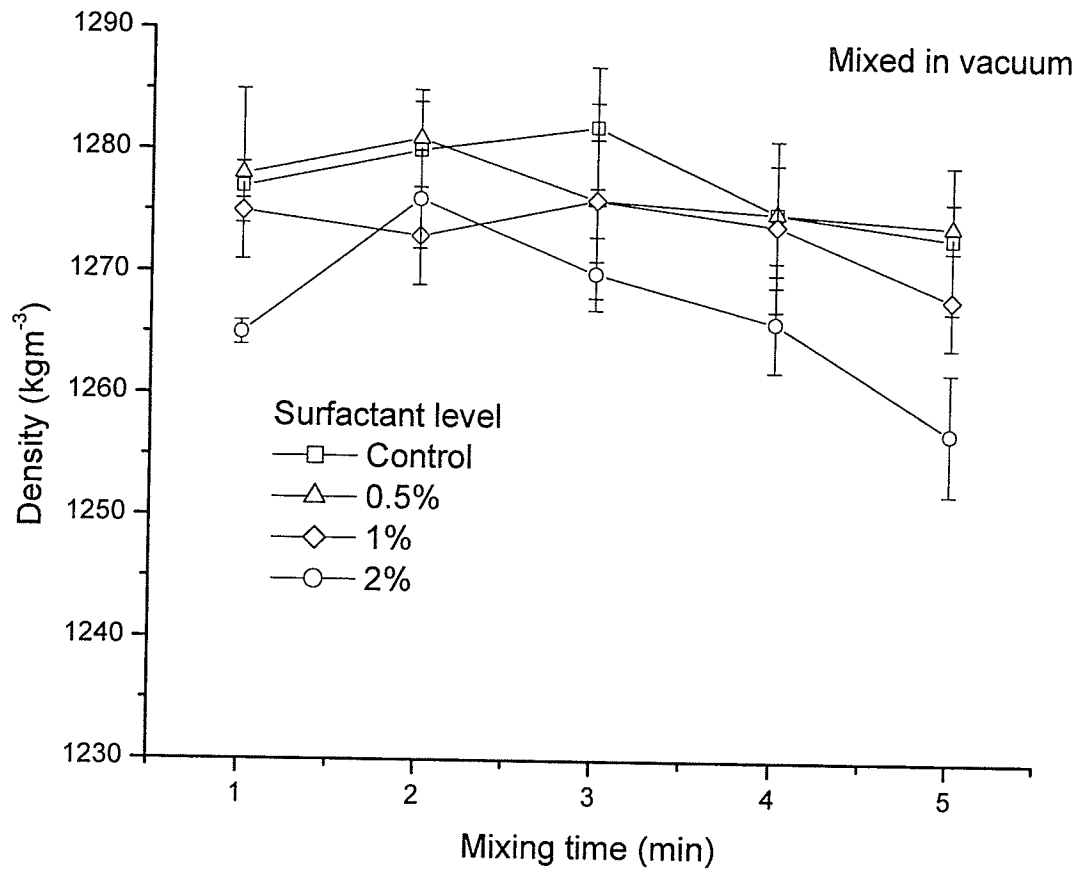


Figure 4.6 Effect of mixing time (in vacuum) on dough density for doughs prepared from SWS flour with various amounts of surfactant (% f.w.b).

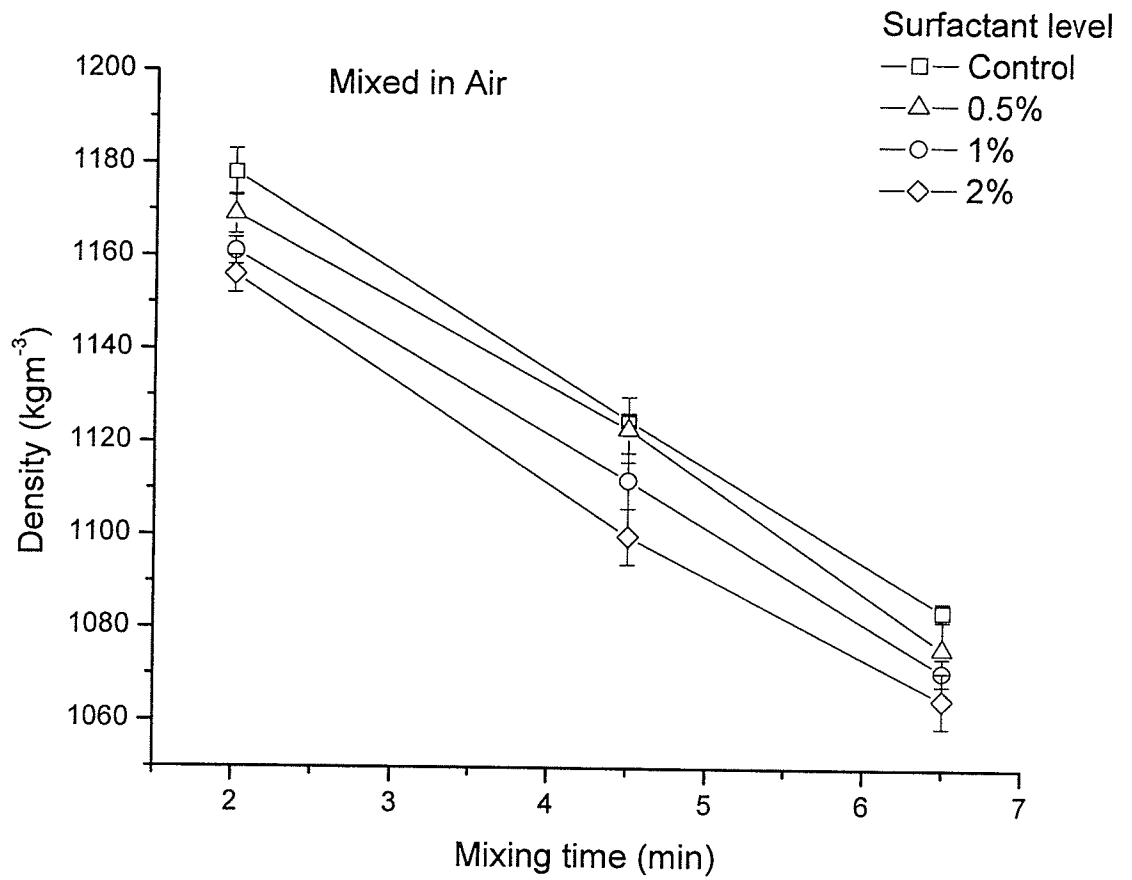


Figure 4.7 Effect of mixing time (in air) on dough density for doughs prepared from CWRS flour with various amounts of surfactant (% f.w.b).

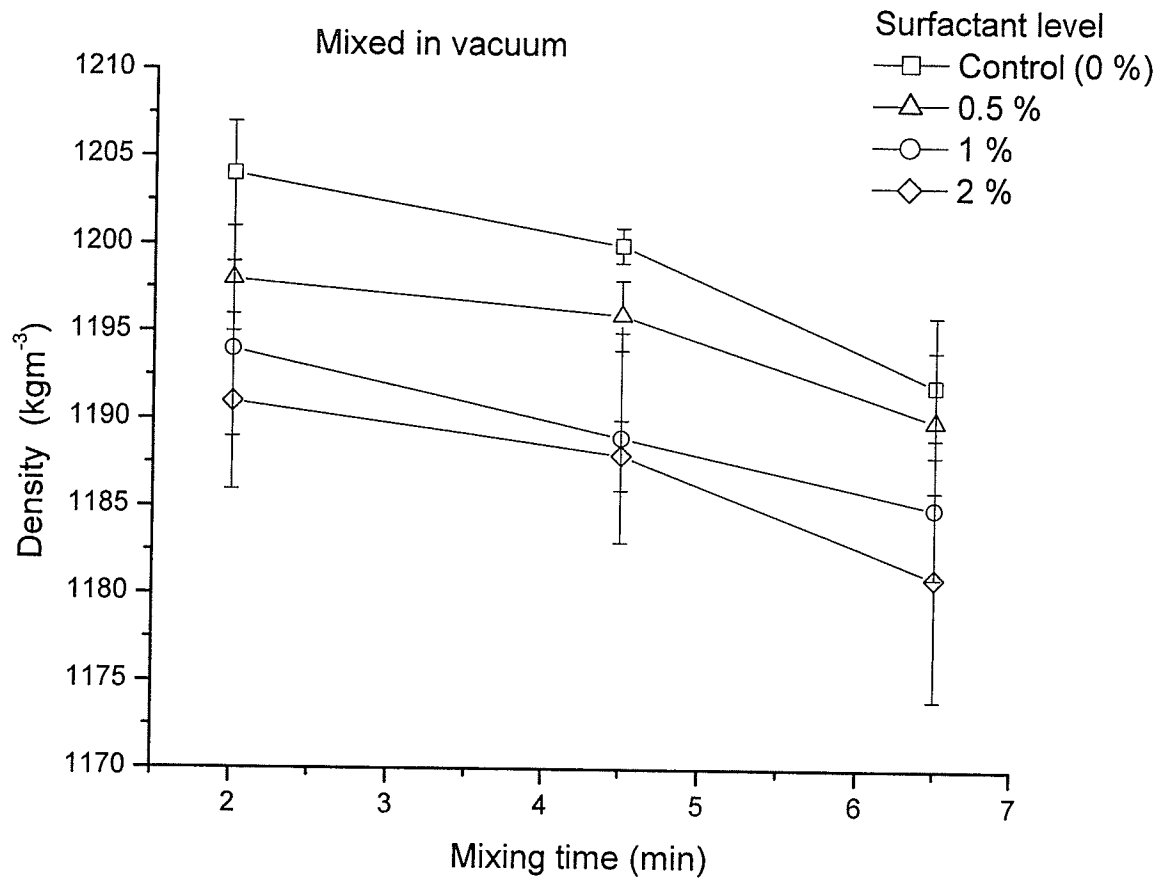


Figure 4.8 Effect of mixing time (in vacuum) on dough density for doughs prepared from CWRS flour with various amounts of surfactant (% f.w.b).

4.3.2. Effects of surfactant on ultrasonic velocity measurements of dough

Ultrasonic velocity as a function of mixing time for doughs prepared from SWS and CWRS flours is shown in Figures 4.9 to 4.12. When doughs were mixed at atmospheric pressure with various amounts of surfactants, for doughs prepared from both flours, the ultrasonic velocity tends to follow the trend of dough density versus mixing time, although the rate of decrease in ultrasonic velocity falls as mixing time increases (Figures 4.9 and 4.11). With the increase in mixing time the ultrasonic velocity was significantly decreased ($p < 0.0001$) indicating that the dough is incorporating more gas cells with the increase in mixing time. The results are consistent with the previous finding of Kidmose *et al.* (1999) and Ross *et al.* (2004) who also found a decrease in ultrasonic velocity with the increase in mixing time. The ultrasonic velocity increased significantly ($p < 0.0005$) with the addition of surfactant, a result that contrasts with the addition of shortening. For example, the dough having 2% surfactant (190 ms^{-1}) had higher velocity than the control dough (160 ms^{-1}) when mixed for the same mixing time (1 min).

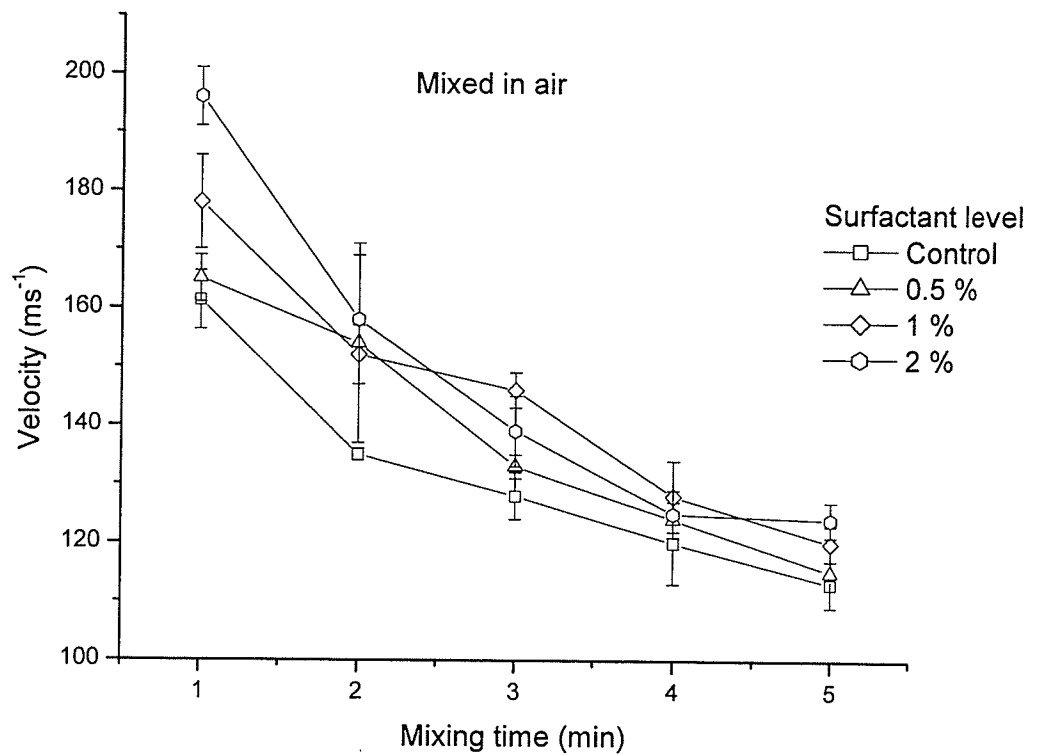


Figure 4.9 Effect of mixing time (in air) on ultrasonic velocity for doughs prepared from SWS flour with various amounts of surfactant (% f.w.b).

To observe the effects of the dough matrix on the ultrasonic parameters independently of the effect of the bubbles, doughs were mixed under vacuum (0.06 atm). The relationship of ultrasonic velocities and mixing time with varying amount of surfactants is shown in Figures 4.10 and 4.12 for SWS and CWRS, respectively. As we know from the density results that the doughs mixed under vacuum have substantially fewer gas cells in comparison to the doughs mixed at atmospheric pressure, it can be concluded that the absence

of gas cells dramatically increased the ultrasonic velocity. As with doughs mixed in vacuum, increasing the dough mixing time had a significant effect ($p < 0.0001$) on ultrasonic velocities as did addition of surfactant ($p < 0.0001$). As was observed for mixing in air, addition of greater amounts of surfactant increased the ultrasonic velocity in the dough at all mixing time. This was true for dough prepared from both strong and weak breadmaking flours.

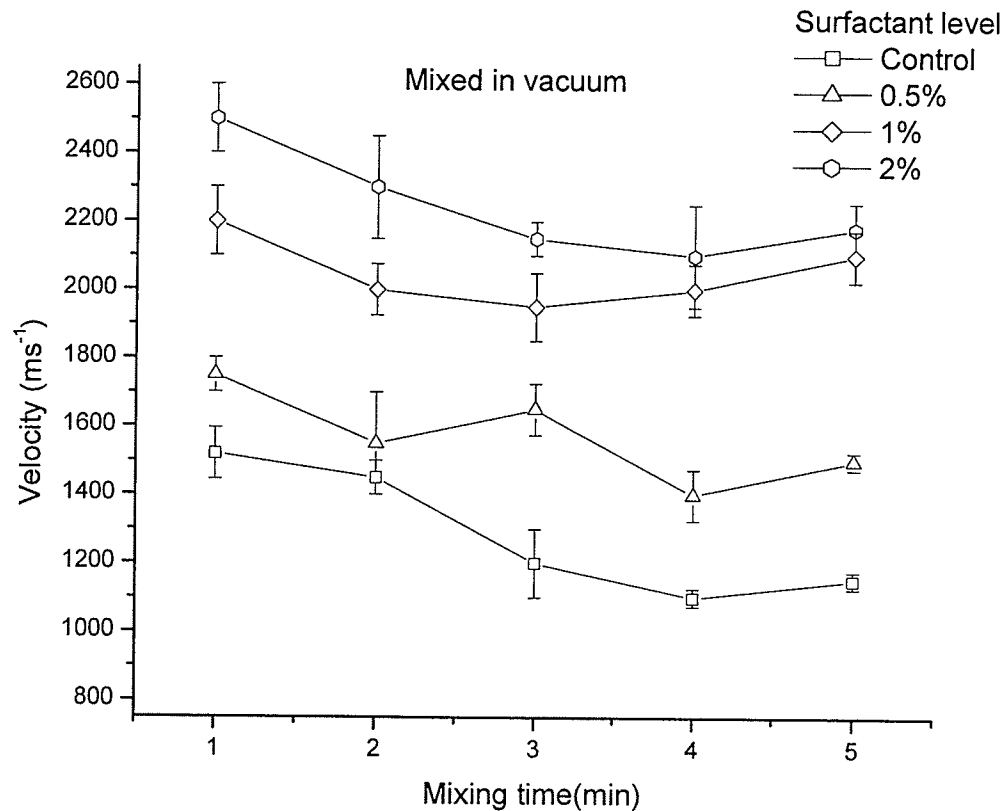


Figure 4.10 Effect of mixing time (in vacuum) on ultrasonic velocity for doughs prepared from SWS flour with various amounts of surfactant (% f.w.b).

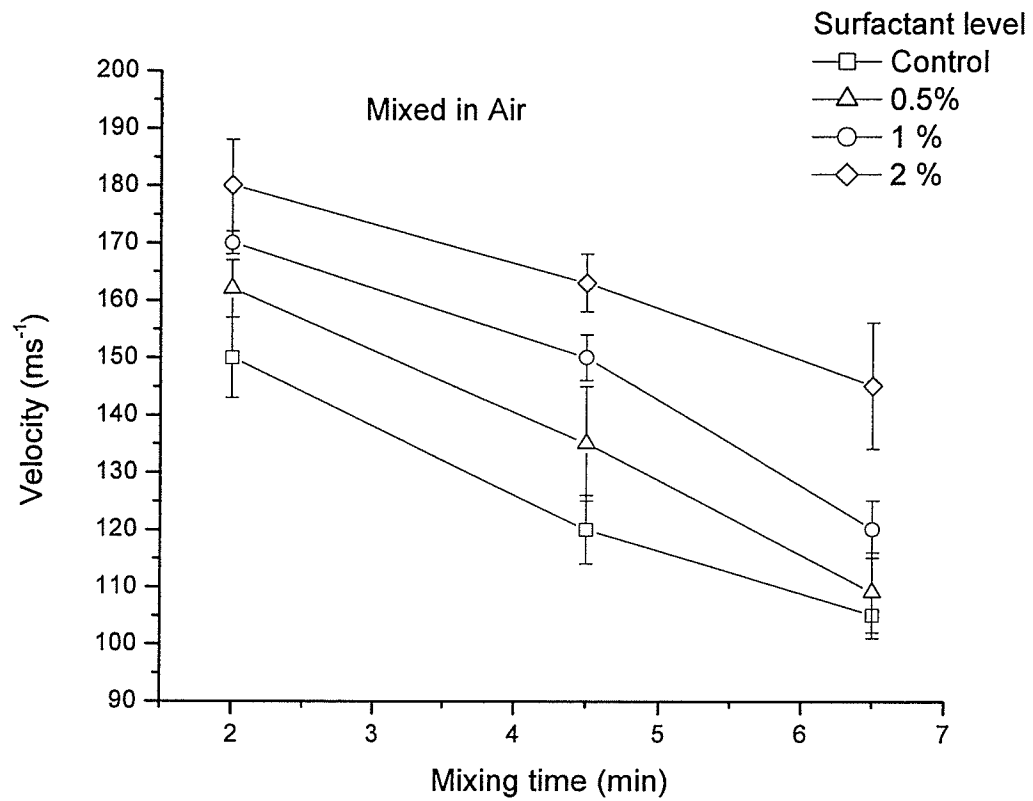


Figure 4.11 Effect of mixing time (in air) on ultrasonic velocity for doughs prepared from CWRS flour with various amounts of surfactant (% f.w.b).

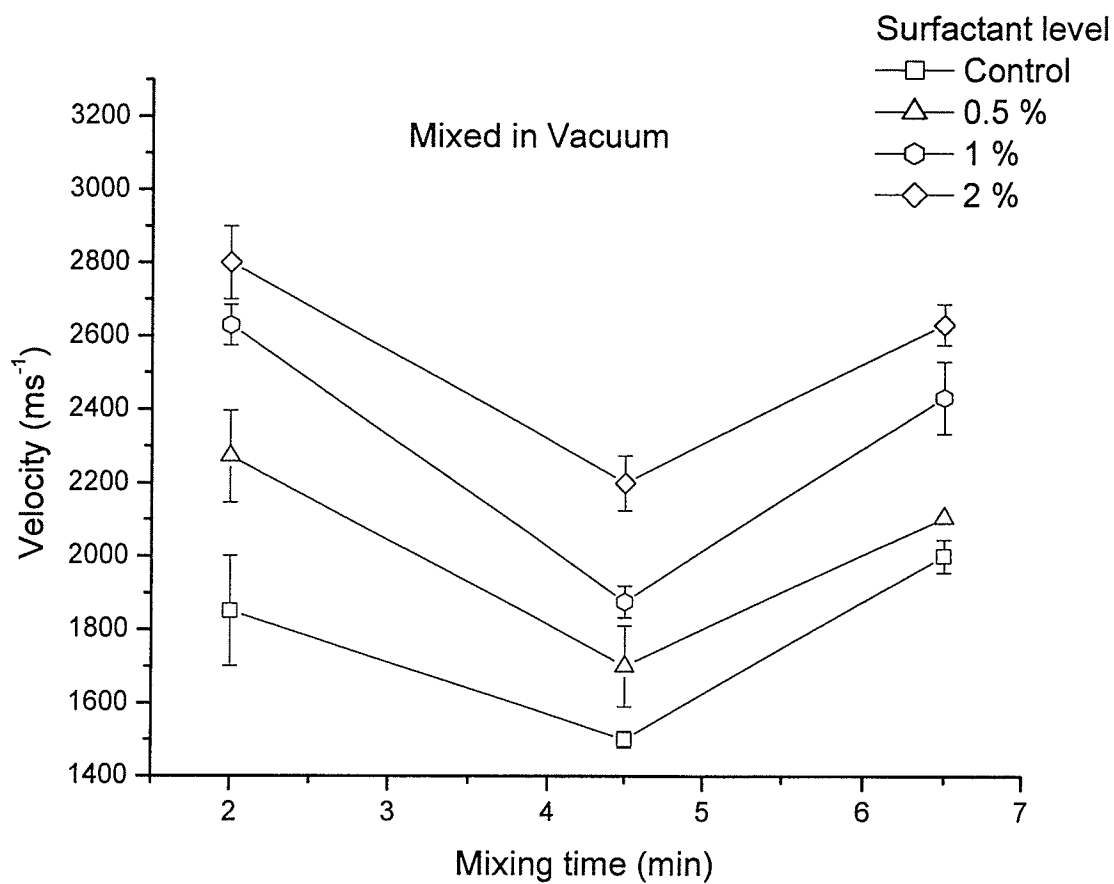


Figure. 4.12 Effect of mixing time (in vacuum) on ultrasonic velocity for doughs prepared from CWRS flour with various amounts of surfactant (% f.w.b).

4.3.3. Effects of surfactant on attenuation coefficient measurements of dough

Figures 4.13 to 4.16 show the attenuation coefficient as a function of mixing time for doughs prepared at atmospheric pressure with various amounts of surfactant. The attenuation coefficient of dough mixed in air generally increased with mixing time as the amount of air trapped in the dough increases (Figures 4.13 and 4.15). Increase in mixing time had a significant effect ($p < 0.0001$) on the attenuation coefficients of dough mixed at atmospheric pressure. The results of attenuation coefficient versus mixing time are consistent with the previous studies by Ross *et al.* (2004). Increasing the amounts of surfactant significantly reduced ($p < 0.0005$) the attenuation coefficient of the doughs. This is a distinct difference to the effect due to shortening (Figure 3.9).

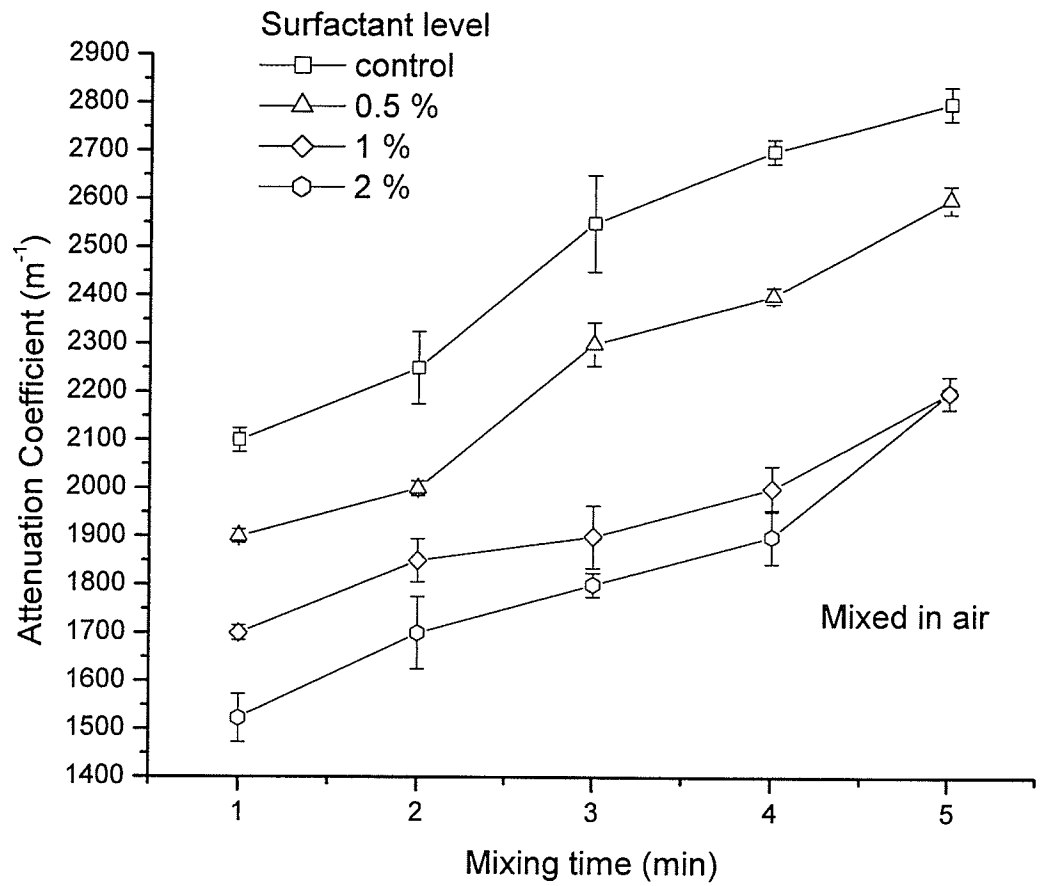


Figure 4.13 Effect of mixing time (in air) on attenuation coefficient for doughs prepared from SWS flour with various amounts of surfactant (% f.w.b).

The relationship between the attenuation coefficients of dough prepared under vacuum for different mixing times for doughs having various amounts of surfactant is shown in Figure 4.14 and 4.16. It can be observed that mixing time had a significant effect ($p < 0.0001$) on the attenuation of doughs. The

changes in attenuation coefficient of doughs are associated with the changes in dough matrix as the amount of gas cells in the dough is very much less, as can be determined from the density graphs. Increasing the amount of surfactant has significantly decreased ($p < 0.0001$) the attenuation coefficient of the doughs.

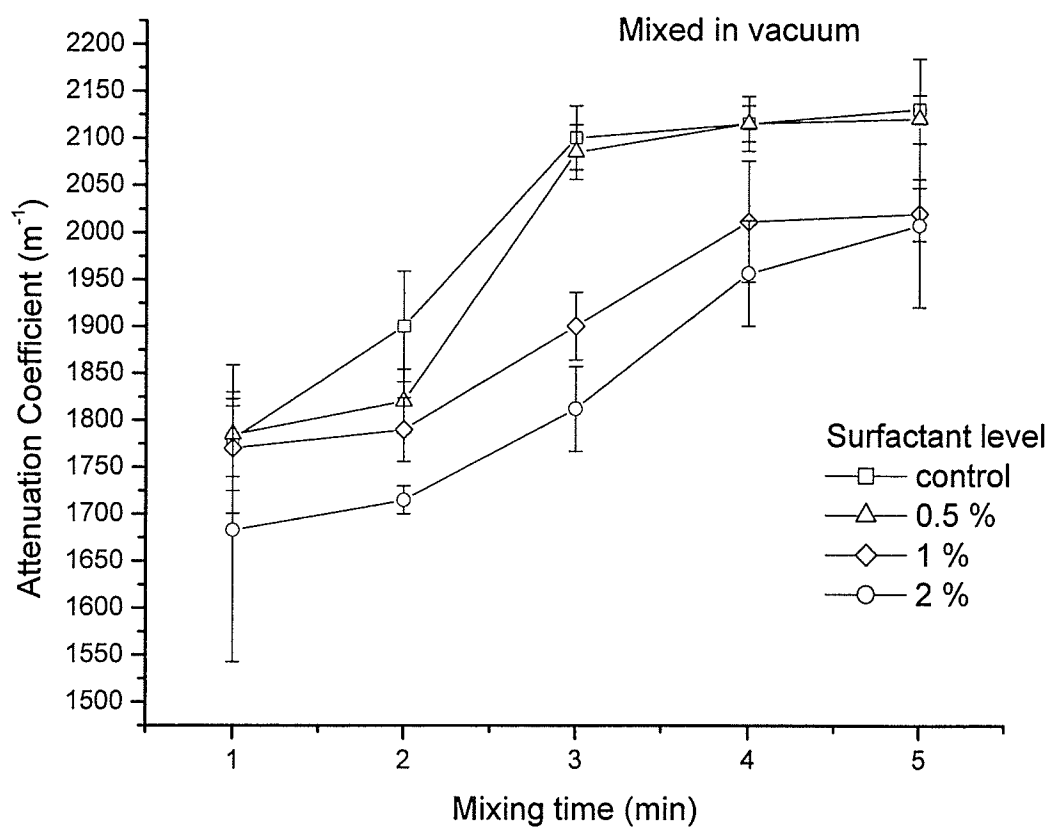


Figure 4.14 Effect of mixing time (in vacuum) on attenuation coefficient for doughs prepared from SWS flour with various amounts of surfactant (% f.w.b).

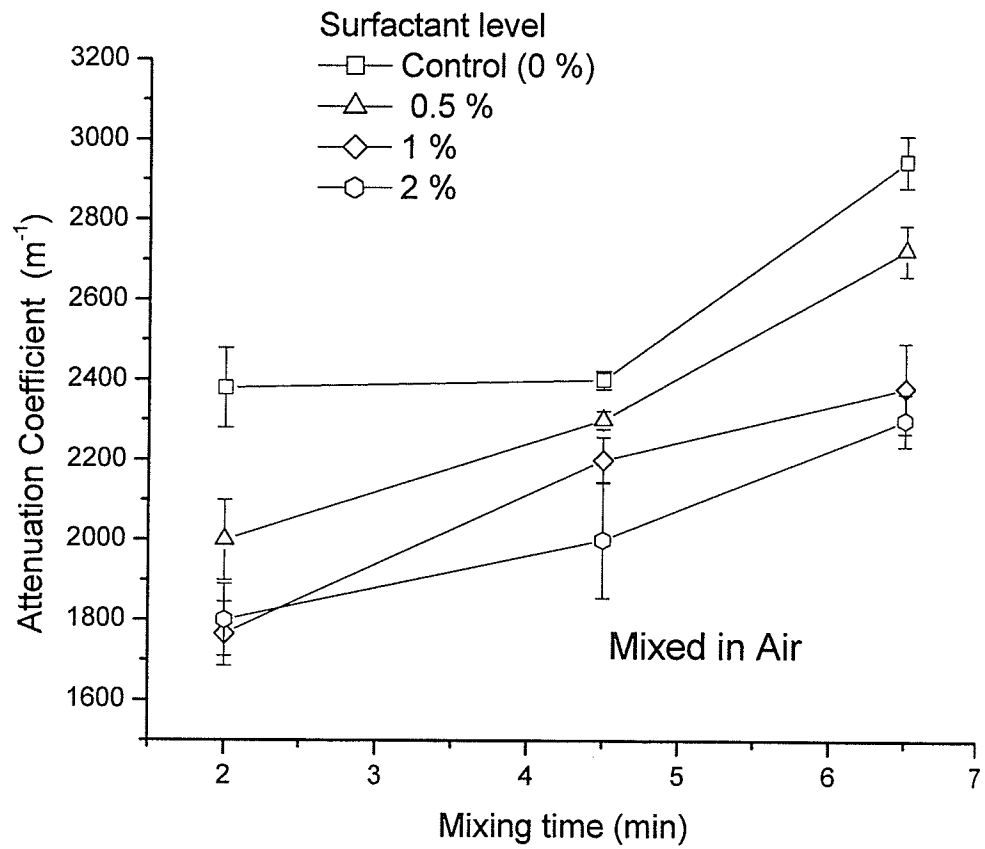


Figure 4.15 Effect of mixing time (in air) on attenuation coefficient for doughs prepared from CWRS flour having various amount of surfactant (% f.w.b).

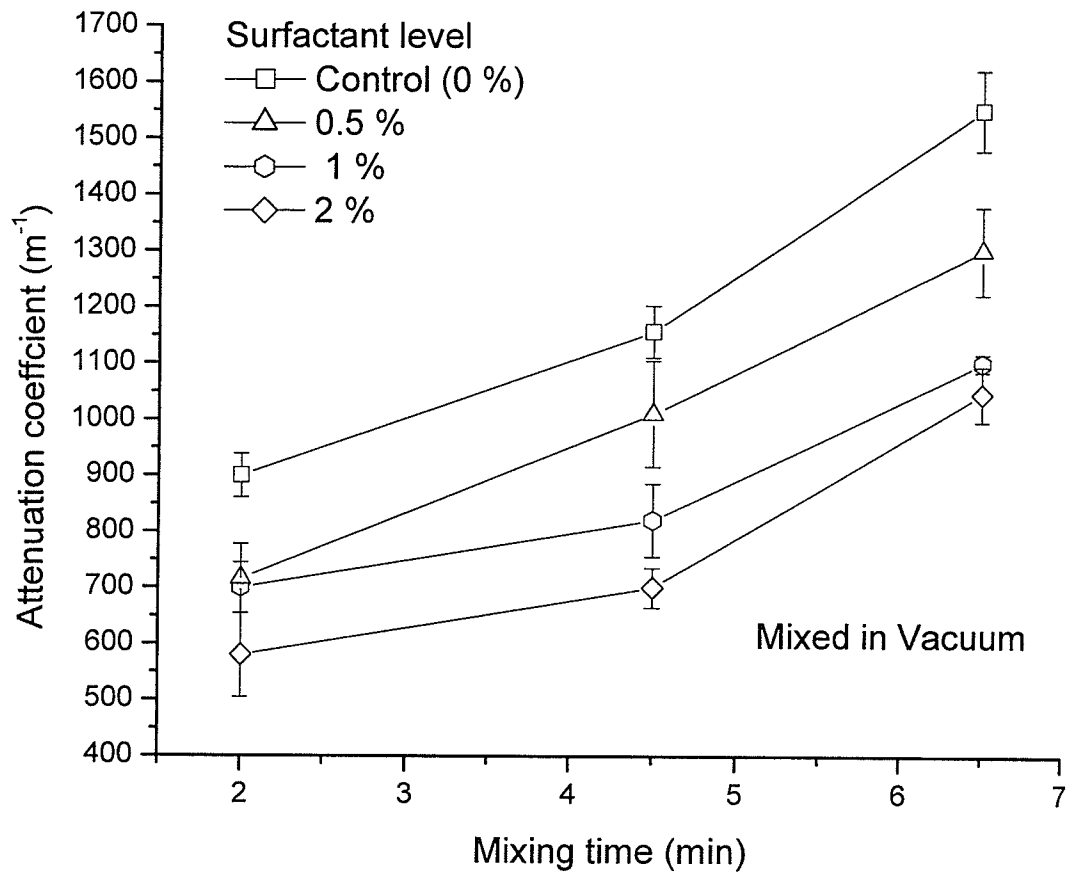


Figure 4.16 Effect of mixing time (in vacuum) on attenuation coefficient for doughs prepared from CWRS flour with various amounts of surfactant (% f.w.b).

4.4. Discussion

The relationship between dough density and the mixing time for doughs prepared separately from two different types of flours (SWS and CWRS flour) is shown in Figure 4.5 and 4.7. These experiments confirm, and are consistent with results of Baker and Mize (1946), that for both types of flours (SWS and CWRS flour) there is a progressive gas occlusion in the doughs mixed at atmospheric pressure as noticed by the reduction in dough density with time. During the initial mixing times (i.e., doughs that are undermixed), as the added water is abundant it quickly hydrates the surface flour particles. During this time the system (mixture of flour and water) is quite fluid so the mixograph curve remains low as there is less resistance to extension (Figure in the Appendix). The flour particles rub against each other, to the pin of the mixer and the surface of the mixer and more unhydrated flour particles are exposed to the water molecules. As the dough is underdeveloped the air in the dough escapes through the hydrated mass of the dough so that higher dough density values are apparent. As the dough mixing continues the gluten network begins to develop from the work input of the mixer so that by the time optimum mixing time is reached all the hydrated gluten proteins are transformed into a continuous film in which the starch granules are embedded. The continuous sheet-like layers of dough are sheared and folded by the mixer blades and during which the gas cells are formed resulting in reduction of dough density.

Irrespective of the type of flour (SWS or CWRS flour), addition of surfactant (0.5, 1, 2% surfactant) to the doughs lowered the dough density when compared to the control doughs (0% surfactant). As the density of the surfactant is lower ($\rho=940 \text{ kgm}^{-3}$) (Rao *et al.*, 1992), it reduces the density of doughs compared to the control doughs having no surfactant. Effects of adding surfactant on the dough density were less substantial when compared to mixing time. For example, for the doughs prepared from SWS flour there were 20 units reduction in the dough density when 2% of surfactant was added to the control dough (0% surfactant), but there were 80 units of dough density reduction when the control dough was mixed from 1 min (undermixed) to 5 min (overmixed). There were similar differences in effects of mixing time and surfactant addition on dough density reduction for doughs prepared from CWRS flour.

To have a better understanding of gas-free dough density, or the matrix density of the dough, the dough densities were converted into volume fraction of bubbles in the dough. Figure 4.17 shows a typical graph used for determining the gas free dough density by linear extrapolation between the dough densities for dough prepared from SWS flour when mixed at atmospheric pressure and under vacuum. According to Campbell *et al* (1998) the decrease in dough density as a function of headspace pressure of the mixing bowl during dough mixing is due to the decrease in the number of gas

cells per unit volume of the dough. He supported his hypothesis based on the measurement of bubble size distribution using microscopy. Elmehdi (2001) also showed the same linear trend (decrease in dough density with the increase in the headspace pressure of the mixing bowl during dough mixing) in results which are consistent with Campbell *et al* (1998). Based on the same hypothesis, the gas free density of the dough is obtained from the intercept at $P=0$ atm. The values of dough density in Figure 4.17 are the average density obtained by measuring the density from ten sub-samples of dough.

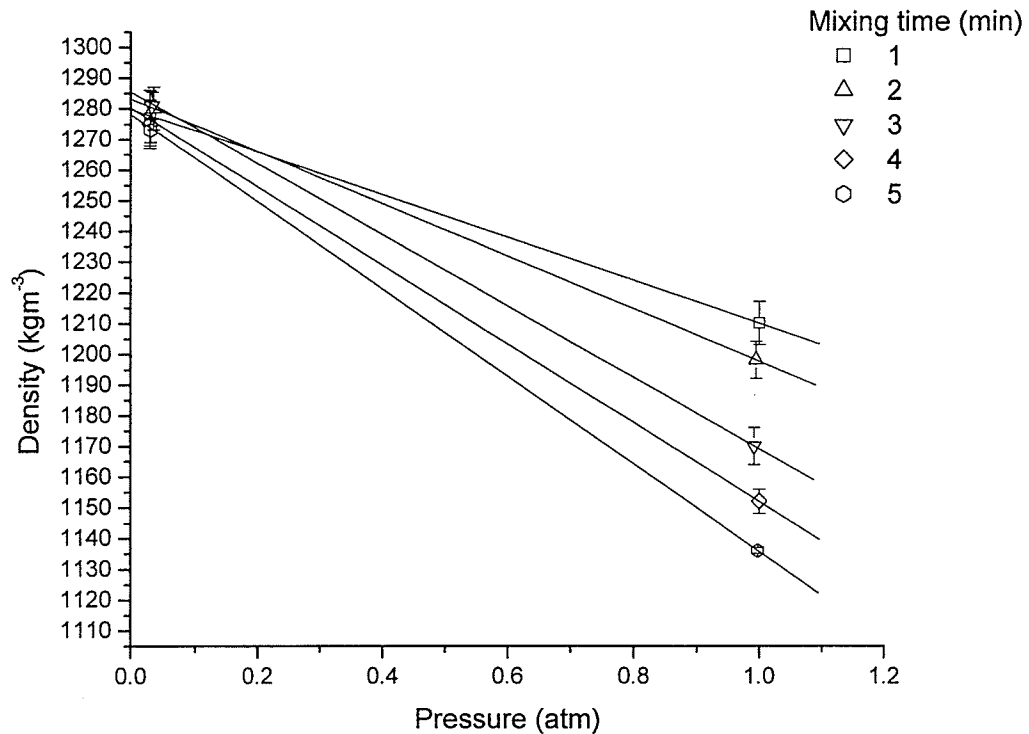


Figure 4.17 Typical graph of density of control dough prepared from SWS flour as a function of mixer headspace pressure (atm) for a given mixing time (min) to determine the gas free dough density.

The relationships between the surfactant level, mixing time and the gas free dough density are shown in Table 4.1. For example, the gas-free dough density (ρ_m) for control dough prepared from SWS flour mixed at 3 min is 1282 kgm^{-3} .

Table 4.1 Effect of surfactant level (f.w.b %) and mixing time on gas free dough density of doughs prepared from SWS flour.

Surfactant level (%)	1 min	2 min	3 min	4 min	5 min	Mean Density (kgm^{-3})
Control	1280	1285	1282	1278	1283	1282 ^a
0.5	1281	1278	1279	1280	1279	1279 ^b
1	1278	1274	1278	1276	1275	1276 ^c
2	1270	1280	1275	1270	1263	1271 ^d

Mean density values are obtained by averaging the density values for doughs mixed at various mixing times (1, 2, 3, 4 and 5 min). Numbers with different superscripts are significantly different.

From Table 4.1 we can observe that for the doughs prepared from SWS flour, the gas free dough density does not change much with mixing time. For example, for control doughs the gas-free dough density for doughs mixed for 1 and 5 min is 1280 kgm^{-3} and 1283 kgm^{-3} respectively. The addition of surfactant has a significant influence on the gas-free dough density values. For

example there is a significant difference in mean density values for control dough (1282 kgm⁻³) and the dough having 2% surfactant (1271 kgm⁻³). The effects of mixing time and the surfactant added on the gas-free dough density for doughs prepared from CWRS flour were consistent with the results obtained for the doughs prepared from SWS flour. The relationship between the gas-free dough density values for doughs prepared from CWRS flour having surfactant and mixing time is shown in Table 1a in the Appendix. A difference in gas free dough densities was observed for dough prepared from CWRS flour in chapters 3 and 4.

This difference may have occurred because the flour obtained for performing the experiments were from wheat grown in two different years.

The void fraction (air content) in the dough can be determined based on the dough density and gas free dough density values as shown in the equation:

$$\phi = 1 - (\rho / \rho_m) \quad \dots\dots\dots (4.4.)$$

Here ρ is the density of dough at a given mixing time for a given surfactant level; ρ_m is the matrix density (gas-free dough density) for a dough obtained (Table 4.1) at a particular mixing time. This relationship is used to convert the mixing time (min) to void fraction, thereby simplifying the

interpretation of ultrasonic results as a function of the aeration properties of the dough.

4.4.1. Velocity measurements

Figure 4.18 shows the relationship between the ultrasonic velocity as a function of void fraction (ϕ) (calculated from Eqn. 4.4) for doughs prepared from SWS flour. The data is made up from two groups. The first group, dough mixed under vacuum having higher velocities with void fractions ranging between ($0.003 < \phi < 0.05$). The second group is the data of doughs mixed at atmospheric pressure with lower values of ultrasonic velocities, where the void fractions are of much wider range ($0.055 < \phi < 0.115$) due to the greater air entrainment during dough mixing. There is a rapid decrease in the ultrasonic velocity with a small increase in the void fractions at lower void fraction range. For example for control doughs prepared from SWS flour the ultrasonic velocity reduced from 2800 to 190 ms^{-1} for void fractions in the range of $0.003 < \phi < 0.05$. At higher ϕ values the decrease in velocity with increases in ϕ is less rapid, for example, for control doughs the velocity reduced from 190 to 100 ms^{-1} for void fractions in the range of $0.05 < \phi < 0.13$. Thus the velocity at this frequency (50 kHz) is extremely sensitive to the presence of gas cells in the dough especially at low ϕ . Similar results were obtained for doughs

prepared from CWRS flours as shown in Figure 4.19. The ultrasonic velocities decreased with the increase in void fractions for doughs prepared from CWRS flour.

The current data on the ultrasonic velocity measurements are consistent with the results obtained in chapter 3 (shortening paper) and with the results reported by Elmehdi *et al.* (2004). The ultrasonic values from the vacuum mixed doughs in these experiments are a bit higher than those of Elmehdi *et al.* (2004), the reason attributable to this might be the better vacuum applied to the mixing bowl during dough mixing which results in the lower ϕ values for vacuum mixed doughs. Another possible reason might be due to the decrease in the moisture content of the dough as the mixing pressure was reduced further than that attained by Elmehdi *et al.* (2004). Stiffening of the dough was noticed by both Elmehdi *et al.* (2004) and Létang *et al.* (2001) as the moisture content in the dough was reduced as dough was mixed at lower headspace pressure. Elmehdi *et al.* (2004) reported a 3.2% loss of moisture when the doughs were mixed at atmospheric pressure and 6.7% loss in the moisture when mixed under vacuum (0.13 atm). Irrespective of the type of flour (SWS or CWRS flour) addition of surfactant resulted in the increase in ultrasonic velocities. Addition of surfactant increases the stiffness of the dough matrix. Tu and Tsen (1978) showed that the complex formed between the surfactant and gluten protein in the flour (both stronger and weaker flours) makes the dough stiffer. But air entrainment in the doughs

during mixing reduces the stiffness of doughs (or matrix). This can be shown with the decrease in velocity as the mixing time is increased. Baker and Mize (1946) showed that the air entrainment capacity of flour reduces with the increase in the flour strength for a particular mixing time. Campbell *et al* (1993) and Chamberlain *et al* (1970) also showed that the good breadmaking flour offer greater resistance to gas occlusion than the poor breadmaking flours. This effect can be seen when comparing Figures 4.5 and 4.7 where the rate at which density decreases with mixing time is greater for dough made from SWS flour. The lower density for CWRS flour mixed under vacuum (Figure 4.8 compared to Figure 4.6) reflects the greater amount of water added to the stronger breadmaking flour.

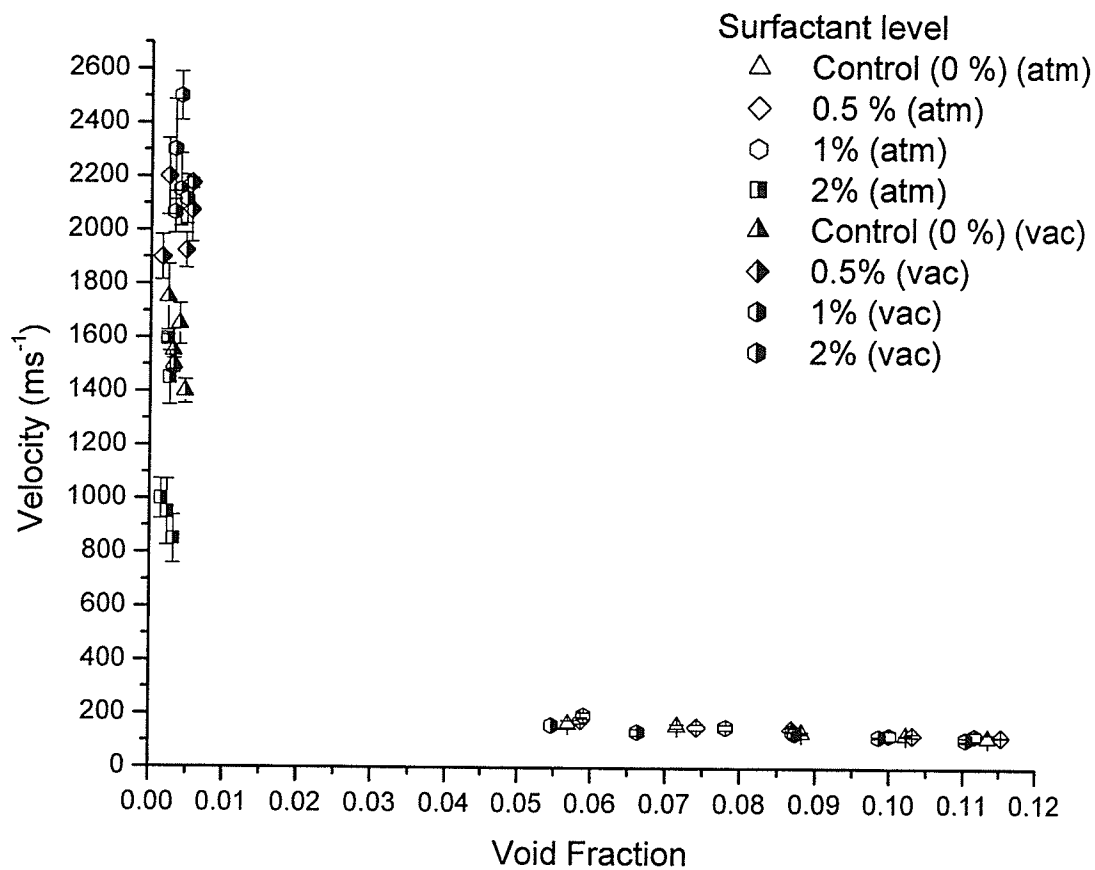


Figure 4.18 Ultrasonic velocity in dough as function of void fraction (ϕ), for doughs prepared from SWS flour with different amounts of surfactant.

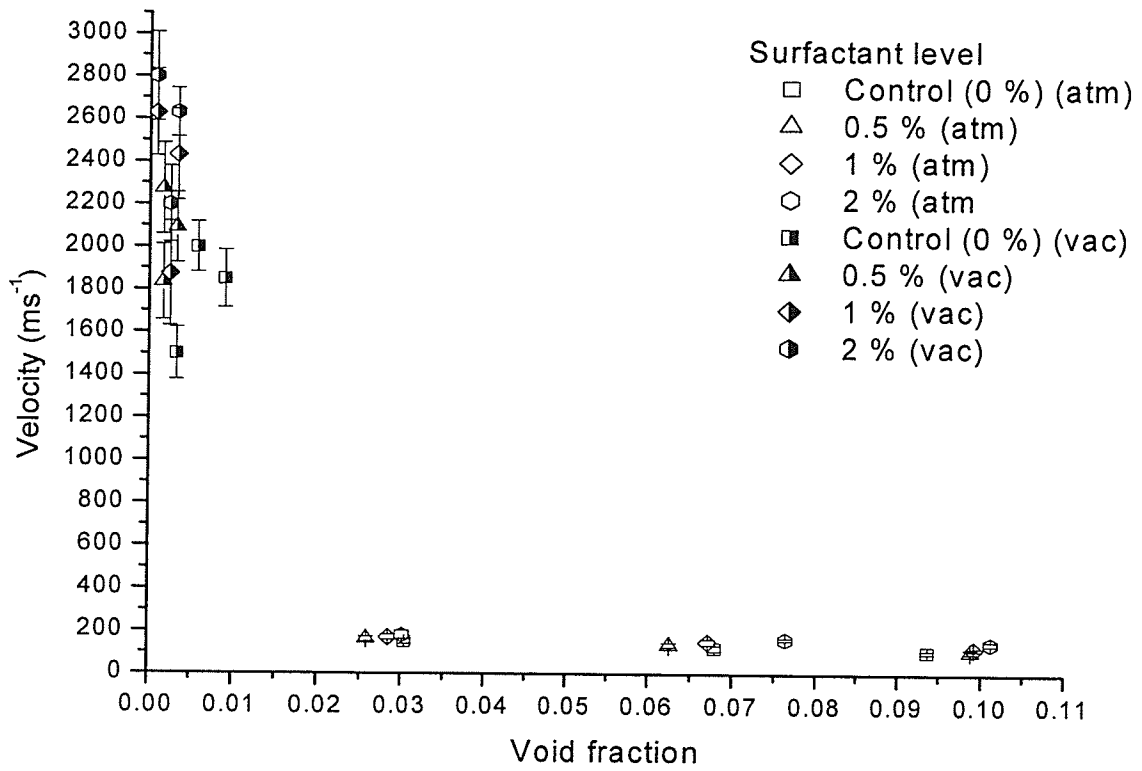


Figure 4.19 Ultrasonic velocity in dough as function of void fraction (ϕ), for doughs prepared from CWRS flour with different amounts of surfactant.

4.4.2. Attenuation measurements

Figure 4.20 and 4.21 shows the relationship between the attenuation coefficient and void fraction (ϕ) for the doughs prepared separately from SWS and CWRS flour, respectively. Irrespective of the type of flour (SWS or CWRS flour) the attenuation coefficient increases with the amount of gas cells in the dough during mixing. For both types of flour (SWS and CWRS flour), the attenuation coefficient values were lower for doughs mixed under vacuum as there were less gas cells in the dough. Doughs mixed under vacuum absorb less acoustic energy and there is less scattering (Elmehdi *et al.* (2004)). The values of the attenuation coefficient at $\phi=0$ is the amount by which the dough matrix contributes to the total attenuation coefficient. Irrespective of the type of flour, addition of surfactant to the dough decreased the attenuation coefficient when compared to the control doughs having no surfactant. From the density results, it was clear that surfactant does not aid much in air entrainment, but there is a clear indication of changes in dough matrix with the addition of surfactant to the dough during the dough mixing.

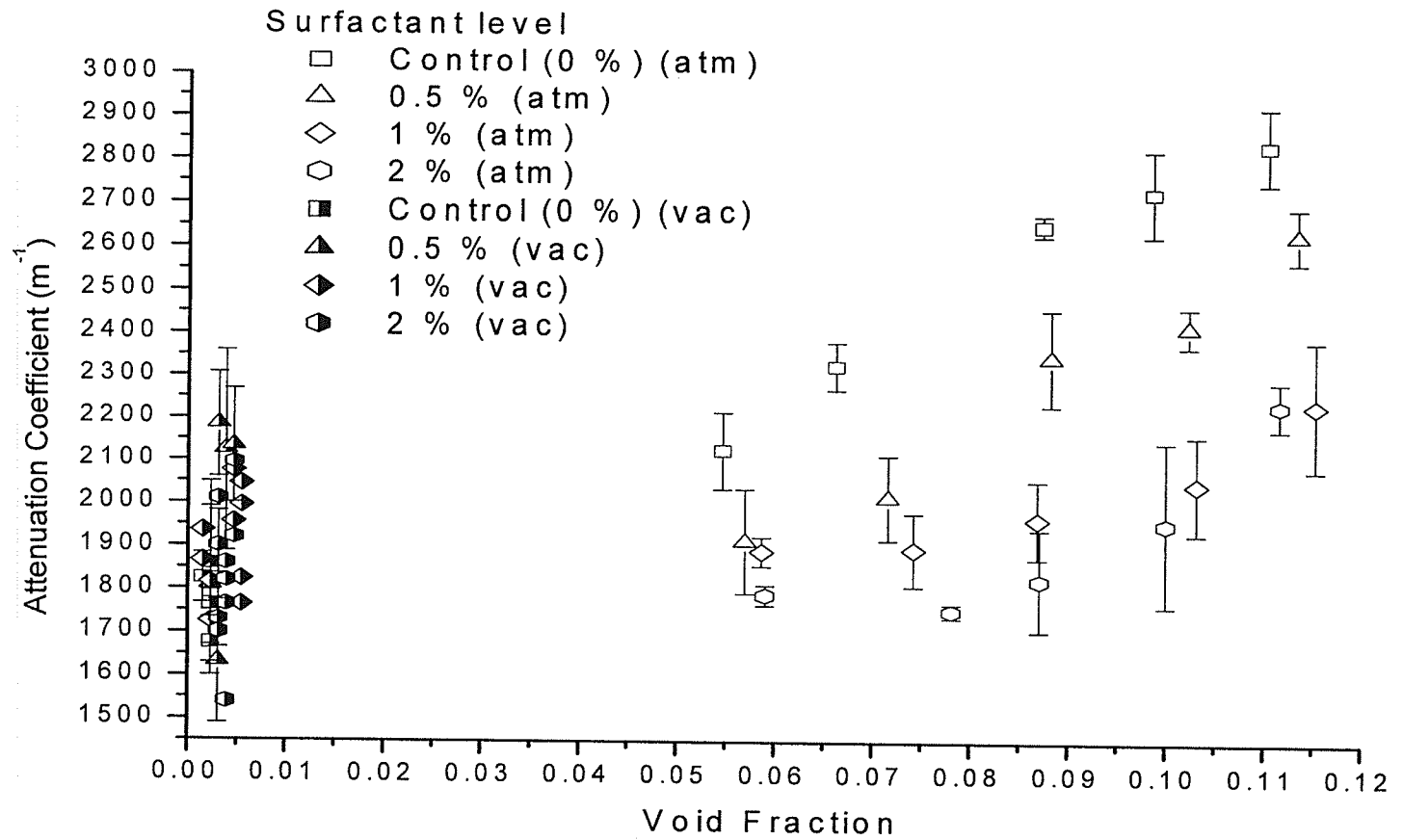


Figure 4.20 Attenuation coefficient of dough prepared from SWS flour as a function of void fraction (ϕ)

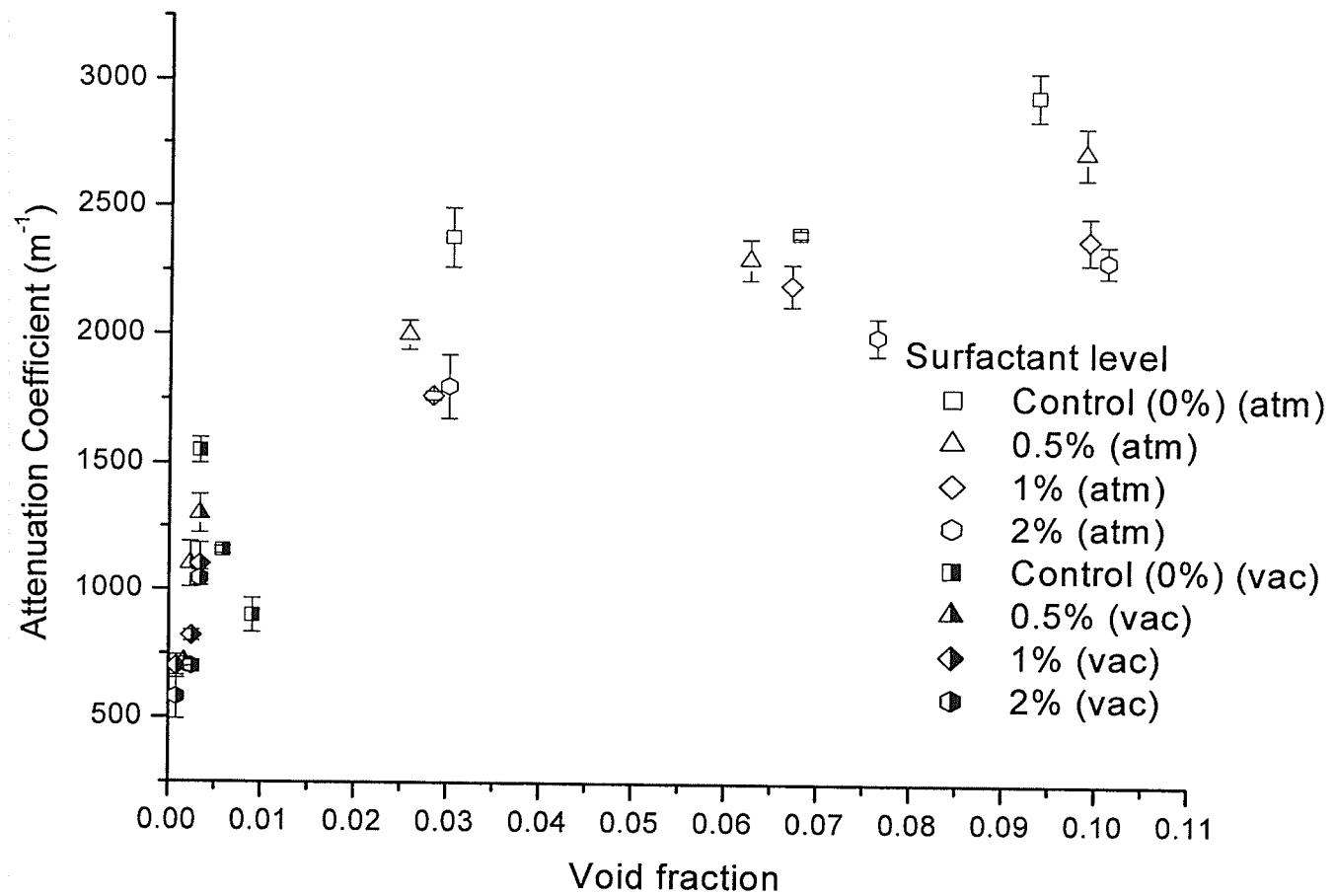


Figure 4.21 Attenuation coefficient of dough prepared from CWRS flour as a function of void fraction (ϕ).

From the attenuation data, we know that the absorption of ultrasonic energy in the dough is appreciable at 50 kHz frequency. Therefore the modulus is complex (Elmehdi *et al.*, 2004), and both velocity and attenuation contribute to the storage and loss moduli, β' and β'' . To relate these changes in ultrasonic parameters (velocity and attenuation coefficient) more directly to the mechanical properties of dough, the longitudinal elastic modulus of the doughs was calculated from the data using Eqn. 2.10 and 2.11. Figure 4.22 and 4.23 are the graphs of the change in longitudinal modulus (β' and β'') with void fraction (ϕ) for the doughs having 0 (control) and 2% surfactant prepared separately from SWS and CWRS flour respectively. The results for 0.5 and 1% surfactant are in the appendix. For both types of flour there is a considerable decrease in both moduli as void fraction increases. These results are consistent to the results found by Elmehdi *et al.* (2004), except in our case the void fraction was manipulated by mixing time at two extreme headspace pressure, rather than by headspace pressure alone. Results reported by Kidmose *et al.* (1999) and by Létang *et al.* (1999) have also indicated that there is a decrease in modulus values as the mixing time increases.

With the addition of surfactant to the control dough prepared from either types of flour (SWS or CWRS flour), the values of both moduli were higher when compared to the control doughs. The comparison of the change in β''/β'

between the control dough (0% surfactant) and dough having 2 % surfactant (both prepared from SWS flour) is shown in Figure 4.24. There is an increase in the β''/β' values with the increase in the void fractions, although changes are small for doughs mixed at atmospheric pressure. The corresponding result for CWRS flour is shown in Figure 4.25.

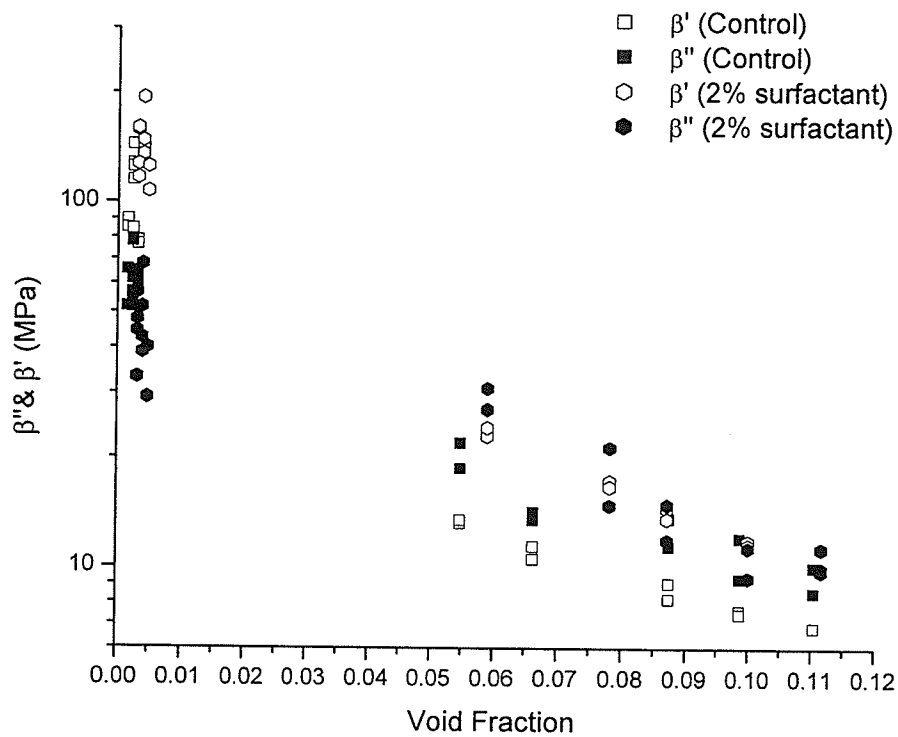


Figure 4.22 Longitudinal moduli (β'' and β') as a function of void fraction for control dough and dough having 2 % surfactant prepared from SWS flour.

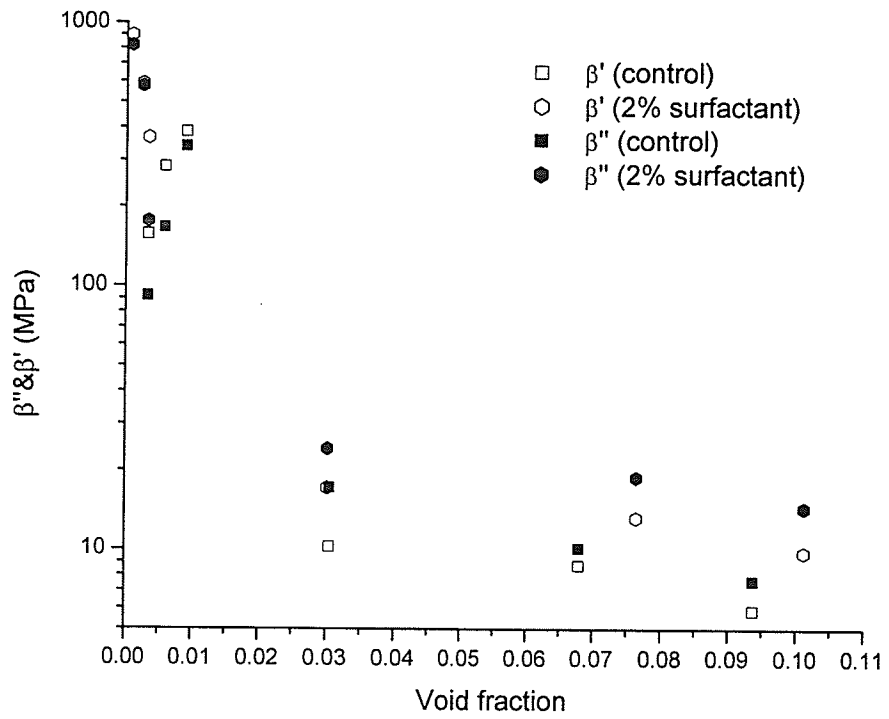


Figure 4.23 Longitudinal moduli (β'' and β') as a function of void fraction for control dough and dough having 2 % surfactant prepared from CWRS flour.

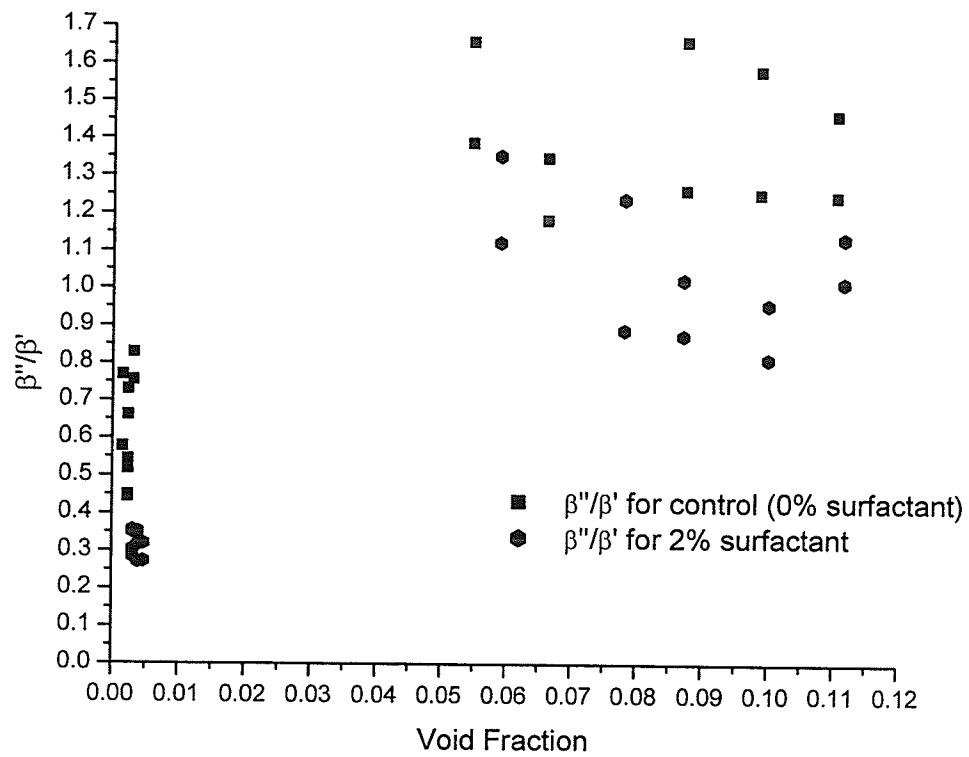


Figure 4.24 Ratio of storage and loss modulus (β''/β') as function of void fraction for dough having 0 and 2 % surfactant which were prepared from SWS flour.

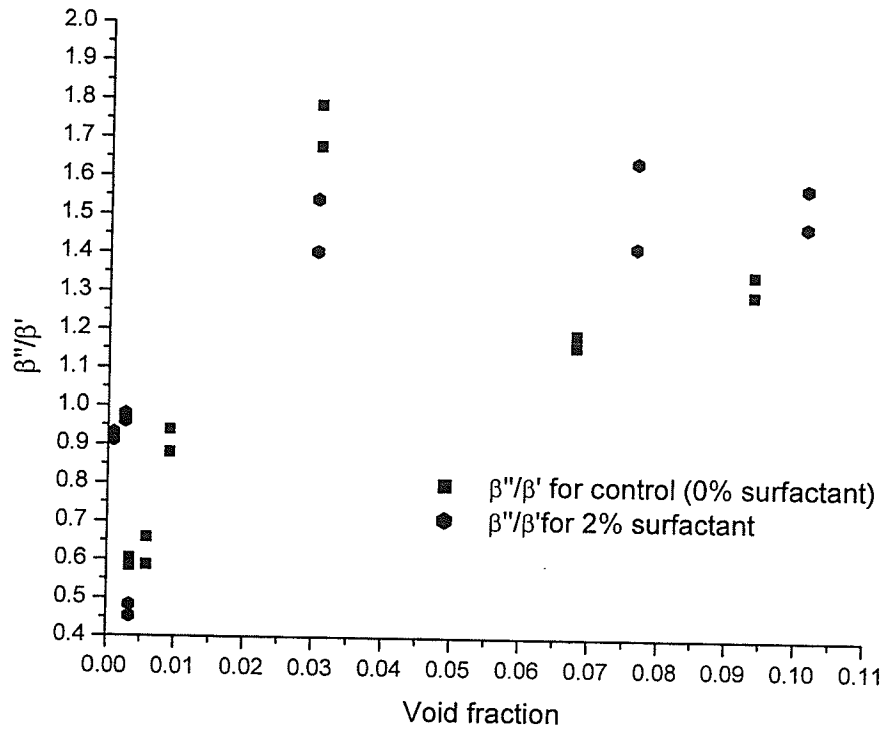


Figure 4.25 Ratio of storage and loss modulus (β''/β') as function of void fraction for dough having 0 and 2 % surfactant which were prepared from CWRS flour.

4.5. Conclusion

Low intensity ultrasound (50 kHz) was used to study the influence of mixing time and addition of surfactant on the mechanical properties of dough. The influence of mixing time and surfactant on the dough density and ultrasonic parameters (velocity and attenuation coefficient) were successfully studied for two flours differing substantially in their breadmaking potential.

In this thesis, mixing time is one of the variables that was used to vary void fraction in the dough. For doughs mixed at atmospheric pressure, the density results show that with increase of the mixing time the amount of air incorporated in the dough increases. The ultrasonic parameters are very sensitive to the presence of the gas cells entrained in the dough during mixing. The ultrasonic velocity changed drastically as the amount of gas in the dough sample varied. The velocity varied by more than an order of magnitude as the void fraction varied from $0.0024 < \phi < 0.055$. The results showed that the attenuation coefficient of dough increased with the amount of gas cells in the dough. The attenuation coefficient at $\phi=0$ can be successfully used to gain insights into the effects of the dough matrix on the mechanical properties of dough.

For both types of flour (SWS and CWRS wheat flour) addition of surfactant reduces the density of dough due to its lower density. From the experiments it can be clearly concluded that mixing time variation has more

superior effects on the gas entrainment in the dough than that of the surfactant. From the density measurements it is quite clear that addition of surfactants does not aid much in entraining air in the dough during dough mixing. From the ultrasonic measurements it is shown that addition of surfactant changes the dough matrix. Irrespective of the type of flour used for preparing the doughs (SWS or CWRS wheat flour) the longitudinal velocity of doughs having surfactant were comparatively higher compared to the control doughs (0% surfactant). The attenuation coefficient of doughs having surfactant were comparatively lower compared to the control doughs (0% surfactant).

The velocity and attenuation of a longitudinal wave propagated through the dough samples were measured and analyzed to calculate the longitudinal elastic modulus of dough, and the modulus values were significantly higher at lower void fractions. From the data it can be concluded that with the increase in mixing time which increases the void fractions in the dough significantly reduces the modulus values. The addition of surfactant increased the modulus values.

5. GENERAL DISCUSSION AND CONCLUSION

The work presented in this thesis investigated the effects of mixing time and bread making ingredients on the mechanical properties of bread dough using low-intensity ultrasound (50 kHz). In breadmaking, mixing is considered to be the most vital unit operation as it controls the nucleation of gas cells and gluten protein development. According to Lee *et al.* (2004) aeration during dough mixing plays an important role for baked loaf to have good volume, structure and texture. Dough mixing directly influences the structural integrity of bread and hence its quality.

Mixing time of dough is considered as one of the most important parameter in breadmaking as it influences the final product quality. According to Aamodt *et al.* (2003) mixing the dough to its optimum mixing time results in dough that is easy to handle (not sticky) and has optimum viscoelastic properties for achieving a good quality product. In this thesis, mixing time is one of the variable that was used to vary void fraction in the dough. For doughs mixed at atmospheric pressure, the density results shows that with increase of the mixing time the amount of air incorporated in the dough increases. The ultrasonic velocity decreases and attenuation coefficient increases with the increase in the mixing time for doughs mixed at atmospheric pressure. The change in ultrasonic velocity and attenuation coefficient with the mixing time for doughs mixed under vacuum illustrates that ultrasound is also

capable of identifying the changes in dough matrix occurring with the increase in mixing time.

For investigating the effects of bread improvers on the mechanical properties of bread dough, shortening and surfactants were used. From the density graphs it is clear that addition of shortening to the dough did not improve gas retention in the dough significantly when compared to the mixing time during dough mixing. A decrease in ultrasonic velocity and an increase in attenuation coefficient was observed with the addition of shortening. Addition of shortening dilutes the polymer concentration per unit volume during dough mixing (MacRitchie, 1983; Manley, 1983). Dilution of polymer may be the reason for changes in the ultrasonic parameters. The addition of shortening reduced the values of modulus derived from the ultrasonic parameters. According to Fu *et al.* (1997) during dough mixing the addition of shortening gives a plasticizing effect to the dough which in turn affects the mechanical properties of dough.

According to Campbell *et al.* (2001) addition of surfactant does not significantly aid gas cell nucleation during dough mixing. Addition of surfactant to the dough reduced the dough density as the density of surfactant was low. From the density results obtained in this thesis, it is clearly visible that surfactant does not aid superior incorporation of gas cells during dough mixing. The ultrasonic results (longitudinal velocity and attenuation coefficient) were different compared to shortening results with the addition of surfactant to the dough during dough mixing. The ultrasonic velocity increased and the

attenuation coefficient decreased with the addition of surfactant to the control dough having 0% surfactant, a result that contrasts markedly with the effect of shortening. According to Stauffer (1990), the interaction of surfactant with the gluten proteins changes the rheological properties of dough. The significant difference in the gas free dough density values between doughs with and without surfactants suggest that addition of surfactant may have an effect on the dough matrix. It was also a result consistent across two flours of very different breadmaking quality. Irrespective of the type of flour (CWRS (good breadmaking) and SWS (poor breadmaking) wheat flour), with the increase in amount of surfactant in the dough, there was an increase in the ultrasonic velocity and a decrease in the attenuation coefficient. The bonding between the lipophilic tail of the surfactant and the hydrophobic regions of the gluten proteins during dough mixing (Stauffer, 1990) may result in changes of the ultrasonic velocity and attenuation coefficient. Increase in surfactant level in the dough results in an increase in the binding between the surfactant and the gluten proteins. The difference in the ultrasonic velocity and the attenuation coefficient values between the good (CWRS, approximately 12.5% protein) and poor (SWS, approximately 9% protein) breadmaking flour is due to the presence of higher protein content in the good breadmaking wheat flour.

Our experimental results have shown that both the ultrasonic velocity and attenuation coefficient are sensitive to the presence of gas bubbles in the dough. Ultrasound can be successfully used to investigate the effects of gas cells on the mechanical properties of bread dough. A general conclusion

related to the addition of shortening and surfactant to the dough is that the presence of bread improvers (shortening or surfactant) in the bread dough affects matrix properties more than they have an effect on improved aeration of the dough by mixing.

LITERATURE CITED

- Aamodt, A., Magnus, E. M., and Faegstad, E. M. 2003. Effect of flour quality, ascorbic acid, and DATEM on dough rheological parameters and hearth loaves characteristics. *Journal of Cereal Science*. 68: 2201-2209.
- Amemiya, J. I. and Menjivar, J. A. 1992. Comparison of small and large deformation measurements to characterize the rheology of wheat flour doughs. *Journal of Food Engineering*. 16:91-108.
- Attenburrow, G., Barnes, D. J., Davies, A. P., and Ingman, S. J. 1990. Rheological properties of wheat gluten. *Journal of Cereal Science*. 12: 1-14.
- Autio, K., Flander, L., Kinnunen, A. and Heinonen, R. 2001. Bread quality relationship with rheological measurements of wheat flour dough. *Cereal Chemistry*. 78:654-657.
- Azizi, M. H. and Rao, G. V. 2004. Effect of surfactant gels on dough rheological characteristics and quality of bread. *Critical Reviews in Food Science and Nutrition*. 44:545-552.
- Bailey, C. H. 1941. A translation of Beccari's lecture: Concerning Grain". *Cereal Chemistry*. 18:555-561.
- Baker. J. C. and Mize, M. D. 1937. Mixing doughs in vacuum and in the presence of various gases. *Cereal Chemistry*. 14:721-734+.
- Baker. J. C. and Mize, M. D. 1941. The origin of the gas cell in bread dough. *Cereal Chemistry*. 18:19-33.

- Baker, J. C. and Mize, M. D. 1942. The relation of fats to texture, crumb and volume of bread. *Cereal Chemistry*. 19: 84-94.
- Baker, J. C. and Mize, M. D. 1946. Gas occlusion during dough mixing. *Cereal Chemistry*. 23:39-51.
- Baldwin, R. R., Johansen, R. G., Keough, W. J., Titcomb, S. T. and Cotton, R. H. 1963. Continuous breadmaking: The role that fat plays. *Cereal Science Today*. 8: 273-276.
- Baldwin, R. R., Titcomb, S. T., Johansen, R. G., Keough, W. J., and Koedding, D. 1965. Fat systems for continuous mix bread. *Cereal Science Today*. 10:42-49.
- Baltsavias, A., Jurgens, A., and T. van Vilet, 1997. Rheological properties of short doughs at small deformation. *Journal of Cereal Science*. 26:289-300
- Basaran, A. and Gocmen, D. 2003. The effects of low mixing temperature on dough rheology and bread properties. *European Food Research Technology*. 217:134-142.
- Benedito, J., Carcel, J., Sanjuan, N. and Mulet, A. 2000. Use of ultrasound to assess cheddar cheese characteristics. *Ultrasonics*. 38:727-730.
- Berger, K. G., Jewell, G. G. and Pollitt, R. J. M. 1979. Oils and fats. In: *Food Microscopy*. Vaughan J. D. (ed.). Academic Press, London. pp. 445-497.

- Berland, S. and Launay, B. 1995. Rheological properties of wheat flour doughs in steady and dynamic shear: Effect of water content and some additives. *Cereal Chemistry*. 72:48-52.
- Bernadin, J. E. and Kasarda, D. D. 1973. Hydrated protein fibrils from wheat endosperm. *Cereal Chemistry*. 50:529-533
- Blitz, J. 1963. *Fundamentals of Ultrasonics*. Butterworths. London, Great Britain.
- Bloksma, A. H. 1975. Thiol and disulfide groups in dough rheology. *Cereal Chemistry*. 52:170-180.
- Bloksma, A. H. 1990. Dough structure, dough rheology and baking quality. *Cereal Foods World*. 35: 237-244.
- Bloksma, A. H. and Bushuk, W. 1988. Rheology and chemistry of dough in: *Wheat: Chemistry and Technology-II*. eds. Pomeranz, Y. American Association of Cereal Chemists. St. Paul, MN.
- Bohlin, L. A. 1980. A theory of flow as a cooperative phenomenon. *Journal of Colloid Interface Science*. 74:423-434.
- Bohlin, L. A. and Carlson, T. L. G. 1980. Dynamic viscoelastic properties of wheat flour dough: dependence on mixing time. *Cereal Chemistry*. 57:174-177.
- Bohn, L. J. and Bailey, C. H. 1937. Effects of fermentation, certain dough ingredients, and proteases upon the physical properties of flour doughs. *Cereal Chemistry*. 14: 335-348.

- Brooker, B. E. 1996. The role of fat in the stabilization of gas cells in bread dough. *Journal of Cereal Science*. 24:187-198.
- Bushuk, W. 1985. Rheology: theory and application to wheat flour doughs. *Rheology of wheat products* (pp.1-26). American Association Cereal Chemists. St. Paul, MN.
- Bushuk, W. 1986. Wheat: Chemistry. *Cereal Foods World*. 31: 218-227.
- Bushuk, W. 1993. Wheat flour proteins: Composition, structure and functionality in breadmaking. *Polish Journal of Food and Nutrition Sciences*. 43: 5-24.
- Bushuk, W. and Kawka, A. 1990. Chemical reactions and interactions in dough. Pages 8-28 in: *Interactions of Cereal Components and Their Implications for the Future*. R Lasztity and R. C. Hosney (eds). Department of Biochemistry and Food technology. Technical University of Budapest. Budapest. Hungary.
- Bushuk, W. and MacRitchie, F. 1989. Wheat proteins: Aspects of structure that determine breadmaking quality. In: *Protein Quality and the Effects of Processing*. Dekker, New York, NY.
- Bushuk, W. and Tsen, C. C. 1968. Reactive and total sulfhydryl and disulfide contents of flours of different mixing properties. *Cereal Chemistry*. 45:58 - 62.
- Bushuk, W., Tsen, C. C. and Hlynka, I. 1968. The function of mixing in breadmaking. *Bakers Digest*. 42: 7-9.

- Campbell, G. M. and Mougeot, E. 1999. Creation and characterisation of aerated food products. *Trends in Food Science and Technology*. 10: 283-296.
- Campbell, G. M., Rielly, C. D., Fryer, P. J. and Sadd, P. A. 1991. The measurement of bubble size distribution in an opaque food fluid. *Transactions of Institution of Chemical Engineers, Food and Bioproducts Processing*. 69:67-76.
- Campbell, G. M., Rielly, C. D., Fryer, P. J. and Sadd, P. A. 1993. Measurement and interpretation of dough densities. *Cereal Chemistry*. 70: 517-521.
- Campbell, G. M., Rielly, C. D., Fryer, P. J. and Sadd, P. A. 1998. Aeration of bread dough during mixing: effect of mixing dough at reduced pressure. *Cereal Foods World*. 43:163-167.
- Campbell, G. M., Herrero-Sanchez, R., Payo-Rodriguez, R., and Merchan, M. L. 2001. Measurement of dynamic density and effect of surfactant and flour type on the aeration during mixing and gas retention during proofing. *Cereal Chemistry*. 78:272-277.
- Carlson, T. and Bohlin, L. 1978. Free surface energy in the elasticity of the wheat flour doughs. *Cereal Chemistry*. 55: 539-544.
- Cauvain, S. P. 2000. Principles of dough formation: it's got form. *European Baker*. 38: 24-28.
- Cauvain, S. P., Whitworth, M. B., and Alava, J. M. 1999. The evolution of bubble structure in the bread doughs and its effect on the bread

- structure, in *Bubbles in Food*, ed by Campbell, G. M., Webb, C., Pandiella, S. S. and Niranjana, K. Eagan Press, Minneapolis, MN.
- Chamberlain, N., Collins, T. N., and Redman, B. I. 1970. The Chorleywood bread process: Effect of reduced pressure during mixing. FMBRA report 40. Flour Millers and Bakers Research Association. Chorleywood, UK.
- Chung, O. K. and Pomeranz, Y. 1979. Recent trends in usage of fats and oils as functional ingredients in the baking industry. *Journal of American Oil Chemist Society*. 60: 1848-1860.
- Chung, O. K., Shogren, M. D., Pomeranz, Y. and Finney, K. F. 1981. Defatted and reconstituted wheat flours. VII. The effects of 0-12% shortening (flour basis) in bread making. *Cereal Chemistry*. 58:69 - 73.
- Collar, C., Armero, E., and Martinez, J. C. 1998. Lipid binding of formula bread doughs. Relationships with dough and bread technological performance. *Zeitschrift fur Lebensmittel Untersuchung und Forschung*. 207:110-121.
- Coupland, J. N. 2004. Low intensity ultrasound. *Food Research International*. 37: 537-544.
- Cumming, D. B. and Tung, M. A. 1975. Dynamic shear behaviour of commercial wheat gluten. *Canadian Institute of Food Science and Technology Journal*. 8: 206-210.
- Cuq, B., Gontard, N. and Guilbert, S. 1998. Proteins as agricultural polymers for packaging production. *Cereal Chemistry*. 75:1-9.

- D'Amico, D. J., Silk, T. M., Wu, J. R. and Guo, M. R. 2006. Inactivation of microorganisms in milk and apple cider treated with ultrasound. *Journal of Food Protection*. 69: 556-563.
- Dackevitch, T., and Autran, J. C. 1989. Prediction of baking quality of bread wheats in breeding programs by size exclusion high performance liquid chromatography. *Cereal Chemistry*. 66: 448-456.
- Danno, G., and Hosney, R. C. 1982. Effect of sodium chloride and sodium dodecyl sulfate on the mixograph properties. *Cereal Chemistry*. 59: 202-204.
- Dempster, C. J. and Hlynka, I. 1958. Some effects of mixing on physical properties of dough. *Cereal Chemistry*. 35: 438-455.
- Dobraszczyk, B. J. and Morgenstern, M. 2003. Rheology and the breadmaking process. *Journal of Cereal Science*. 38: 229-245.
- Dobraszczyk, B. J., and Roberts, C. A., 1994. Strain hardening and dough gas cell wall failure in biaxial extension. *Journal of Cereal Science*. 20: 265-274.
- Dogan, N., McCarthy, M. J. and Powell, R. L. 2005. Application of an in-line rheological characterization method to chemically modified and native corn starch. *Journal of texture Studies*. 36.: 237-254.
- Dreese, P. C. Faubion, J. M., and Hosney, R. C. 1988. Dynamic rheological properties of flour, gluten and gluten-starch doughs. Effect of various processing and ingredient changes. *Cereal Chemistry*. 65: 354-359.

- Eliasson, A. C. 1990. Rheological properties of cereal proteins. Pages 67-110 in: Dough Rheology and Baked Product Texture. H. Faridi and J. M. Faubion eds. AVI Van Nostrand Reinhold, New York.
- Eliasson, A. C. and Larsson, K. 1993. Cereals in Breadmaking, a Molecular Colloidal Approach. Marcel Dekker, Inc., New York, NY. 376 pp.
- Elmehdi, H. M. 2001. An ultrasonic investigation of the effect of voids on the mechanical properties of bread dough and role of gas cells in determining the cellular structure of freeze-dried breadcrumb. Ph. D Thesis, University of Manitoba, Winnipeg, MB.
- Elmehdi, H. M., Page, J. H. and Scanlon, M. G. 2003. Monitoring dough fermentation using acoustic waves. Transactions of the Institution of Chemical Engineers. 81:217-223.
- Elmehdi, H. M., Page, J. H. and Scanlon, M. G. 2004. Ultrasonic investigation of the effect of mixing time under reduced pressure on the mechanical properties of bread dough. Cereal Chemistry. 81:504-510.
- Ewart, J. A. D. 1968. A hypothesis for the structure and rheology of glutenin. Journal of the Science of Food and Agriculture. 19: 617-623.
- Ewart, J. A. 1969. Isolation and characterization of a wheat albumin. Journal of the Science of Food and Agriculture. 20: 730-733.
- Fitchett, C. S., and Fraizer, P. J. 1987. Action of oxidants and other improvers. In: Chemistry and Physics of Baking. Burlington House: London, UK

- Frazier, P. J., Daniels, N. W. R. and Eggitt, P. W. R. 1975. Rheology and the continuous breadmaking process. *Cereal Chemistry*. 52:106-111
- Frazier, P. J., Fitchett, C. S. and Eggitt, P. W. R. 1985. Laboratory measurements of dough development. 151-175 pp in: *Rheology of wheat products*. H. Faridi ed. American Association of Cereal Chemist, St. Paul, MN.
- Fu, J., Mulvaney, S. J. and Cohen, C. 1997. Effect of Added Fat on the Rheological Properties of Wheat Flour Doughs. *Cereal Chemistry*. 74: 304-311.
- Gan, Z., Ellis, P. R. and Schofield, J. D. 1995. Mini Review. Gas cell stabilization and gas retention in wheat bread dough. *Journal of Cereal Science*. 21: 215-230.
- Gras, P. W., Anderssen, R. S., Keentok, M., Bekes, F. and Appels, R. 2001. Gluten protein functionality in wheat flour processing: a review. *Australian Journal of Agricultural Research*. 52:1311-1323.
- Grasberger, A., Schieberle, P., and Koehler, P. 2003. Fractionation and reconstitution of wheat flour- effect on dough rheology and baking. *European Food Research Technology*. 216:204-211.
- Graveland,, A., Bosveld, P., Lichtendonk, W. J., Moonen, J. H. E. and Scheepstra, A. 1982. Extraction and fractionation of wheat flour proteins. *Journal of the Science of Food and Agriculture*. 33:1117-1128

- Graveland, A., Bosveld, P., Lichtendonk, W. J., Moonen, J. H. E. and Scheepstra, A. 1985. A model for the molecular structure of the glutenins from wheat flour. *Journal of Cereal Science*. 3: 1-16.
- Graveland,, A., Henderson, M.H., Paques, M. and Veerman, S. M. 1994. Practical applications of molecular glutenin structures: breakdown and reassembly in a wheat flour dough. Pages 393-403 in: *Gluten Proteins Assoc. Cereal Res. Detmold, Germany*.
- Gray, V. M. and Schoch, T. J. 1962. Effects of surfactants and fatty adjuncts on the swelling and solubilization of granular starches. *Starke*. 14:239-246.
- Hayman, D., Hosney, R. C., and Faubion, J. M. 1998. Bread crumb grain development during baking. *Cereal Chemistry*. 75:577-580.
- He, H. and Hosney, R. C. 1991. Differences in gas retention, protein solubility and rheological properties between flours of different baking quality. *Cereal Chemistry*. 68: 526-530.
- Hibberd, G. E. 1970. Dynamic viscoelastic behaviour of wheat flour doughs; Part II. Effect of water in the linear region. *Rheologica Acta*. 9:501-505.
- Hosney, R. C. 1984. Functional properties of pentosans in baked foods. *Food Technology*. 38 (3): 114-117.
- Hosney, R. C. 1985. The mixing phenomenon. *Cereal Foods World*. 30: 453-457.

- Hoseney, R. C. 1986. Proteins. In: *Principles of Cereal Science and Technology*, American Association of Cereal Chemist. St. Paul, MN.
- Hoseney, R. C. 1994. Yeast leavened products. In: *Principles of Cereal Science and Technology*. American Association Cereal Chemists. St. Paul, MN.
- Hoseney, R. C. and Rogers, D. E. 1990. The formation and properties of Wheat Flour Doughs. *Critical Reviews in Food Science and Nutrition*. 29:73-93.
- Inoue, S., Tugita, K., Koike, S., Maruzeni, S. and Kamoj, I. 1995. Effects of fatty acids species of monoglycerides on breadmaking properties. *Journal of the Japanese Society of Food Science and Technology*. 42:634-642.
- Janssen, A. M., van Vliet, T., and Vereijken, J. M., 1996. Fundamental and empirical rheological behaviour of wheat flour doughs and comparison with bread making performance. *Journal of Cereal Science*. 23: 43-54.
- Junge, R. C. and Hoseney, R. C. 1981. A mechanism by which shortening and certain surfactants improve loaf volume in bread. *Cereal Chemistry*. 58: 408-412.
- Junge, R. C.; Hoseney, R. C. and Varriano-Marston, E. 1981. Effect of surfactant on air incorporation in dough and crumb grain of bread. *Cereal Chemistry*. 58:338-342.

- Kamel, B. S. 1992. Characteristics of bread and buns made with lard and vegetable oils of different iodine values. *Journal of American Oil and Chemist Society*. 69: 794-796.
- Kamel, B. S. and Hoover, R. 1992. Production of bread using sodium stearoyl lactylate as a replacement for shortening. *Food Research International*. 25: 285-288.
- Kasarda, D. D., Bernadin, J. E. and Nimmo, C. C. 1976. Wheat Proteins. In: *Advances in Cereal Science and Technology*. Eds. Pomeranz, Y. American Association of Cereal Chemists. St. Paul, MN.
- Kent, N.L., and Evers, A.D. 1969. Variation in protein composition within the endosperm of hard wheat. *Cereal Chemistry*. 46: 293-300.
- Khan, A. and Bushuk, W. 1979. Studies of Glutenin. XIII. Gel filtration, isoelectric focusing, and amino acid composition studies. *Cereal Chemistry*. 56: 505-512.
- Khatkar, B. S. 2004. Effect of mixing time on dynamic rheological properties of wheat flour dough. *Journal of Food Science and Technology*. 41:320-322.
- Khatkar, B. S., Bell, A. E. and Schofield, J.D. 1995. The dynamic rheological properties of glens and gluten sub-fractions from wheats of good and poor bread making quality. *Journal of Cereal Science*. 22: 29-44.
- Khatkar, B. S., Bell, A. E. and Schofield, J. D. 1996. A comparative study of the inter-relationships between mixograph parameters and bread

- making qualities of wheat flours and glutens. *Journal of the Science of Food and Agriculture*. 72: 71-85.
- Kidmose, U., Pedersen, L., and Nielsen, M. 1999. Use of ultrasonics for measurements of rheological characteristics of dough. *Berrcht. Uberdie Tagung Fur Lebensmittel Rheologie*. 6: 127-150.
- Kidmose, U., Pedersen, L. and Nielsen, M. 2001. Ultrasonics in evaluating rheological properties of dough from different wheat varieties and during ageing. *Journal of Texture Studies*. 32: 321-334.
- Kieffer, R., Wieser, H., Henderson, M. H. Graveland, A. 1998. Correlations of the breadmaking performance of wheat flour with rheological measurements on a microscale. *Journal of cereal Science*. 27:53-60.
- Kilborn, R. H. and Tipples, K. H. 1972. Factors affecting mechanical dough development. I. Effect of mixing intensity and work input. *Cereal Chemistry*. 49: 34-47.
- Knightly, W. H. 1973. The evolution of softeners and conditioners used in baked foods. *Bakers Digest*. 47(3): 64-74.
- Knightly, W. H. 1981. The evolution of softeners and conditioners used in baked goods. *Bakers Digest*. 55(7): 45-67.
- Knightly, W. H. 1981. Shortening Systems: Fats, oils, and surface-active agents-present and future. *Cereal Chemistry*. 58: 171-174.
- Knightly, W. H. 1988. Surfactants in baked foods: current practice and future trends. *Cereal Foods World*. 33: 400-412.

- Kokelaar, J.J., van Vliet, T., Prins, A., 1996. Strain hardening properties and extensibility of flour and gluten doughs in relation to breadmaking performance. *Journal of Cereal Science*. 24: 199-214.
- Kovacs, E. and Vamos- Kardos, E. 1993. Changes in the composition of protein fractions in the wheat dough systems made with and without emulsifiers. *Mitteilungen aus dem Gebiete der Lebensmitteluntersuchung u. Hygiene*. 84: 630-639 (Abstract).
- Kovacs, E., Vamos- Kardos, E., Kiss-Laszlavik, M. and Pallaqi, E. 1992. Effect of emulsifier on the properties of pasta products. *Acta. Alim.* 21:205-217.
- Krog, N. J. 1981. Theoretical aspects of surfactants in relation to their use in breadmaking. *Cereal Chemistry*. 58: 158-164.
- Krog, N. J. 1990. Food emulsifiers and their chemical and physical properties. In: *Food Emulsions* pp. 127-180. eds. Larson, K. and Friberg, S. E. Marcel Dekker, Inc., New York. NY.
- Krog, N. J. and Nybojensen, B. 1970. Interaction of monoglycerides in different physical states with amylose and their anti-firming effects in bread. *Journal of Food Technology*. 5:77-85.
- Kuchel, H., Langridge, P., Mosionek, L., Williams, K. and Jeffries, S. P. 2006. The genetic control of milling yield, dough rheology and baking quality of wheat. *Theoretical and Applied Genetics*. 112: 1487-1495
- Kudryashov, E. D., Hunt, N. T., Arikainen, E. O., and Buckin, V. A. 2001. Monitoring acidified milk gel formation by ultrasonic shear wave

- measurements. High frequency viscoelastic moduli of milk and acidified milk. *Journal of Dairy Science* 84:375-388.
- Legendijk, J., and Pennings, H. J. 1970. Relation between complex formation of starch with monoglycerides and firmness of bread. *Cereal Science Today*. 15: 354-361.
- Lang, C. E., Neises, E. K., and Walker, C. E. 1992. Effects of additives on the flour mixograms. *Cereal Chemistry*. 69:587-591.
- Larsson, H., Eliasson, A. C., Johansson, E., and Svensson, G. 2000. Influence of added starch on mixing of dough made with three wheat flours differing in high molecular weight subunit composition: Rheological behaviour. *Cereal Chemistry*. 77: 633-639.
- Lasztity, R. 1984. *The chemistry of cereal proteins*. CRC Press, Inc., Boca Raton, FL. 203 pp
- Leach, H. W., L. D. McCowen and T. J. Schoch. 1959. Structure of the starch granule. I. Swelling and solubility patterns of various starches. *Cereal Chemistry*. 36: 534-546.
- Lee, H. O., Luan, H., and Daut, D. G. 1992. Use of ultrasonic technique to evaluate the rheological properties of cheese and dough. *Journal of Food Engineering*. 6:127-150.
- Lee, S. Y., Pyrak-Nolte, L. J. and Campanella, O. H. 2004 Determination of ultrasonic based rheological properties of dough during fermentation. *Journal of Texture Studies*. 35: 33-51.

- Létang, C., Piau, M. and Verdier, C. 1999. Characterization of wheat –flour-water doughs: Part I: rheometry and microstructure. *Journal of Food Engineering*. 41:121-132.
- Létang, C., Piau, M., Verdier, C. and Lefebvre, L. 2001. Characterization of wheat-flour-water doughs: a new method using ultrasound. *Ultrasonics*. 39:133-141.
- Lister, D. 1984. *In Vivo Measurement of Body Composition in Meat Animals*. Elsevier Applied Science Publishers, London, England.
- Lord, D. D. 1950. The action of polyoxyethylene monostearate upon starch with the reference to its softening action in bread. *Journal of Colloid Science*. 11: 23-41.
- Macche-Rezzoug, Z., Bouvier, J. M., Allaf, K., and Patras, C. 1998. Study of mixing in connection with the rheological properties of biscuit dough and dimensional characterization of biscuits. *Journal of Food Engineering*. 35:43-56.
- MacRitchie, F. 1976. The liquid phase of dough and its role in baking. *Cereal Chemistry*. 53: 318-324.
- MacRitchie, F. 1983. Role of lipids in baking. In: *Lipids in Cereal Technology* P.J. Barnes ed. pp. 165-188, Academic Press, London.
- MacRitchie, F. 1984. Baking quality of wheat flours. *Advanced Food Research*. 29: 201-277.
- MacRitchie, F. 1985. Studies of the methodology for the fractionation and reconstitution of wheat flours. *Journal of Cereal Science*. 3: 221-230.

- MacRitchie, F. 1986. Physicochemical processes in mixing. In: Chemistry and Physics of Baking. Royal Society of Chemistry. London, UK
- MacRitchie, F. 1987. Evaluation and contribution from wheat protein fractions to dough mixing and breadmaking. *Journal of Cereal Science*. 6:259-268.
- MacRitchie, F. 1992. Physicochemical properties of wheat proteins in relation to functionality. In: *Advances in Food and Nutrition Research*, (J.E. Kinsella, ed.), Academic Press, New York, NY.
- MacRitchie, F. 1997. Reversibility of protein adsorption. In: *Adsorption of proteins at interfaces* (R. Miller and D. Moebius, eds), Marcel Dekker, New York, pp 293-323.
- MacRitchie, F. 1999. Wheat proteins: characterization and role in flour functionality. *Cereal Foods World*. 44:188-193.
- Mahdi, J. G., Varriano-Marston, E., and Hosney, R. C. 1981. The effect of mixing atmosphere and fat crystal size on dough structure and bread quality. *Baker's Digest*. 55:28-42.
- Maher Galal, A., Varriano-Marston, E., and Johnson, J. A. 1978. Rheological dough properties as affected by organic acids and salt. *Cereal Chemistry*. 55:683-698.
- Mani Lindborg, K., Trägårdh, C., Eliasson, A. C., and Dejmek, P. 1997. Time-resolved shear viscosity of wheat flour doughs-effect of mixing, shear rate, and resting on the viscosity of doughs of different flours. *Cereal Chemistry*. 74:49-55.

- Manley, D. J. 1983. Technology of Biscuits, Crackers and Cookies. (A. J. C., Andersen, and P.N. Williams, eds). Horwood Ltd. Chichester, UK.
- Matz, S. A. 1992. Chemically leavened bread and rolls. In: Bakery Technology and Engineering. Van Nostrand Reinhold. 3rd ed. AVI. New York, NY.
- Mazur, P. Y., Nazarenko, E. A., Abakumova. T. N., Shishikina, T. I. 1981. Effect of aeration on liquid yeast activity and bread quality. *Izvestiya Vysshikh Uchebnkh Zavedenii Pishchevaya Tekhnologiya*. 14: 98-101 (Abstract).
- McClements, D. J. 1997. Ultrasonic characterization of foods and drinks: principles, methods and applications. *Reviews in Food Science and Nutrition*. 37: 1-16.
- McMaster LD, Kokott S. A, and Slatter P. 2005. Micro-encapsulation of bifidobacterium lactis for incorporation into soft foods. *World Journal of Microbiology and Biotechnology*. 21: 723-728.
- Mecham, D. K., Sokol, H. A., and Pence, J. W. 1962. Extractable protein and hydration characteristics of flours and doughs in dilute acid. *Cereal Chemistry*. 39: 81-93.
- Mecham, D. K., Cole, E. G. and Pence, J. W. 1965. Dough-mixing properties of crude and purified gluteins. *Cereal Chemistry*. 42: 409-420
- Menjivar, J. A. 1990. Fundamental aspects of dough rheology in: *Dough Rheology and Baked Product Texture*. Faridi, H., and Faubion, J. M. Van Nostrand Reinhold, New York, NY

- Ministry of Industry. 2005. Food Composition in Canada. Catalogue no. 32-229-XIB. Part 2005. Statistics in Canada. Minister of Industry. Ottawa.
URL: [www. Statcan.ca](http://www.Statcan.ca)
- Mohsenin, N. N. 1986. Physical properties of plant and animal materials. Gordon and Breach Science Publishers, New York, NY.
- Morris, V. H., Alexander, T. L., and Pascoe, E. D. 1945. Studies of the composition of the wheat kernel. I. Distribution of ash and protein in center sections. *Cereal Chemistry*. 22: 351-361.
- Mullen, J. D. and Smith, D. E. 1965. Studies on short - and long - mixing flours. Solubility and electrophoretic composition of proteins. *Cereal Chemistry*. 42: 263-274.
- Muller, H. G. 1975. Rheology and the conventional bread and biscuit making process. *Cereal Chemistry*. 52:89-105.
- Navickis, L. L. 1989. Rheological changes of fortified wheat and corn flour doughs with mixing time. *Cereal Chemistry*. 66: 321-324.
- Nielsen, M. and Martens, H. J. 1997. Low frequency ultrasonics for texture measurements in cooked carrots. *Transactions of the ASAE*. 40:1741-1748.
- O'Brien, C. M., Grau, H., Neville, D. P., Keogh, M. K., Reville, W. J. and Arendt, E. K. 2000. Effects of microencapsulated high-fat powders on the empirical and fundamental rheological properties of wheat flour doughs. *Cereal Chemistry*. 77: 111-114.

- Paredes-Lopoez, O. and Bushuk, W. 1982. Development and underdevelopment for wheat doughs by mixing: physicochemical studies. *Cereal Chemistry*. 60:19-23.
- Peighambardoust, S. H., Van Der Goot, A. J., Van Vliet, T., Hamer, R. J. and Boom, R. M. 2006. Microstructure formation and rheological behaviour of dough under simple shear flow. *Journal of Cereal Science*. 43:183-197.
- Pomeranz, Y. 1987. Physical properties and structure. *Modern Cereal Science and Technology*. VCH Publishers. New York. NY.
- Pomeranz, Y. 1988. Composition and functionality of wheat flour components. In *Wheat: Chemistry and Technology-2* ed. Pomeranz, Y. American Association of Cereal Chemists. St. Paul, MN.
- Pomeranz, Y., Meyer, Y. and Seibel, W. 1984. Wheat, wheat-rye, and rye dough and bread studied by scanning electron microscopy. *Cereal Chemistry*. 61:53 - 59.
- Porceddu, E., Lafiandra, D. and Scarascia Mugnozza, G. T. 1983. Genetics of seed proteins in wheat. In: Gottschalk W, Muller HP (ed) *Seed proteins; biochemistry, genetics, nutritive value*, pp 77-142.
- Povey, M. J. W. 1989. Ultrasonics in food engineering part II: applications. *Journal of Food Engineering*. 9: 1-20.
- Povey, M. J. W. 1997. *Ultrasonic Techniques for Fluids Characterization*. Academic Press, London, U. K.

- Povey, M. J. W. 1998. Rapid determination of food material properties. In M. J. W. Povey and Mason eds, *Ultrasound in Food Processing*. Blackie Academic and Professional, London, U. K.
- Povey, M. J. W. and Harden, C. A. 1981. An application of ultrasonic pulse echo technique to the measurement of crispiness of biscuits. *Journal of Food Technology*. 16:167-175.
- Preston, K. R., Kilborn, R. H. and Black, H. C. 1982. The GRL pilot mill. II. Physical dough and baking properties of flour streams milled from Canadian red spring wheats. *Canadian Institute of Food Science and Technology Journal*. 15:29-36.
- Progieter, J. 1992. Emulsifiers in bakery. *Food Review*. 18:23-25.
- Pyler, E. J. 1982. *Baking Science and Technology*. 2nd Edition. Chicago. IL.
- Rao, P. A., Nussinovitch, A. and Chinachoti, P. 1992. Effects of selected surfactants on amylopectin recrystallization and on recoverability of bread crumb during storage. *Cereal Chemistry*. 69: 613-618.
- Rao, V. K., Mulvaney, S. J. and Dexter, J. E. 2000. Rheological characteristics of long and short mixing flours based on stress relaxation. *Journal of Cereal Science*. 31:159-171.
- Resa, P., Elvira, L., and Montero de Espinosa, F. 2004. Concentration control of alcoholic fermentation processes from ultrasonic velocity measurements. *Food Research International*. 37: 587-594.

- Rha, C. K. and Pradipasena, P. 1986. Viscosity of proteins. In: Functional Properties of Food Macromolecules. Eds. Mitchell, J. R. and Ledward, D. A. Elsevier Applied Science Publishers, London, England.
- Roach, R. R. and Hosney, R. C. 1995. Effect of certain surfactants on the starch in bread. *Cereal Chemistry*. 72:578-582.
- Rogers, D. E., Zeleznak, C. S. Lai, C. S. and Hosney, R. C. 1988. Effect of native lipids, shortening, and bread moisture on bread firming. *Cereal Chemistry*. 65: 398-401
- Ross, K. A., Pyrak-Nolte, L. J., Campanella, O. H. 2004. The use of ultrasound and shear oscillatory tests to characterize the effect of mixing time on the rheological properties of dough. *Food Research International*. 37:567-577.
- Safari-Ardi, M. and Phan-Thein, N. 1998. Stress relaxation and oscillatory tests to distinguish between doughs prepared from wheat flours of different varietal origin. *Cereal Chemistry*. 75:80-84.
- Sai Manohar, R. and Haridas Rao, P. 1997. Effects of water on the rheological characteristics of biscuit dough and quality of biscuits. *European Food Research and Technology*. 209:281-285.
- Sai Manohar, R. and Haridas Rao, P. 1999. Effect of emulsifiers, fat level and type on the rheological characteristics of biscuit dough and quality of biscuits. *Journal of the Science and Food and Agriculture*. 79:1223-1231.

- Salazar, J., Alava, J. M., Sahi, S. S., Turo, A., Chavez, J. A., and Garcia, M. J. 2002. Ultrasound measurements for determining rheological properties of flour-water systems. 2002 IEEE Ultrasonics Symposium. 877-880.
- Samari, S. 1994. Ultrasonic inspection methods for food products. *Lebensmittel Wissenschaft und Technologie*. 27: 210-213.
- Scanlon, M. G. 2004. Editorial: Low-intensity ultrasound for food research and the food industry. *Food Research International*. 37:535-536.
- Schroeder, L. F. and Hosney, R. C. 1978. Mixograph Studies. II. Effect of activated double-bond compounds on dough-mixing properties. *Cereal Chemistry*. 55:348 - 359.
- Self, G., Povey, M. J. W., and Wainwright, H. 1992. Ultrasonic Evaluation of Post-Harvest Attributes of Fruit and Vegetables. *Abstracts of the Association of Applied Biologists*. 38: 82-85.
- Shewry, P. R. and Mifflin, B. J. 1985. Seeds storage proteins of economically important cereals. In: *Advances in Cereal Science and Technology*. American Association of Cereal Chemists. St. Paul, MN. pp. 8-21.
- Shewry, P. R. and Tatham, A. S. 1997. Disulphide bonds in wheat gluten proteins. *Journal of Cereal Science*. 25:207-227.
- Shiau, S. Y. 2004. Effects of emulsifiers on dough rheological properties and texture of extruded noodles. *Journal of Texture Studies*. 35: 93-110.
- Silva, R. 1993. Lecithin and phospholipids in baked goods in: *Advances in Baking Technology*. Eds. Kamel, B. S. and Stauffer, C. E. Blackie Academic and Professional. Glasgow.

- Simmonds, H. and Orth, R. A. 1973. Structure and composition of cereal proteins as related to their potential industrial utilization. In: Industrial uses of cereals. Y. Pomeranz, ed. St. Paul, MN.: American Association of Cereal Chemistry. pp. 51-120.
- Singh, N., Bajaj, I. K., Singh, R. P. and Gujral, H. S. 2002. Effect of different additives on mixograph and bread making properties of Indian wheat flour. *Journal of Food Engineering*. 56: 89-95.
- Skeggs, P. K., Kingswood, K. K. 1981. Mechanical dough development- Pilot scale studies. *Cereal Chemistry*. 58:256-260.
- Skerritt, J. H., Hac, L., and Bekes, F. 1999. Depolymerisation of glutenin macropolymers during dough mixing: I. Changes in levels, molecular weight distribution, and overall composition. *Cereal Chemistry*. 76:395-401.
- Slade, L. and Levine, H. 1995. Glass transitions and water-food structure interactions. *Advances in Food and Nutrition Research*, New York, p. 103-269.
- Slade, L., Levine, H., and Finley, J. W. 1989. Protein-water interface. Water as a plasticizer of gluten and other protein polymers. in: *Protein quality and the effects of processing*. Marcel Dekker, New York, NY.
- Smith, P. R. and Johansson, J. 2004. Influences of the proportion of solid fat in a shortening on loaf volume and staling of bread. *Journal of Food Processing and Preservation*. 28: 359-367.

- Smith, D. E. and Mullen, J. D. 1965. Studies on short- and long-mixing flours. II. Relationship of solubility and electrophoretic composition of various fractions. *Cereal Chemistry*. 42:275-287.
- Stampfli, L., Nersten, B., and Molteberg, E. L. 1996. Effects of emulsifiers on farinograph and extensigraph measurements. *Food Chemistry*. 57:523-530.
- Stauffer, C. E. 1983. Dough conditioners. *Cereal Foods World*. 28: 729-730.
- Stauffer, C. E. 1990. *Functional Additives of Bakery Foods*. Van Nostrand Reinhold, New York, NY.
- Stauffer, C. E. 1999. *Emulsifiers*. Eagan Press, St. Paul, MN.
- Steffe, J. F. 1996. Introduction to Rheology. In: *Rheological Methods in Food Process Engineering*. Freeman Press. East Lansing, MI. pp. 1-45.
- Stojanovic. J., and Silva, J. L. 2006. Influence of osmoconcentration, continuous high-frequency ultrasound and dehydration on properties and microstructure of rabbit eye blueberries. *Drying Technology* 24: 165-17.
- Tanaka, K. and Bushuk, W. 1973. Changes in flour proteins during dough mixing. Solubility results. *Cereal Chemistry*. 50: 590-596.
- Tkachuk, R. and Hlynka, I. 1968. Some properties of dough and gluten in D₂O. *Cereal Chemistry*. 45:80-87.
- Tolstoguzov, V. 1997. Thermodynamic aspects of dough formation and functionality. *Food Hydrocolloids*. 11: 181-193.

- Tsen, C. C. and Weber, J. 1981. Dough properties and proof times of yeasted doughs affected by surfactants. *Cereal Chemistry*. 58:108-181.
- Tschoegl, N. W., Rinde, J. A., and Smith, T. L. 1970. Rheological properties of wheat flour doughs. 1. Method for determining large deformation and rupture properties in simple tension. *Journal of the Science of Food and Agriculture*. 21: 65-70.
- Tu, C. C. and Tsen, C. C. 1978. Effects of mixing and surfactants on microscopic structure of wheat glutenin. *Cereal Chemistry*. 55:87-95
- Uthayakumaran, S., Newberry, M., Phan-Tien, N., Tanner, R., 2002. Small and large strain rheology of wheat gluten. *Rheologica Acta*. 41:162-172.
- Van Vliet, T., Janssen, A.M., Bloksma, A.H., Walstra, P. 1992. Strain hardening of dough as a requirement for gas retention. *Journal of Texture Studies*. 23: 439-460.
- Verbruggen, I. M. and Delcour, J. A. 2003. Extension properties of wheat flour dough fortified with characterized wheat gluten fractions. *Journal of Cereal Science*. 37:151-156.
- Verdier, C. and Piau, M. 1997. Acoustic wave propagation in the two-phase viscoelastic fluids: the case of polymer emulsions. *Journal of the Acoustical Society of America*. 101:1868-1876.
- Walker, C. E., and Hazelton, J. L. 1996. Dough rheological tests. *Cereal Foods World*. 41:23-28.
- Weegels, P. L., Van de pijpekamp, A. M., Graveland, A., Hamer, R. J. Schofield, J. D. 1996. Depolymerisation and re-polymerisation of wheat

- glutenin during dough processing. I. Relationships between glutenin macropolymer content and quality parameters. *Journal of Cereal Science*. 23:103-111.
- Weipert, D. 1990. The benefits of basic rheometry in studying dough rheology. *Cereal Chemistry*. 67: 311-317.
- Weipert, D. 1992. Descriptive and fundamental rheometry in a new light. *Cereal Foods World*. 37: 15-24.
- Williams, A. 1975. *Breadmaking: The Modern Revolution*. Hutchinson Benham, London, UK. pp. 29-73.
- Wooding, A. R., Kavale, S., MacRitchie, F., and Stoddard, F. L. 1999. Link between mixing requirements and dough strength. *Cereal Chemistry*. 76:800-806.
- Xu, A., Chung, O. K., and Ponte, J. G. 1992. bread crumb amylograph studies. Effects of storage time, shortening, flour lipids, and surfactants. *Cereal Chemistry*. 69:495-501.
- Zdunek. A., and Bednarczyk. J. 2006. Effect of mannitol treatment on ultrasound emission during texture profile analysis of potato and apple tissue. *Journal of Texture Studies*. 37 : 339-343.
- Zhao, F. J. Salmon, S. E., Withers, P. J. A., Evans, E. J., Monaghan, J. M., Shewry, P. R. and McGrath, S. P. 1999. Responses of breadmaking quality to sulfur in three wheat varieties. *Journal of the Science of Food and Agriculture*. 79:1865-1874.

APPENDIX

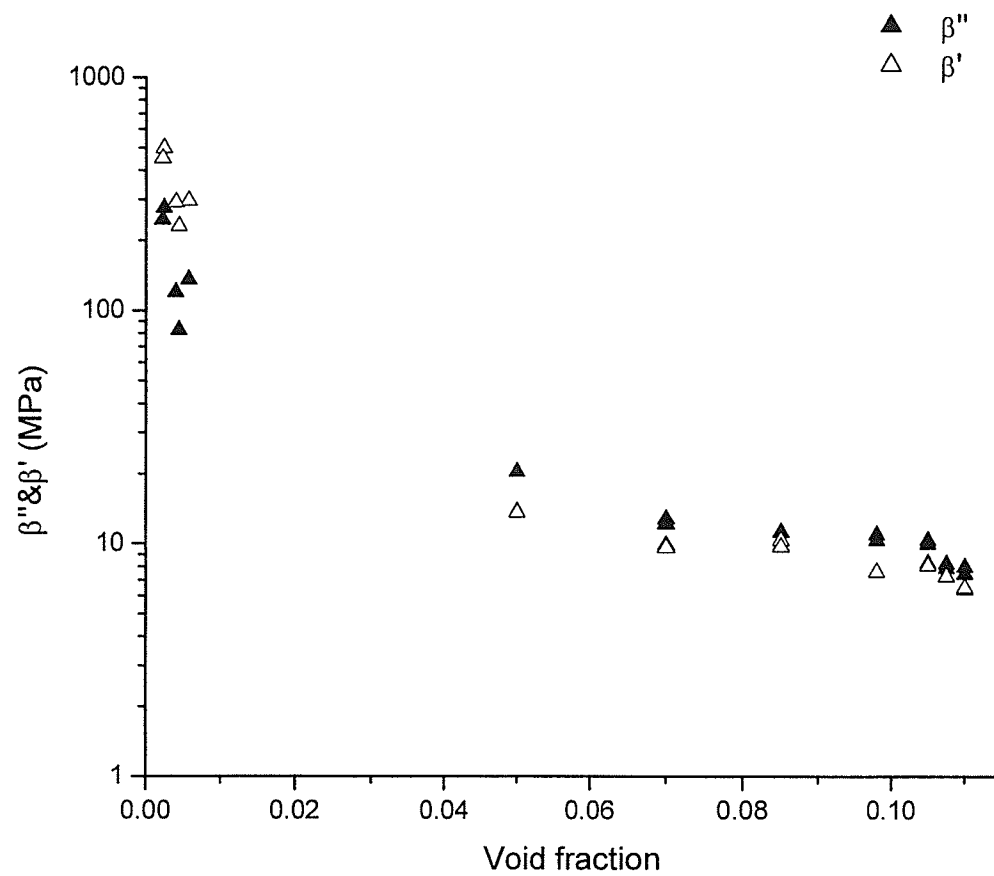


Figure 1a Longitudinal moduli (β'' and β') as a function of void fraction for dough prepared from CWRS flour having 2% shortening.

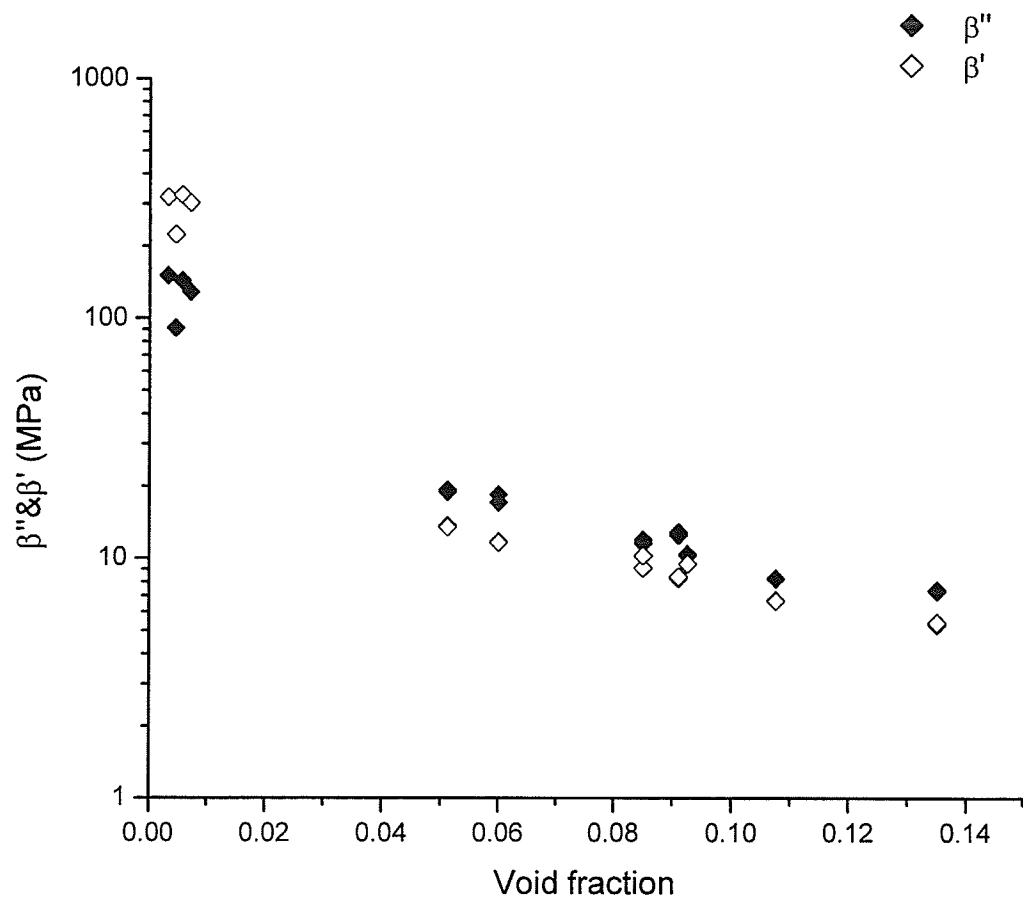


Figure 2a Longitudinal moduli (β'' and β') as a function of void fraction for dough prepared from CWRS flour having 4% shortening.

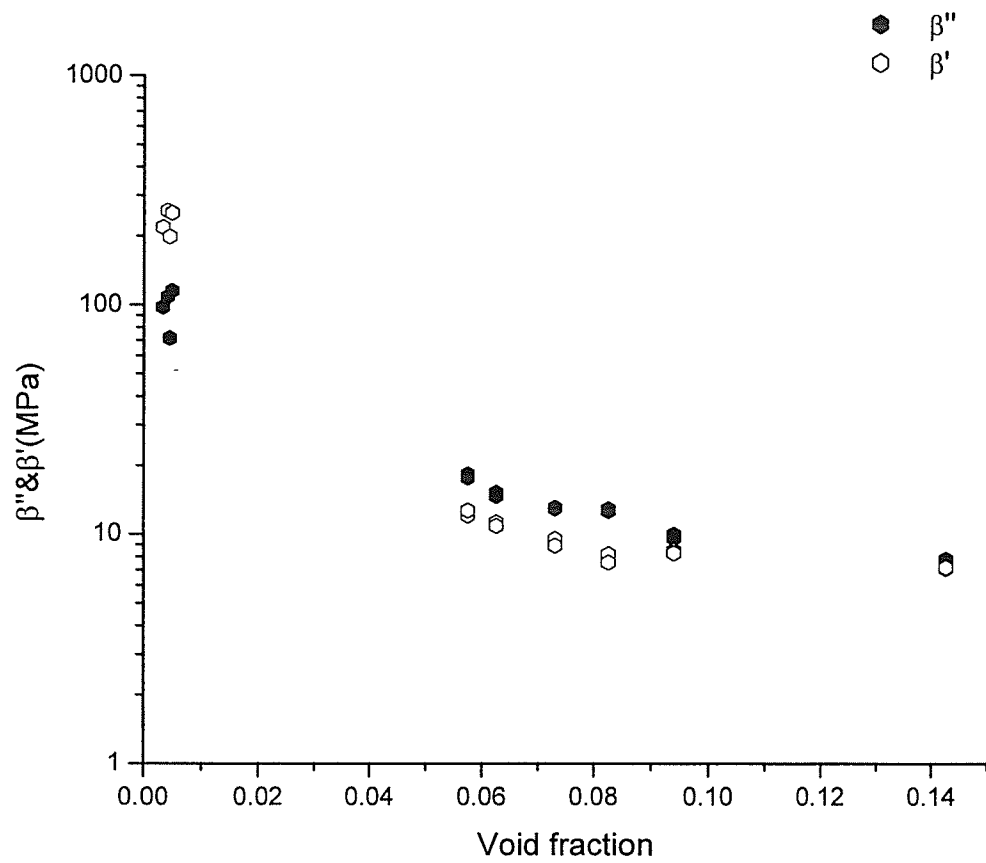


Figure 3a Longitudinal moduli (β'' and β') as a function of void fraction for dough prepared from CWRS flour having 8% shortening.

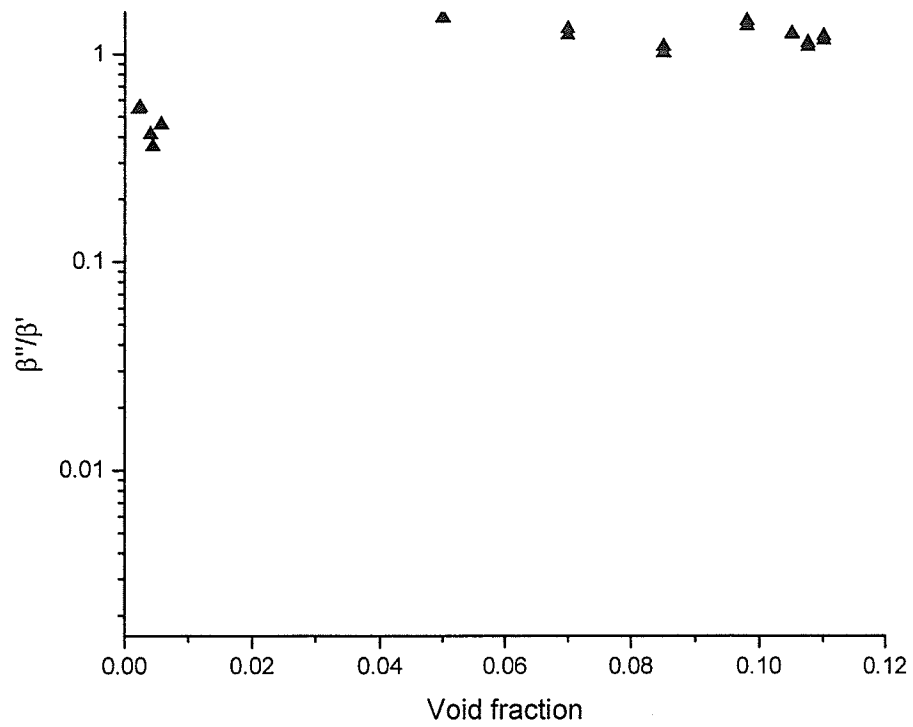


Figure 4a Ratio of loss and storage modulus (β''/β') as a function of void fraction for dough prepared from CWRS flour having 2% shortening

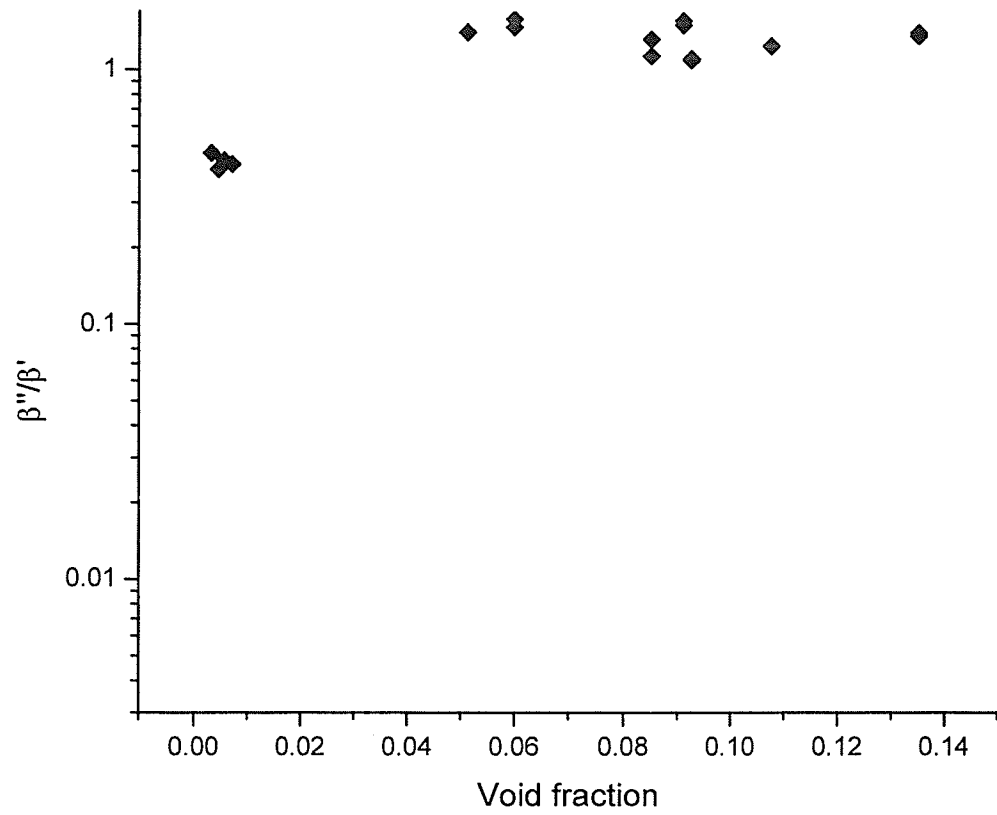


Figure 5a Ratio of loss and storage modulus (β''/β') as a function of void fraction for dough prepared from CWRS flour having 4% shortening.

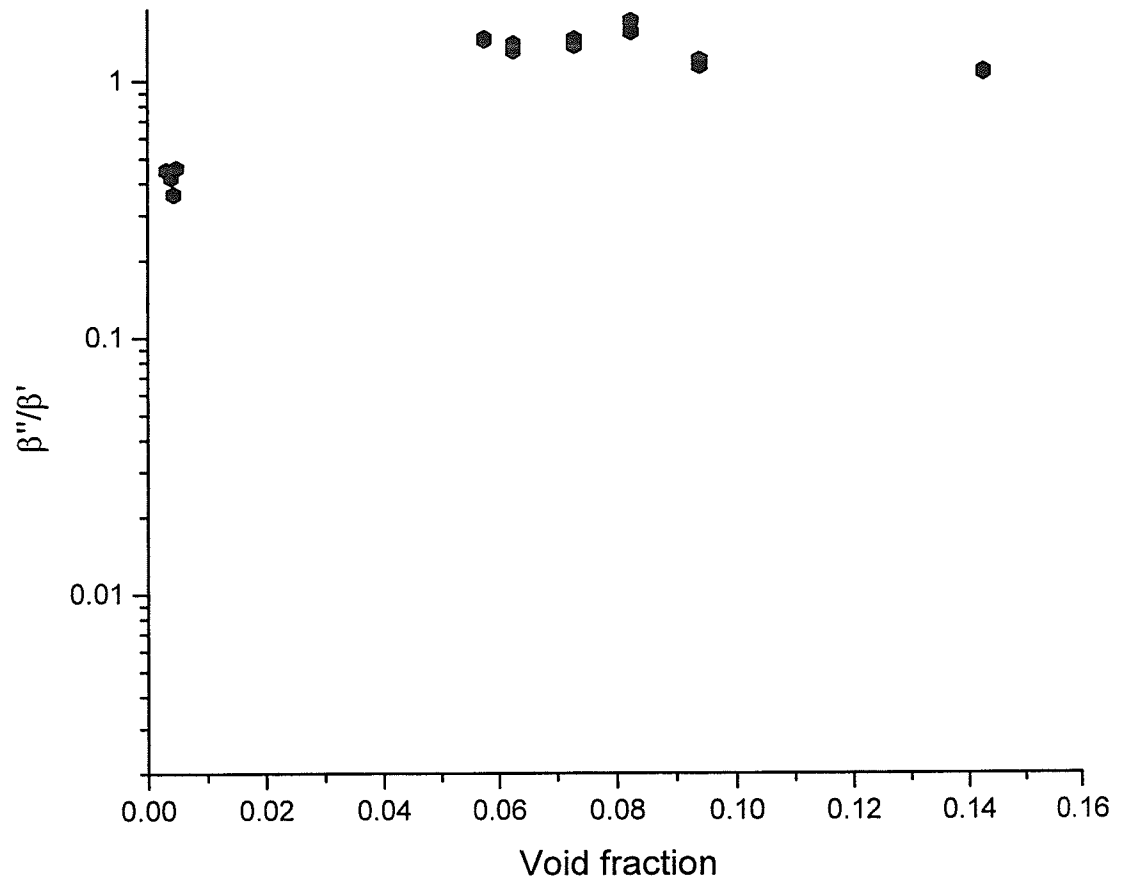


Figure 6a Ratio of loss and storage modulus (β''/β') as a function of void fraction for dough prepared from CWRS flour having 8% shortening

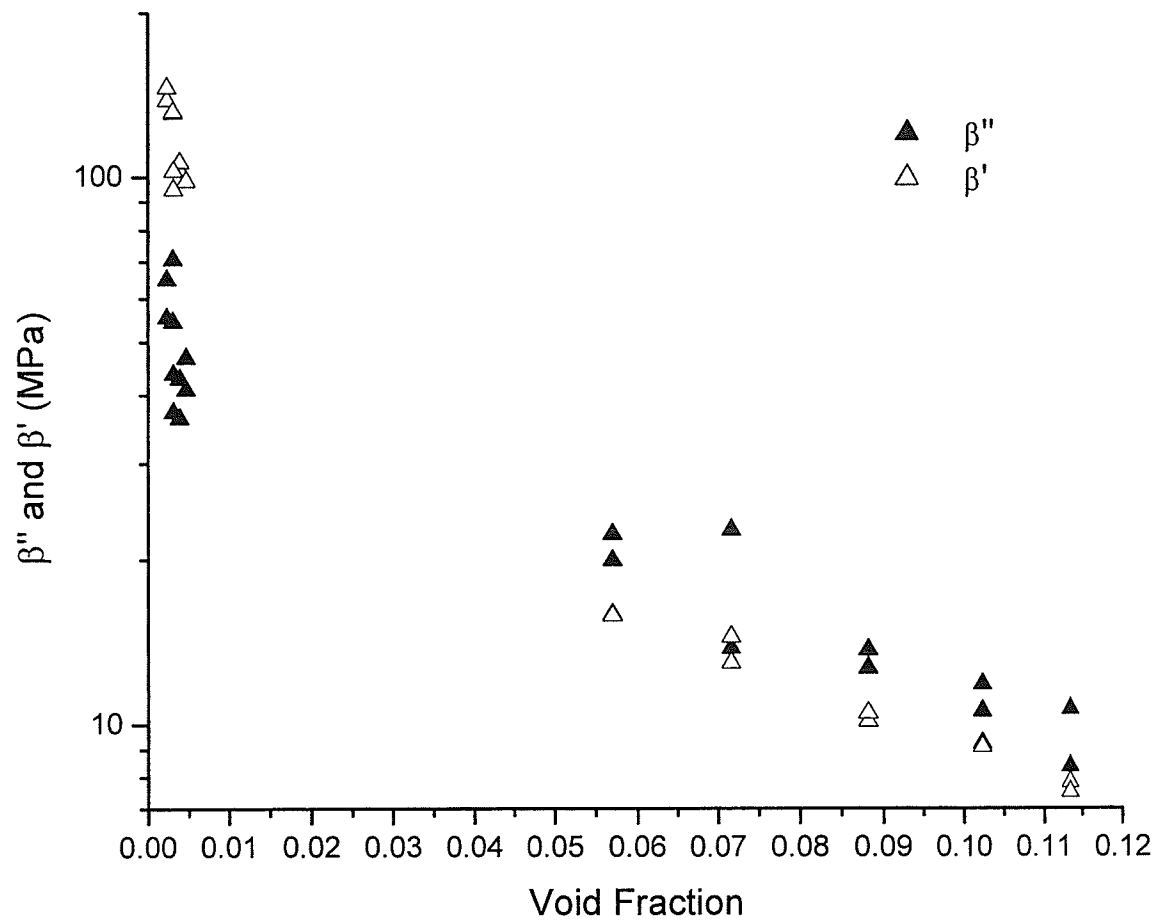


Figure 7a Longitudinal moduli (β'' and β') as a function of void fraction for dough prepared from SWS flour having 0.5% surfactant.

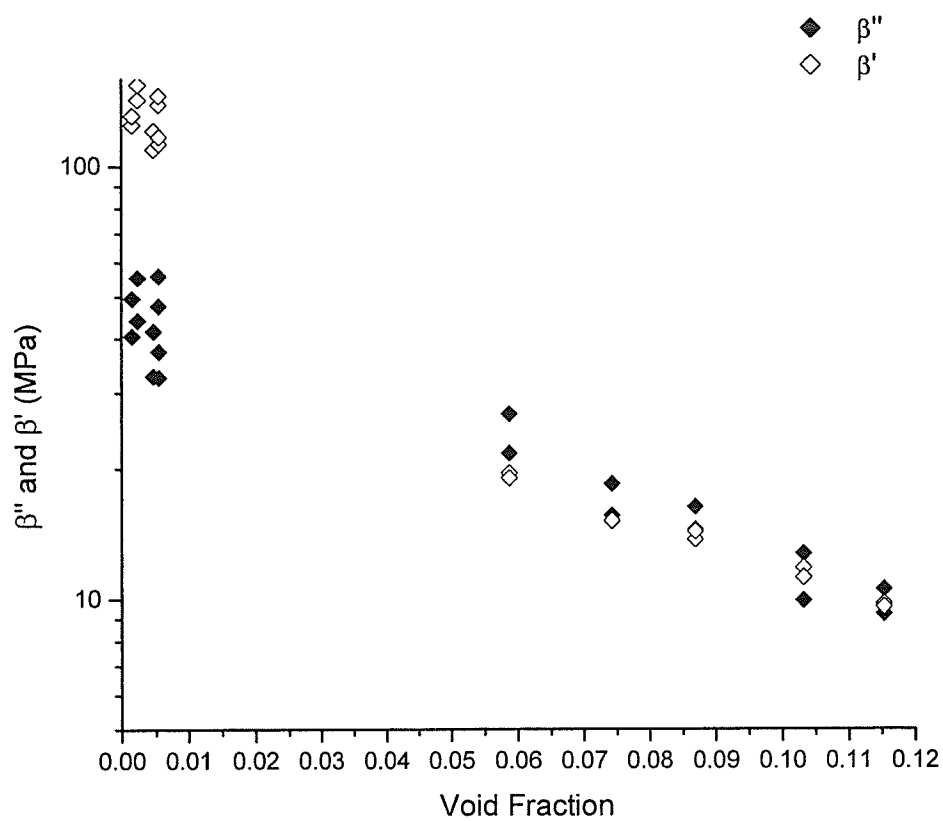


Figure 8a Longitudinal moduli (β'' and β') as a function of void fraction for dough prepared from SWS flour having 1% surfactant.

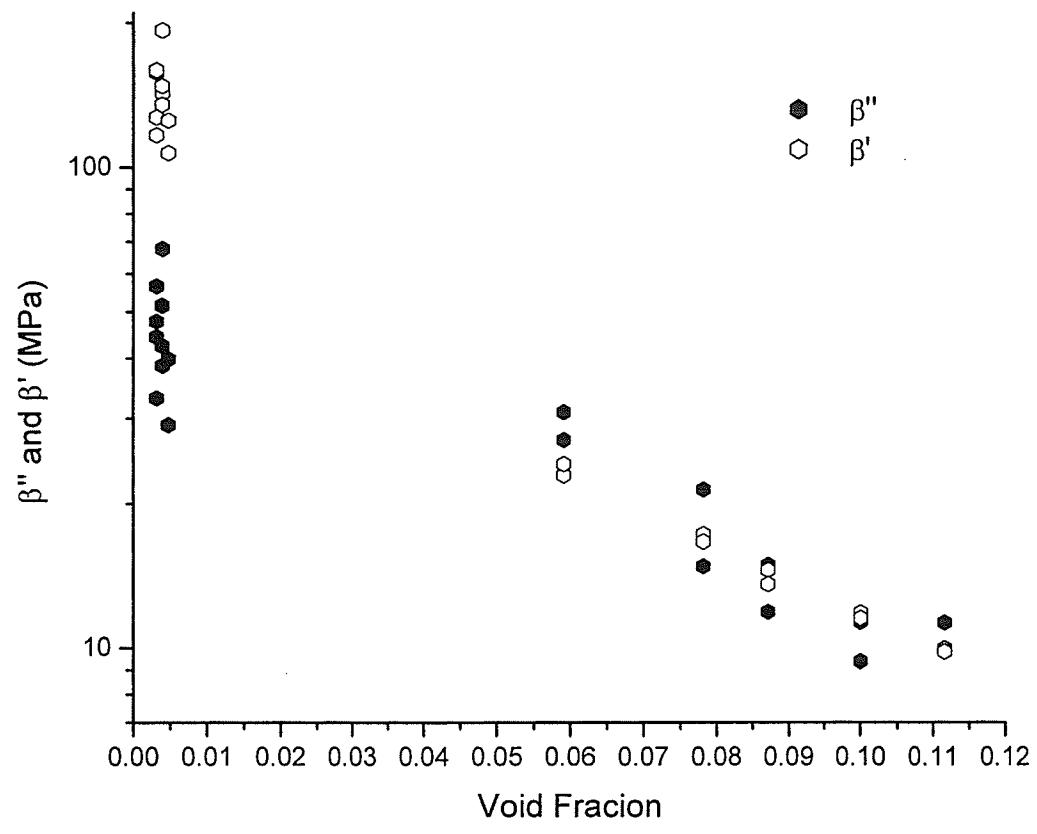


Figure 9a Longitudinal moduli (β'' and β') as a function of void fraction for dough prepared from SWS flour having 2% surfactant.

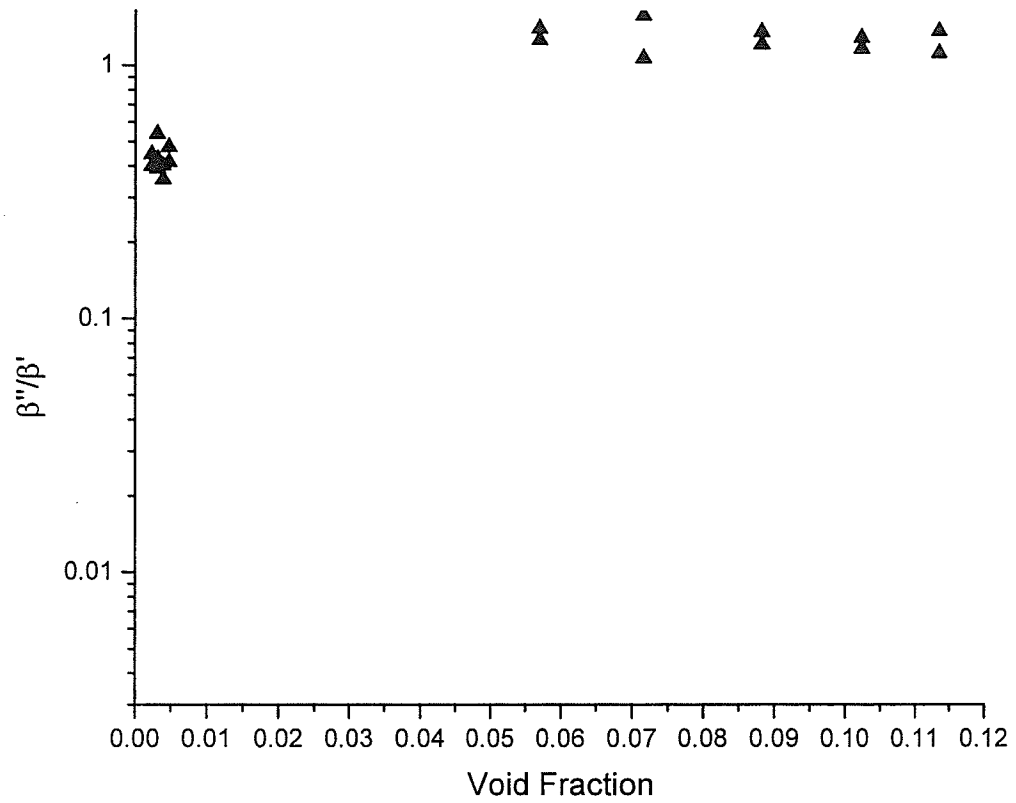


Figure 10a Ratio of loss and storage modulus (β''/β') as a function of void fraction for dough prepared from SWS flour having 0.5% surfactant.

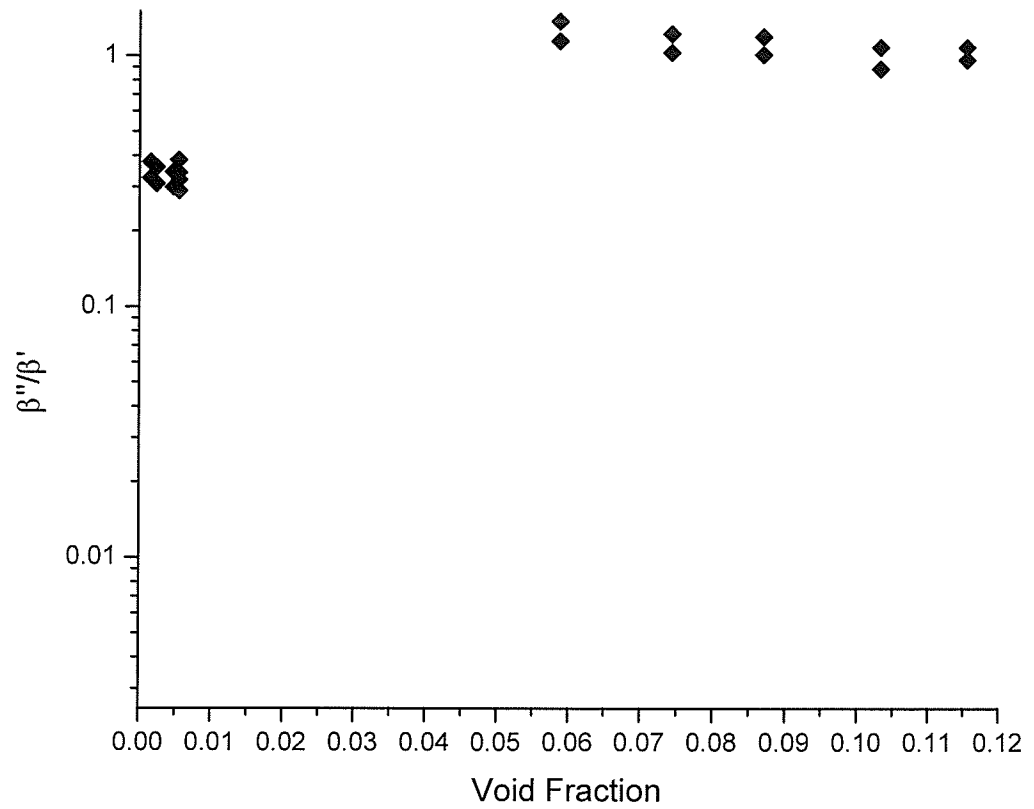


Figure 11a Ratio of loss and storage modulus (β''/β') as a function of void fraction for dough prepared from SWS flour having 1 % surfactant

Table 1a. Effect of surfactant level (f.w.b %) and mixing time on gas free dough density of doughs prepared from CWRS flour.

Surfactant level (%)	2min	4.5 min	6.5 min	Mean Density (kgm ⁻³)
Control	1209	1207	1203	1206 ^a
0.5	1200	1198	1196	1198 ^b
1	1193	1192	1189	1191 ^c
2	1190	1191	1185	1188 ^d

Mean density values are obtained by averaging the density values for doughs mixed at various mixing times (2, 4.5 and 6.5 min).

Numbers with different superscripts are significantly different.