RHEOLOGICAL PROPERTIES OF WHEAT FLOUR DOUGH

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Summary

Wheat flour dough is one of the most complex rheological systems, which has been studied by a number of cereal scientists, food technologists, and rheologists through many decades. Research on fundamental rheological properties of wheat flour dough appears to be increasing in importance recently because of the application of continuous and automatic food processing operations such as extrusion, MDD bread making, and sheeting in modern bakery industries.

Among all of the cereal flours only wheat flour dough has unique viscoelastic properties. These viscoelastic properties are necessary to produce the spongy structure of bread loaf after the flour is mixed with water, fermented by yeast and baked (Hoseney and Rogers, 1990). Also the unique properties of wheat flour make it suitable for breadmaking because gas cells can be retained in the dough during mixing and proofing (Janssen, 1995). Wheat cultivars often differ, however, in their breadmaking performances. Gluten proteins are largely responsible for these differences (Janssen, 1995).

A possible correlation between fundamental rheological properties of wheat flour dough and processing conditions during breadmaking, notably MDD mixing behaviour and sheeting, was focused on in this study.

Rheological measurements including Dynamic Oscillation, Shear Stress Growth Test, Relaxation Test, Planar Extensional Flow Test, and Extrusion Test were carried out to study the rheological properties of wheat dough.

Results from both small and large deformation tests, showed that the fundamental rheological properties of flour dough mainly depend on the sample moisture content and the energy used to mix the dough, known as work input. Small deformation tests (Dynamic Oscillation) showed that optimum-mixed dough had a slightly higher elastic behaviour (higher storage modulus G' and lower phase angle (δ)). Rheological properties of non-mixing dough were also determined. Non-mixing dough was prepared by mixing flour and ice finely ground. Moisture distribution of non-mixing dough was very difficult to control because the dough

needs to be mixed with very fine ice particles to reach a good distribution when the dough is warmed up. Non-mixing dough gave similar values of storage modulus than mixed doughs. However, moisture content of non-mixing dough was lower than that of mixed dough despite the same water absorption was used as the amount of ice utilised was calculated taking into account in density.

Results of large deformation tests, namely the Shear Stress Growth Test, the Planar Extensional Flow Test and the Extrusion Test showed that there were significant differences among doughs prepared with different mixing conditions (under-mixed, optimum-mixed and over-mixed dough). The rheological properties were also depending on the type of flour used.

Slippage of the dough samples during the measurement was minimised by using sandpaper attached to the test plates. Serrated plates and smooth parallel plates were also used to compare with the results obtained using sandpaper.

It was found water absorption affects the fundamental rheological properties of dough dramatically. Decreasing water absorption increased the storage modulus G' and decreased the phase angle.

Confocal microscopy was used to observe the difference among Bakers (a strong flour) and Soft flour (a weak flour) dough prepared with various mixing conditions. A new deep frozen and cutting method was used to prepare the specimen. There were clear and significant differences between optimum MDD mixed dough and dough prepared with other level of mixing energy. Microscopy showed that optimum developed doughs had an uniform and well-developed structure.

Sheeting has a similar function as mixing but is more gently. Results showed that sheeting could develop dough. Using both weak flour (Halo) and strong flour (Beta) large deformation tests (Shear Stress Growth Test and Planar Extensional Flow Test) showed very consistent results and the presence of an optimum number of sheeting passes. This optimum appeared to agree whit the optimum determined by a baking test.

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CHAPTER ONE

INTRODUCTION

1. Introduction

Among all cereals, wheat is the most abundant food crop worldwide. Wheat is commonly milled to wheat flour which could be further treated by other chemical methods depending on its utilisation. There are more than thousands bakery products using wheat flour as the main ingredient around the world. However, the most important use of wheat flour is for bread (Kokelaar, 1994). Due to its viscoelastic behaviour, which is not yet fully understood wheat flour doughs are complex systems that create great challenges in process engineering and product development research. Szczesniak (1988) gives the most striking definition of dough--'it is alive'--referring to its condition of a dynamic system continually changing due to physical and chemical factors.

Many scientists are interested in wheat flour dough rheology because wheat flour dough is unique and different from other flour doughs. Also, during breadmaking, dough undergoes different type of deformation in every phase of the conversion of wheat flour into baked products. During mixing, dough is subjected to extreme deformations that may exceed its rupture limit. During sheeting, fermentation, proofing, shaping and baking, the properties of wheat dough vary largely (Hoseney, 1986). All of these changes affect the final quality of baking products. If the rheological properties of wheat flour dough were fully understood it would facilitate quality control of baking products and improvement of the bread making process.

Dough is "alive" which means the properties of dough are always varying once the flour is mixed with water. Water content is the most important factor affecting the rheological properties of dough. Ingredients used, temperature and resting time are other major factors affecting the rheological properties of dough. The relationship between rheological properties and baking performance still need to be researched.

Breadmaking is both a chemical and a physical process: chemical because of the formation of cross-links between protein chains by disulphide bonds. The action of oxidants, the reaction between different components in the dough and the transformation of sugars into carbon dioxide and ethanol by yeast, the development of flavours and the browning of the crust are also results of chemical reactions occurring during the breadmaking process (Janssen, 1995).

Breadmaking, however, can also be regarded as a physical process. Air bubbles are entrapped and subdivided in the dough mass during mixing. The composite material formed by the mixture of dough and air makes it be considered as a foam (Kokelaar, 1994). During fermentation and baking, yeast cannot produce new gas cells. That means that the mixing processing is a very important factor of the breadmaking process. In fact, the main purpose of the mixing may be considered as a process of entrapping air bubbles, enlarged it to a certain size during proofing, and keeping the holes to form a sponge-like structure towards the end of baking.

Viscoelastic properties of dough vary continuously during the baking processes as once the wheat flour is mixed with water and rested a strong gluten matrix is formed.

Viscoelastic properties of dough such as stiffness were usually measured by empirical methods. With the advance of new rheological instruments mechanical properties can be more quantitatively measured and viscoelastic properties can be determined. The meaning of these properties and how these can be measured will be described later in this thesis. Better knowledge of the viscoelastic behaviour of dough is necessary for quality control, improving processes such as baking or extrusion, and for elucidation of the interactions occurring among dough components (Navickis et al., 1982).

1.1 Background

Bread doughs is a viscoelastic material with explicit, non-linear shear thinning, thixotropic behaviour (Weipert, 1990) and strain hardening. The viscoelasticity of dough is a result of the interaction between gluten proteins and water.

Wheat cultivars often differ in their breadmaking performances. Gluten proteins are largely responsible for these differences (Janssen, 1995). The breadmaking process, another important factor, also affects the quality of final products. The correlation between dough fundamental rheological properties and processing conditions (especially mixing intensity) is a key aspect to understand how quality of bread can be optimised and controlled. However, to understand rheological properties of bread dough and build up scientific methods to control the quality of bread is still the greatest challenge in the cereal science area (Szczesniak, 1988).

During breadmaking the mixing operation has two main functions: (1) mixing all the ingredients uniformly and (2) forming a viscoelastic dough which is necessary to form a loaf of bread. This process can be done automatically in short times using different levels of energy input. It is believed that mixing with different energy inputs can affect the final volume and structure of bread. In fact, many researchers and bakers have empirically proved this. But why and how do the things happen is not fully understood yet. The use of fundamental rheological properties may help to understand the basic behaviour and response of bread dough and will play an important role in the development of continuous automatic breadmaking processes.

Knowledge of basic principles on rheology and how is applied to other materials such as cheese and polymer will help to design new methods to determine rheological properties of dough and establish the links between dough performance and the breadmaking process. Unfortunately, although protein and polysaccharides are high-molecular-weight polymers, they are very different to polymers such as polyethylene, which is made up of a single monomer unit. The complexity of biopolymers makes rheological measurement more difficult to carry out and interpret. Technologists and researchers have a good understanding of how to use empirical methods (e.g. Mixograph, Farinograph, Extensograph, etc) to determine the properties of the wheat flour dough and predict the quality of final bread which is commonly measured by carrying out baking tests. However, there is no a well-established correlation between empirical baking test and fundamental rheological properties. It is well known by bakers that wheat flour has to be mixed with water at an optimum work input to form a good visco-elastic dough. Empirical methods have shown that only the optimum mixed dough can provide a loaf of bread with good quality (both loaf volume and structure). Under mixed and over mixed dough can not provide bread with good quality. However, what's happening with the fundamental rheological properties when the wheat flour dough is mixed with different work input or non-mixed is not fully understood.

Recently new rheological instruments have been developed. These rheometers can provide very small deformation to the sample. By measuring the stress and the deformation strain, these instruments can determine viscoelastic properties such as storage modulus G', loss modulus G" and loss tangent δ. These instruments have been successfully used in studies related to the properties of polymers. For wheat flour dough, researchers (eg Mani, et al. 1992) have started to carry out work but more information is still necessary.

Using fundamental rheology, researchers concentrated their effort on measurements of dough properties during mixing. By using an universal testing machine (Instron) and rheological equipment, considerable research has been carried out on fundamental rheological measurements of different dough flours. Some of the studies focused on the measurements of the rheological properties of dough prepared with different additives and water absorption, which were added into the flour dough to improve the quality of the bread or the production process (Kilborn, and Tipples, 1972). Weipert (1990) and Mani et al (1992) studied the effect of mixing conditions on dough behaviour.

Rheological measurements of dough are not very easy to be determined because of the complex response of the bread dough at large deformations and the difficulties in setting up the measurement parameters. For small deformations, researchers mentioned that the dough specimen would give a linear response at very small deformations (strain 2×10^{-4} - 2×10^{-5}) (Janssen, 1995; Mani, et al, 1992). Using dynamic rheometers, dough samples prepared with different mixing conditions can be tested under very small strain at different temperatures and resting times. It may be helpful to understand the properties of dough and build up links between industrial breadmaking and research work.

Another important tool to investigate the properties of dough is the microscope. The conventional microscopy needs considerable sample preparation which makes unsuitable for fresh dough. A new microscope, the Confocal Laser Scanning Microscope, is now available for microstructure research of food materials including dough.

1.2 The Objective of this research

Preliminary postgraduate research work (Zheng, 1997) showed that the rheological properties of dough measured at small deformations were not sensitive enough to differentiate doughs prepared with various mixing conditions. A biaxial compression test also did not show a significant difference between doughs prepared with different energy input. Improving measurement conditions such as elimination of slippage, reduction of temperature gradients and a better control of the sample resting time to improve reproducibility have been attempted in this project. Large deformation measurements including a shear stress growth test, a new planar extensional flow test and an extrusion test were included to measure the rheological properties of dough. In order to reduce slippage serrated and smooth plates coated with sandpaper were used for both small and large deformation. Other fundamental rheological measurements measured included shear stress relaxation.

Specific objectives of this work were the development of rheological and microscopical methods to study the effect of the following parameters on dough properties and microstructure:

- Mixing Energy (or Work Input)
- Type of flour
- Water Absorption
- Resting Time
- Oil Content
- Dough Sheeting

CHAPTER TWO

LITERATURE REVIEW

2.1 Wheat Flour and Wheat Flour Dough

Many types of wheat are grown around the world. A variety of methods for the classification of wheats have been developed. The three most important classification criteria are based on kernel texture (hard or soft), bran colour (red or white) and growth habit (spring or winter). Wheat is used for bread-type products for which strong elastic dough is needed. Other types of wheat are used to manufacture cookies, biscuits, crackers, cakes, or pasta. In general, the properties of wheat and its application depend on its texture which is controlled by a single gene (Bushuk, 1995).

Milling of wheat is accomplished by a gradual reduction system. In this system, wheat is ground on rolls and separated by sieving into many streams, each of which is generally ground again. The net result is a separation of the grain into its anatomical parts, i.e., pericarp, germ, aleurone, and endosperm. As a result of milling, the protein content of the resulting flour is reduced about 1%, the minerals and vitamins are reduced, and essentially only starch is increased (Bushuk, 1995).

Usually wheat flours contain 70-80% starch, 8-15% protein, 11-14% moisture, 1.5-2.5% lipids, and a small content of minerals. Hard wheat flours tend to have higher protein content than soft wheat flours. Regarding the starch content, there is an inverse relationship between the amount of protein and starch (Janssen, 1995).

Because of the intrinsic difference in the structure of hard and soft wheat, they must be milled differently. Hard wheat usually has a vitreous, translucent endosperm that appears almost waxy, whereas the endosperm of soft wheat is white and completely opaque. The cell structure of soft wheat is very weak and readily broken. Under a microscope, hard wheat flour appears to be quite hard and crystalline, whereas soft flour is quite "woolly" and not at all crystalline. In addition, the endosperm of soft wheat appears to adhere more strongly to the bran (Bass, 1988).

There are a number of factors affecting the final quality of wheat flour during milling. They are wheat type, tempering, feed rate, and roll surface, roll speed, the presence of corrugation spirals, grinding pressure and roll temperature. Starch damage is a parameter frequently measured after milling in order to recognise differences between flour specifications because it can affect water absorption and gas production in fermenting doughs (Bass, 1988).

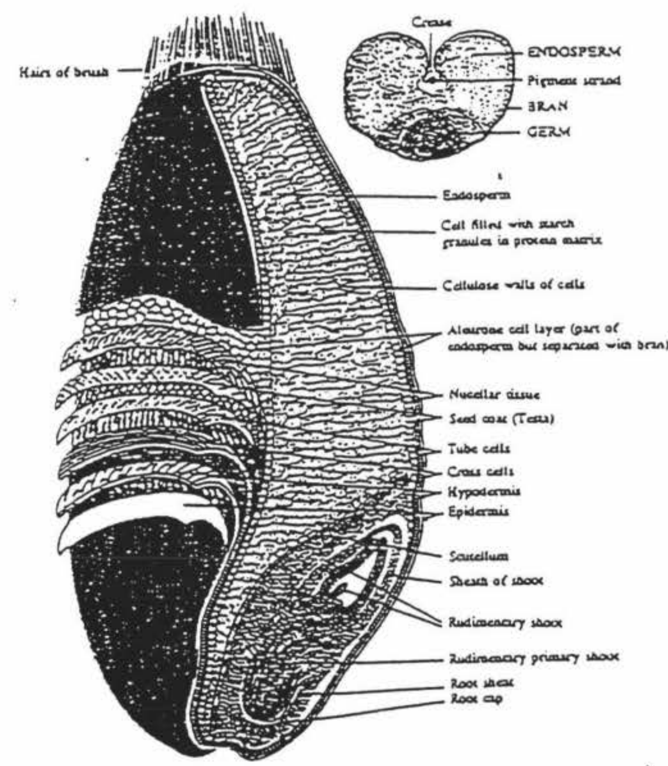


Figure 2.1 A microscopic structure of the wheat kernel

Wheat flour dough is formed by mixing wheat flour with water. The process of mixing seems to be simple but various factors affecting the dough structure during mixing make the dough a complex system. A solid phase such as protein and starch, a liquid phase (water), and gas are all involved in the dough system. Different ingredients such as salt, sugar, yeast, fat oil, emulsifiers, oxidizing and reducing agents, and processing conditions such as temperature, resting time, and energy input to name a few, will also affect the system. For the sake of conciseness and organization each of these variables will be discussed separately.

2.1.1 Wheat Flour Gluten and its Components

There are five fractions of protein in the wheat flour: (1) albumin, soluble in water; (2) globulin, soluble in salt solutions; (3) gliadin, soluble in 70%(v/v) alcohol; (4) glutenin, soluble in dilute acid or alkali; and (5) a residual fraction, which is frequently considered to be part of glutenin (Janssen, 1995).

When flour-water dough is gently washed with an excess of water, a rubbery mass called gluten, can be obtained. Gluten is made up of two groups of proteins: gliadin and glutenin.

These are both complex mixtures of proteins. The gliadin, ranging from 30,000 to 100,000 Da in molecular weight, has been separated into some 50 different proteins. The outstanding characteristic of gliadin is that when isolated it is very sticky. They are apparently responsible for the cohesive property of gluten. The glutenin proteins are much larger than the gliadin, with an average molecular weight of about 3×10^6 Da. Glutenin are physically resilient and not cohesive but rather short (not extensible). These proteins appear to give the gluten its elastic properties (Janssen, 1995).

Based on theoretical considerations, there are two factors that are very important in dough processing. They are 1) the quantity and quality (solubility, amino acid composition, molecular weight distribution, and structure) of the protein components of the gluten complex, and 2) the interactions (disulfide bonds, hydrogen bonds, electrostatic and hydrophobic interactions) between the protein fractions present in the gluten complex (Lasztity, 1996).

In practical terms, ***protein quality*** may be defined as the inherent ability of the flour protein for the production of bread. If two flours of the same protein content give different loaf volumes under optimised baking conditions, their proteins are said to be of different quality. The total amount of gluten protein in flour, ***the protein quantity***, is also important. Normally, the flours with high gluten have a good bread making performance (Janssen, 1995). Janssen (1995) also reported that the ratio between gliadin and glutenin in the gluten from different wheat flour is an important effect on the breadmaking performance. Before of this finding researchers believed that no consistent relationship existed between the gliadin content of flour and its baking quality as judged by the loaf volumes obtained.

To explain the uniqueness of the protein in wheat flour, we should start with its amino acid composition. As is well known, proteins consist of about 20 different amino acids. Compared to other cereals, wheat gluten is unusual in that it contains a very large amount (35%) of glutamine. The neutral glutamine promotes hydrogen bonding because they can both accept and donate electrons (Hoseney and Rogers, 1990).

The next most abundant amino acid in wheat gluten is proline (14%). One significant effect related to the presence of proline is that this amino acid has a ring structure. Therefore, the protein chain is not free to rotate around this position. In effect, the protein chain has a built-in link at each proline residue. Those links keep the protein from forming the type of three-dimensional structure that is typical for many proteins (Hoseney and Rogers, 1990).

The third major point concerning gluten's amino acid composition is the relatively low level of basic amino acids. Because of this, gluten proteins have very low charge density. The high level of glutamine and the low charge density would suggest a high degree of hydrogen bonding in wheat flour dough (Hoseney and Rogers, 1990).

2.1.2 Wheat Starch and other Components

Wheat flour normally contains about 70%-80% starch. When wheat is milled into flour, starch granules are subjected to physical damage. Hard wheat flours usually contain higher damaged starch than soft wheat flours (Bushuk, 1995). The combined effect of starch damage and amylase activity is extremely important in determining the water absorption of flour. Normally, undamaged starch granules are relatively insoluble and absorb only half their own weight of cold water. Conversely damaged granules absorb considerably more water (twice their own weight).

Wheat flour also contains gums, water-soluble and water-insoluble pentosan. The water-soluble fraction of wheat flour has been shown to be important in producing an optimum loaf volume. The mechanism of its action is not clear but may be just an increase in the viscosity of the aqueous phase (Bushuk, 1995).

Lipids are also present in wheat flour. It is convenient to classify flour lipids into two groups, non-polar and polar lipids. The non-polar lipids are detrimental to loaf volume, whereas the polar lipids are beneficial. Bushuk (1995) mentioned that if flour can be defatted in a way that gluten is not damaged, the flour still produces a reasonable loaf of bread. However, if the lipids are added back to the flour, the bread volume increases. It is thought that polar lipids, particularly glycol lipids, were involved in this experiment (Bushuk, 1995).

2.2 The Structure of Wheat Flour Dough

It is clear that the presence of an insoluble protein matrix is an essential prerequisite for the formation of cohesive dough. Not only must the protein be insoluble, but there must be a sufficient amount of it to form a continuous protein phase in the presence of starch and water (Lastztity, 1996). If the gluten protein is removed from flour, the property of forming a viscoelastic dough is lost.

From a colloidal point of view, dough is largely a continuous aqueous protein with dispersed phases of starch granules and air cells (Bohlin and Carson, 1980). There is a general agreement that gluten forms the framework of the dough structure. Starch is not simply a filler, but rather an active participant in determining the dough viscoelastic properties (Matsumoto, 1979). That means all of components of dough and added ingredients form a dynamic and complex system that contains air, free water, soluble components and insoluble solid material. This system is continuously changing once formed with various biochemistry and physical reactions happening during the whole process.

In order to understand the dough physical and rheological properties, is important to determine the interaction of gluten itself and with other components.

Although the idea that the dough structure based on three-dimensional network of protein subunits joined together by disulfide bonds seems to be phasing out and the role of other noncovalent binding, is being stressed there is no doubt that thiol groups and disulfide bonds play an important role in determining gluten and dough properties. Hydrogen bonds and hydrophobic interactions may also affect the rheological properties of dough.

As discussed previously gluten is formed by three types of proteins, gliadin, glutenin, and residual protein, packed together by covalent and noncovalent linkages. An early model of the possible structure of the gluten system is shown in Figure 2.2. The possible distribution and interaction of proteins in gluten is shown in Figure 2.3 whereas the location of lipid in the gluten network and glutenin network is shown in Figures 2.4 and 2.5

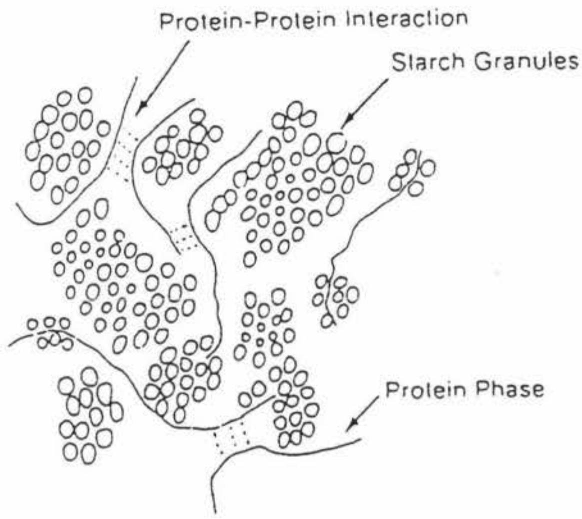


Figure 2.2 Schematic representation of the dough structure.

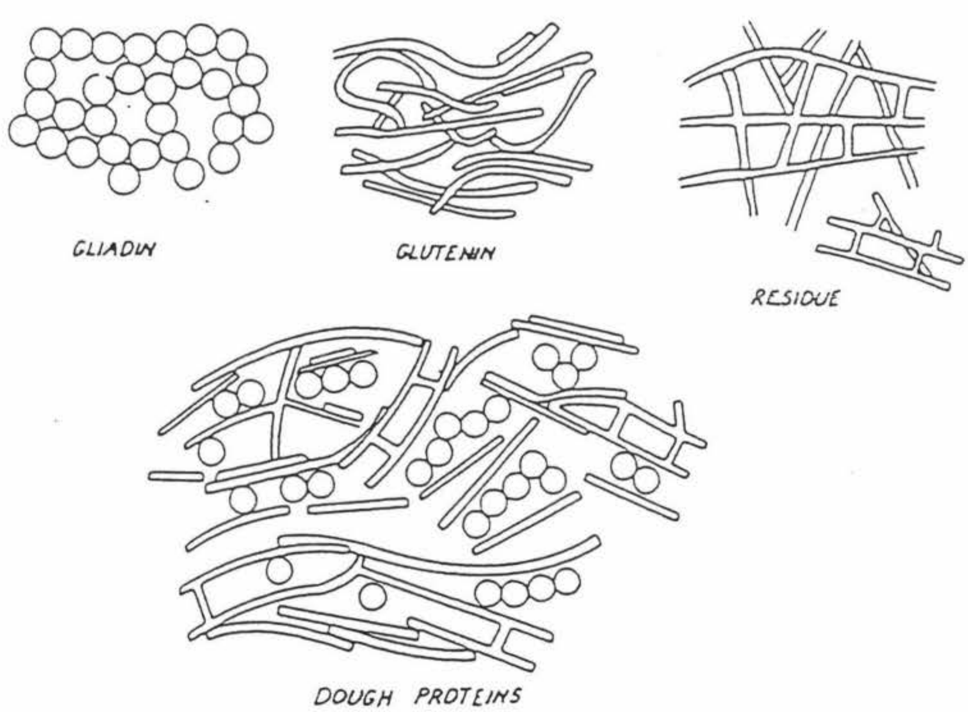


Figure 2.3 Model of interactions of wheat protein in dough (Wall, 1979)

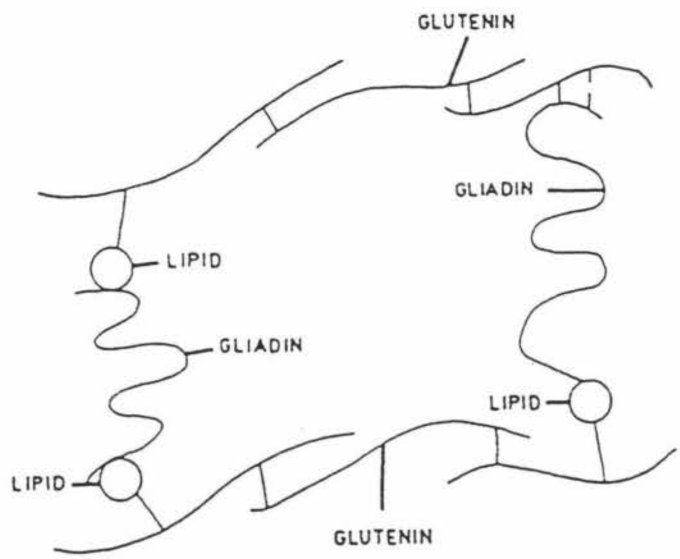


Figure 2.4 Possible location of lipids in the gluten network (Lastztity, 1996)

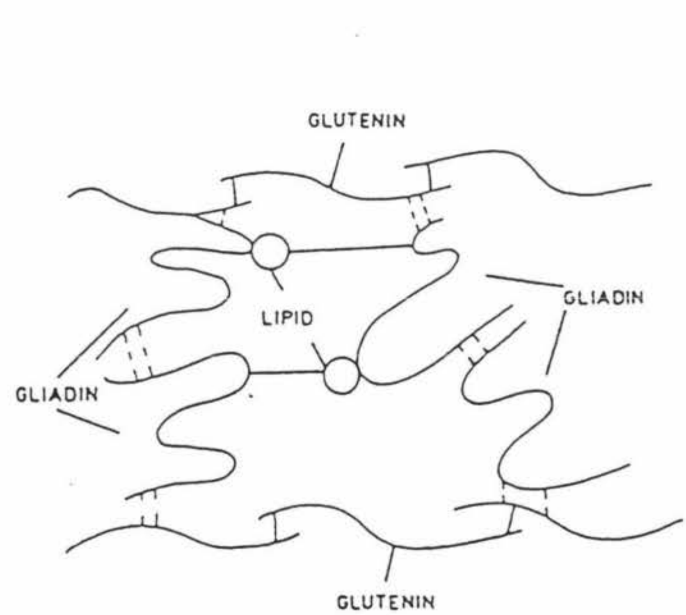


Figure 2.5 Possible location of lipids in the glutenin network (Lastztity, 1996)

2.3 Factors Affecting the Properties of Wheat Flour Dough

Bread doughs are viscoelastic materials. Viscoelasticity occurs because the gluten proteins are water compatible and thus in presence of water it will swell and interact each other. Doughs are also unique in the property of gas retention. This property appears to result from a slow rate of gas diffusion in the dough. The third major unique property of wheat flour doughs is their ability to set in the oven during baking, and thereby to produce a rigid loaf of bread. Although not clearly understood, this appears to be a heat-induced cross-linking of the gluten proteins (Hoseney and Rogers, 1990). Rheological properties of dough are very important "macroscopic" properties that can give a very good representation of the dough structure and how is affected by processing and ingredients.

2.3.1 Water Absorption

The amount of water that the baker add to a given weight of flour (also known as water absorption) determines how much dough will be obtained and how stiff or slack the dough will be after mixing and, subsequently, at make-up. Dough consistency affects mixing time for optimum dough development. Slack dough containing more water takes longer to develop than stiff dough with less water, dough that contains too much water, and is too slack, causes problems during make-up, particularly at the dividing and moulding stages.

The amount of water used for bread making may vary from 50 to 70 percent water absorption (based on flour weight), and depends on the type of bread, formula, flour, process and other factors. Generally, the amount of water used is higher for higher protein flours in short- or no-fermentation baking methods than for lower protein flours in long-fermentation methods (Janssen, 1995). It is considered that about 1 kg of water is absorbed by 1 kg of gluten. Thus, flours with higher protein content would take more water. Larsen and Greenwood (1991) mentioned that the water content is not related to the loaf volume of the bread, but it affects the structure of bread largely.

The amount of water present in a wheat flour dough significantly affects both the rheological properties of the dough and the quality of the finished baked product (Abdelrahman and Spies, 1986: Hibberd 1970a, 1970b: Hibberd and Paker, 1975b; Navickis et al., 1982; Dresse et al., 1988).

Viscoelastic properties of dough can be described by an elastic response at short times and a viscous response at long times. The water content of doughs affects the dough viscoelastic behaviour during resting time. Dough optimally mixed, tested immediately and 30 minutes after mixed, showed that increased water absorption caused both the viscous and elastic responses of dough to change at different rates (Abdelrahman and Spies, 1986).

2.3.2 Dough Mixing Conditions

Dough mixing has two main purposes: uniform dispersion of ingredients into a homogeneous mixture, and adequate development of the gluten into a structure that has the necessary physical characteristics of pliability, elasticity and extensibility. These physical characteristics are collectively referred to as rheological properties. The mixing process may be separated in four distinct phases or steps: blending of ingredients, hydration of flour, development, and breakdown (Bushuk, 1995), all of which give different physical properties which may affect the final quality of bread.

When water is added to flour a sticky mass is obtained. It has been determined, with the aid of microscopy, that during mixing water hydrates the outside of the flour particles. Proteins form fibrils in excess of water, making the system viscous. With no mixing, the system changes very slowly. It takes time for water to diffuse into the dense flour particles. With mixing, however, the hydrated outer surfaces of the flour particles are stripped away, exposing a new layer of the flour particles to be hydrated. This continues until all the flour particles hydrate completely and disappear (Hoseney and Rogers, 1990).

The process of mixing of water and flour and the development of dough is illustrated in Figure 2.6. The curve obtained during the mixing process is known as a mixograph. At the beginning of mixing and during hydration of the flour an increase of the dough consistency is observed. This is due to the formation of cross-linking and interaction between proteins. After the hydration period the consistency of the dough reaches a maximum value (peak). The reason for this peak lies in the fact that after all the protein is fully hydrated further mixing produces de-polymerizition of the protein network formed with the consequent decrease in dough consistency. That period, known as the breakdown period, is dependent on the type of flour. Four different mixing levels can be considered:

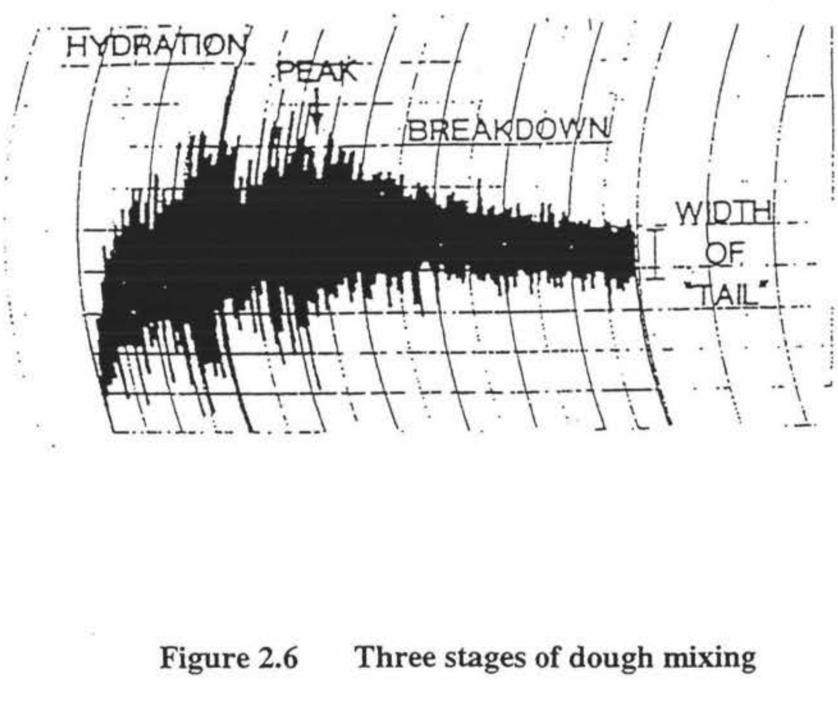


Figure 2.6 Three stages of dough mixing

(a) Non-mixing dough

Non-mixing dough means under developed dough. However, it is different than that defined by many researchers as un-mixed dough and used to describe the process, in which flour-water dough is mixed at a certain speed, stopped and remixed again. Non-mixing dough can be obtained by blending flour, ice particles and other ingredients at very low temperature (-8°C) (Campos, et al 1996). The mixture is then slowly heated up to 32 °C without mechanical energy input. Non-mixing dough is a cohesive but undeveloped dough. The size of ice particles plays a very important role and may affect the hydration of wheat flour particles. This system provides a useful model system for the study of fundamental rheological properties of wheat flour dough. Non-mixing dough also could provide a means of comparing rheological properties of flours without considering the mixing energy as one of the variables.

(b) Under-mixed dough

This dough is mixed with a low level of mechanical energy input. Under-mixed dough produces a poor quality bread because the dough can not form a matrix that is able to retain gas bubbles during the fermentation process (Bushuk, 1982). If the dough is mixed initially at high mixing speed, then at low mixing speed, the dough produced can be under developed and is usually known as unmixed dough (Tipples and Kilborn, 1979). It is worth nothing that this concept is different than the one that will be used in this work to define under-mixed dough. In this work under-mixed dough is defined as the dough mixed with a low level of mechanical energy but constant speed.

(c) Optimal-mixed dough

Usually the dough is mixed up to the peak of the mixograph if the best quality bread is to be obtained. It is only after dough has been developed to its optimum point that the full breadmaking potential of that dough can be obtained. This is called optimum mixing. The mixing of dough at optimum conditions includes both the optimum water absorption and optimum energy input. To achieve optimum development of a dough, two basic requirements must be satisfied: Mixing intensity (impeller speed) must be above a minimum critical level that varies with both flour and mixer, and the work input to the dough must be at a critical amount dependent on the flour used (Kilborn and Tipples, 1972).

(d) Over-mixed dough

Over-mixed dough means the dough is mixed to surpass the peak of the Mixograph, with a high-energy input exceeding the maximum requirements. If dough is over-mixed, its resistance to extension is decreased because disulphide bonds of the gluten proteins are broken and the gluten proteins are partially depolymerized. This results in greater solubility and lower viscosity (Hoseney, 1990). Over mixed dough does not have the ability of retain gas bubbles as well as optimally mixed doughs.

2.3.3 Temperature

Temperature, obviously, plays a very important role in the breadmaking process. The dramatic changes in the mechanical and rheological properties such as large increases in dough viscosity and elasticity at temperatures between 50 and 100 °C during baking are responsible in part, along with starch gelatinization, for the transformation from a predominantly viscous dough to a predominantly elastic baked crumb (Dreese et al., 1988a). Dreese et al. (1988b) also observed irreversible rheological changes due to the heating of dough to more than 55 °C. Elasticity of the dough increased rapidly between 55 and 75 °C. In general the ratio between the viscous and the elastic components drops significantly during heating in the range of 55-75 °C and the magnitude of the temperature-dependent rheological changes is proportional to starch content.

2.3.4 Resting Time

Although resting time is a variable commonly used in the bakeries, only few studies related to the effect of resting time on rheological properties of dough have been carried out. It is known that if dough is rested for 30 minutes it looks more uniformly soften overall, and the moisture is better distributed. Rheological measurement using small deformations, however, showed that there is no significant differences between un-rested and rested dough (Zheng, 1997). Abdelrahman and Spies (1986) mentioned that the viscoelastic properties of dough changed with the resting time, whereas opposite results were reported by Piazza and Schiraldi (1997) and Watanabe et al (1998). Complex biochemical reaction and moisture loss make the dough hard to be tested. However, resting and its effect on rheological property measurement are a factor that needs to be studied and understood.

2.3.5 Fermentation of Bread Dough

Before bread dough can yield a light, aerated loaf of bread, it must be fermented for a sufficiently long time to permit yeast to act on available carbohydrates and convert them into alcohol and carbon dioxide as the principal end products.

The most apparent physical change during the course of dough fermentation is the steady increase in the volume of the dough mass. The dough expands four to five times its original volume before it recedes, assuming at the same time a light, spongy characteristic. The rheological properties of fermented dough are very difficult to determine because of the continuous change of dough properties with time. The fragility of fermented dough, which can be disturbed by very low stresses or deformations, makes very difficult the determination of its rheological properties.

It has been demonstrated that fermentation causes dough to become more elastic (Cullen-Refai et al., 1988). As fermentation progresses, the ratio of elastic to viscous components of the dough changes, with the elastic component becoming more dominant (Hoseney et al., 1979; Hoseney, 1985).

2.3.6 Use of Additives

(a) Effects of Salt and Sugar

Sodium chloride, common table salt, is a basic dough ingredient that is generally used at levels of 1.50% to 2.25%. The primary reason for using salt is taste. Salt, as cooks and bakers through the ages have learned, enhances and augments the natural bread flavour

(Bushuk, 1995). It also stabilises or regulates yeast fermentation and has a toughening effect on the gluten proteins. This, in turn, increases mixing requirements by as much as 10% to 20% (Bushuk, 1995). It has been also reported that increases in salt concentration produces increases in the dough elasticity (Abdelrahman, and Spies, 1986).

Sugar has a similar function than salt. Sugar can also be used as a substrate for the yeast. Usually sugar is added at levels of 0.5% to 1%. Some bread may use more depending on the specification of the final product.

(b) Effects of Oxidizing Agent (Ascorbic Acid)

Ascorbic acid, an oxidising agent or improver, affects physical properties of dough, thereby improving loaf volume and crumb grain if it is added in appropriate amounts (Bushuk, 1995). Usually it was used in bread making in combination with potassium bromate in New Zealand. The use of potassium bromate has been discontinued due to safety considerations. Ascorbic acid makes the dough harder and elastic and also has a bleaching action. Normally it is used in concentrations of 10-100 ppm, depending on the breadmaking process and the flour utilised.

Potassium bromate was used in the past, and its fast-acting oxidant capacity increased the elasticity of the dough.

(c) Effects of Reducing Agent (L-cysteine)

Adding the thiol compound cysteine to dough reduces dough elasticity due to the blocking of disulphide bonds.

Basically, L-cysteine is considered as a chemical dough development agent. L-cysteine is supposed to split disulphide bonds rapidly, facilitating the unfolding of protein molecules during mixing and thereby aiding dough development As consequence of this, a normal mixing process with cysteine can develop the protein network up to the same extent than a high-speed mixing process without cysteine. Frazier et al, (1975) found, using an Extensograph, that cysteine decreased the resistance and increased the extensibility of the dough.

As a reducing agent, L-cysteine is quite effective in shorten the mixing time. However, the dough can be mixed to breakdown quickly when too much L-cysteine is used, and good gluten would not be formed. (Bushuk, 1995).

2.3.7 Effects of Emulsifiers, Oil and other ingredients

Lipids (both fat and oil) can be divided in two groups, polar and non-polar. The primary application of fats and oils is as lubricants. Fats and oils are also utilized for their unique ability to stabilize air cells in emulsions, fondants, and batters, thus providing a means of incorporating air into complex macromolecule networks and achieving desirable textural attributes in those products.

Researchers reported that lipids in wheat flour had little or no effect on the dough rheological properties. More-highly saturated fatty acids had little effect on Farinograph curves, and unsaturated fatty acids increased dough development times. Water-absorption is unaffected, and mixing tolerance was improved by adding non-polar or total lipids. Some researchers mentioned that adding up to 8% hydrogenated cottonseed oil, dairy butter, or lard significantly lowered water-absorption as measured by the Farinograph (Pomeranz, 1988).

Yeast, milk, shortening, sweeteners, anti-microbial agents, surfactants, amylases, and protease also play a significant role in bread making. All of them provide different functions to make the bread has a better taste, flavour, or texture or to make the process easy. These also make the dough system more complex and it is more difficult to understand the behaviour of dough when tested using both fundamental and empirical rheological methods.

2.4 Sheeting

The sheeting of doughs is a commercially important unit operation in a wide variety of food processes. Repeated sheeting of under-developed dough results in its development (Kilborn and Tipples, 1974).

Basically, sheeting has the same function than mixing. The amount of energy necessary to develop dough by sheeting is about 15% of that required when the work is done by mixing (Levine, and Drew, 1990).

It was observed that the extractability of gluten increased, and the composition of the extracted gluten changed as the dough was processed, either by repeated passes through rollers or by decreasing the gap between the rollers (Levine, and Drew, 1990). Repeated sheeting results in the organization of a protein network within the dough. Excessive sheeting tended to break down this organization in the same way than overmixing does.

2.5 Evaluation of the Quality of Dough

Evaluation of bread quality and the dough that can produce it consists of two type of determinations (1) the volume of the bread and (2) structure of crumbs. The volume of bread is simply measured by a volume displacement technique whereas the assessment of the crumbs structure is highly subjective, and influenced by ethnic, cultural and personal preferences. The quality factors assessed and the standards applied may also vary with the type of bread being consumed. However, the ultimate measure of the quality of commercial breads must be the level of consumer satisfaction.

Rheological properties are important in determining the behaviour of wheat flour doughs during mechanical handling in addition to their influence on the quality of the finished products. The knowledge and research on rheological behaviour and dough properties are becoming more important as the baking industry becomes more automated. Also the application of rheological concepts to study the behaviour of doughs seems a natural requirement to research the interrelationships among flour composition, added ingredients, process parameters and the characteristics of the loaf of bread (Szczesniak, et. al., 1983).

Through several hundred of years, bakers and researchers always wished to understand fully the principles and properties of wheat flour dough, but they do not completely understand the interactions involved in their formation or the factors affecting their properties, because dough is a difficult system to work with because exhibits both viscous and elastic behaviour. This viscoelastic behaviour tends to be non-linear. But many of the tests currently in use in bakeries are not based on fundamentally sound rheological principles (Spies, 1989). The difficulty of testing the basic rheological properties of a system as complex as wheat flour doughs largely explains the delay in the application of rheological principles in the bread making industry. The lack of adequate information on the rheological properties of doughs has forced bakers to rely on empirical measurements in quality control and research situations (Weipert, 1992).

Dough rheology research and empirical observations have enabled us to understand many events that take place during dough development. Dough development is the mixing of all ingredients into a homogenous mass. The bakery always hopes to shorten the production process time. Through a high-energy input, mechanical dough development (MDD) accelerates the process and sufficient gas retention is obtained by the mixing process and a short fermentation. The application of automatic machinery and computers is nowadays more and more common in the baking industry. Not only we need to accurate measure wheat flour dough parameters but also we need to set up methods to control and adjust the properties of the dough and the quality of final baked products.

In accordance with improving the qualities of bread and other baked products, scientists have designed instruments which can measure texture sensitively by imitating the sensitivity of human beings, like biting, chewing, squeezing, pulling, and pressing. But, up to now, no easy method has been found to determine the properties of dough. A link between fundamental rheological properties and bread making performance has to be established if we want to control the quality of bread in the future. Hopefully, an ideal tool, which is a simple and cheap apparatus, can help bakers to control the mechanical properties of the bread dough. The most important aspects of future research are to be able to transfer the results from fundamental measurements to practical tests in the bakeries. However, the first thing to be sorted out is to understand the changes of fundamental properties of the bread dough at the different production processing stages.

The flow and deformation behaviour of doughs is recognised to be central to the successful manufacturing of bakery products.

Wheat flour dough is a complex composite biological material (Bloksma and Bushuk, 1988). In addition, controlled rheological measurements of wheat flour doughs are difficult and time consuming. Consequently, making reproducible measurements on dough is often a humbling experience. Despite the challenges, however, the progress in understanding flour and its biochemical components is obvious, as it is in the fields of colloid chemistry, rheology, polymer rheology, and instrumentation. Therefore, the challenge ahead is to use new technologies of these supporting sciences to increase our understanding of dough rheology.

The evaluation of dough in bakeries is very subjective as until today the consistency and physical properties of dough is tested by the operator using a " touch and feel approach". There are, however, empirical rheological methods used by the milling companies to determine the quality of the flours they are producing. This information is generally passed on to the bakers. Currently there is no much fundamental rheological methods used in the daily bakery operation. In general, methods to determine the rheological properties of dough can be classified in Empirical and Fundamental Rheological Methods. They are described below:

2.5.1 Empirical Rheological Methods

Flours from different wheat, mills and geographic origins can differ considerably in their contents of protein, ash, moisture, enzymatic activity, and in overall baking performance. It is essential for the baker to be aware of any changes that may have occurred in these characteristics prior to placing flours into production. The purpose of individual flour tests is to disclose the specific property or character being tested for.

The intensive efforts over the past 60 years to arrive at an objective measurement of the rheological properties of wheat flour dough have resulted in the development of a number of precise and sensitive instruments that yield records of the mixing, water absorption, enzymatic activity, fermentation and oxidation characteristics of flours. The more widely used empirical testing methods can be divided into two broad categories: (1) viscosity measuring instruments and (2) elasticity measuring instruments.

Most of the empirical rheological work made on doughs uses equipment that applies large deformations to the samples. These instruments, however, do not provide information regarding the sample's fundamental rheological properties, because the non-linearity of dough under such large deformations and because the deformation is not well defined and uniform.

The advantages of empirical rheological testing, however, are:

- It is relatively easy and fast to perform. This makes it practical.
- It provides a great deal of heuristic knowledge, which has been accumulating over the past 50 years.
- The instruments needed to perform the tests are relatively inexpensive.
- Users do not require much training in physical sciences, since the methods are already established (Pyler, 1988).

Empirical dough testing instruments include the following:

(a) Mixograph

The Mixograph is a miniature high-speed recording dough mixer. A typical Mixograph plot is shown in Figure 2.7. The plot illustrates the various empirical parameters that can be determined from the curve. A Mixograph will provide a good indication of the time required by flour to reach optimum dough development and will thus differentiate between flours with short and long mixing times.

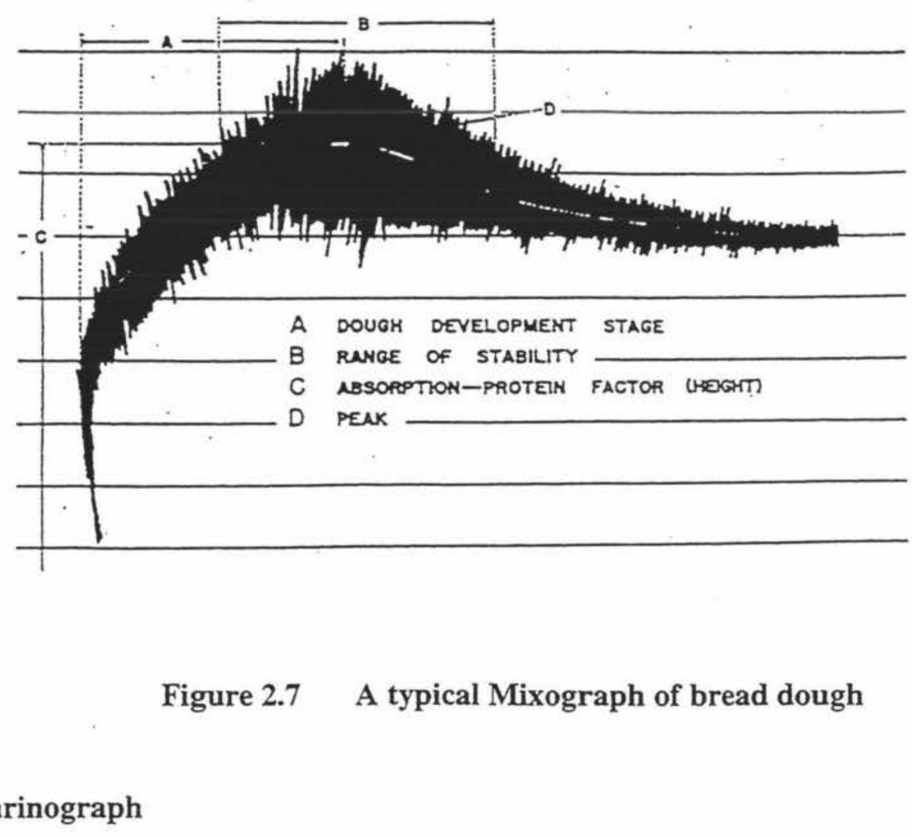


Figure 2.7 A typical Mixograph of bread dough

(b) Farinograph

The Brabender Farinograph has gained a wider acceptance in cereal laboratories than any other experimental dough-testing instrument. The apparatus incorporates a high-speed mixer and is designed to measure the resistance of the dough against a constant mechanical shear. The instrument produces a real time graph that gives a visual record of the quality characteristics of the wheat flour being tested.

Figure 2.8 shows a typical Farinograph along with the principal empirical parameters determined from the measurement.

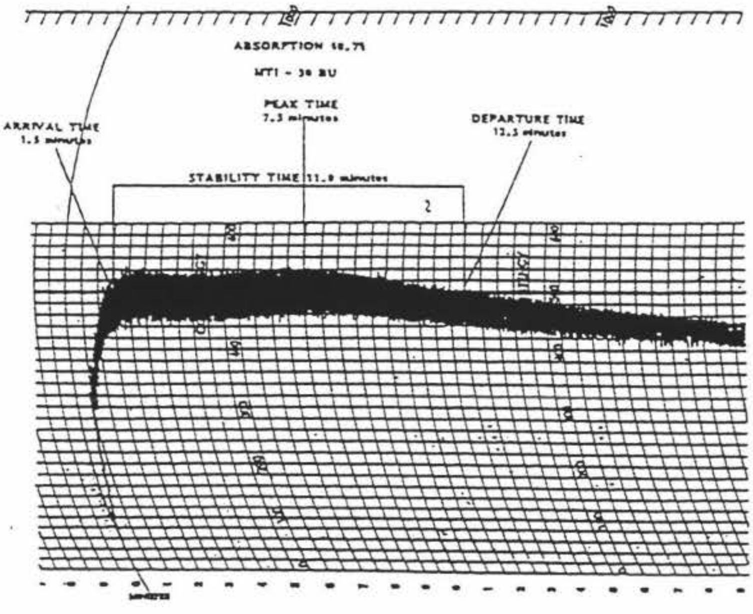


Figure 2.8 A typical Farinograph of bread dough

The dough development or peak time is an indication of protein quality, with stronger flours normally requiring a longer development time than weaker flours. It also reflects, to some extent, the level of water absorption used in the test. The stability time or mixing tolerance is a primary index of flour quality and is one of the more significant parameters measured by the Farinograph. All doughs eventually break on sustained mixing. This phase is indicated in the farinogram by the descending part of the curve. The sooner this break occurs, the less fermentation and mechanical abuse the flour is likely to tolerate.

A heavy-duty version of the Farinograph, called the Brabender Do-Corder, is available for estimating the performance of flours in continuous mixing and high-speed mechanical dough development processes.

(c) **Rheograph**

The Rheograph represents an adaptation of a small-calibrated bench mixer provided with a three-pronged beater and a bowl. The mixer is housed in a cabinet with controlled temperature and humidity. Its beater is provided with a floating gear that is connected to a transducer that transmits its signal to the recording device. The flour-water dough is mixed until fully fatigued, i.e., unable to remain on the kneaded prongs. The time needed to reach this point gives a practical information about the flour's protein content, gluten quality, water absorption, milling intensity, and optimum levels of ingredient usage. The device produces data that correlates flour composition with its baking performance. A typical Rheograph is illustrated in Figure 2.9.

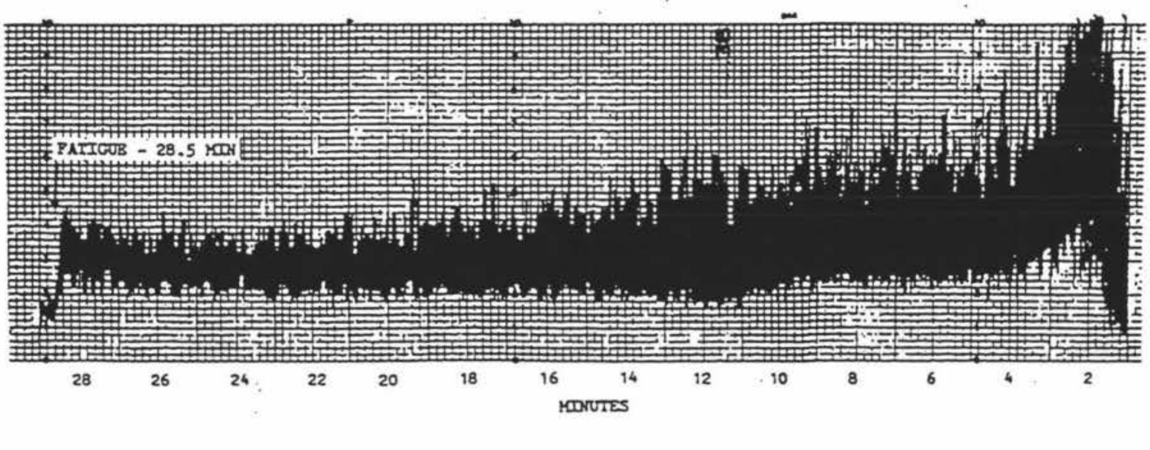


Figure 2.9 A typical Rheograph of bread dough

(d) **Mixatron**

Commercial bakers operating high-speed mixing equipment need to estimate rapidly the optimum water absorption levels and mixing requirements of new flours.

Attempts to determine dough consistency or to predict the absorption and mixing requirements of flour have generally followed two lines of approach. One is to use small recording dough mixers; e.g., the Farinograph or Rheograph described before, that yield mixing curves from which valid conclusions regarding the practical mixing requirements of flour can be drawn. The other approach is to connect Wattmeters to the mixer motor to measure the energy input into the dough. Wattmeters, however, are generally unsuited for measuring changes in dough consistency during the mixing cycle; they merely record or control the amount of energy required by the dough to achieve the optimum development. Changes in dough consistency that take place during the commercial mixer operation are recorded by using an apparatus known as the Paterson Mixatron. This is a precision electronic instrument that converts induced electric currents into watt-hour impulses. These impulses are then integrated into a single line curve that reflects the relative consistency of dough and plotted continuously against time. The chart, moving from left to right whenever the mixer is operated, provides an immediate record of dough consistency and the actual mixing time of each dough.

The advantages of the Mixatron include the following: (a) it simplifies the determination of optimum absorption levels and mixing times of new flours; (b) it ensures uniformity; (c) it permits a close control of the dough properties and hence to the maximum absorption capacities of the flour; and (d), it largely eliminates human and mechanical errors and failures in the mixer operation

(e) Alveograph

The Alveograph, also known by its earlier name as the Chopin Extensograph, is an instrument designed to measure the resistance to expansion and the extensibility of a thin sheet of dough. A typical Alveograph is illustrated in Figure 2.10.

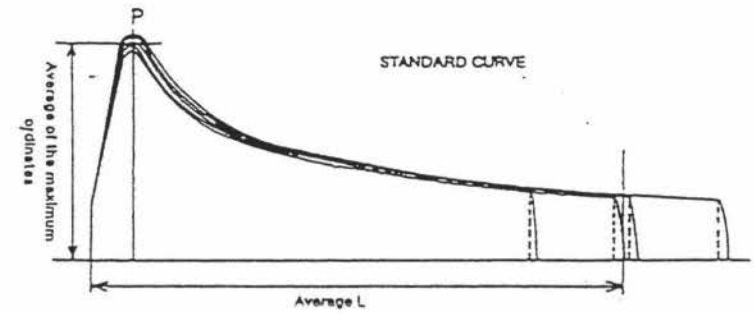


Figure 2.10 A typical Alveograph of wheat flour dough

The parameter of interest measured with the alveograph are the Peak force and the extension to breakage indicated in the figure as P and L respectively

(f) Extensograph

Dough extensibility and resistance to extension can also be measured by the Brabender Extensograph or Extensograph. A typical Extensograph along with the parameters determined during the measurements is illustrated in Figure 2.11.

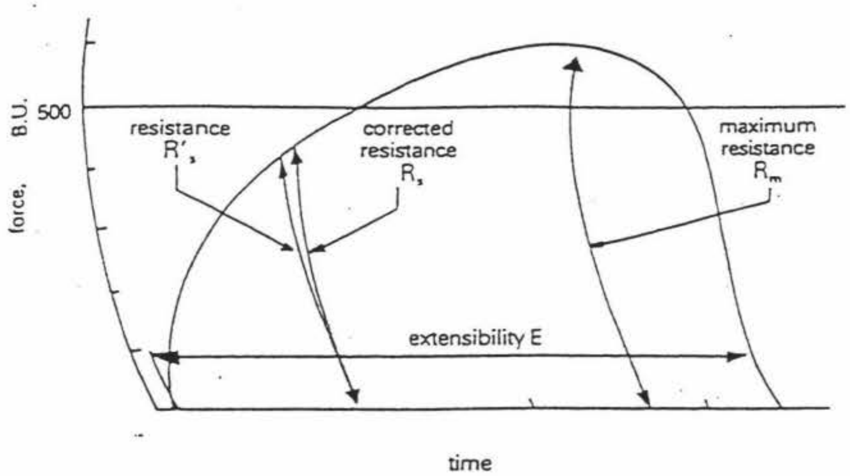


Figure 2.11 A typical Extensograph of wheat flour dough

(g) Baking Test

While the various physical and physicochemical flour testing methods provide useful and often adequate information, it is ultimately the baking test the one that yields the most reliable index to flour's potential performance in production. Since the baking test is carried out under more or less standardised and controlled laboratory conditions, its results must still be interpreted by taking into account the variables that normally are important into large-scale commercial production.

The type of test used will depend on a variety of factors. If the purpose of a baking test is to estimate the loaf volume and crumb grain potential of an unknown flour, then, as Finney (1950) has amply demonstrated, both the test formula and mixing time must be optimised and balanced so that none of the added ingredients becomes limiting. If, on the other hand, the aim of the baking test is to verify the uniformity of the flour and to evaluate its suitability for production requirements of a bakery, to determine the effects of formula changes, and/ or to test the efficacy of a new ingredient, a more standardised test baking method is required.

2.5.2 Fundamental Rheological Methods

Rheology is defined as the study of the deformation and flow of matter. Deformation concerns to matter, which is solid, whereas flow to matter which is liquid. The rheological property of interest in solids is their elasticity whereas in liquids their viscosity. Foods, in general, cannot be categorised in a so clear-cut manner as solids and liquids.

From a rheological point of view, there are four different kinds of materials: (1) liquids, (2) solids, (3) viscoelastic and (4) plastic. Liquids and solids deform irreversibly or reversibly respectively depending on the action of a force; plastics exhibit either liquid or solid behaviour depending on the magnitude of the applied force; and viscoelastic materials exhibit either liquid or solid behaviour depending mainly on the time during which the force is applied. Dough is a very classical example of a viscoelastic material.

In rheology it is more convenient to use stress and strain measurements rather than force and deformation or flow. Stress and strain for a component test are defined by equation (2.1) and (2.2).

Stress (σ)

$$\sigma = \frac{Force}{Area} = \frac{F}{A} \tag{2.1}$$

Strain (γ)

$$\gamma = \frac{Extension}{Original\,Strain} = \frac{\Delta L}{L} \tag{2.2}$$

The definition of strain given by Equation (2.2) is the strain for either a material subjected to extension or compression. When a material is deformed by shear as shown in Figure 2.12 a shear strain can be defined as:

$$\dot{\gamma} = \frac{aa'}{ad} = \tan\alpha \qquad (2.3)$$

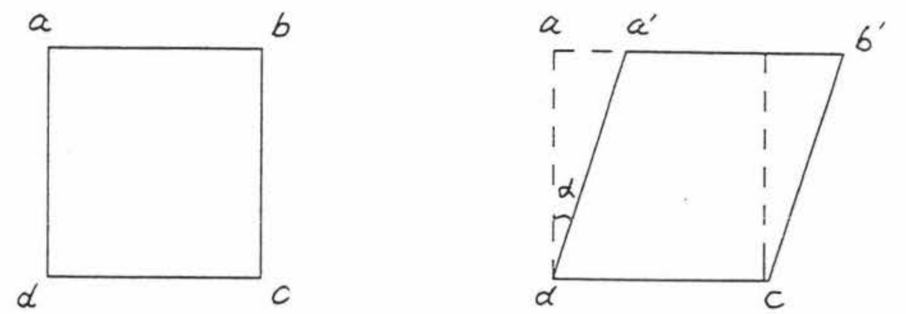


Figure 2.12 Schematic view of shear deformation

In the simplest situation, stresses and strains set up are in one direction. However, it should be apparent that, if the length increases, the cross-sectional area will decrease. Therefore, stresses and strains will be set up in a direction at right angles to the main force. If the material is prepared in the form of a thin wire, then the main stresses take place along the wire, whereas, if the material is in the form of a cube, three-dimensional stresses will occur. One-dimensional stress situation is much easier to handle than three-dimensional situations. Thus, by careful choice of experimental conditions, the complex stress situation can be simplified, enabling only one stress component to be considered.

Further definitions can be made by considering ideal materials. In an ideal solid (Hookean) the resultant strain will be directly proportional to the stress placed on the sample, but will be independent of the strain rate. Thus, for a solid material

$$\sigma = E\gamma \qquad (2.4)$$

Where E is the Young's modulus.

For an ideal Newtonian liquid the stress will be proportional to the strain rate. Equation (2.5) can apply only for a shear deformation and the stress and strain are known as shear stress and shear rate.

$$\sigma = \mu \dot{\gamma} \qquad (2.5)$$

For the elastic solid, the energy used to deform the sample is totally recoverable, and when the stress is removed the sample will return to its original state. Conversely all the energy to deform the liquid is irreversibly lost.

(a) Small Deformation Test – Dynamic Measurements

Small Deformation Shear Tests or Dynamic measurements are used to determine rheological properties of viscoelastic materials. In this method the sample is either deformed or a stress applied using a sinusoidal varying waveform (either strain or stress) at deformations small enough to avoid the breakdown of the sample.
Assuming that a sinusoidal strain is applied

$$\gamma = \gamma_0 \sin(\omega t) \qquad (2.6)$$

Where γ_0: amplitude of the strain
ω: Angular frequency (rad / sec)
t: time (sec)

The resulting stress will be

$$\tau = \tau_0 \sin(\omega t + \delta) \qquad (2.7)$$

Equation (2.7) shows that as a result of the strain a stress with the some frequency is obtained but with a certain phase lag between the two waveforms.

The phase angle or loss angle can be used to calculate two important viscoelastic properties: the storage modulus G' and the loss modulus G" as:

$$G'(\omega) = \frac{\tau_0}{\gamma_0}\cos\delta \qquad (2.8)$$

$$G''(\omega) = \frac{\tau_0}{\gamma_0}\sin\delta \qquad (2.9)$$

The ratio between the loss modulus and storage modulus is given by the following equation.

$$\tan\delta = \frac{G''(\omega)}{G'(\omega)} \qquad (2.10)$$

G' (storage modulus) is a measure of the sample elasticity, or energy stored in the sample, during the deformation cycle, whereas, G" the loss modulus is a measure of viscosity, or energy lost during the deformation cycle. The ratio of the moduli is a measure of the relative contributions of the viscous and elastic components to the rheological characteristics of the sample and is expressed as the tangent of the angle by which the stress and strain are out of phase:

In a purely elastic solid, stress and strain will be in phase, and in a purely viscous fluid, stress and strain will be 90 degrees out of phase.

Viscoelastic properties of dough using small deformations have been studied by several researchers. Faubion et al (1985) reviewed the results of these measurements. It was found that dough only exhibits linear viscoelastic at very low strains. There are reports that strain smaller than 2×10^{-4} are needed to satisfy the requirement of linear viscoelastic behaviour.

The review of Faubion also details that water is the ingredient that has a major effect on the dough rheological properties. In general it was found that the increase of water content reduces the storage modulus but does not change the loss tangent. This would be indicating that water acts as a dilution rather than a plasticising agent.

A plasticiser agent would change the solid/liquid like behaviour of the dough, which would be evidenced, by a change in the phase angle.

(b) Relaxation and Creep Tests

These tests, known as static tests, are commonly used to study the viscoelastic behaviour of food materials like dough and gain insight into their mechanical behaviour. These tests can use small and large deformations. Stress relaxation involves applying an instantaneous deformation to a body and keeping this deformation or strain constant throughout the test. The way that the resultant stress relax (or is alleviated) by the material is monitored as a function of time. Stress relaxation is commonly achieved by the use of a universal-testing machine by allowing the crosshead to compress the sample to a particular deformation, then stopping it. The constant strain is therefore maintained and the manner by which the sample attempts to alleviate the imposed stress is recorded. Stress relaxation can be performed under conditions of compression or tension. If rotational viscometers are used relaxation experiments under shear conditions can be used.

The other basic test, known as creep, consists on the application of an initial constant load or stress to the sample and the resultant sample deformation is monitored as a function of time. Similarly a creep shear test can be carried using a rotational rheometer.

(c) Extensional Flow Tests – Large deformation

Extensional tests are commonly carried out by Universal Testing Machines (eg the Instron). These tests are based on the application of a shear-free deformation.

One of the tests commonly used for dough is called biaxial extensional or uniaxial compression test. It is extremely simple testing method. However, such tests have some serious problems with the computation of the elastic moduli because of the effects of bonding and lubrication between the sample and the plate.

In a biaxial extensional compression test, a cylindrical sample is compressed between two lubricated parallel plates. The velocity of approximaties between plates is constant. For this situation, Chatraei et al., (1981) define the extensional strain ε as:

$$\varepsilon = \ln(\frac{h_t}{h_o}) \qquad (2.11)$$

h_0 is the original height of the sample and h_t is the height at time t (see Fig.2.13 A). The extensional strain rate can be calculated as:

$$\dot{\varepsilon} = \frac{d\varepsilon}{dt} = \frac{1}{h_t}\frac{dh}{dt} = \frac{V}{h_t} \qquad (2.12)$$

where the V is the compression rate. Based in the extensional flow strain a biaxial extensional rate can be defined as:

$$\dot{\varepsilon}_B = -\frac{\dot{\varepsilon}}{2} = -\frac{V}{2h_t} \qquad (2.13)$$

Since the radius on which the force F acts is constant, the normal stress difference σ_{rr} - σ_{zz} (see Fig.2.13 B) can be written as:

$$\sigma_{zz} - \sigma_{rr} = \frac{F}{\pi R^2} \qquad (2.14)$$

The apparent biaxial extensional viscosity η^*_{BE} is defined by the ratio between the stress and the biaxial extensional strain rate can then be calculated as:

$$\eta^*_{BE} = \frac{\sigma_{rr} - \sigma_{zz}}{\dot{\varepsilon}_B} \qquad (2.15)$$

From Equations (2.13), (2.14) and (2.15) is obtained

$$\eta^*_{BE} = \frac{2F_t h_t}{\pi R^2 V} \qquad (2.16)$$

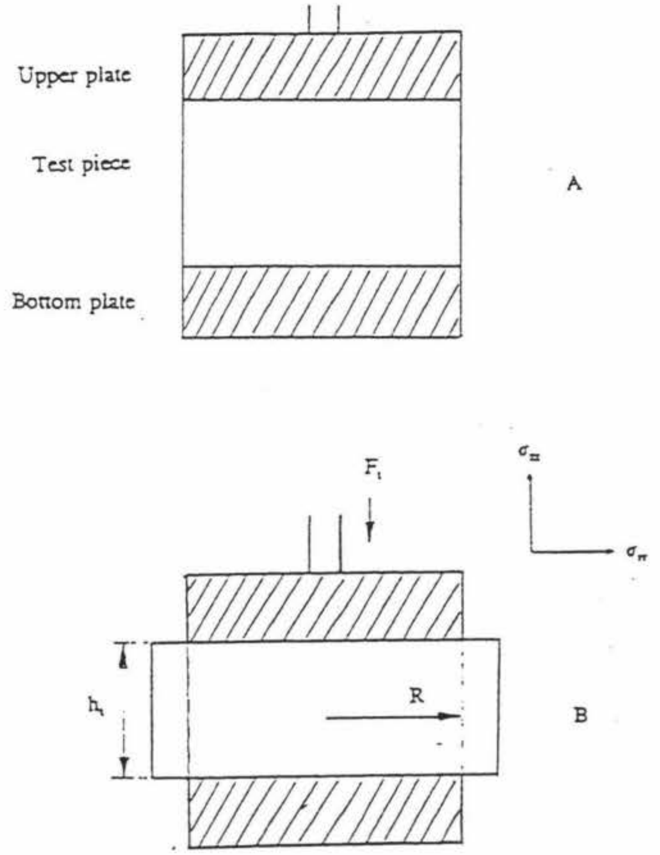


Figure 2.13 Schematic view of the geometry for an uniaxial compression test

A: Initial stage if the experiment; B: compression (Janssen, 1995).

(d) Planar Extensional Flow Test

Morgenstern, et al (1996) presented a method to determine the rheological properties of pastry dough. A sheet-deforming device, shown on Figure 2.14 A, was used to apply this test. It consists of two perplex plates with a circular aperture in the middle. A sheet of dough is placed between the plates. The sheet is held by eight sharp pins that are set in a circle 20 mm from the edge of the apertures of both plates. A flat probe, with rounded edges, is attached to an Instron machine. The dough sheet is deformed by the probe, which moves, with constant speed, vertically down the centre of the aperture.

Elongation (deformation) and elongation rate are calculated as follows: The 'length', (l), of the sheet (see Figure 2.14 B) is given by:

$$l(t)=\sqrt{(l_0)^2+v^2\cdot t^2} \tag{2.17}$$

Where: l_0 is the distance (gap) between probe and aperture perimeter and v is the (constant) cross head speed. The elongation rate is:

$$\frac{d\varepsilon}{dt}=\frac{1}{l}\cdot\frac{dl}{dt}=\frac{1}{t}\cdot\frac{x}{1+x^2} \tag{2.18}$$

Where a characteristic time for the experiment, t_c, is defined and the time t is made dimensionless using this characteristic time:

$$t_c=\frac{l_o}{v} \qquad x=\frac{t}{t_c} \tag{2.19}$$

By integrating Equation (2.18) yields the extensional strain as a function of time:

$$\varepsilon(x)=\frac{1}{2}\cdot\ln(1+x^2) \tag{2.20}$$

The force on the probe, F(t), is measured as a function of time. The average stress in the sheet is calculated by dividing the force component in the direction of the sheet, Fs, by the average cross sectional area A. Thus,

$$\sigma(t)=\frac{F_s(t)}{A(t)}=\frac{F(t)\cdot\cos(\alpha(t))}{A(t)} \tag{2.21}$$

and the average cross-sectional area A can be calculated as:

$$A(x)\cdot l(x)=2\pi R\cdot l_0\cdot h_0=constant \tag{2.22}$$

By substituting l(t) given by Equation (2.17) and (2.19) yields:

$$A(x)=2\pi R\cdot h_0\cdot\frac{1}{\sqrt{1+x^2}} \tag{2.23}$$

Where R is the average radius between probe and aperture perimeter, and h_0 is the initial thickness of the dough sheet. The average stress is then:

$$\sigma(t)=\frac{F(t)}{2\pi R\cdot h_0}\cdot x \tag{2.24}$$

An apparent elongational viscosity can be defined as the ratio of the stress and the elongation rate.

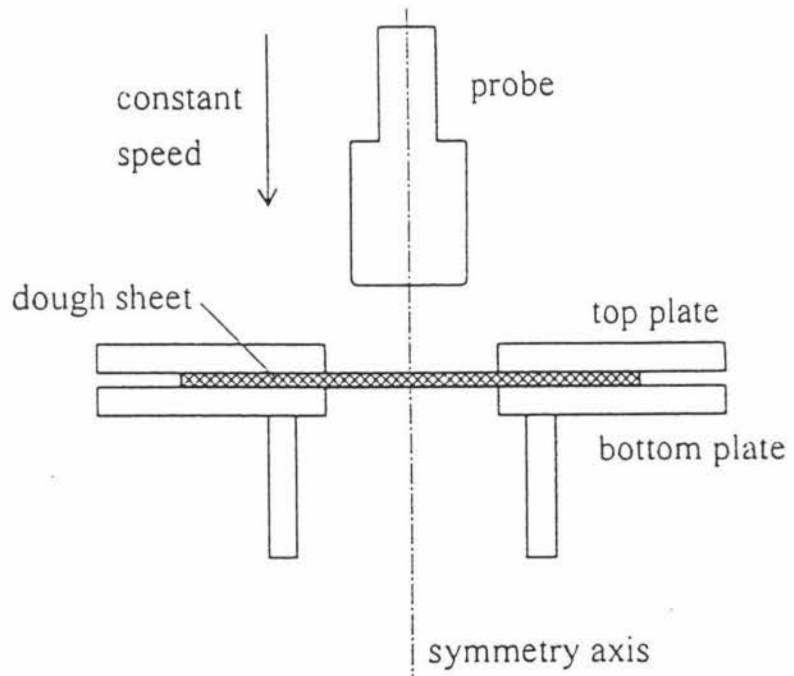


Figure 2.14 (A) Schematic view of Cross section of sheet deformation set-up

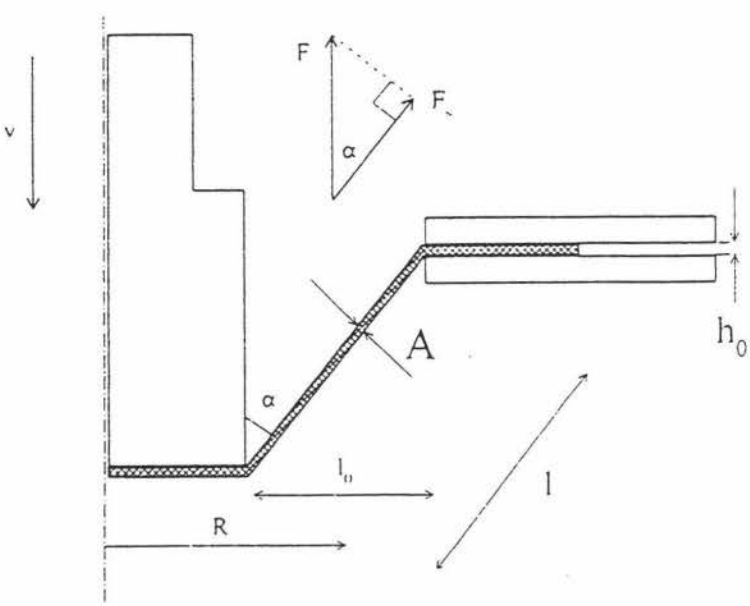


Figure 2.14 (B) Diagram of the sheet deformation set-up with symbols used in the equation

2.6 Non-linear behaviour of flour-water dough:

Early studies by Hibberd and Wallace (1966) determined that for dough produced from a flour of a single wheat variety, viscoelastic behaviour was linear at very low strain amplitudes (less than 0.0022%). At higher strain amplitudes, both storage and loss moduli were highly strain dependent. Later reports (Smith et al., 1970, Navickis et al., 1982: Szczesniak et al., 1983) concluded that both G' and G" decrease with increasing strain and that non-linearity exists at practically all strains.

Frequency of oscillation also affects viscoelastic properties of wheat doughs. In this case, the frequency dependence is positive, i.e. G' and G" increase with frequency (Hibberd and Wallace, 1966; Smith et al., 1970; Cumming and Tung, 1977). Dresse et al., (1988a, 1988b) confirmed the general observation of a positive dependence of G' with frequency.

2.7 Effect of Mixing on Rheological Properties of Dough

Effect of mixing on rheological properties of dough has been researched for many years. Unfortunately, no definitive results have been reported so far because of the difficulties occurring during dough mixing, handling and rheological property testing. Lindborg (1995) found that viscosity measurements could differentiate between doughs of different flours. The maximum viscosity measured a at constant shear rate increased with mixing time to the point of optimum development, but the storage modulus (G') decreased with mixing time. Similar results were reported and published by Mani et al (1992a, 1992b). These works clearly show that dough exhibits a maximum consistency when is optimally mixed.

2.8 Confocal Laser Scanning Microscope

Microscopy has always played an important part in the food science area. As soon as the light microscope (LM) became available, those engaged in quality control of foods found very useful for the detection of adulteration or admixture (Vaughan, 1979). After this first development some useful alternatives to the light microscope appeared when the electron microscope both transmission (TEM) and scanning (SEM) was developed. Recently, the confocal laser-scanning microscope (CLSM) with the support of powerful computer programs provides a more advanced method to detect microstructure of food no matter it is solid or liquid. All of these microscopy methods can be used to research the dough structure.

No matter it is LM, TEM, or SEM, the high-resolution, good-quality images of the microstructure can be obtained only from thin smears or thin sections so the sample microstructure can be destroyed by shear and compression. Moreover, sectioning requires tedious fixation and embedding, which may introduce artifacts. A technique that circumvents the need for making thin specimens prior to microscopical observation was therefore mandatory.

The introduction of the confocal scanning microscope has increased the potential of light microscopy enormously. Maximum resolved micro-structural information can be obtained from bulk specimens, with a minimum of sample preparation, owing to the ability of this microscope to produce optical sections in contrast to the physical sections obtained using knives (Blonk and Aalst, 1993).

Confocal laser scanning microscopy is set to revolutionise light microscopy (Brooker, 1991; Heertje et al., 1987). The CLSM technique uses a laser to illuminate and scan points in a very thin plane of the sample. Only the information from this very thin plane (down to 0.5 um) passes through the confocal pinhole, this leads to increased resolution CLSM has also the possibility of identifying up to 4 separate food components by specific fluorochrome labelling, deep non-invasive penetration of the sample (up to 100 μm) and the ability to obtain sequential optically thin sections through a sample (Brooker, 1991). These sequential sections may be reassembled, using powerful computer software, to form three-dimensional images.

Confocal laser scanning microscopy also offers a number of advantages over conventional techniques in studying the relation between the composition, processing and final properties of food products. Sample preparation is easy and avoids artifacts. Methods are available for three-dimensional simultaneous observation of dynamic changes like the development of the structure of wheat dough during proofing and location of additives in the wheat gluten protein. Also CLSM has increased the potential of light microscopy enormously. Maximum resolved micro-structural information can be obtained from bulk specimens, with a minimum of sample preparation, owing to the ability of this microscope to produce optical sections in contrast to the physical sections obtained using knives (Blonk and Aalst, 1993).

2.9 Preparation of Dough Sample for CLSM

Food products contain a limited number of main components; protein, fat, carbohydrates, water and air. In general the properties of foods are determined by careful selection of components based on their chemical and physical properties and in combination with well-defined processing conditions. The resulting microstructure determines, among others, appearance, taste perception, rheology and shelf life and forms the bridge between the molecular properties of the individual components and the desired macroscopic properties of the products.

Food components like lipids and proteins can be stained selectively prior to processing of the product but also by diffusion of the stain into the product. Specific stains are available for labelling lipids and proteins. These stains will be adsorbed or can be covalently coupled to the microstructure of interest. Immune-techniques allow highly selective labelling of specific proteins: antibodies raised against the specific proteins can be coupled with fluorescent markers that can be detected by CSLM. A technique based on specific affinity of pectin for carbohydrates can be used to label carbohydrates and proteins containing carbohydrate residues (Blonk and Aalst, 1993).

Foods such as butter, ice cream, low-fat spreads that were difficult to study for conventional light microscopy, now can easily be researched using CLSM. For the CLSM, some specimen preparations still has to be done before the samples are placed in the CLSM instrument to be observed. For liquid samples, a solution like Nile Blue which contains trace amounts of fluorochrome Nile Red that partitions into the disperse oil phase and is excited at a wavelength of 488 nm is usually used to stain the lipid phase. Staining a solid sample such as cheese can be achieved by placing a few crystals of a fluorescent dye on the surface of the foodstuff and allowing it to diffuse into the sample. A method introduced by McKenna (1995) which was used to stain processed cheese uses crystals of Fast Green (FCF) for aqueous phase staining and a filter block for excitation at 568 nm for examining. Few reports have been found for studying the microstructure of the dough during mixing by using CLSM.

Other dyes used are FITC, Rhodamine and Texas Red which are suitable to localise proteins. Nile Red and Nile Blue are the most suitable dyes to stain lipids. The combination FITC-Nile Red excited with the Ar/Kr laser gives excellent results in double-labelling experiments.

CHAPTER THREE

MATERIALS AND METHODS

3.1 Materials

Flours

Bakers and Soft flour (AERO Locally Grown) milled by South Canterbury Milling Co. were used in the experiments. Other flours used in the sheeting experiments include Beta (strong flour) and Halo (weak flour) flour (milled by Manawatu Champion Flourmills Co.)

The properties of Bakers and Soft flours were determined by the New Zealand Crop & Food Research Institute, Christchurch (using a 125-g MDD mixer). Information for Beta and Halo flours was supplied by Manawatu Champion Flourmills Co, (Farinograph). Mixing graphs for Bakers and Soft flours are shown in Figures 3.1 and 3.2, whereas the Farinographs of the Manawatu flours are given in Figures 3.3 and 3.4. Other baking parameters for the flours used are given in Table 3.1.

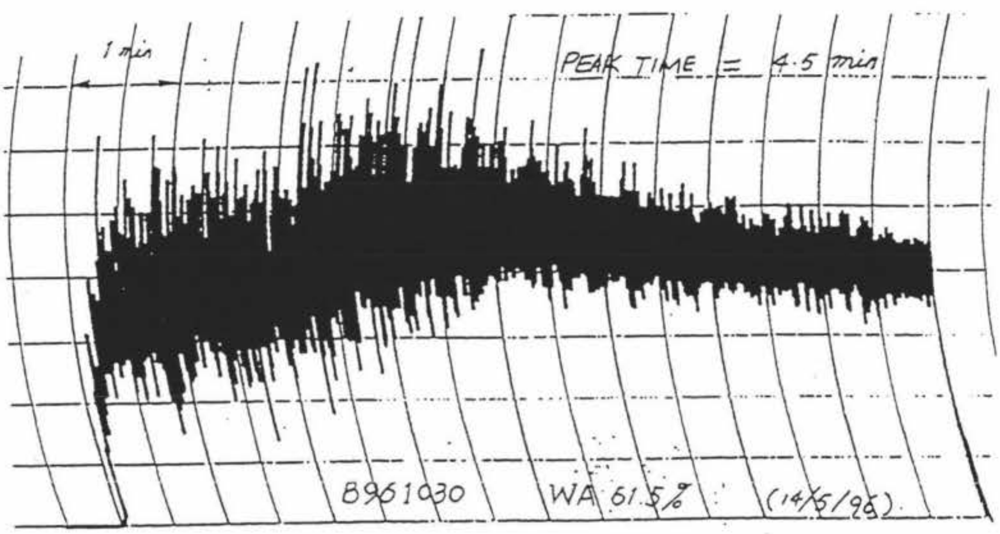


Figure 3.1 A Mixograph of Bakers flour

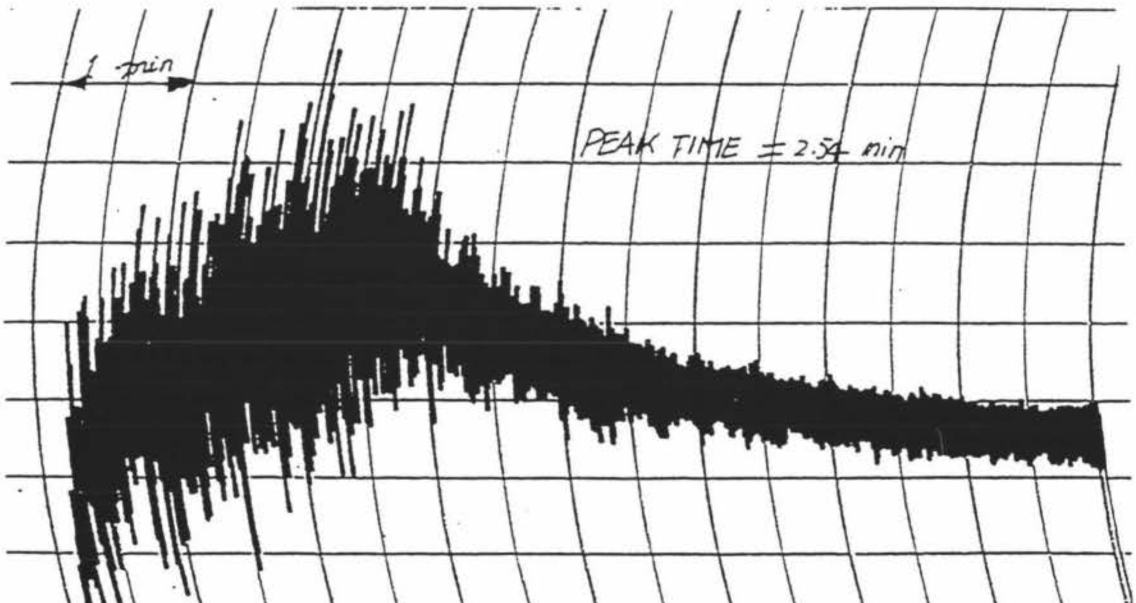


Figure 3.2 A Mixograph of Soft flour

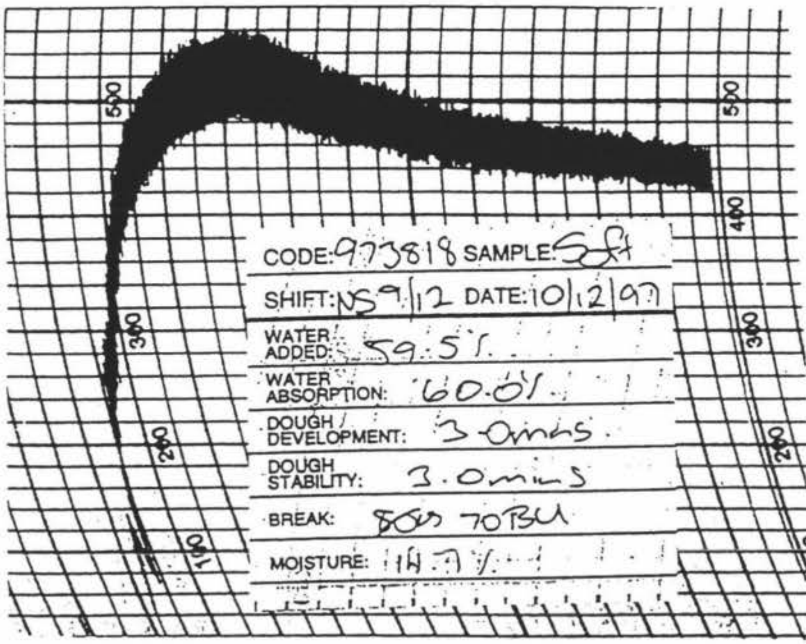


Figure 3.3 A Farinograph of Halo (weak) flour

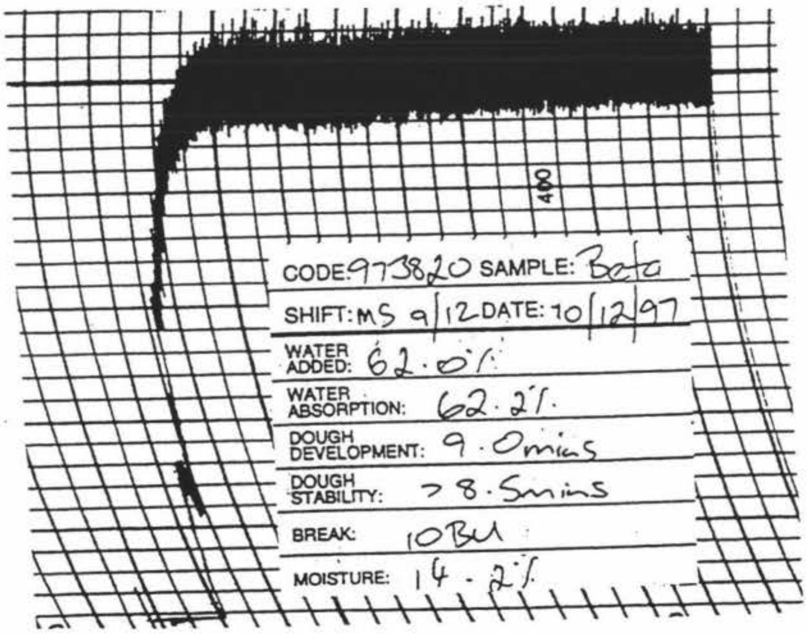


Figure 3.4 A Farinograph of Beta (strong) flour

Table 3.1 Basic parameters of four wheat flours

	Bakers	Soft	Beta	Halo
MDD* WI (W. hr/kg)	18	9.7	22.7	10.4
MDD* WA (%)	59	59	61	57.5
Protein** (%)	12.6	10.4	11.5	9.9
Ash (%)	0.46	0.52	0.55	0.55
Moisture (%)	14.1	14.5	13.8	14.2
Colour***	--	--	2.5	2.2
Falling Number (sec)	--	--	400	384
Farinograph WI	--	--	17	5
Farinograph WA(%)	--	--	62	60
MDD* Texture	8	8.5	9	8
MDD Volume (ml)	--	--	810	725
MDD baking score	28	26	--	--
Dough Develop (min)	--	--	8.0	2.5
Dough Stability (min)	--	--	10-12	2.5

* 125g MDD mixer and test bake system (Crop & Food Research)
** 14% moisture basis
*** Kent-Jones Units

Ingredients used were:

Water: Hard water

Table salt: SAXA salt (Cerebos-skellerup LTD. Auckland)

Sugar: Sugar was bought from supermarket

Ascorbic acid: SEAAOL Ingredients (Goodman Fielder Ltd.)

Vegetable Oil: Soybean & salad oil

Yeast: Fresh yeast was bought from the bakery shop and the dried yeast was Fermipan (200 grams/pack, made in Delft-Holland)

3.2 Dough Preparation Equipment

3.2.1 The 50 g MDD system

The 50-g MDD mixer used in this research was designed by Crop & Food to mix small amounts of sample. The electrical power consumed by the mixing operation is recorded and loaded in a computer through a data acquisition system, DASTC. The mixer has a control that enables the supply of a known amount of energy to the sample. That energy can be translated into work input and given in W. h/kg units. The fact that the mixer can provide mixing levels reproducibly makes the mixer an essential tool for the proposed research. This feature offers large advantages when compared with mixers such the Hobart in which the work input is measured by the mixing time. Results obtained with the 50 g MDD mixer can be scaled-up to a 125 g MDD and even to industrial MDD mixers (Wilson, 1983). A photograph of the 50 g MDD mixer is shown in Figure 3.5

Figure 3.5 The 50-g MDD mixer

3.2.2 The Hobart mixer

A Hobart mixer (Hobart Corporation) equipped with a hook-shaped dough blade was used because this mixer is a small version of the type of mixer used in some bakeries. Dough mixing was accomplished by means of the hook-shaped blade that also rotates in an orbital manner. The mixer bowl was able to rotate freely up to a stop in which a strain gauge was attached. The strain gauge was able to measure values of force applied during the mixing. The measured force was multiplied by the distance between the point of application and the centre of rotation of the mixer bowl to calculate the applied torque. A data acquisition unit (DASTC) was set up to record all of the data from the mixer and converts it to torque. The measurements of toque give the amount of energy applied to the dough sample.

The Hobart mixer has three mixing speeds (60 rpm, 128 rpm, and 256 rpm). Only 60 rpm was used in this project. A photograph of the Hobart mixer is given in Figure 3.6

Figure 3.6 The Hobart mixer

3.2.3 The 1 kg-MDD mixer

A 1 kg MDD mixer was used for mixing the dough in a very short time. The meter of the MDD mixer indicated that 17 counts are equivalent to 1 W. hr/kg depending on the water content of the dough. This MDD mixer can apply vacuum during the mixing of the dough. A photograph of the 1 kg MDD mixer is given in Figure 3.7

Figure 3.7 The 1 kg-MDD mixer

3.2.4 Sheeter

A large number of sheeters are used in bakeries. In this experiment a manual sheeter with an adjustable gap was used to sheet the dough. Basically the gap was set at 2-5mm. The speed of sheeting was about 1-1.5 seconds for each of dough piece. The manual sheeter used in this research is illustrated in Figure 3.8.

Figure 3.8 Manual Sheeter

3.3 Rheological Instruments

3.3.1 Bohlin rheometer:

The Bohlin VOR rheometer (manufactured by Bohlin Instrument International) is illustrated in Figure 3.9. The rheometer was used under two different modes, Dynamic or Oscillation Mode and Steady state or Viscometry Mode. The parameters used with the Bohlin rheometer are listed in Tables 3.2 and 3.3

Table 3.2 Parameters used for the Dynamic/Oscillation Mode

Oscillation Parameters	Value
Geometry	Parallel plates
Gap between Parallel Plates (mm)	1-4
Temperature (°C)	32
Amplitude (%)	1-5 (approximately linear range)
Strain	$2.7\times10^{-4} - 3.48\times10^{-3}$
Torsion Bar (g cm)	42.9, 96.2, and 315
Frequency (Hz)	0.01 – 20

Table 3.3 Parameters used for the Viscometry Mode

Shear	Bohlin VOR
Shear rate (1/s)	0.001 – 0.5
Gap (mm)	1 – 5
Measuring interval times (sec)	2 – 10
Measuring temperature (°C)	32

(a)

(b)

Figure 3.9 **(a) Bohlin VOR rheometer**

(b) Geometry used, sandpaper was used to prevent slippage

3.3.2 Instron Universal Testing Machine:

An Instron Universal Testing Machine is a rheological equipment capable of measuring the force to deform a sample with a constant deformation rate. The equipment is manufactured by Instron Instrument Co. USA and the model 4500 used in this project is shown in Figure 3.10.

Figure 3.10 The Instron 4500 Universal Testing Machine. The attachment for the extrusion test described later can be seen on the base of the Instron

The Instron Universal Testing Machine was used for two different rheological tests (1) Planar Extensional Test and (2) Extrusion Test. The parameters used for both tests are given in Table3.4

Table 3.4 Parameter used for Instron Instrument

Compression Parameters	Values
Data logger	0.5-5 (points/sec)
Compression Distance	60 –180 mm
Crosshead Speed	60 mm/min
Relaxation Time	30 seconds
Temperature	22 °C (room temperature)
Load Cell	10, 100, 1000 (Newton)

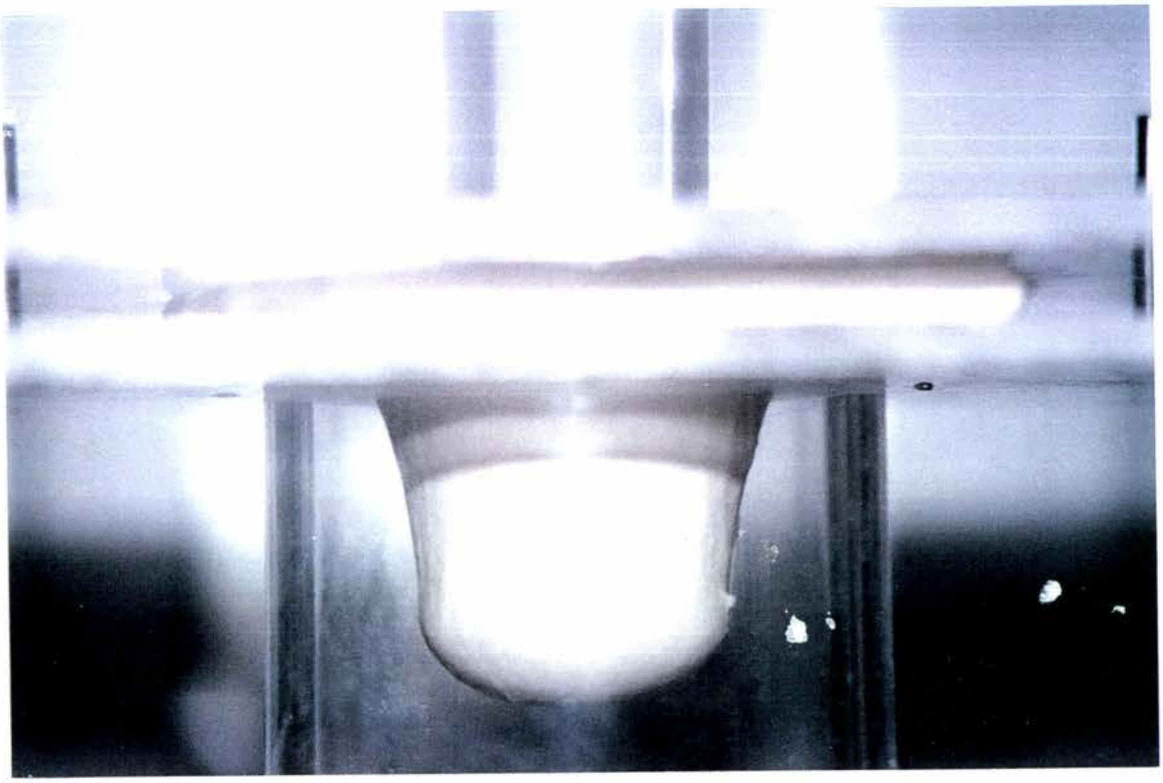
(1) Planar Extensional Test

A Planar extensional test was carried. This test is classified as a large deformation test. The test was carried out using a load cell range from 10 N to 1000 N. The probe used for the planar extensional test is illustrated in Figure 3.11a. Figure 3.11b shows the deformation of the sample during the test.

(2) Extrusion Test

An extrusion test was carried out using a Teflon cylindrical attachment (Figure 3.10). It consists of a plunger, a cylinder of 120 mm height and 20 mm diameter and a attachment with a 4 mm diameter hole at the end of the cylinder.

(a)



(b)

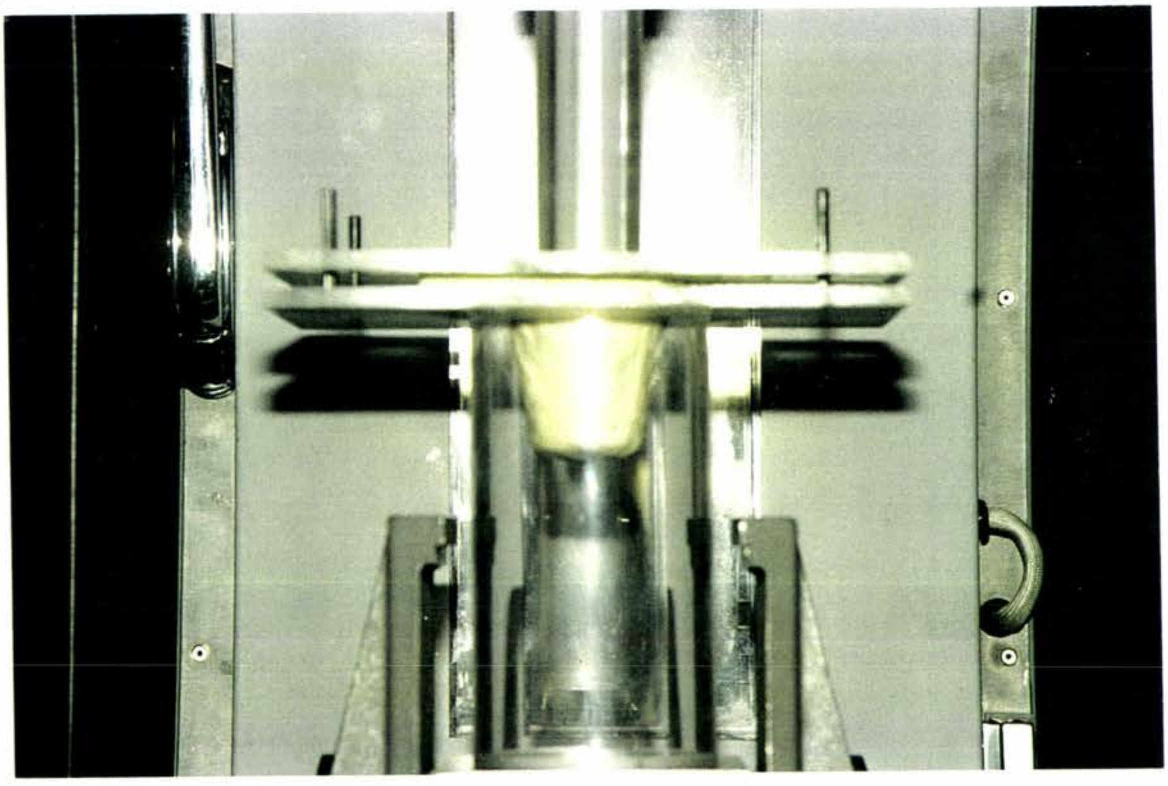


Figure 3.11 a & b Planar Extensional Test

3.3.3 Physica UDS 200 Rheometer:

The Physica UDS200 is manufactured by Physica Paar Instrument Co. Germany. A shear creep test is available in this instrument. The Physica rheometer is illustrated in Figure 3.12

The Physica rheometer is a more modern and versatile instrument than the Bohlin VOR is. The Physica rheometer does not need change of torsion bar for coves all the measurement range. It has also two operational modes: (1) controlled stress mode and (2) controlled strain rate mode for both dynamic/oscillation and viscometry tests.

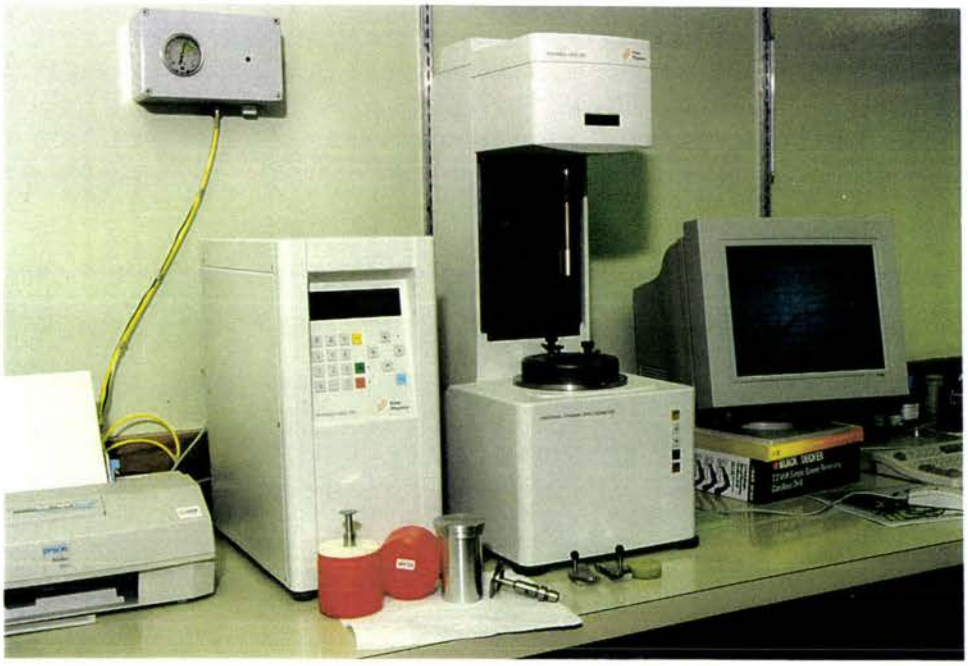


Figure 3.12 The Physica UDS200 rheometer

3.4 Confocal Laser Scanning Microscopy

Confocal Laser Scanning Microscopy is a new instrument in Massey university. It has a powerful computer software supporting program and the high resolution 3D picture image processing makes this instrument a powerful tool for microscopy studies. With an appropriate dye solution, starch and gluten could be presented in a clear 3D imagine picture, which may aid to the understanding on dough microstructure.

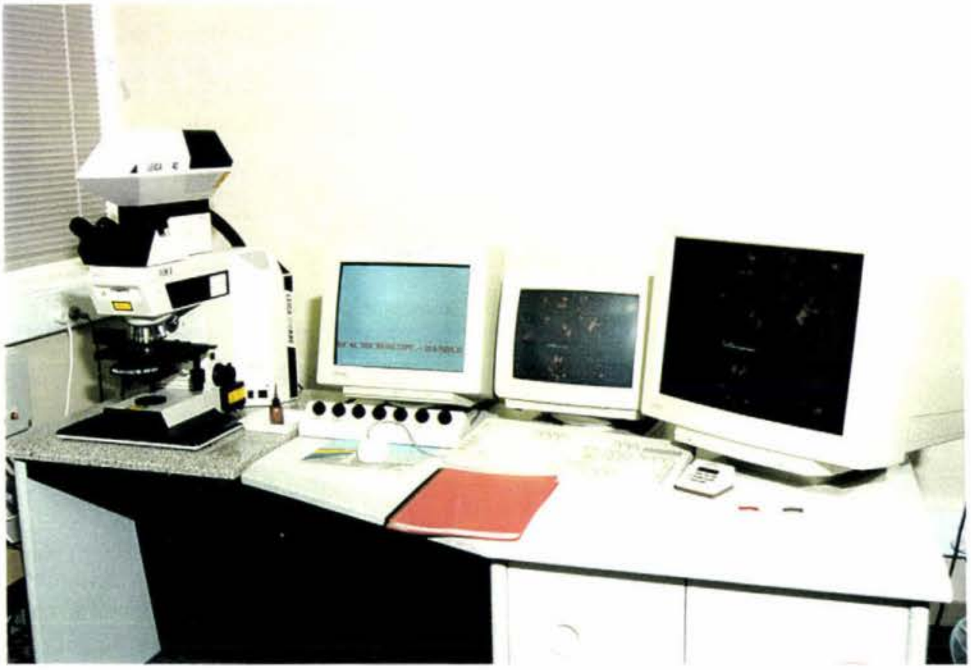


Figure 3.13a A Confocal Laser Scanning Microscope with its image analysis system

Figure 3.13b A Confocal Laser Scanning Microscope

3.5 Cryostat Fast Deep Frozen Cutting Machine

The Cryostat fast deep frozen cutting machine is mainly used for animal tissue sample preparation. By using a Tissue-Tek O.C.T. compound the fresh dough sample can be bound to a special aluminium plate then frozen. Tissue-Tek O.C.T. compound contains 10.24% (w/w) polyvinyl alcohol, 4.26% (w/w) polyethylene glycol and 85.5% (w/w) non-reactive ingredients. At the frozen state the sample is cut as a thin slice without structure damage. A frozen piece of a 50 μm thickness was cut and then placed on a glass slide. The dough sample was then created for further microscopy.

Figure 3.14a Cryostat Fast Deep Frozen Cutting Machine (Cutting Knife and Control Panel

Figure 3.14b Cryostat Fast Deep Frozen Cutting Machine

3.6 Methods

3.6.1 Dough preparation

3.6.1.1 Non-mixing dough

Non-mixing dough samples were prepared by mixing flour, salt, sugar, ascorbic acid, and ice particles which were sieved between two sieves in order to have particles of sizes between 50 um and 150 um. The whole mixing process was carried out at -20°C and then the dry powder mixture was kept overnight in a -20 ° C freezer. The quantity of the ice used was calculated to provide samples with different moisture contents. The standard recipe used was a ratio flour to ice of 5 : 3. The powder mixture was then placed in a 37 °C temperature room for more than 4 hours until temperature was equilibrated and a dough was formed (Campos, et al. 1996).

3.6.1.2 MDD dough preparation

The flour was transferred from a -20 °C freezer to a 0 °C chiller and leave it overnight. Thus, the flour temperature was close to 0 °C at the moment of using the flour. Fifty grams of this flour were slowly added into a 50-g MDD mixer then mixed with a standard solution containing salt, sugar, and ascorbic acid. The standard recipe for the bakers and soft flour is showed in the Table 3.5

Table 3.5 Basic recipe of the dough samples

	Bakers flour	Soft flour
Flour	50 g	50 g
Water*	29.5 ml (59% absorption)	29.5 ml (59% Absorption)
Salt	1 g (2%)	1 g (2%)
Sugar	0.375 g (0.75%)	0.375 g (0.75%)
Ascorbic Acid	100 PPM	100 PPM

* Water was changed depending on the water absorption used.

Dough samples were prepared with different work input which are showed in Table 3.6

Table 3.6 Different typical mixing conditions of Bakers and Soft flour

Samples Number	Bakers flour (B)	Soft flour (S)
Sample 1	No-mixing	No-mixing
Sample 2	5.0 wh/kg	3.0 wh/kg
Sample 3	10.0 wh/kg	6.0 wh/kg
Sample 4 (optimum mixed)	18.0 wh/kg	9.7 wh/kg
Sample 5	25.0 wh/kg	13.0 wh/kg
Sample 6	30.0 wh/kg	20.0 wh/kg
Sample 7	50.0 wh/kg	30.0 wh/kg

Measurements were repeated from three times and up to ten times when the measurements showed poor repeatability.

Before measuring, the dough samples were covered by a plastic film to prevent surface drying. Also a thin film of Vaseline was used to cover the dough surface during the measurements.

3.7 Rheological Methods

3.7.1 Oscillation/Dynamic Test

The oscillation tests were carried out using both the Bohlin and Physica rheometer in order to compare results from two different instruments. For the oscillation test carried out on the Bohlin, an appropriate torsion bar was chosen (from 42.9 to 315 g-cm). Both frequency sweep and strain amplitude sweep tests were carried out. The amplitude strain sweep was carried out to identify the region of linear viscoelastic behaviour. Testing on the Physica UDS200 followed the same procedures but no torsion element was used as the machine can change the range automatically.

3.7.2 Viscometry/Shear Stress growth Test

The application of a small and constant shear rate whereas monitoring the stress growth of dough at different shear strain can provide information about the dough properties at very large deformations. The test is known as shear sweep. With both rheometers, a shear rate sweep test was firstly carried out to find out the value under which the tests gave more repeatability. A shear rate of 0.5 1/s was found the more appropriate for both the Bohlin VOR and the Paar Physica UDS200. However, due to the limiting maximum shear stress on the Bohlin VOR, a shear rate of 0.05 1/s was used with this instrument to carry of the shear stress growth test.

One of the main problems found while carrying out this test was that of slippage. The use of sandpaper #42 attatched to both plates substantially reduced the slippage problem. This was proved by using a double mark in the plates and the sample as indicated in Figure 3.15a, b.

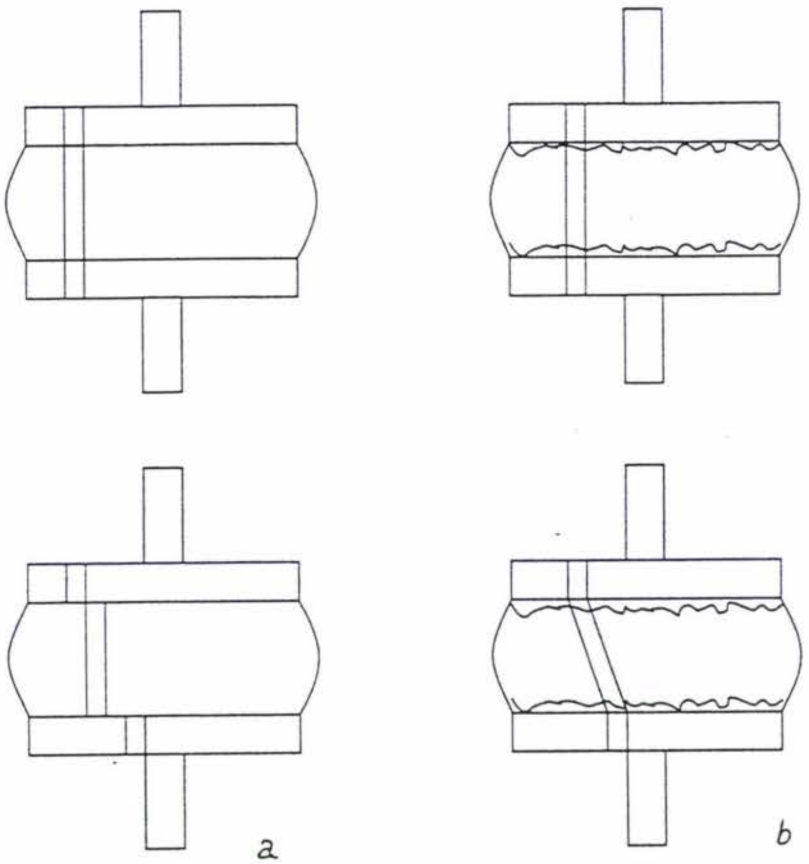


Figure 3.15 Schematic view of the geometry for test plates before and after rotation

a: Plates without sandpaper

b: Sandpaper attached

3.7.3 Relaxation Test

The relaxation tests were carried out using the Bohlin VOR Rheometer. The sample was suddenly deformed until a set strain and the decay of the shear stress with time was measured. No filter was used to retrieve the shear stress decay data.

3.7.4 Planar Extensional Flow, and Extrusion Tests

Planar Extensional Flow and Extrusion tests were carried out using an Instron (4500) Universal Testing Machine. For the Planar Extensional Flow test, dough samples were sheeted to form a 2 - 4.5 mm thickness sheet and then fixed on the test fixture. The sample was not allowed to rest.

For the Extrusion test, the dough sample was shaped as a 75 g roll by hand to form a long and narrow rod that was suitable to place it into a Teflon cylinder of 120 mm height and 20 mm diameter. Then the sample was extruded through a hole of 4 mm diameter. By pushing it with a plunger attached to the Instron crosshead the change in force was measured with time. Measurements were carried out at 25 °C and a crosshead speed of 60 mm/min.

3.8 Water Content Measurement

The sample moisture content was measured using an oven method. Temperature of the oven was set at 108 °C. Moisture content of the sample was determined by weighing the sample before drying and after drying up to constant weight. That takes approximately 24 hours.

3.9 Preparation of Dough for Confocal Microscope Observation

The flour was mixed with water and two drops of a solution of the appropriate dye (1% of Fast Green) and mixed up to various work input levels in the 50 g MDD mixer. The dough sample was then carefully cut down in about 1 gram of pieces. Fresh dough was then fixed on an aluminium plate for freezing. After a fast freezing (2–5 minutes), the dough sample was cut off with a very sharp knife. Then the thin slice of dough was placed on a glass slide. The procedures were carried out trying to minimise damage of the dough structure. Because the dough film was about 50 um thick it was then dehydrated quickly to form a dough specimen for observation in the microscope.

3.10 Baking Tests

MDD baking tests were carried out to test the relationship between rheological measurement and final product performance. Dough samples were proved at 40 ^{o}C for 50 minutes. Baking was carried at 220 ^{o}C for 25 minutes. The volumes of final products were measured by using a seed displacement method.

CHAPTER FOUR

RESULTS

4.1 Introduction

Fundamental rheological properties of wheat flour doughs after it is subjected to deformations similar than those encountered in the breadmaking process notably mixing and sheeting were studied. The effects of breadmaking operations on dough rheological properties along with those produced by ingredients such as water, oil, and the types of flour were also investigated. The rheological measurements used in this work included (1) Small Deformation Shear Tests and (2) Large Deformation Tests.

(1) Small Deformation Shear Test
- Dynamic oscillatory measurements

(2) Large Deformation Tests
- Shear Stress Growth Test (at low shear rates)
- Planar Extensional Flow Test
- Extrusion Test (Shear-Extensional Flow Test)

Rheological measurements showed that energy input plays a very important role in the preparation of dough. Water addition is also important, but these two variables are closely related as a high level of water leads to a less energy input when wheat flour is mixed for a certain time.

Results showed that there are significant differences on the rheological properties of dough prepared with different levels of energy. These findings agree with those obtained from empirical tests, which show that dough consistency increases with mixing up to a peak known as the dough optimum development is achieved and after decreases.

Results from small deformation tests (dynamic oscillation measurements) showed that mixing significantly affected the viscoelastic properties of dough.

Water level also had a large effect on the viscoelastic properties of dough determined using small deformation shear tests.

Results from large deformation tests (shear stress growth test) showed that there are significant differences among doughs prepared with different mixing conditions and different flours. Both Bakers and Soft flour doughs showed that an optimal mixing level produced a well-developed dough exhibiting the highest shear stress. That stress was highly depending on the shear rate used showing the shear thinning behaviour of wheat doughs.

The effect of slippage on the rheological measurement was also considered. In order to prevent slippage sandpaper was attached to the testing plates using a double side glue tape. Serrated plates and smooth parallel plates were also used and the rheological properties obtained compared with those determined using the plates covered with sandpaper. Results of the small deformation test had a very large variation, when smooth parallel plates were used. Results also varied with the set gap between plates. The reason for this was attributed to slippage. It was thought that there were no slippage when either sandpaper or serrated plates were used because results were more consistent and with less variation.

For the shear stress growth tests (large deformation) both smooth plates and serrated plates were not suitable for the measurements. Only the use of sandpaper gave consistent and reproducible results.

A visual test as that described in section 3.7.2 was carried out to verify that slippage was not present during the measurements when sandpaper was used.

Planar Extensional Flow Tests showed that there are significant differences between doughs prepared with different levels of work input. Different flour also had different behaviour. Optimum-mixed Bakers flour dough had a higher extensional stress than optimum-mixed Soft flour. These differences were less evident when the dough has either under or over-mixed.

Sheeting has a similar function than mixing but is more gently. Results obtained in this work showed that sheeting can develop dough. Using two different flours, it was shown that the rheological properties of dough were modified when the dough was sheeted.

The microstructure of doughs prepared with different flours and different mixing levels was studied using a Confocal Laser Scanning Microscope. Samples specimens were prepared using a deep frozen cutting method in a Cryostat instrument. Micrographs showed qualitative-differences between doughs prepared with different levels of work input.

4.2 Rheological Measurements

4.2.1 Introduction

Dough is a complex system and the choice of appropriate measurement parameters is very important in the determination of its rheological properties. Dough could also exhibit slippage when shear tests are carried out. Thus, experiments were designed to try to minimise slippage. This section is devoted to describe how the main rheological parameters used for the measurements were set.

4.2.2 Determination of the Linear Viscoelastic Region

Results obtained from small deformation tests rely in that the deformations applied to the sample are within the linear viscoelastic region so that the equations used to calculate the storage modulus G' and the loss modulus G" are valid. Modern rheometers have already set routines to determine the linear viscoelastic behaviour of the sample. Results obtained in a Physica UDS 200 Rheometer using a small deformation oscillatory shear test is shown in Figure 4.1. This figure clearly illustrates that it is very difficult to distinguish a region of true linear viscoelastic behaviour and only at very low strains (less than 0.001) the material behaves linearly. Unfortunately the use of very low deformation is limited by the range of application of the rheometer and a practical choice of 0.01 strain was used for the experiments. Similar result have been found by Hibberd and Wallace (1966) and Hibberd (1979a,b)

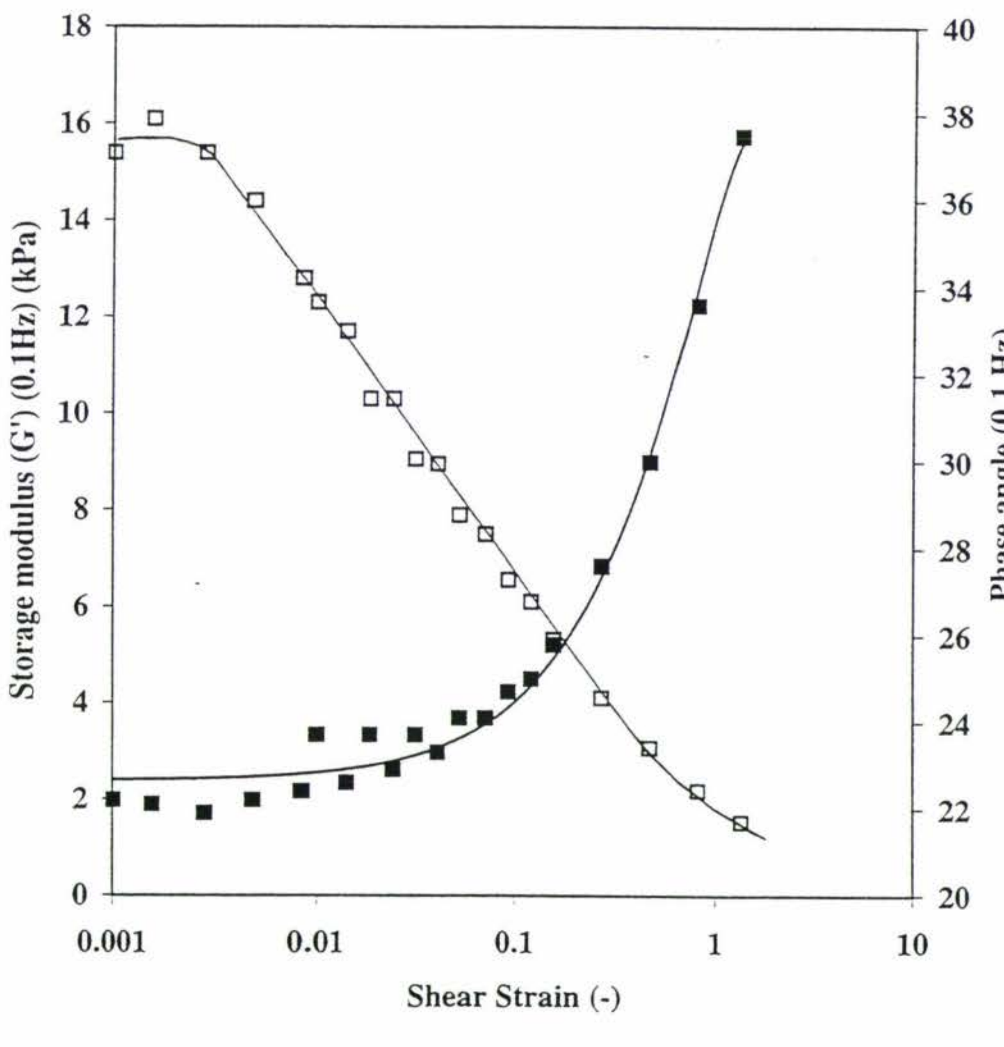


Figure 4.1 Strain sweep test. Physica UDS200 Rheometer. Dough was prepared with Bakers flour and the standard recipe, a water absorption of 59% and a work input of 18 W. hr/kg. The sample was tested with a parallel plate geometry using a 2 mm gap and plates covered with sandpaper. Measurement temperature was 32 °C.

4.2.3 Effect of Gap

Theoretically and under the absence of artifacts such as slippage the rheological properties determined by shear tests (small and large deformations) using parallel plate geometry should be independent of the gap between the plates. It is a common practice in the area of polymer rheology to investigate the effect of the plate's gap on the measured properties in order to assess the presence of slippage. Since slippage is one of the main problems that can affect measurements. The effect of the plate gap on the rheological properties of dough was investigated.

Dough was prepared with Bakers flour, a standard recipe, 59% WA and 18 W. hr/kg work input. The Physical UDS200 Rheometer and a set of parallel plate geometry were used. Two types of tests were conducted: (1) Small Deformation Shear Test (oscillation test) and (2) Large Deformation Shear Stress Growth Test. For both tests the measurement temperature was 32 °C and the plates were covered with sandpaper. For the small deformation test a strain of 1% was used while for the stress growth test the shear rate was continuously changed from 0 to 1 s^{-1}. For both tests the gap plate was modified from 1 mm to 4 mm.

Figure 4.2a shows values of the storage modulus G' measured at different frequencies and for different gaps. It is clear in the figure that curves for different gaps follow the same trend but there are differences between them. In general the higher the gap the lower the values of the storage modulus. These results are opposite to those obtained when slippage is present. Thus, the presence of slippage in these measurements has to be ruled-out. Obviously the use of sandpaper contributed to eliminate slippage but unfortunately, as the data is showing, can affect the measurements. The effect is more evident when a small gap (1 mm) is used. It is thought that for gaps smaller than 1 mm the sample height has the same order of magnitude than the sand particles attached to the paper which could interfere with the measurements. Measurements with gaps between 2-4 mm gave closer results. Thus, this experiment enabled to fix a gap ranging between 2-3 mm for the small deformation experiments. Results showing the phase angle for different gaps are illustrated in Figure 4.2b.

Results of the large deformation shear stress growth test are shown in Figure 4.3. The figure clearly illustrates that for a shear rate smaller than 0.3 (1/s) results obtained with different gaps are in good agreement. Only the 4-mm gap was giving slightly lower values. This experiment enabled to select a shear rate smaller than 0.2 (1/s) to carry out the large deformation shear stress growth tests.

4.2.4 Relaxation Experiments

As discussed in section 4.2.2 it is very important to identify the linear viscoelastic region to be able to measure values of storage and loss modulus. Within this linear region these rheological properties are only a function of time (or frequency). These parameters enable the calculation of a very important rheological parameter of viscoelastic fluids known as the Relaxation Modulus G(t). The relationship between the relaxation modulus G (t) and the storage and loss modulus are given by the following equations (Ferry, 1970)

$$\frac{G'(\omega)}{\omega} = \int_0^\infty G(t) \sin \omega t \, dt \qquad (4.1)$$

$$\frac{G''(\omega)}{\omega} = \int_0^\infty G(t) \cos \omega t \, dt \qquad (4.2)$$

When the material is deformed with a strain larger than that given by the linear viscoelastic region the material exhibits a non-linear behaviour. Within this non-linear behaviour is not possible to determine G'(ω) and G"(ω) using the conventional small deformation oscillation shear test. Furthermore, the relaxation modulus is a function of both time and the strain complicating further the measurements. Although small deformations oscillatory tests can not be used to determine the storage and loss modulus and thus the relaxation modulus modern rheometers enable the determination of the relaxation modulus directly. In the relaxation test a sudden and constant strain is applied to the sample and the shear stress measured while the sample is deformed. The shear stress decay with time can give the value of the relaxation modulus as:

$$G(t) = \frac{\tau(t)}{\gamma_o} \qquad (4.3)$$

$\tau(t)$ is the decaying shear stress, t time and γ_0 the constant strain applied. Under non-linear behaviour measured parameters are a function of the strain γ_o, thus:

$$G(t, \gamma_0) = \frac{\tau(t)}{\gamma_0} \qquad (4.4)$$

Figure 4.4 shows values of the relaxation modulus for different strains. It is clear from the figure that for small strains (1-5%), the relaxation modulus is a time depending function but it is a weak function of the shear strain. For all shear strains the sample follows a typical non-linear behaviour with the relaxation modulus decreasing with increasing strain. As dough is a viscoelastic liquid only very short relaxation times (up to 1 second) were considered. The experiments were carried out in the Bohlin rheometer. The sample was a Bakers flour dough prepared with the standard recipe, 59% water absorption and 18 W. hr/kg work input. Parallel plate geometry with a 2-mm gap was used and the plates were covered with sandpaper. The measurement temperature was 32 °C and no smoothing routine was used during data acquisition of the relaxation data. Although out of the scope of this work this data could be used to estimate the relationship between the relaxation modulus and the strain and therefore to predict the behaviour of dough at large deformations.

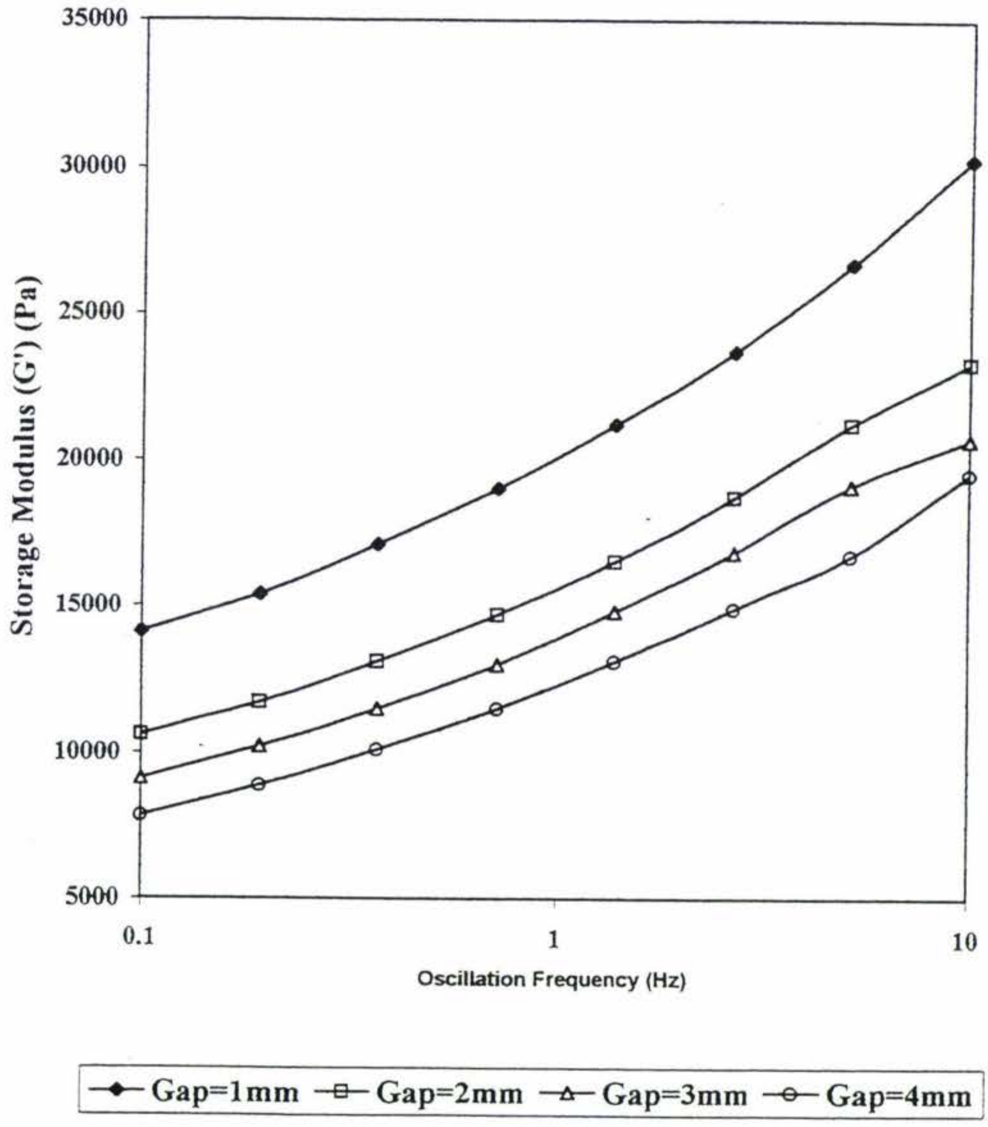


Figure 4.2a. Small deformation test. Effect of gap in the Storage Modulus. Physica UDS200 Rheometer, Bakers flour dough prepared with the standard recipe, water absorption of 59% and a work input of 18 W. hr/kg was used. The sample was tested with a parallel plate geometry covered with sandpaper. Measurement temperature was 32 °C.

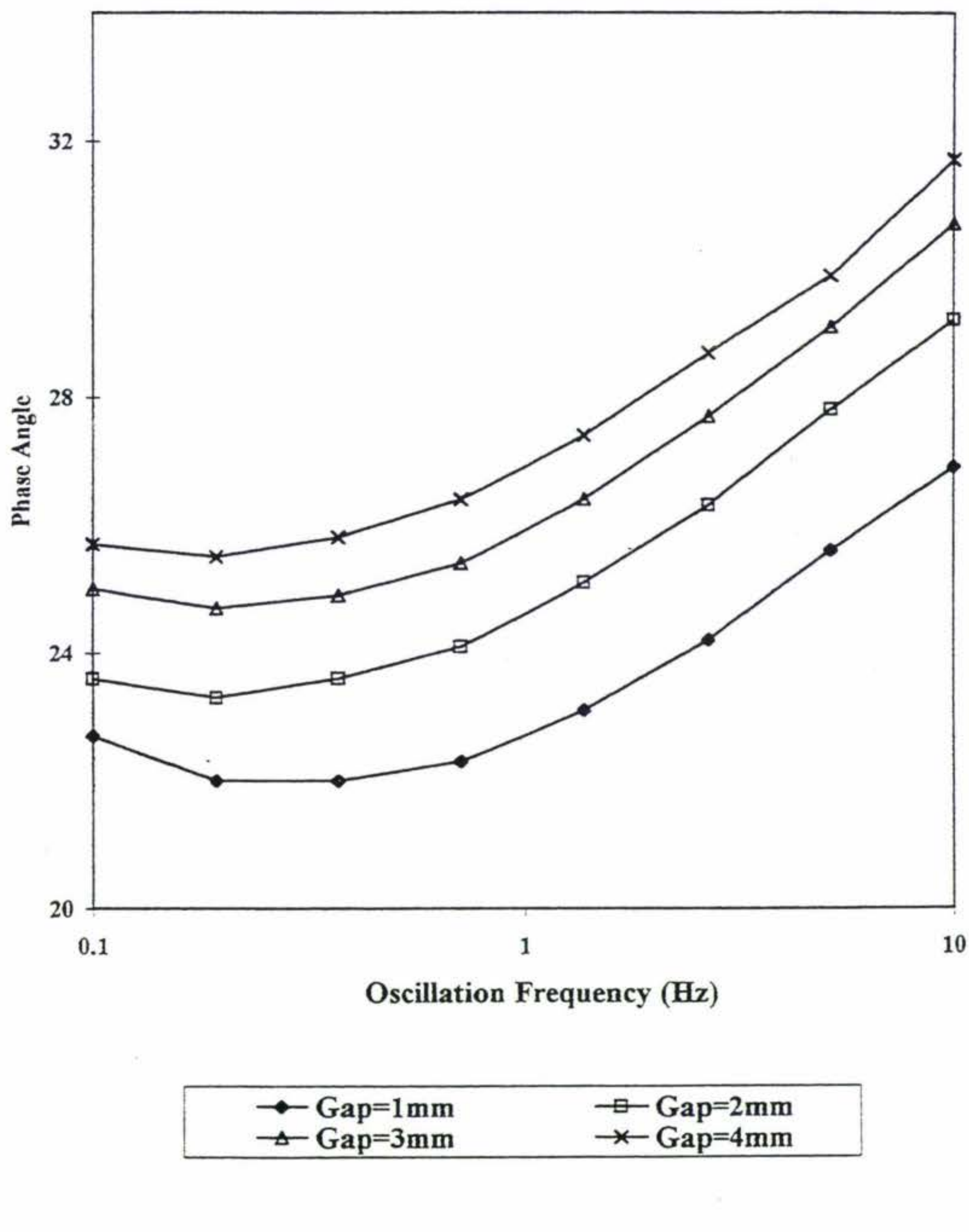


Figure 4.2b. Small deformation test. Effect of gap in the Phase Angle. Physica UDS200 Rheometer, Bakers flour dough prepared with the standard recipe, water absorption of 59% and a work input of 18 W. hr/kg was used. The sample was tested with a parallel plate geometry covered with sandpaper. Measurement Temperature was 32 °C.

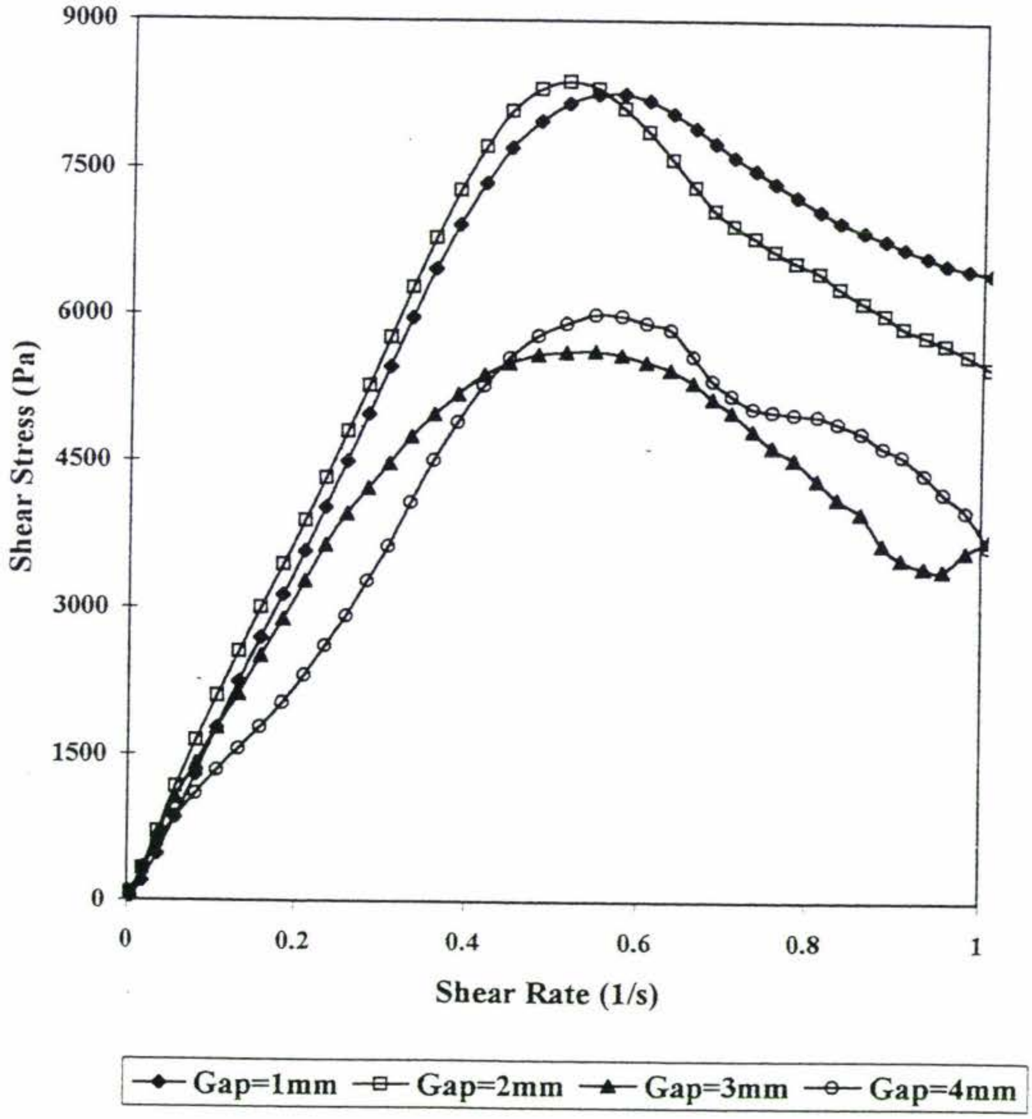


Figure 4.3 Shear rate sweep test. Physica UDS200. Bakers flour dough was prepared with the standard recipe, 59% WA and a work input of 18 W. hr/kg. The sample was tested with a parallel plate geometry and plates covered with sandpaper. Measurement temperature was 32 °C.

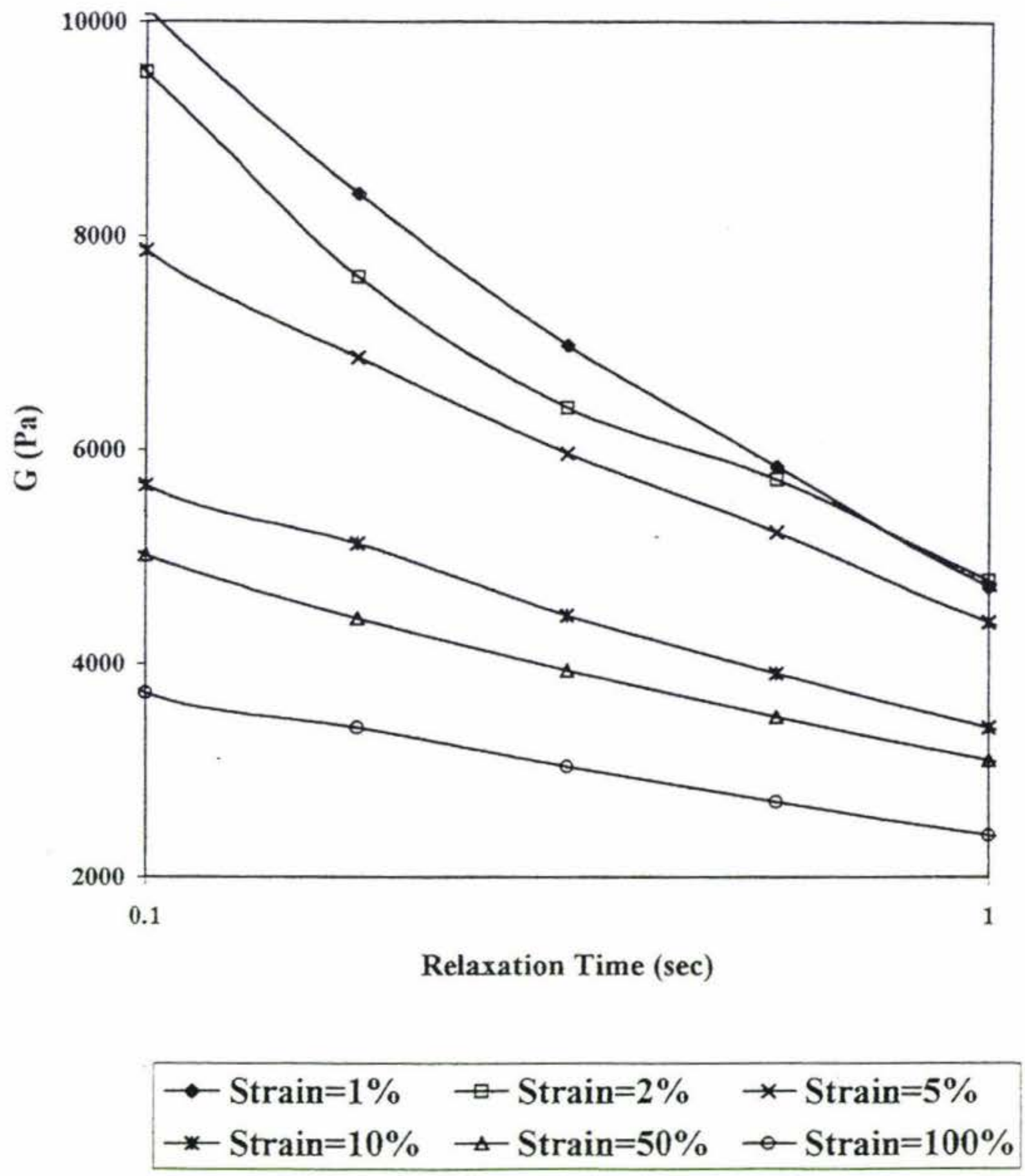


Figure 4.4 Effect of shear strain on the Relaxation Modulus G. The test was carried out using the Bohlin Rheometer, parallel plates geometry with a 2 mm gap and plates covered with sandpaper. Bakers flour dough was prepared with the standard recipe, 59% WA and 18 W. hr/kg work input. Measurement temperature was 32 °C.

4.3 Effect of Mixing

4.3.1 Mixing behaviour of Bakers and Soft flour

A 50 g MDD mixer was used to prepare the dough samples. Typical mixing curves for the flours used in this research (Bakers and Soft) are illustrated in Figures 4.5 and 4.6. Under-mixed, optimum-mixed, and over-mixed dough levels are indicated with arrows on the figures. Non-mixing doughs prepared as described in Chapter 3 were also used in this research.

It is worth nothing in figures 4.5 and 4.6 that the torque (converted to voltage by the computer A/D card) as a function of mixing time is obtained during the mixing of dough. The Work Input (WI), as the mixing progress, can be calculated by integration of this curve over time. The integration procedure largely reduces the noise in the data observed in the figures. The power drawn by the mixer motor is related to the work input and thus used to prepare dough with well-defined levels of work input. The figures also show that the maximum voltage obtained for both flours were similar (about 0.07 Volts). This is not surprising as both flours were mixed with different amount of water which was adjusted to produce a similar voltage (or torque). That is in fact, how the water absorption (WA) is determined routinely in bakeries. Since each of flour was mixed with the correct amount of water to reach the previously determined WA-level the developed peak heights were similar. Figures 4.5 and 4.6 also show that the strong flour (Bakers flour) needed about 150 seconds to reach the optimum whereas Soft flour needed about 60 seconds. The time to achieve the optimum mixing can be used to calculate the optimum work input. They were calculated as 18 W. hr/kg, and 9.7 W. hr/kg for the Bakers and Soft flours respectively.

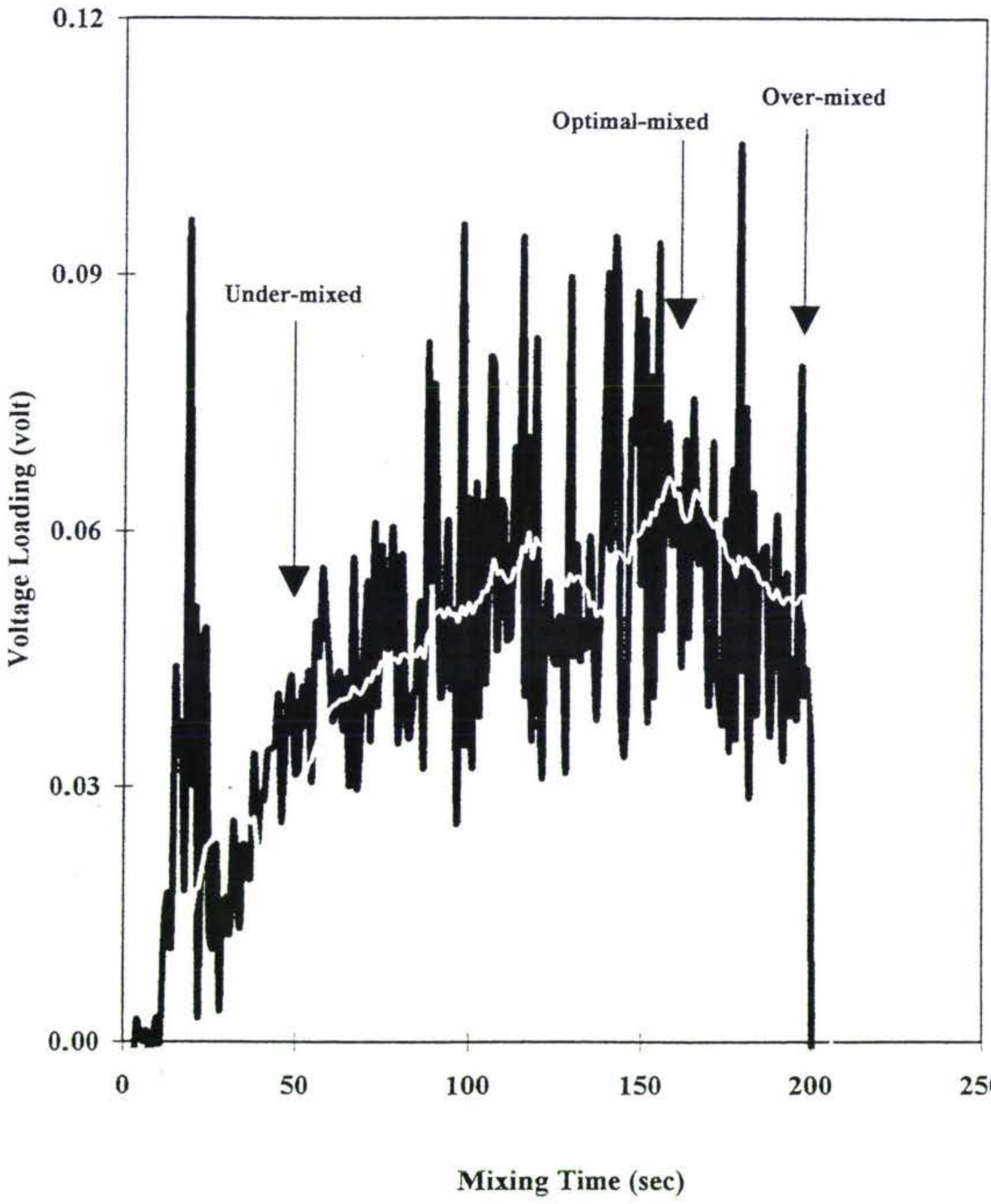


Figure 4.5 A typical 50 g MDD mixing curve of Bakers flour (strong flour). A standard recipe with 59% WA was used and the mixing temperature was 32 °C. Under mixed dough (WI=5 W. hr/kg) was mixed for about 50 seconds, optimum-mixed dough (WI=18W. hr/kg) 160 seconds and over-mixed dough (WI=25 W. hr/kg) 200 seconds.

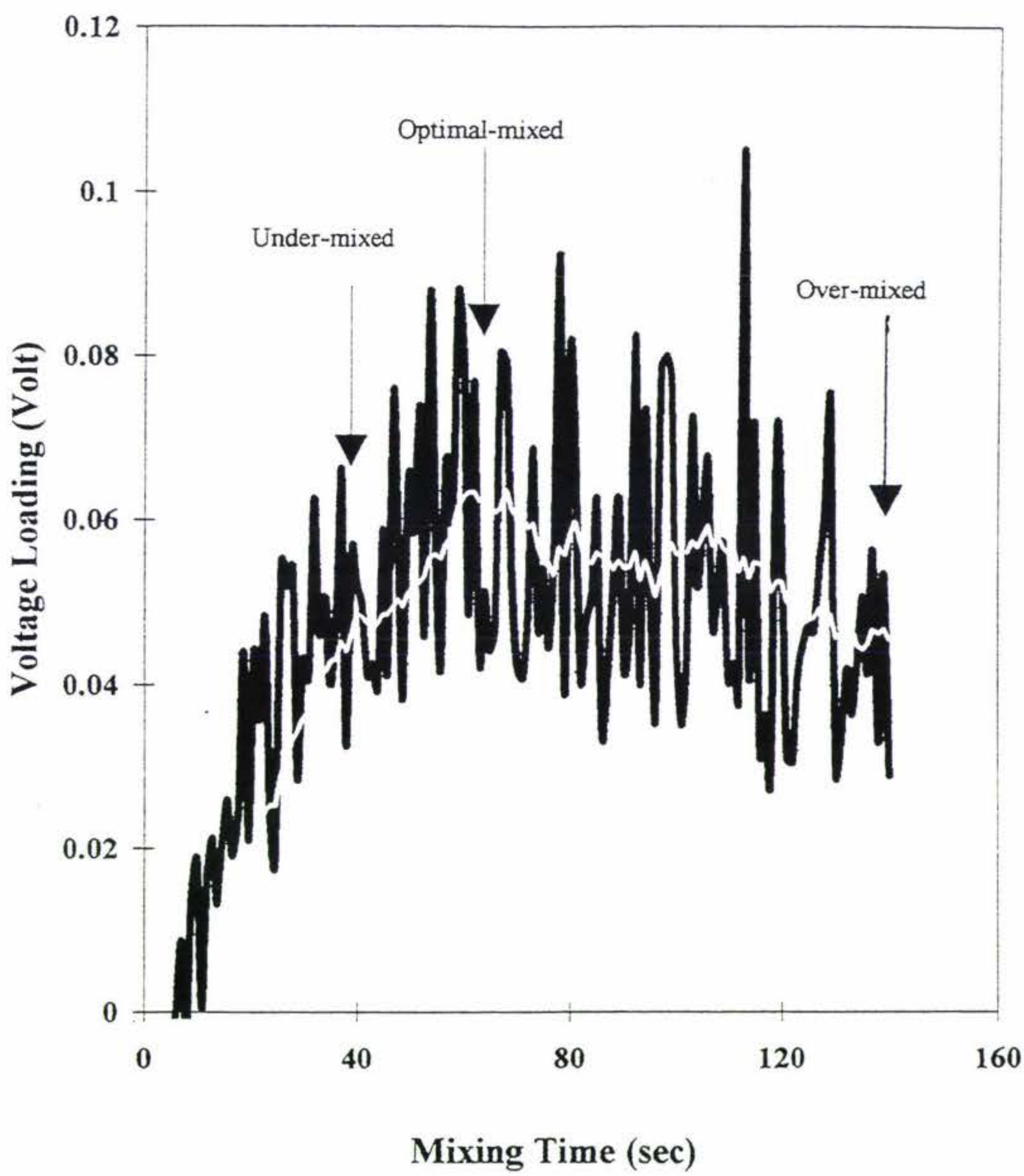


Figure 4.6 A typical 50 g MDD mixing curve of Soft flour (weak flour). A standard recipe with 59% WA was used and the temperature was 32 °C. Under mixed dough (WI=3 W. hr/kg) was mixed for about 35 seconds, optimum-mixed dough (WI=9.7 W. hr/kg) 60 seconds and over-mixed dough (WI=13 W. hr/kg) was about 130 seconds.

4.3.2 Empirical Fermentation Test Results

Bakers and Soft flour were mixed in the 50g MDD mixer using the MDD standard recipe plus 1% dried yeast. Volumes of dough for both flours were measured at different fermentation times.

Both doughs were prepared with the same water absorption (59%) and the fermentation temperature was 37 °C.

Measured volumes as a function of time are given in Figure 4.7. The figure shows that optimum-mixed dough produced the highest volume at a relatively shorter time than that of under and over mixed dough. Figure 4.8 illustrates the effect of work input on the dough volume after 150 minutes of fermentation. The figure illustrates that for both flours dough mixed with optimum work input exhibited the highest volume after fermentation.

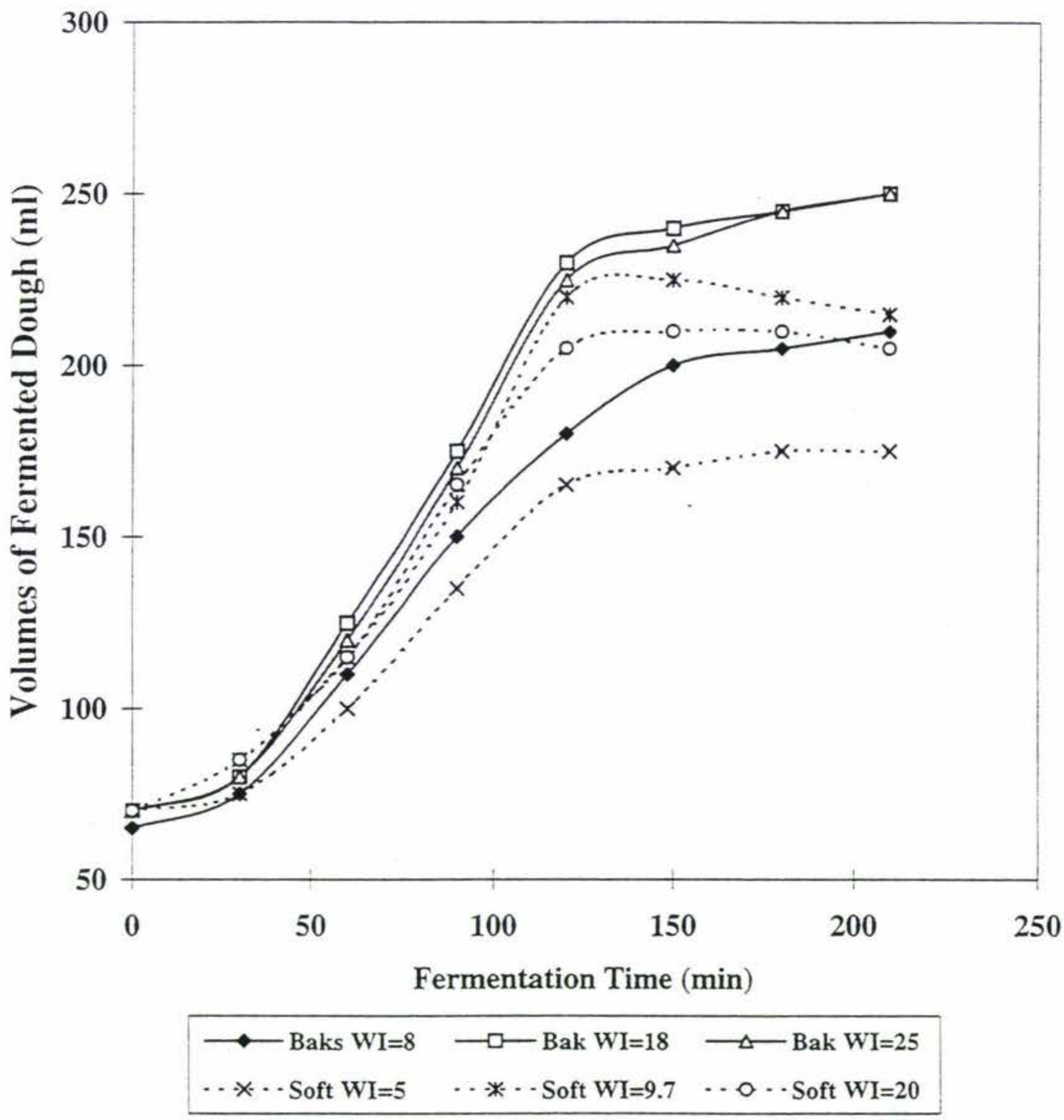


Figure 4.7 Effect of mixing time (Work Input) on dough fermentation. Bakers and Soft flours were used and the water absorption (WA) for both flours was the same and equal to 59%. A standard recipe with 1% dry yeast was used. Mixing was carried out in a 50 g MDD mixer at 32 °C

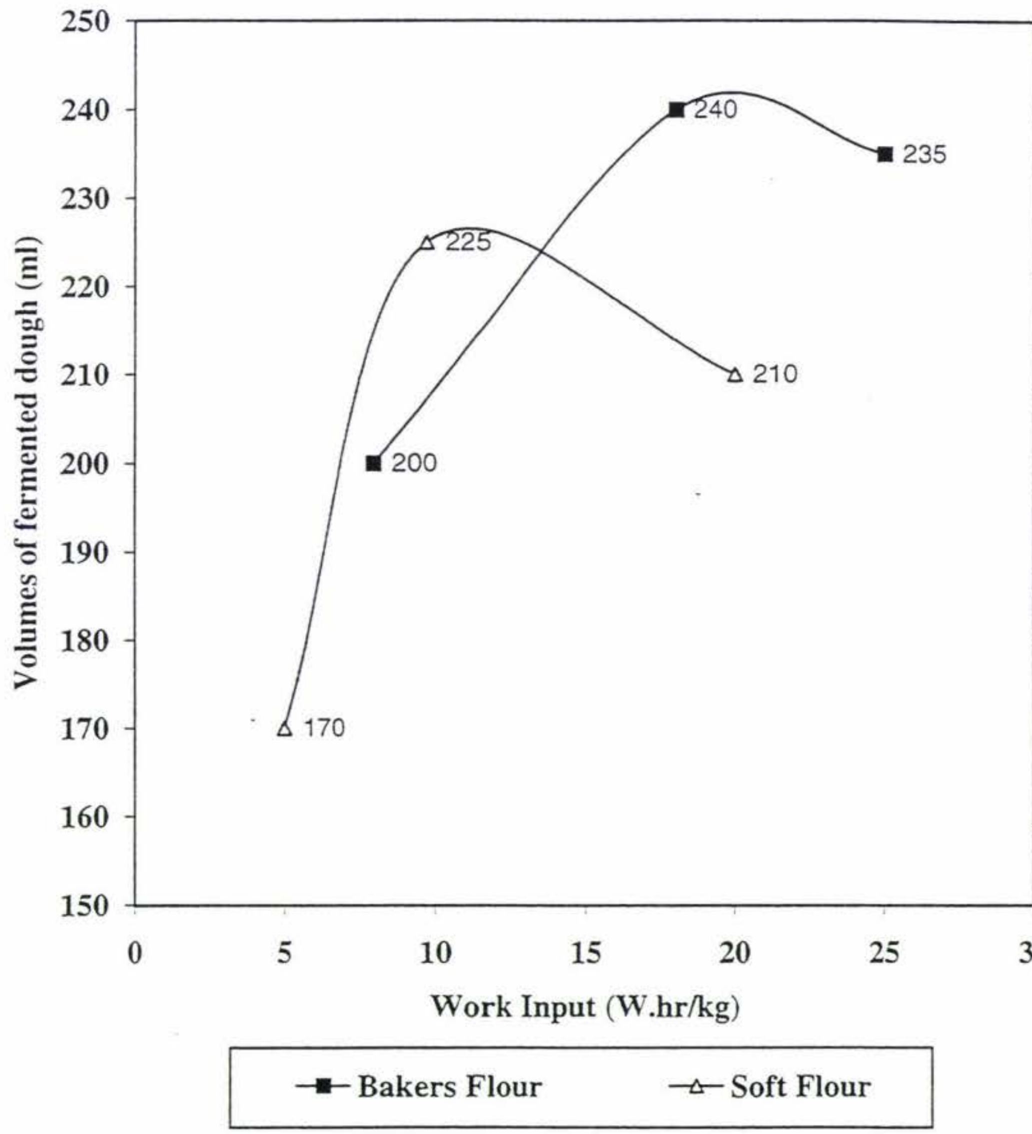


Figure 4.8 Effect of work input on the dough volume after 150 minutes fermentation time. Bakers and Soft flours were used and the water absorption (WA) for both flours was 59%. A standard recipe with 1% dry yeast was used. Mixing was carried out in a 50 g MDD mixer at 32 °C

4.3.3 The microstructure difference of Bakers and Soft Doughs

Dough prepared with two different flours and different levels of work input, namely non-mixing dough, under-mixed dough, optimal-mixed dough and over-mixed dough were observed in a Confocal Laser Scanning Microscope.

Plates 4.1 to 4.8 illustrate the microstructure of doughs prepared with Bakers and Soft flour at different work input levels. Both Bakers and Soft flour were mixed using the standard recipe and 59% water absorption. Under-mixed level for Bakers flour is 5 W. hr/kg, and 3 W. hr/kg for Soft flour. Optimal-mixed level for Bakers flour was 18 W. hr/kg and 9.7 W. hr/kg for Soft flour. Over-mixed level for Bakers flour was set as 30 W. hr/kg and 13 W. hr/kg for Soft flour. Non-mixing doughs were prepared following the method described in Chapter 3. The scale bar shown in the pictures is 100 μm and a resolution of 100 was used to study the microstructures of all doughs.

It can be seen in these plates that for both flours optimum-mixed doughs have a more uniform and well-developed gluten network. The gluten network presented a smooth and continuous link around the gas cells (dark area). The structure of under mixed dough showed that gluten network did not expand well and seems to be restricted together. Gluten network of over-mixed dough does not look as smooth as optimum-mixed dough meaning that chemical bonds (e.g. disulfide bond) responsible to held proteins together could be partly damaged due to excessive mixing.

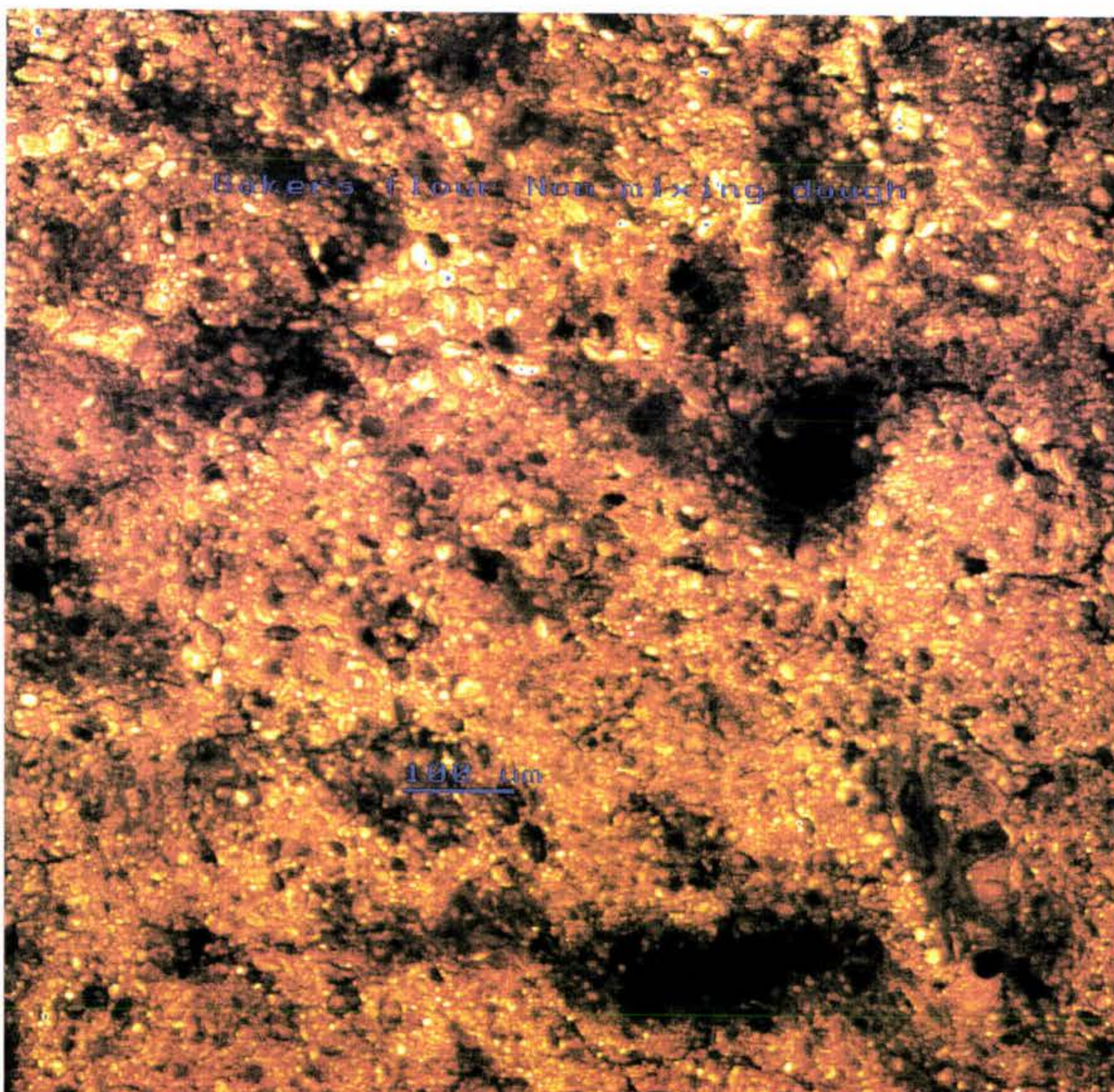


Plate 4.1 Microstructure of non-mixing Bakers flour dough

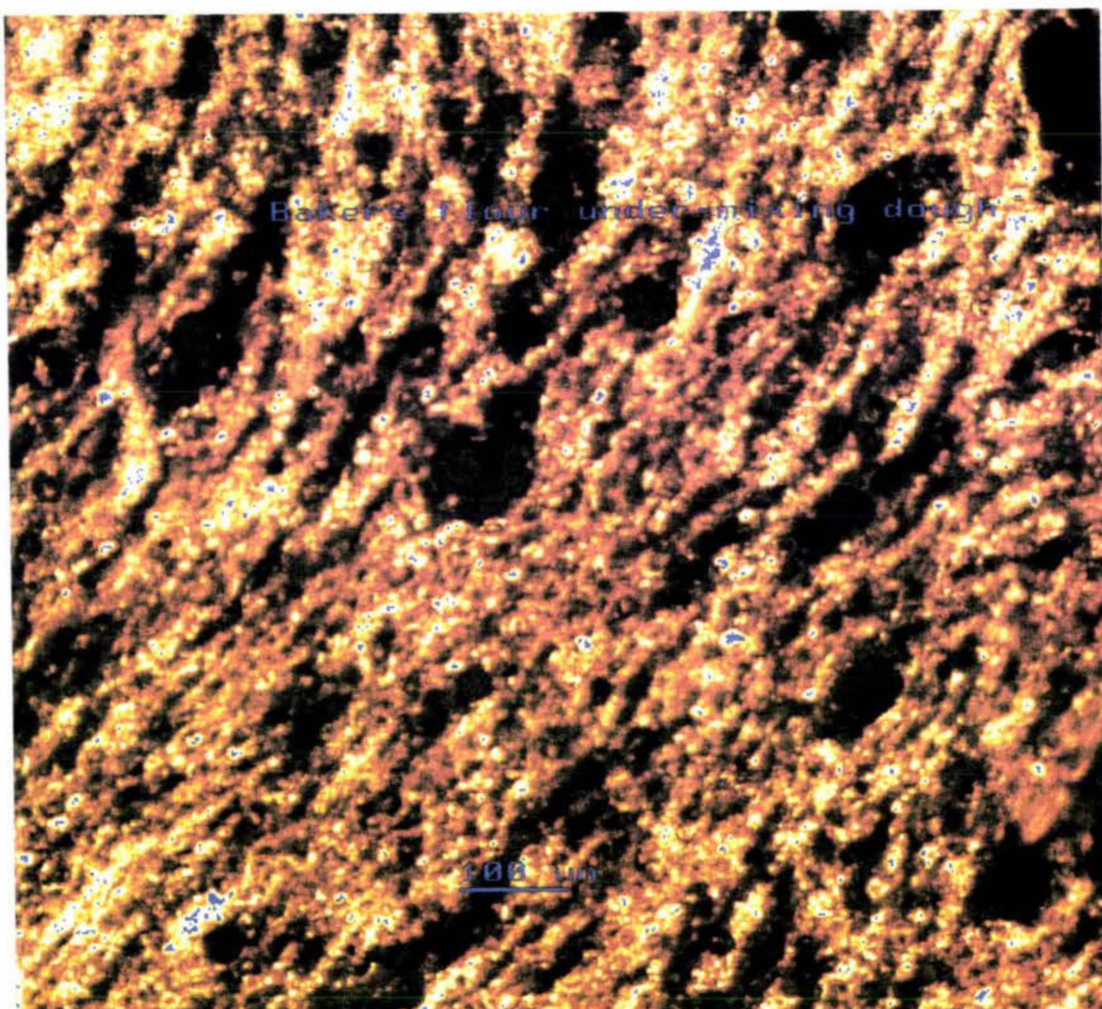


Plate 4.2 Microstructure of under-mixed Bakers flour dough

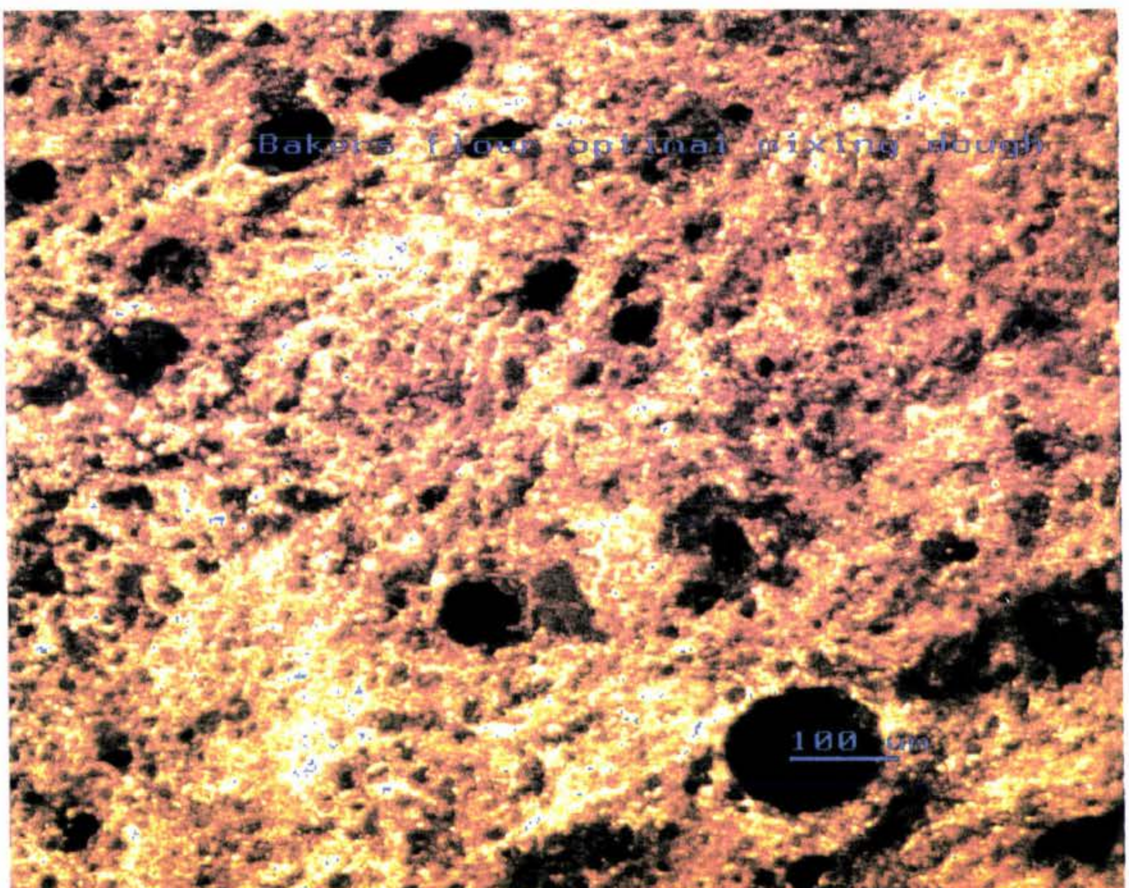


Plate 4.3 Microstructure of optimal-mixed Bakers flour dough

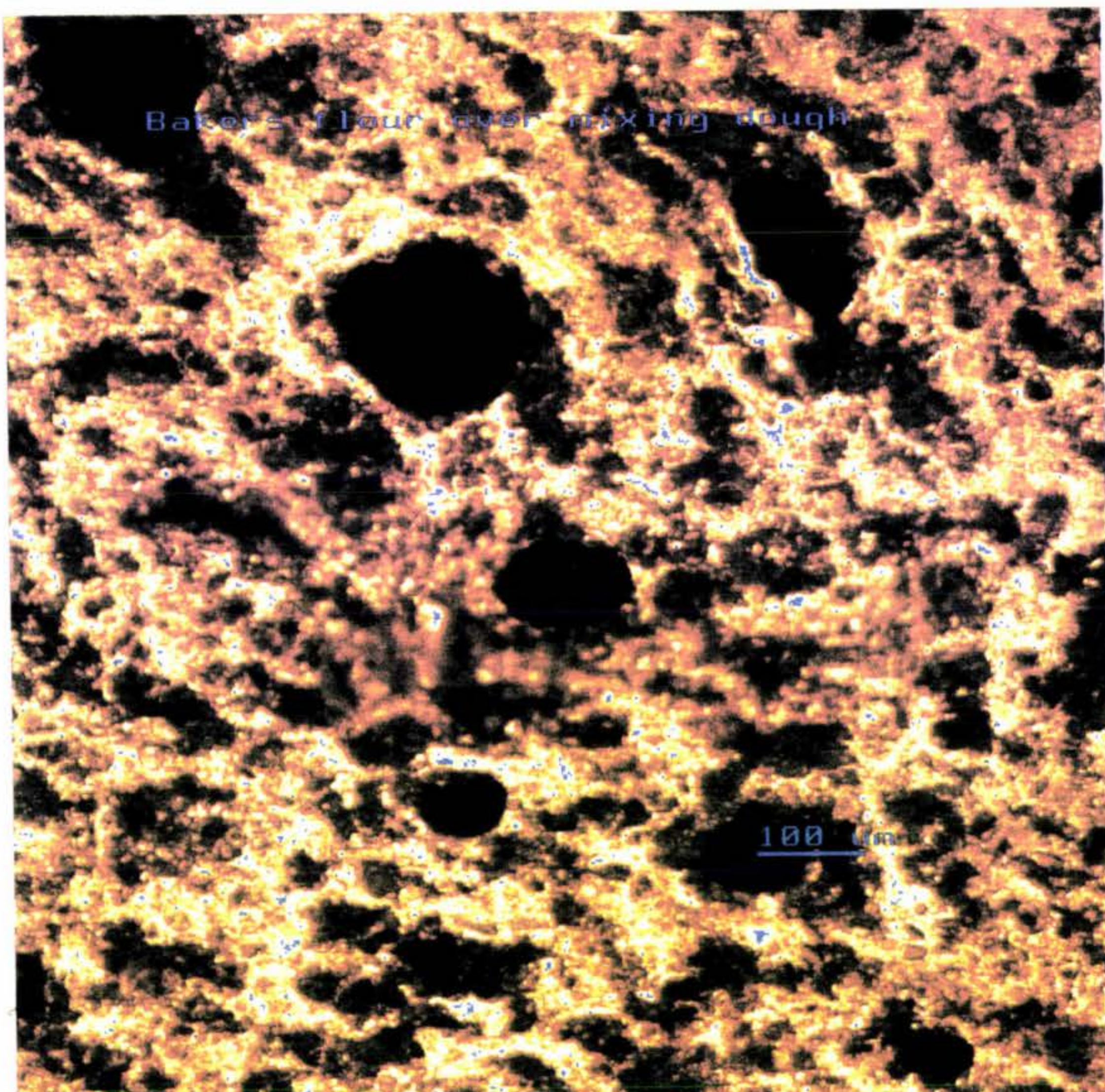


Plate 4.4 Microstructure of over-mixed Bakers flour dough

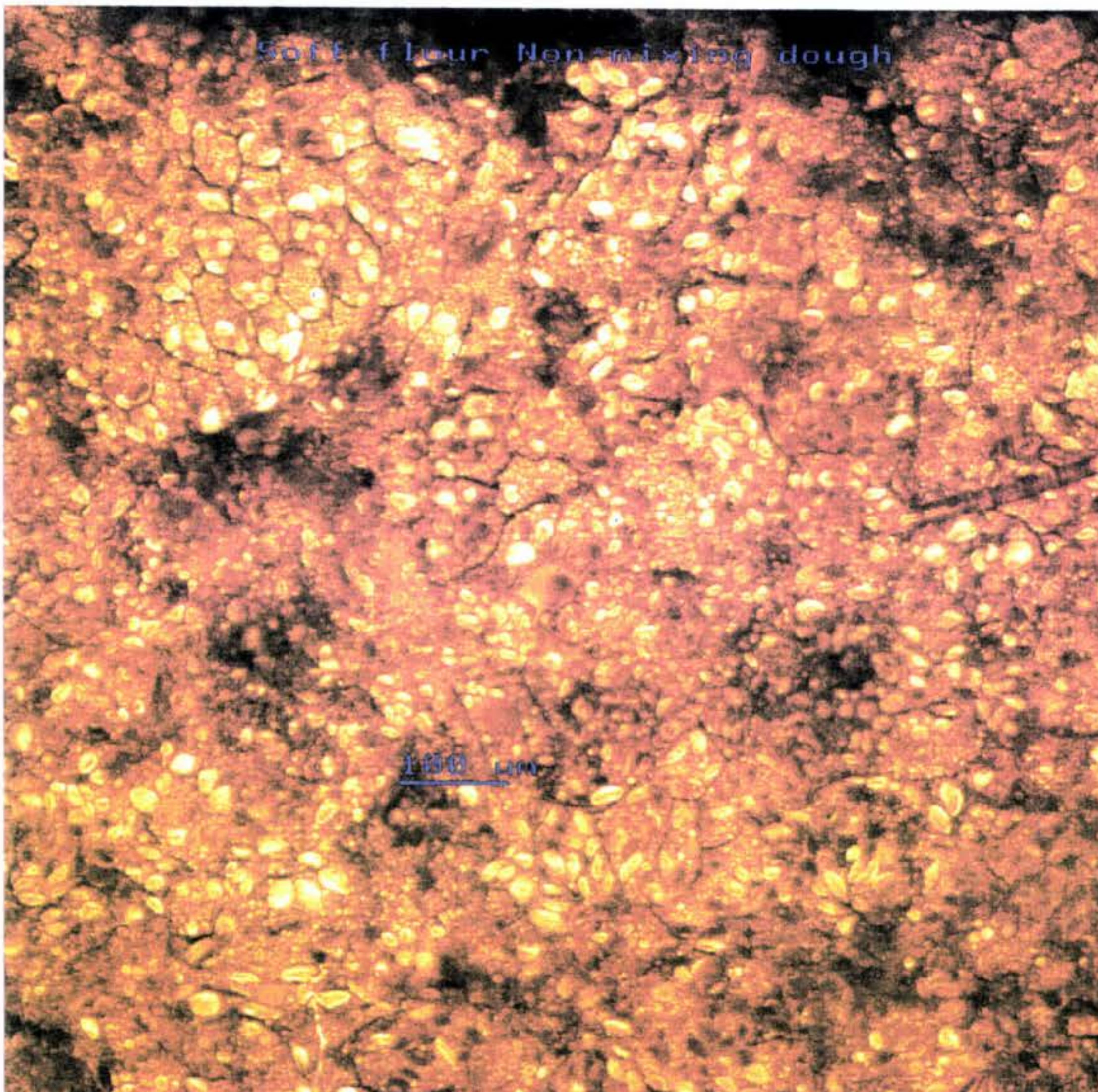


Plate 4.5 Microstructure of non-mixing Soft flour dough

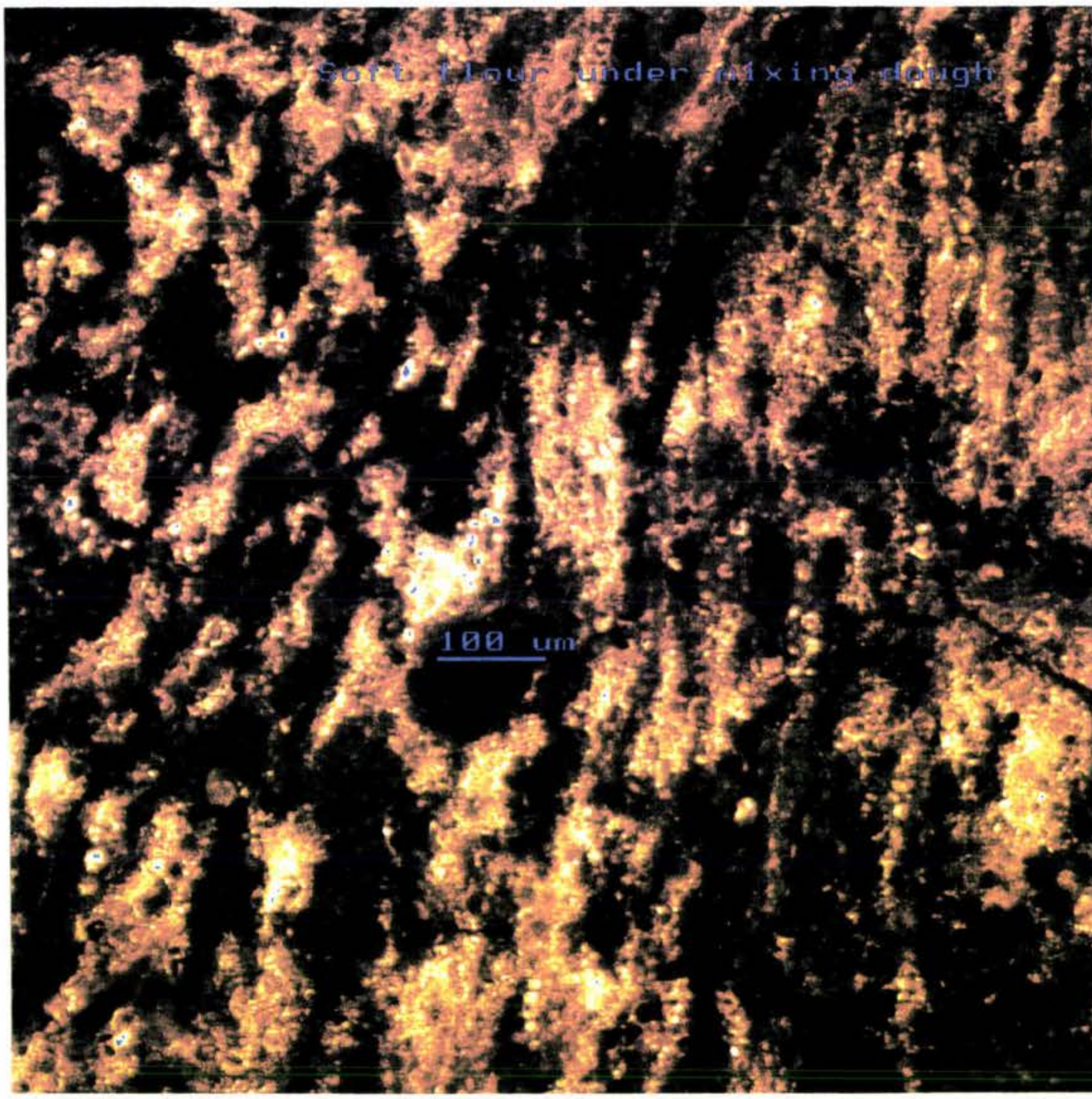


Plate 4.6 Microstructure of under-mixed Soft flour dough

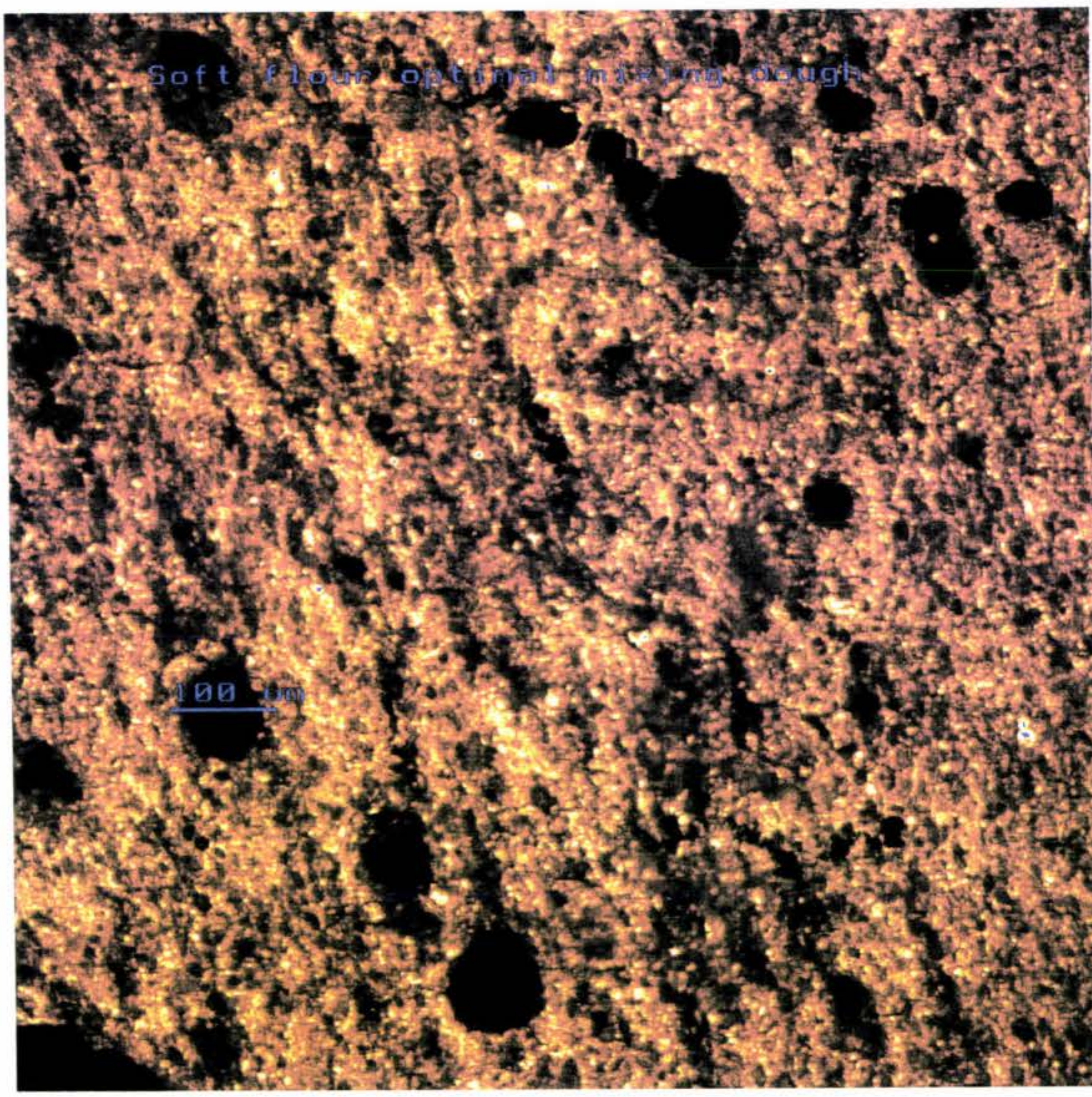


Plate 4.7 Microstructure of optimal-mixed Soft flour dough

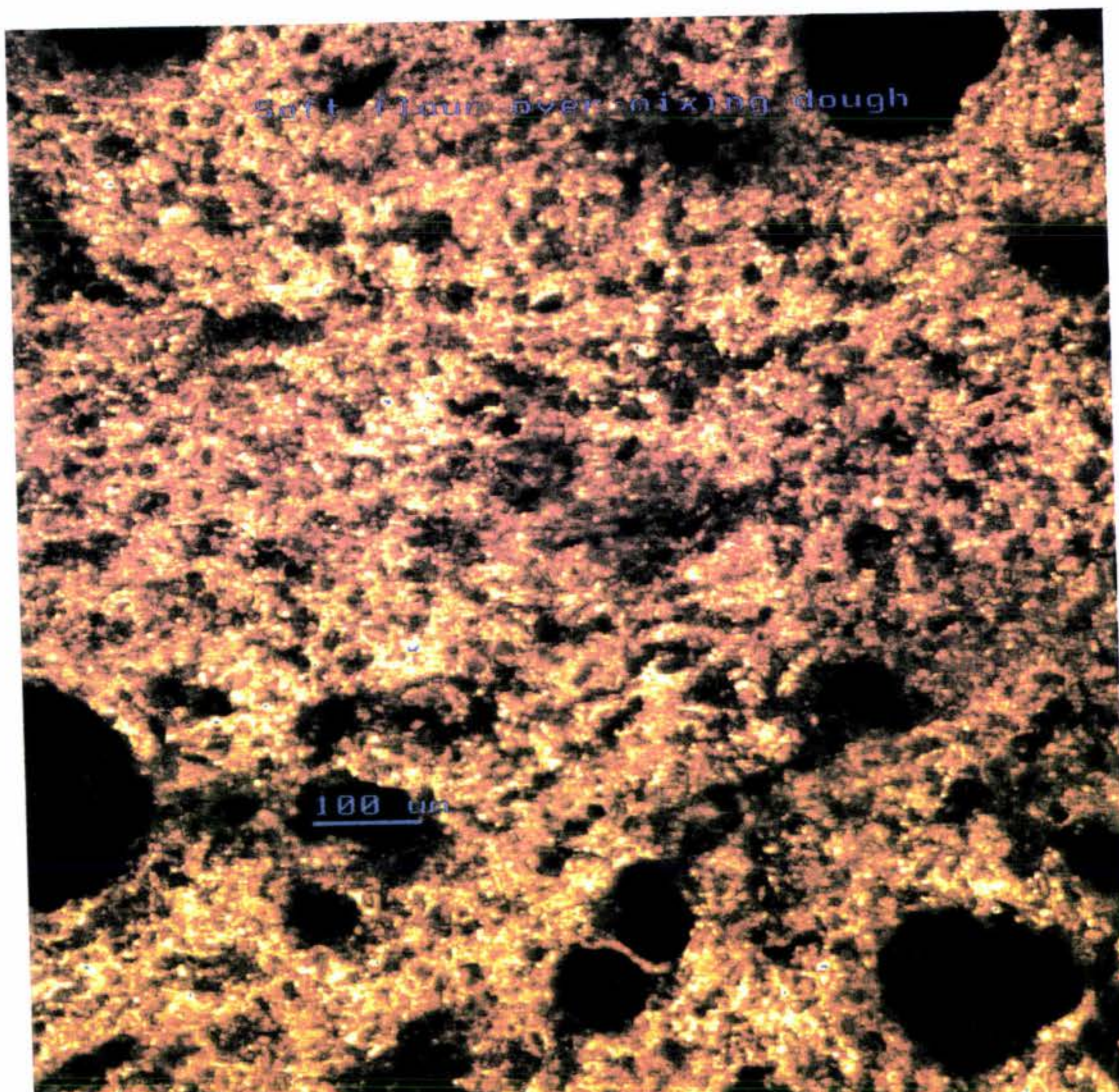


Plate 4.8 Microstructure of over-mixed Soft flour dough

4.3.4 Effect of mixing on the dough Rheological properties

(a) Small deformation test

Oscillation measurements were carried out using both a Bohlin VOR and a Physica UDS200 Rheometer. For the measurements carried out on the Bohlin, different plate configurations were used: (a) smooth parallel plate, (b) serrated plates and (c) parallel plates with sandpaper attached. With the Physica US200 rheometer, only parallel plates covered with sandpaper were used. The diameter of the plates for both rheometers was 30mm. Measurements obtained with the sandpaper-covered plates exhibited good reproducibility whereas those obtained with serrated plates and smooth parallel plates exhibited large deviations. Gaps of 2 mm and 3 mm were used to see the effect of the gap in the measurements. This type of test is very useful to investigate the effect of slip of the measurements.

Results of storage modulus, G' for Bakers flour obtained using both the Physica and the Bohlin viscometer are given in Figure 4.9a. PP30 stands for parallel plates 2 mm gap, SP30 serrated plates 3 mm gap, both using the Bohlin viscometer, and MP30 stands for parallel plates covered with sandpaper 2 mm gap using the Physica UDS200 viscometer. Although there are variation among the data, all appear to follow a similar trend with a maximum value of storage modulus at the optimum work input as determined from the mixing curve. Values of the phase angle (δ) obtained from the same tests are illustrated in Figure 4.9b.

As noted in the figure 4.9b, although there are differences among results obtained with the different geometry used, all the results appear to follow the same trend with minimum values of phase angle for samples prepared with an optimal work input. This along with the measured storage modulus would be indicating that at the optimal mixing input dough has a more elastic behaviour than that of dough under or over-mixed.

Figure 4.10 illustrated the viscoelastic properties storage modulus (G') and phase angle (δ) for Soft flour dough prepared with different levels of work input. The figure shows that the behaviour of this weak flour is similar than that of the strong flour (Bakers) illustrated in Figures 4.9ab. In fact given the characteristics of the flour and the lower protein content, it is not surprise that the values of storage modulus (G') are slightly lower and the values of the phase angle (δ) are slightly higher than those of Bakers flour (a strong flour). The figure, however, shows a more dramatic decrease in storage modulus and phase angle after the optimum mixed is reached. These curves resemble the Mixograph and Farinograph curves described in Chapter 3 (section 3.1) and the mixing curves obtained with the 50-g MDD (section 4.3.1). The decrease observed in dough consistency was attributed to the limited capacity of the flour to stand excessive mixing. The fundamental rheological data obtained in this research are showing that due to excessive mixing the dough loses its elastic characteristics. This, as described in the literature, has been associated to a de-polymerization of the gluten.

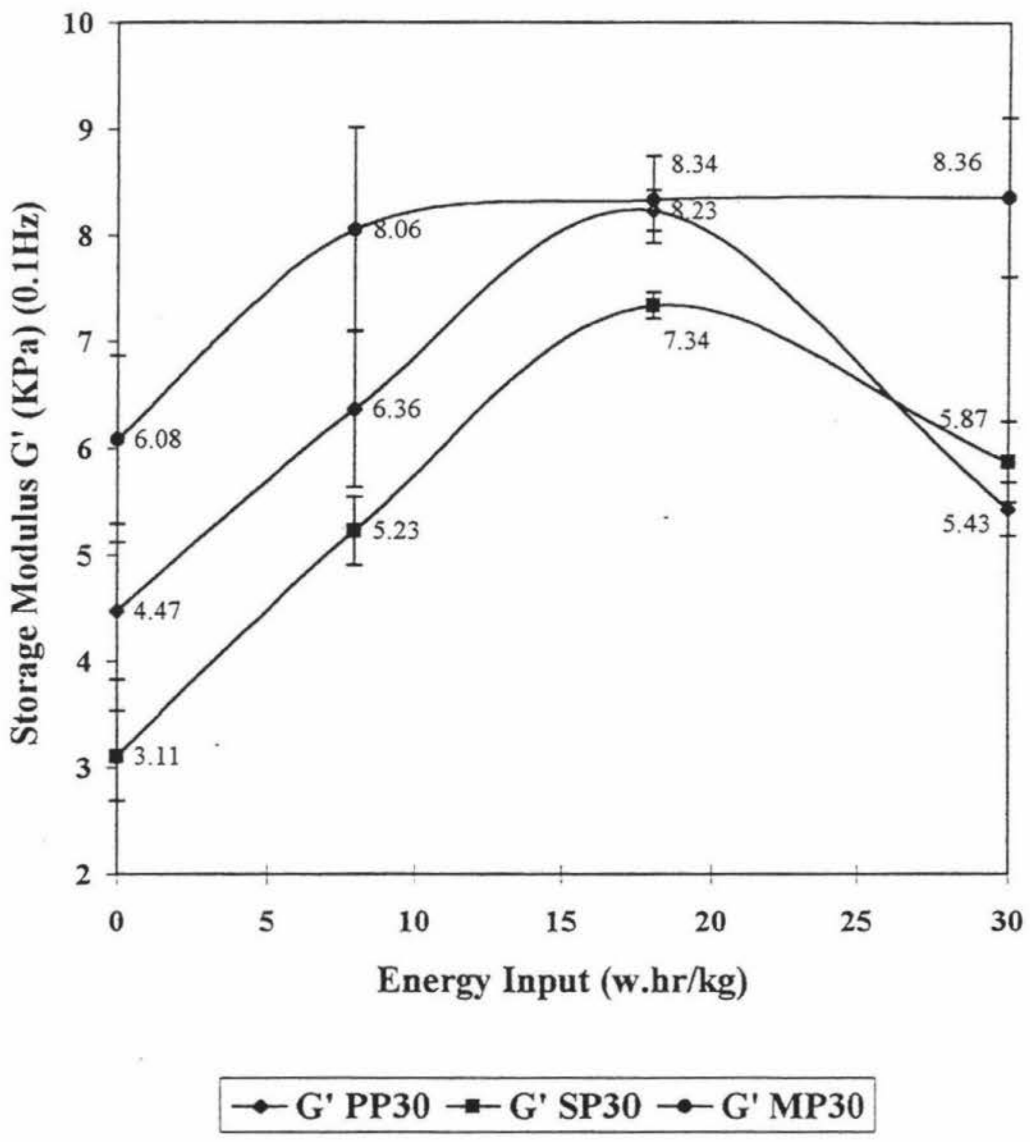


Figure 4.9a Bakers flour Storage Modulus G' measured at 0.1 Hz frequency as a function of the mixing Work Input. Small Deformation Test. Shear Amplitude 1%. Temperature 32 °C, Water Absorption (WA) 59%. PP30 smooth parallel plates, 2mm gap Bohlin Rheometer. SP30 Serrated Plates, 3mm gap, Bohlin Rheometer. MP30: Plates covered with sandpaper, 2 mm gap. Physica UDS200 Viscometer.

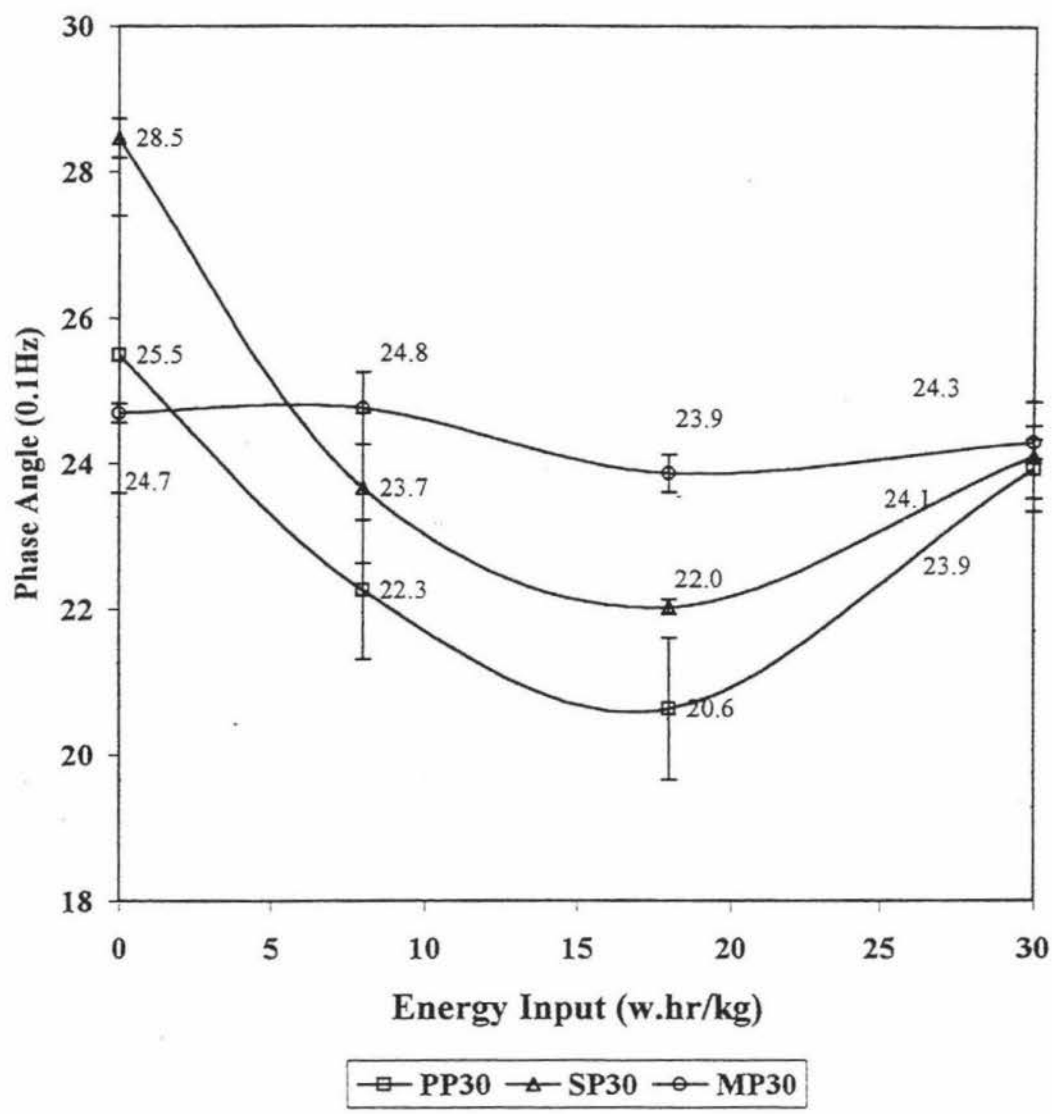


Figure 4.9b Bakers flour Phase Angle (δ) measured at 0.1 Hz frequency as a function of the mixing Work Input. Small Deformation Test. Shear Amplitude 1%, Temperature 32 °C, Water Absorption (WA) 59%. PP30 smooth parallel plates, 2mm gap Bohlin Rheometer. SP30 Serrated Plates, 3mm gap, Bohlin Rheometer. MP30: Plates covered with sandpaper, 2 mm gap. Physica UDS200 Viscometer.

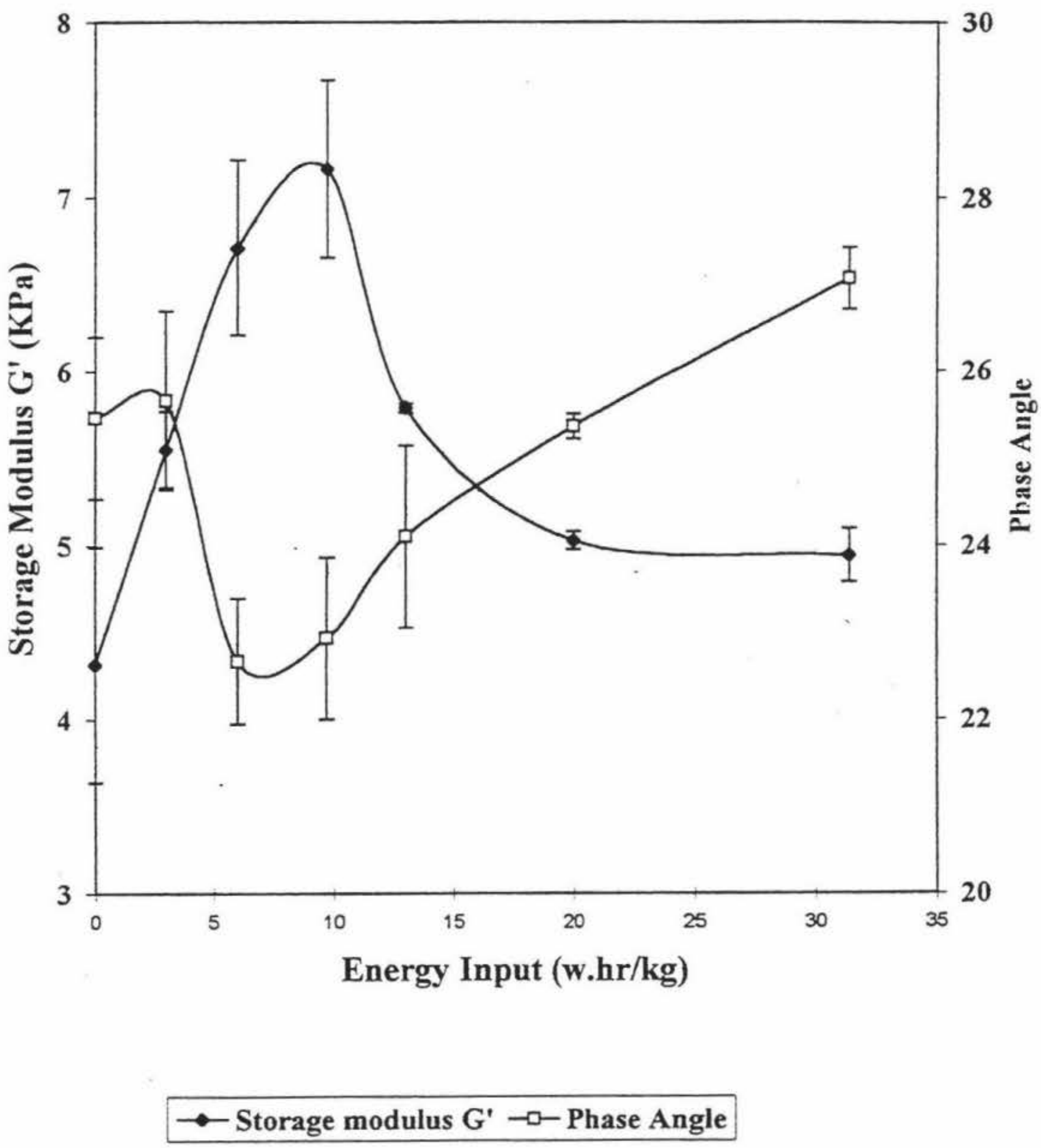


Figure 4.10 Small deformation test results for Soft flour dough (Storage modulus G' and Phase angle δ) Tests were carried out using a Bohlin VOR Rheometer, Parallel plate geometry, 2 mm gap and an amplitude of 1% was used. A 50g MDD mixer and a standard recipe with 59%WA were used to prepare the doughs. Test temperature was 32 °C.

(b) Large Deformation

Shear Stress Growth Test

Results of the shear stress growth experiments, using the Physica UDS200 Rheometer, for dough prepared with Bakers flour at different mixing levels are showed in Figure 4.11a, whereas those for Soft flour measured in a Bohlin VOR rheometer are shown in Figure 4.12a. It can be observed in all the figures, and for the entire shear rates utilised, that the shear stress increases with time or strain (calculated as $\gamma{\cdot}t$) until a peak stress and after decreases. The strain at which the stress reaches the peak varies with the work input but ranges between a strain of 6 and 10. Similar values of strain were obtained by Lindborg (1995). The behaviour was explained as a strain hardening effect of dough when is deformed at a constant shear rate.

Results from the stress growth measurement show that there are significant differences among doughs prepared with the two flours at different mixing levels. Optimum-mixed Bakers and Soft flour doughs gave the highest shear stress and strain peaks for all shear rates utilised but the shear stress varied with shear rate. It also worth nothing that values of peak stresses for dough prepared with Bakers flour was significantly higher than those obtained with Soft flours. This was the reason why two different rheometers had to be used. For this experiment, shear stresses obtained from the Bakers flours were considerably higher to be tested in the Bohlin rheometer.

Peak shear stresses from Figure 4.11a and 4.12a are plotted against work input to obtain Figures 4.11b and 4.12b. As observed in the figures optimum-mixed dough exhibited the highest shear stress peak.

Figure 4.13a shows the shear thinning behaviour of Bakers flour dough as the peak viscosity decreases with increases in shear rate. The shear thinning behaviour of the dough prepared with Soft flour is clearly illustrated in Figure 4.13b in where a decrease of the viscosity with increasing shear rate is also observed. It is worth nothing in Figure 4.13a that for low shear rates the decrease in viscosity is less pronounced than that at high shear rates. The reason of this behaviour could be related to the very complex behaviour of shear thinning material which is illustrated in Figure 4.13c.

As noted in the Figure 4-13c at low and high shear rates there is no a large change in viscosity with shear rate. It is probable that the low shear rates used in this experiment are within the region of small viscosity variation. But when the shear rate is changed to 0.05 1/s it moves to the intermediate shear region in where the varieties of rheological properties (viscosity or shear stress) are more pronounced.

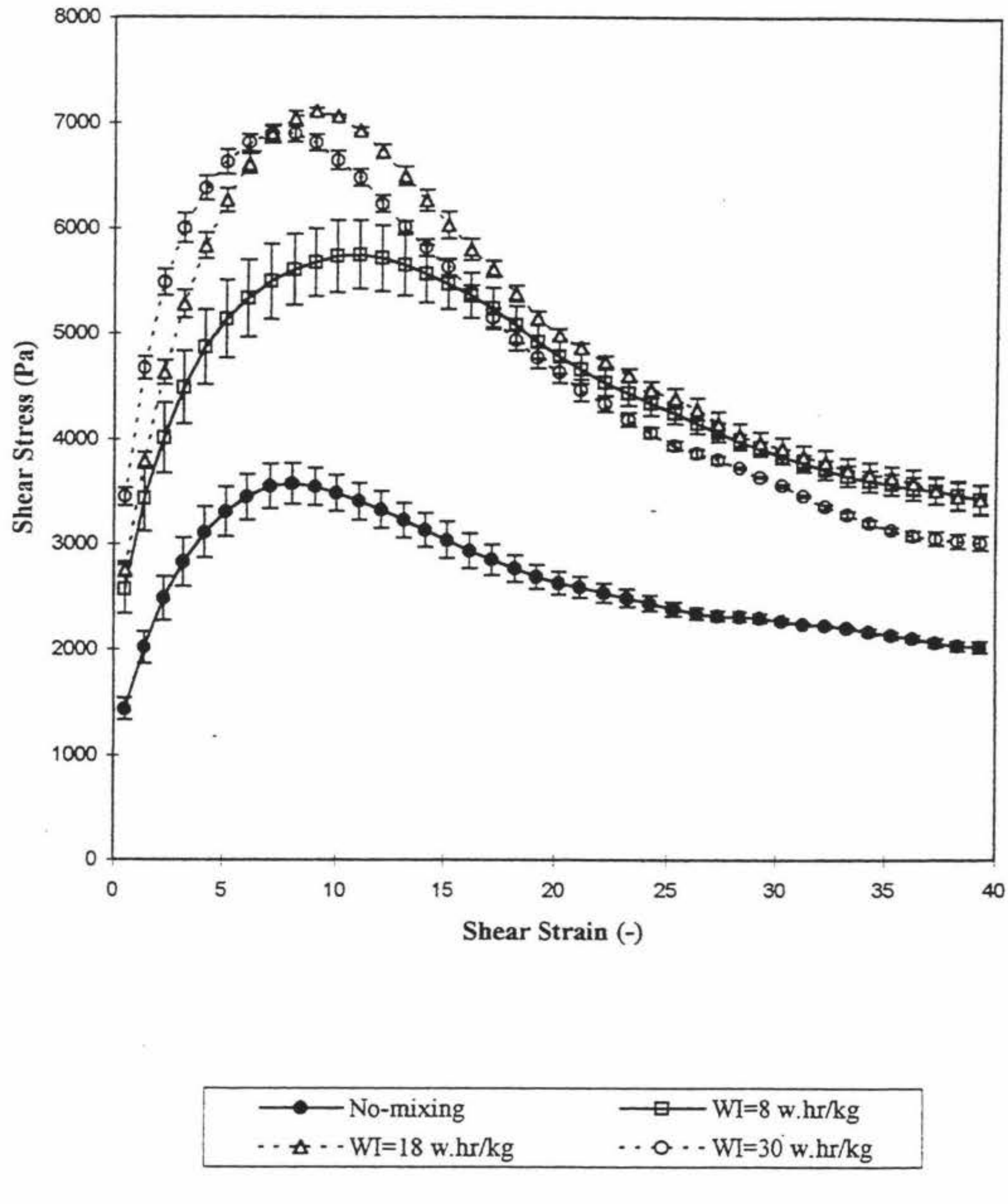


Figure 4.11a Effect of work input on Bakers flour dough prepared with the standard recipe and 59% WA in a 50g MDD mixer at 32 °C. Large deformation shear stress growth tests were carried out on the Physica UDS200 Rheometer with MP30 parallel plates covered with sandpaper and a 2mm gap, 0.5 1/s shear rate and 32 °C.

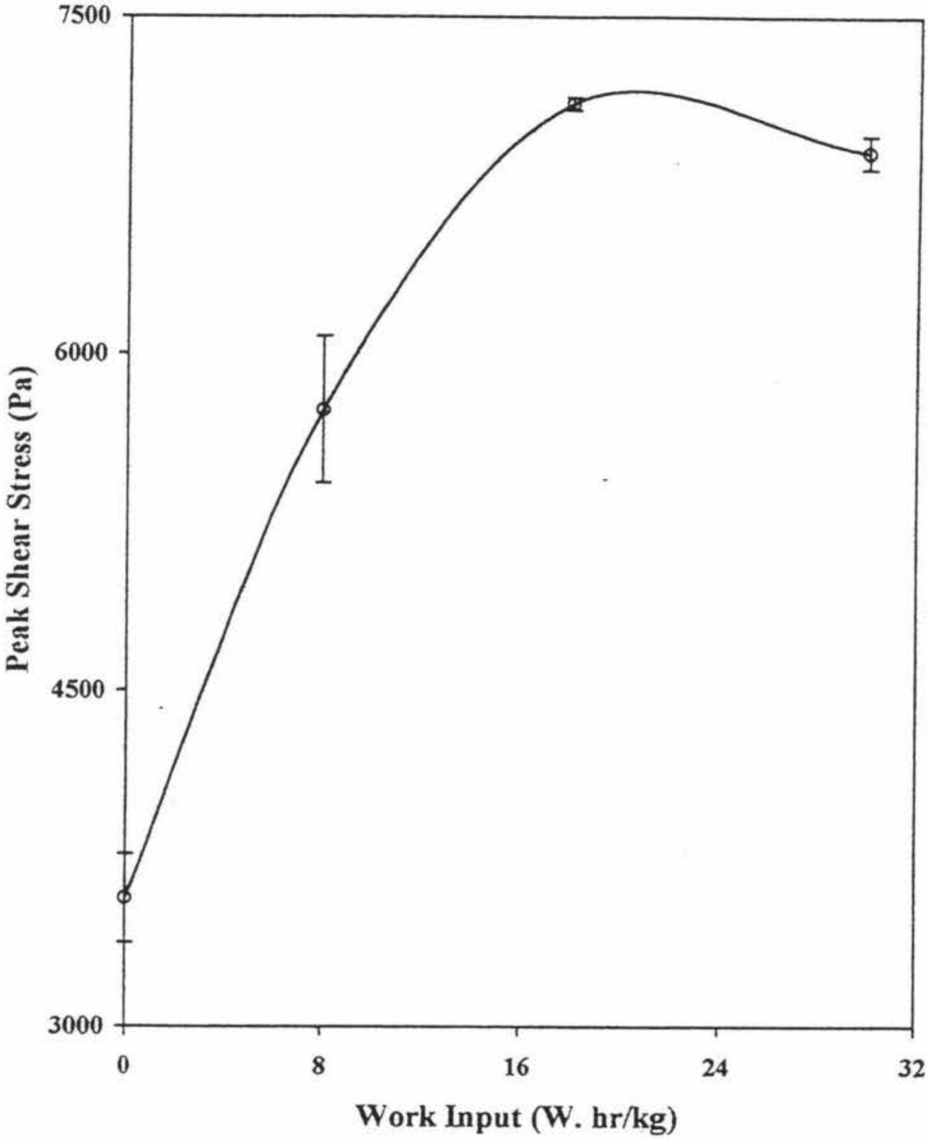


Figure 4.11b Effect of work input on Bakers flour dough prepared with the standard recipe and 59% WA in a 50g MDD mixer at 32 °C. Large deformation shear stress growth tests were carried out on the Physica UDS200 Rheometer with MP30 parallel plates covered with sandpaper and a 2mm gap, 0.5 1/s shear rate and 32 °C.

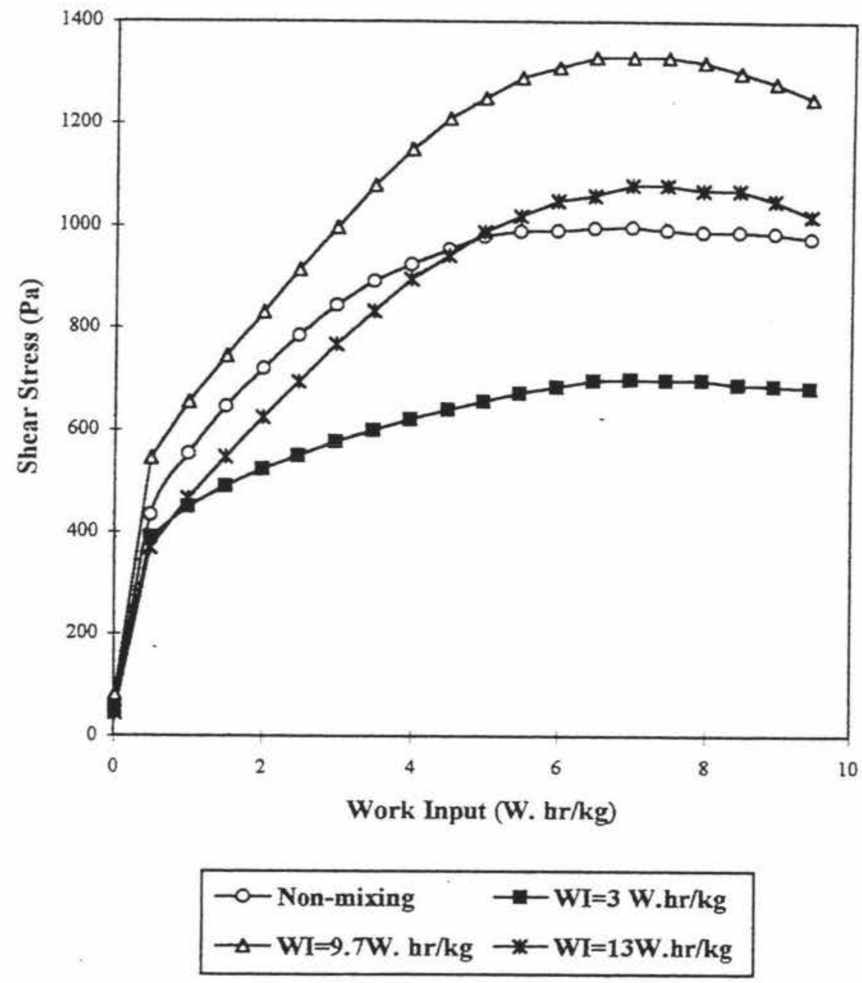


Figure 4.12a Effect of work input on Soft flour dough prepared with the standard recipe and 59% WA in a 50g MDD mixer at 32 °C. Large deformation shear stress growth tests were carried out on the Bohlin VOR Rheometer with PP30 parallel plates covered with sandpaper and a 2mm gap, 0.05 1/s shear rate and 32 °C.

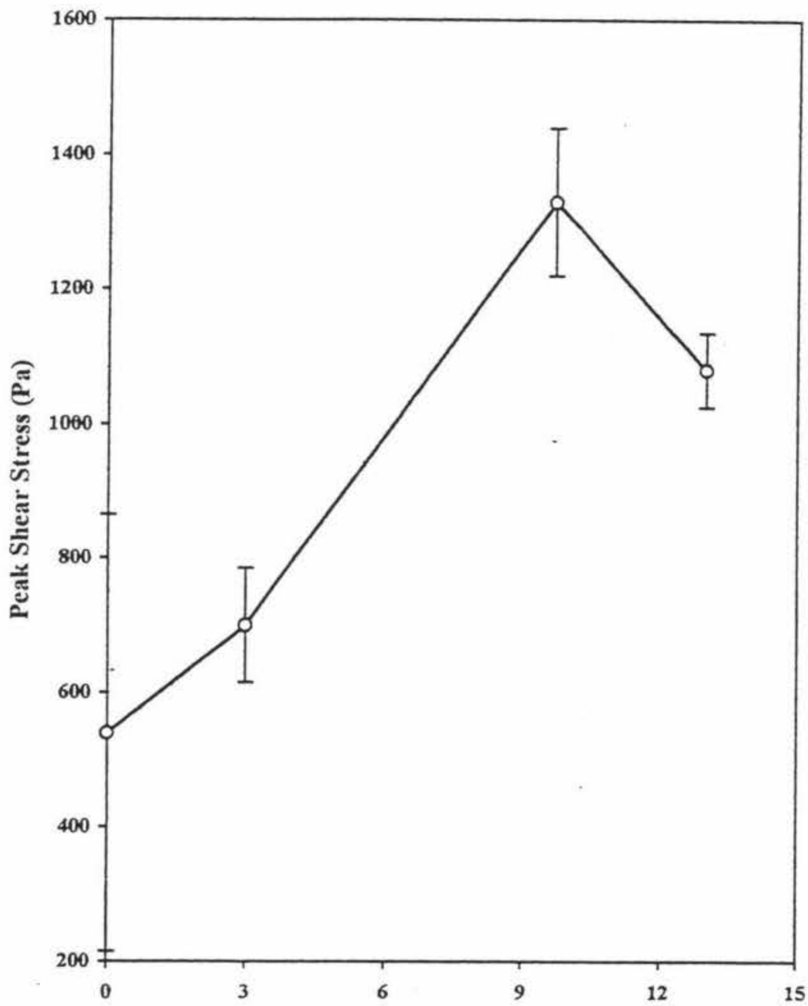


Figure 4.12b Effect of work input on Soft flour dough prepared with the standard recipe and 59% WA in a 50g MDD mixer at 32 °C. Large deformation shear stress growth tests were carried out on the Bohlin VOR Rheometer with PP30 parallel plates covered with sandpaper and a 2mm gap, 0.05 1/s shear rate and 32 °C.

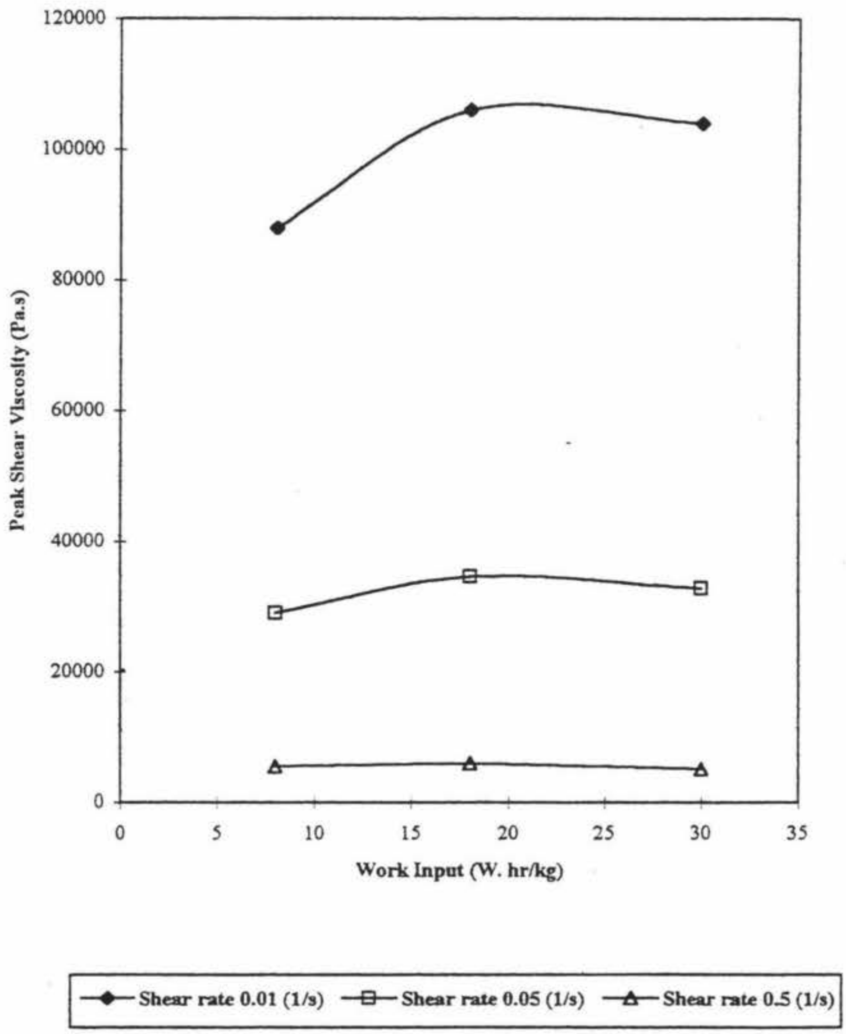


Figure 13a Effect of Shear Rate used in rheological property measurement. Bakers flour doughs were prepared with the standard recipe, 59% WA and 18 W. hr/kg. Tests were carried out on Bohlin VOR rheometer with PP30 2mm gap and sandpaper attached. Test Temperature was 32°C.

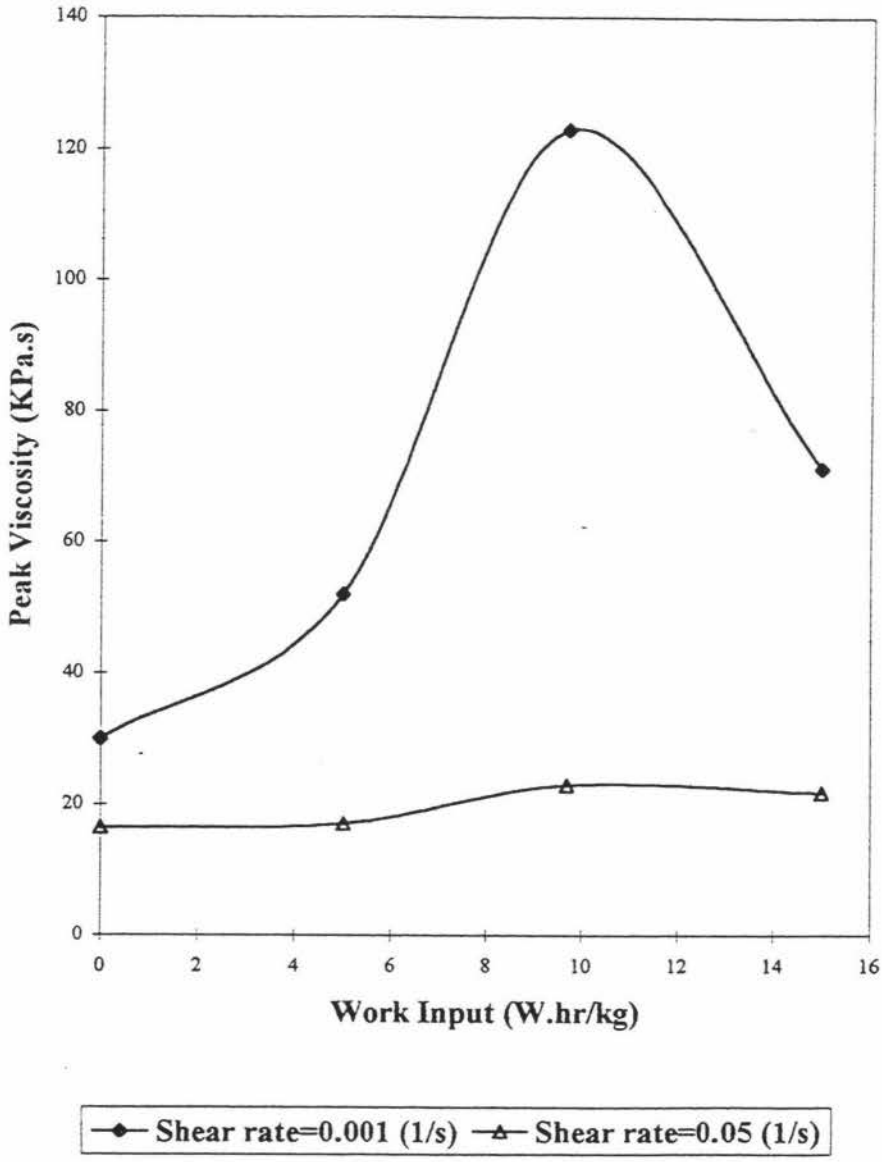


Figure 13b Effect of Shear Rate. Soft flour doughs were prepared with the standard recipe, 59% WA and 9.7 W. hr/kg. Tests were carried out on Bohlin VOR rheometer with parallel plates covered with sandpaper and a 2 mm gap. Test Temperature was 32°C.

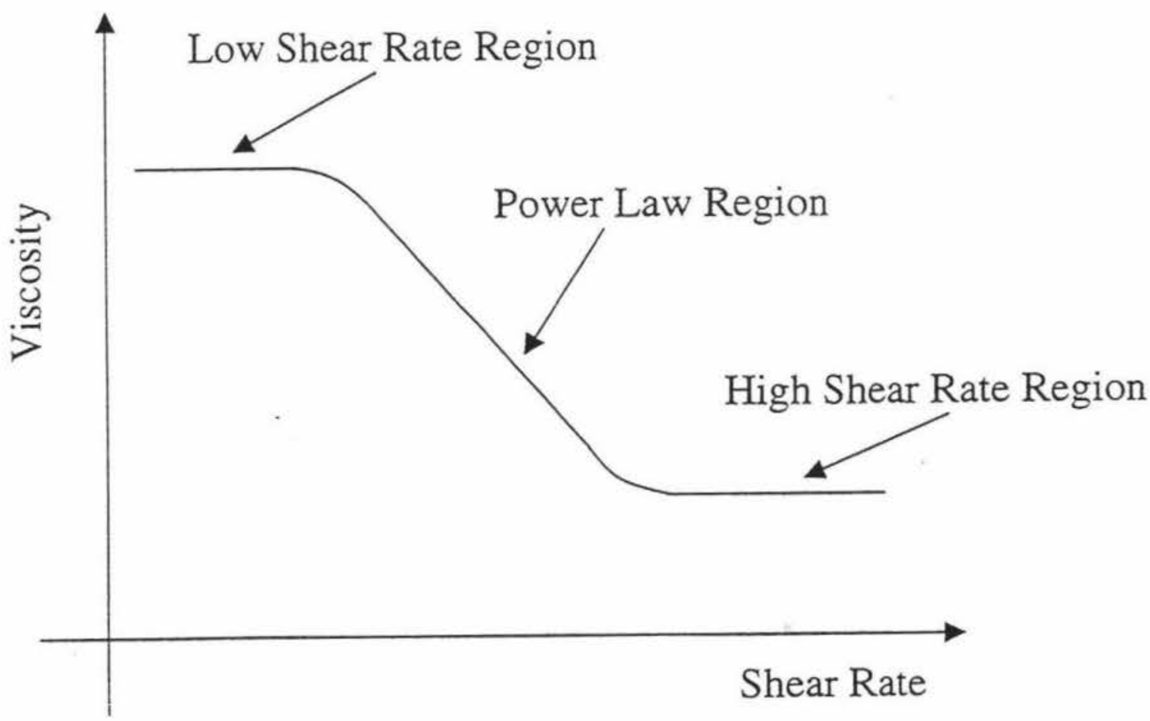


Figure 4.13c Schematic of a complete flow curve of a pseudo-plastic material

Results from the Extrusion Test

Although the extrusion test appears to be somewhat empirical it providers information concerning both extensional and shear flow properties of the dough. It has been demonstrated by Cogswell (1972) that the force to extrude a viscoelastic material through an orifice is given by the following equation:

$$F = \frac{9(n+1)^2}{128} \pi D_p^{\ 2} \mu_S \eta_E \dot{\gamma}_a^{\ 2} \qquad (4.5)$$

Where n is the power law index, Dp the piston diameter, $\dot{\gamma}_a$ the shear rate of the sample prior to entering into the orifice and μ_S and η_E are the apparent shear and elongational viscosities respectively. Equation (4.5) assumes that the shear flow of dough follows a power law behaviour given by $\tau = k\dot{\gamma}^n$, where τ is the shear stress, $\dot{\gamma}$ the shear rate and k and n are the consistency index and the flow index respectively.

Ramkumar (1998) showed that for Cheddar cheese dynamic oscillatory experiments and the maximum force obtained from an extrusion test were highly correlated.

These results clearly showed that the extrusion test enabled the characterisation of the elastic behaviour of the sample.

Figures 4.14a and 4.15a show the raw data obtained from the extrusion test for Bakers and Soft flours, whereas Figures 4.14b and 4.15b show values of extrusion force as a function of the work input. These figures illustrate that the extrusion test results follow the same trend than those obtained from the shear stress growth tests. Similarly to the results presented previously for small deformation and shear stress growth test the optimum-mixed had the highest extrusion force.

It can be noted in the figures that for all the samples the force varies while the material is being extruded. The variation of the force can be attributed to the compression of the sample prior exiting the die and also due to friction between the piston and the cylinder which although largely minimised can not fully eliminated. The figures clearly show that there is a large increase in the extrusion force in the last 10-15 seconds of the test. This agrees with the time at which the material starts to come out from the die. The value of the maximum extrusion force was recorded, as the measured value.

Determined "extrusion forces" are plotted as a function of work input to obtain Figures 4.14b and 4.15b for Bakers and Soft flours respectively. These figures clearly show, and in agreement with small deformation results, that at the optimum mixing levels dough exhibits maximum resistance to both extensional and shear flow. Unfortunately, as shown by Equation 4.5, it is not possible in this experiment to separate the effect of the extensional and shear viscosities and only experiments designed to apply one type of flow can give information about them. Figures 4.14b and 4.15b also illustrate that for doughs prepared with the same recipe and water absorption the strong flour (Bakers) had a higher resistance to extensional and shear flow than those prepared with a weak flour (Soft). Results of the shear test under large deformation (shear stress growth) were already discussed in the previous section. Pure extensional (shear free) tests under large deformation will be described in the next session.

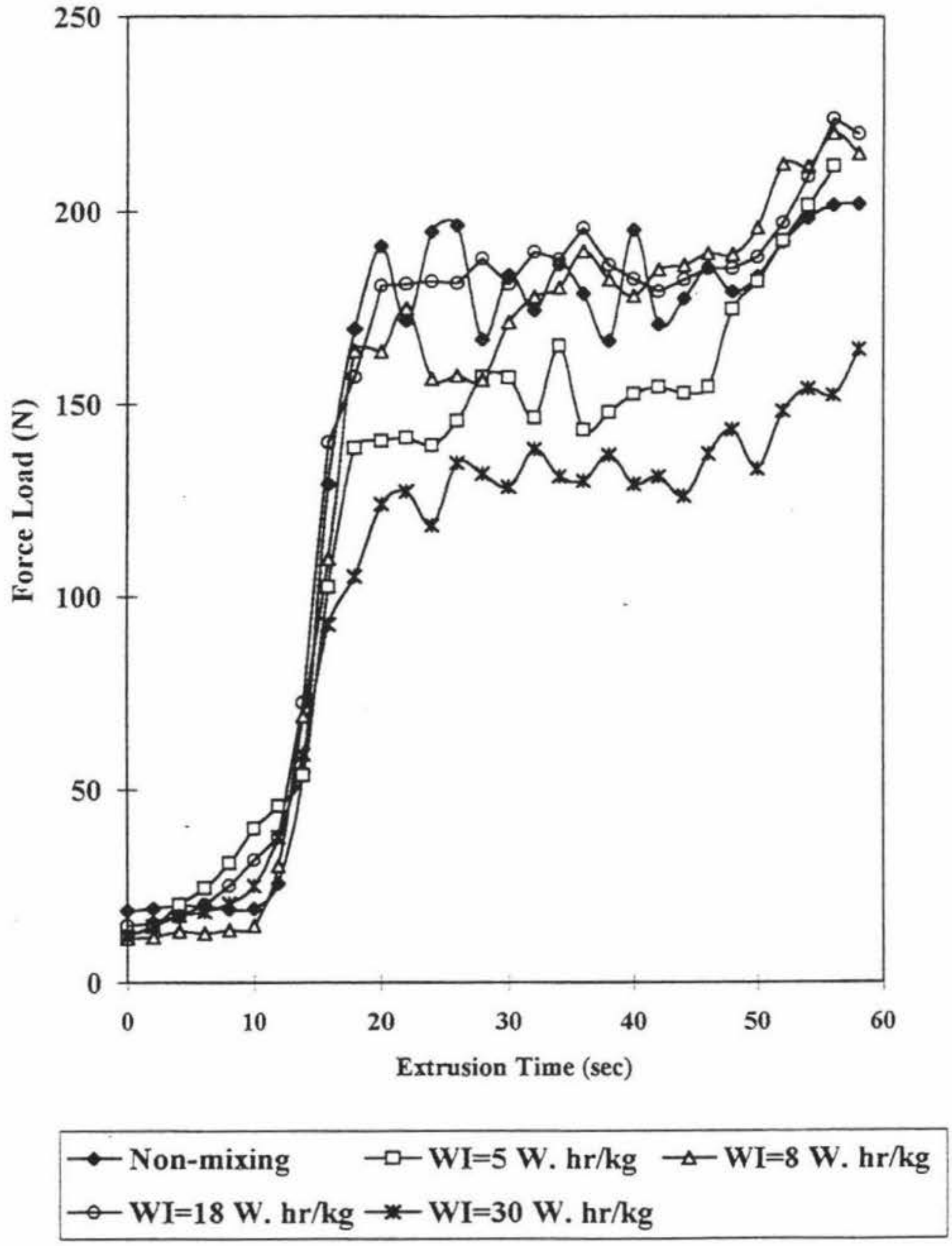


Figure 4.14a Raw data obtained from the extrusion test carried out in an Instron Universal Testing Machine for dough prepared with Bakers flour and different work inputs. Crosshead speed was 60 mm/min and the dough was prepared using the standard recipe and a water absorption (WA) of 59%. Test temperature was 25 °C.

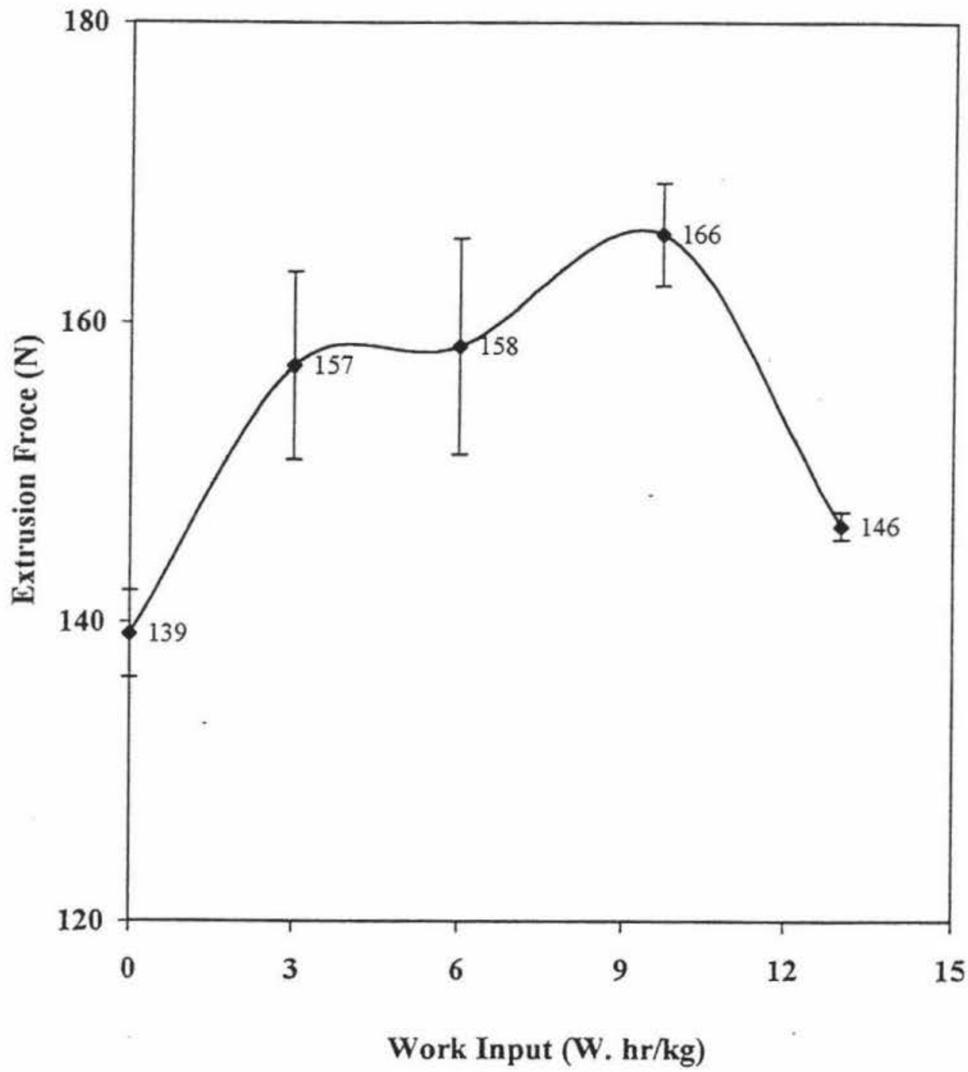


Figure 4.14b Effect of work input on Bakers flour dough prepared with the standard recipe and 59% WA in a 50g MDD mixer at 32 °C. Large deformation extrusion tests were carried out in an Instron Universal Testing Machine with an extrusion test set shown on Fig. 3.11. Crosshead speed was 60 mm/min. Test temperature was 25 °C.

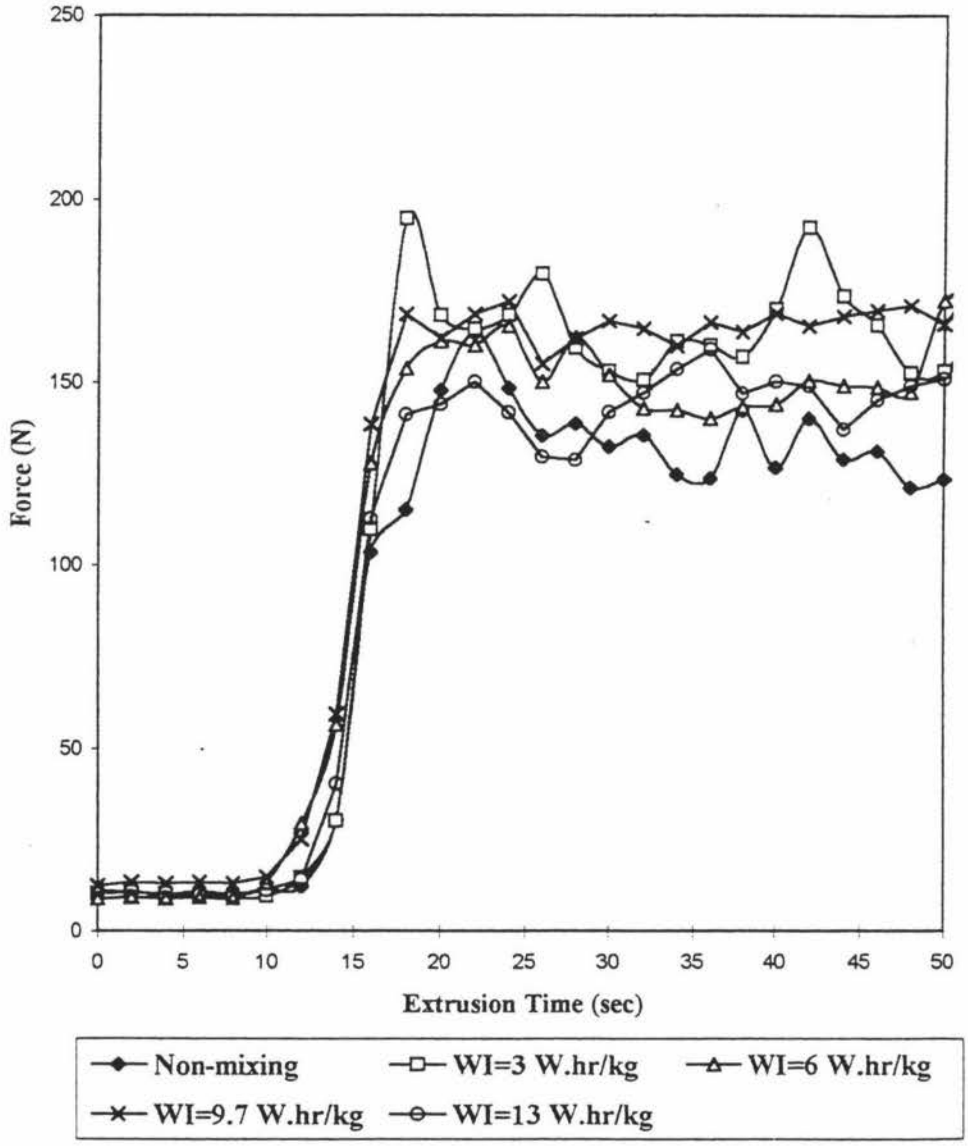


Fig. 4.15a Raw data obtained from the extrusion test carried out in an Instron Universal Testing Machine for dough prepared with Soft flour and different work inputs. Crosshead speed was 60 mm/min and the dough was prepared using the standard recipe and a water absorption (WA) of 59%. Test temperature was 25 °C

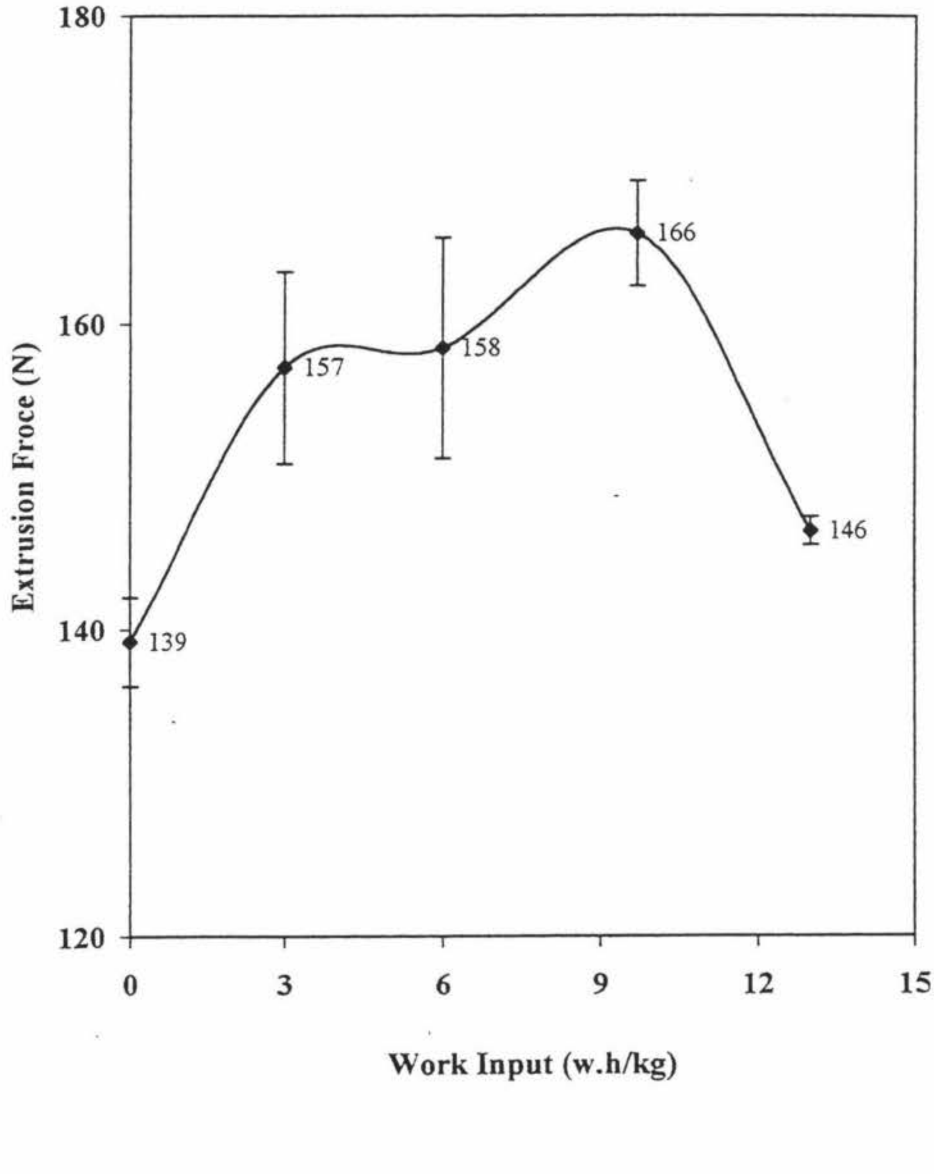


Figure 4.15b Effect of work input on Soft flour dough prepared with the standard recipe and 59% WA in a 50g MDD mixer at 32 °C. Large deformation extrusion tests were carried out in an Instron Universal Testing Machine with an extrusion test set shown on Fig. 3.11. Crosshead speed was 60 mm/min. Test temperature was 25 °C .

Planar Extensional Flow Test

It was shown in the previous section that dough prepared with an optimum mixing level exhibits maximum resistance for both extensional and shear flow. The test carried out (extrusion test), however, does not enable to separate the contribution of each of these two flows. As previously shown by the shear flow tests under small and large deformations discussed in the previous section, optimum mixing provides dough with higher shear viscosity (large deformation shear test) and more elastic characteristics (small deformation test) than doughs obtained with other mixing levels. It was necessary therefore to study the effects of mixing level on the extensional rheological properties of the dough samples. A planar extensional flow test described in Chapter 3 was used to determine these properties.

Planar extensional flow tests of Bakers flour dough prepared with various levels of work input and a water absorption of 59% (standard recipe) were carried out to investigate the effect of mixing on the extensional properties of these doughs. Results of the measured extensional stress as a function of strain for Bakers flour doughs prepared with different work inputs are shown in Figure 4.16a. The value of the stress at selected strains were determined and plotted as a function of the work input in Figure 4.16b. This figure clearly illustrates that at each of the selected strain the extensional stress varies with the work input following a similar trend than that obtained from shear tests.

Figure 4.16b shows that at large strains the effect of the mixing level becomes more evident. This is in agreement with the finding of other researchers (Lindborg, 1995) that found that small deformation tests, albeit under shear flow, were not sensitive enough to establish clear differences between samples prepared with different levels of mixing energy. Conclusions of this research described in previous sections also agree with those findings.

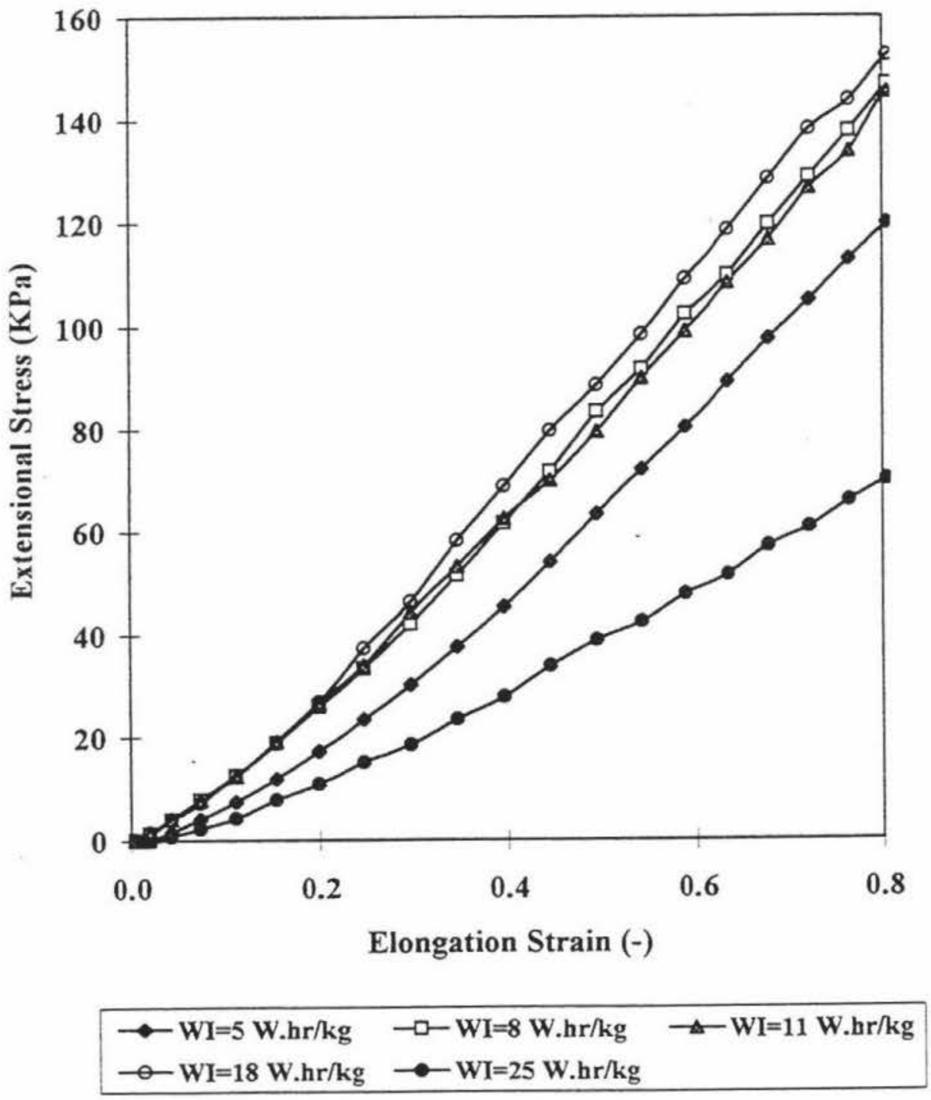


Figure 4.16a Results of the Planar Extensional Flow Test for Bakers flour prepared with different levels of work input. The measurement temperature was 25 °C and the deformation rate 60 mm/min. A standard recipe with 59% WA was used.

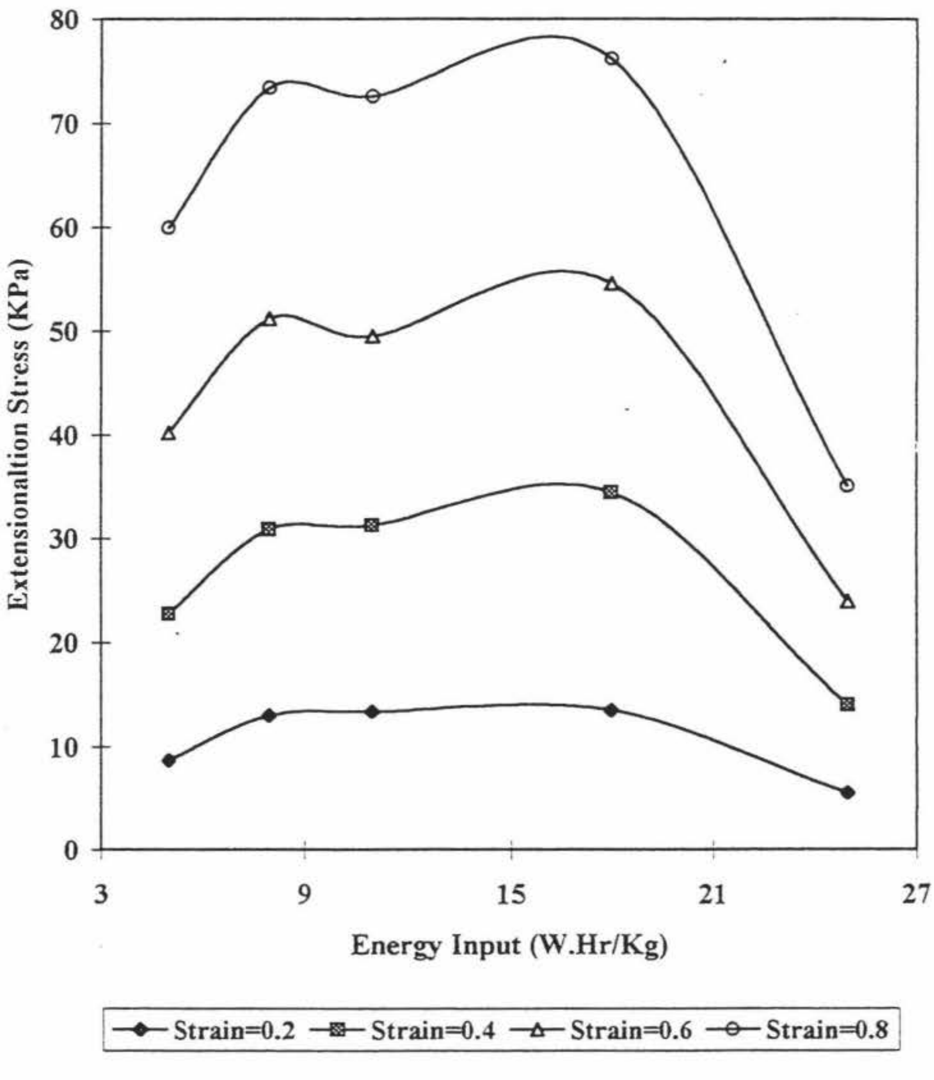


Figure 4.16b Extensional Stress as a function of the energy input at different strain for Bakers flour. Dough was prepared with the standard recipe and 59% WA. The deformation rate was 60 mm/min and the measurement temperature was 25 °C.

4.4 Effect of dough ingredients and resting time on the rheological properties of dough

Variables such as water absorption, resting time, additives, notably oil, are commonly used in the daily operation of a bakery to control the quality of bread and other bakery products. Although there are considerable information in the literature concerning the effect of ingredients in bakery products quality most of them are concerned to empirical rather than fundamental tests. In the first part of this research considerable time was spent in developing sound rheological methods that enable the characterisation of dough using well-defined rheological parameters. The suitability of the developed methods in detecting differences among doughs was tested using dough prepared with different work input and different flours. In the second part of this research some of the developed tests are used to study the effects of added ingredients, water, oil, and processing variables, resting time. Two methods (1) small deformation oscillation shear test and (2) large deformation shear stress growth test were selected to study the effect of moisture content (water absorption), resting time, and oil content on the rheological properties of dough.

4.4.1 Water Absorption

Water absorption has a major effect on the rheological properties of dough. A bread dough formulation basically depends on the type of flour and uses about 54% to 60% water absorption for a proper mixing. Previous work showed that storage modulus G' had a drastic increase as water content decrease within this range (Zheng, 1997). However, the storage modulus increased slowly when the water absorption was less than 54%.

Results from small deformation tests carried out using the Bohlin rheometer on doughs prepared with different Water Absorption (WA), Bakers flour and an optimum mixing level of 18 W. hr/kg are illustrated in Figure 4.17. Storage modulus measured at a frequency of 0.1 Hz decreases with the water absorption. Conversely the phase angle appears to follow a transition-type behaviour with a drastic change occurring between 55% to 60% WA. It would appear that for this range of water absorption the dough becomes more mobile as indicated by the large increase in the value of the phase angle. Although, out of the scope of this work the change in dough mobility could be attributed to a change on the material glass transition temperature. Thus, these results would be showing that for a water absorption in the range 55% to 60% water would act as a plasticiser.

Results of the large deformation shear stress growth test for optimal mixed Bakers flour doughs prepared with different water absorption levels are illustrated in Figures 4.18a and 4.18b. Figure 4.18a shows the values of the shear stress as a function of shear strain. It can be seen in the figure that for all the water absorption the curves exhibit a peak shear stress at a strain of about 5. Similar results are reported by Mani et al, (1992ab). The values of the peak shear stress at a strain of 5 as a function of water absorption are plotted in Figure 4.18b. Interestingly, and when compared with the results obtained from the small deformation oscillating test, both tests give a 4-fold reduction in their measured rheological properties, notably storage modulus and peak shear stress when water absorption is increased from 52 to 64% WA.

Results are not surprising; as demonstrated by Ramkumar (1998) for grated cheese, results from small and large deformations should be in agreement. It has been reported that the stress produced by the deformation of a viscoelastic material can be calculated as

$$\tau(t) = \int_{-\infty}^{t} G(t - t', \gamma)\dot{\gamma}(t')dt' \qquad (4.6)$$

Where τ is the shear stress, G (t-t') is the Shear Relaxation Modulus, $\dot{\gamma}$ is the shear strain, and $\dot{\gamma}$ the shear rate and t is time. It was demonstrated for polymeric materials that the Shear Relaxation Modulus can be expressed as:

$$G(t, \gamma) = G(t) \times h(\gamma) \qquad (4.7)$$

Where h (γ) is a function of strain and G(t) the shear relaxation modulus calculated under small deformation. Ferry (1970) has shown that the shear relaxation modulus G(t) is closely related to the storage modulus (see also Equations (4.1) and (4.2)), in fact both parameters measure the same rheological properties. By replacing Equation (4.7) into Equation (4.6) the following equation results

$$\tau\ (t) = \int_{-\infty}^{t} G(t) \cdot h(\gamma) \cdot \dot{\gamma}(t')dt' \qquad (4.8)$$

For tests within the linear viscoelastic range h $(\gamma) = 1$, so it is not difficult to see that the stress, the Relaxation Modulus and the Storage Modulus will be closely related. For large deformation tests Equations (4.8) or (4.6) show, at least qualitatively, that the stress will be related to the viscoelastic properties notably the storage modulus determined from a small deformation test. Application of Equation (4.8) to food materials has been carried out by Campanella and Peleg (1987).

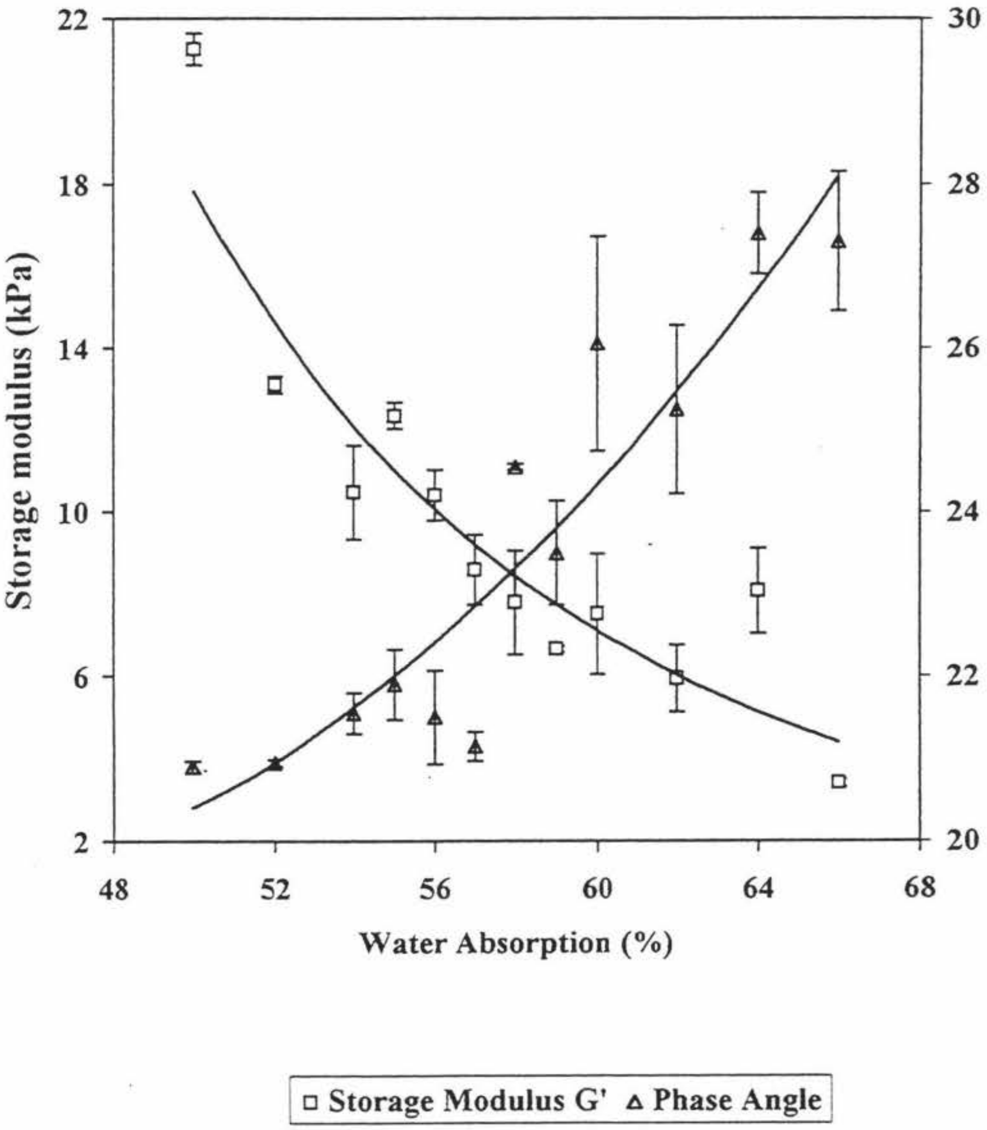


Figure 4.17 Effect of water absorption on the viscoelastic properties of Bakers flour dough optimally mixed. The standard recipe was used and the measurement temperature was 32 °C. The Bohlin rheometer, parallel plates geometry with a 2mm gap and sandpaper were used.

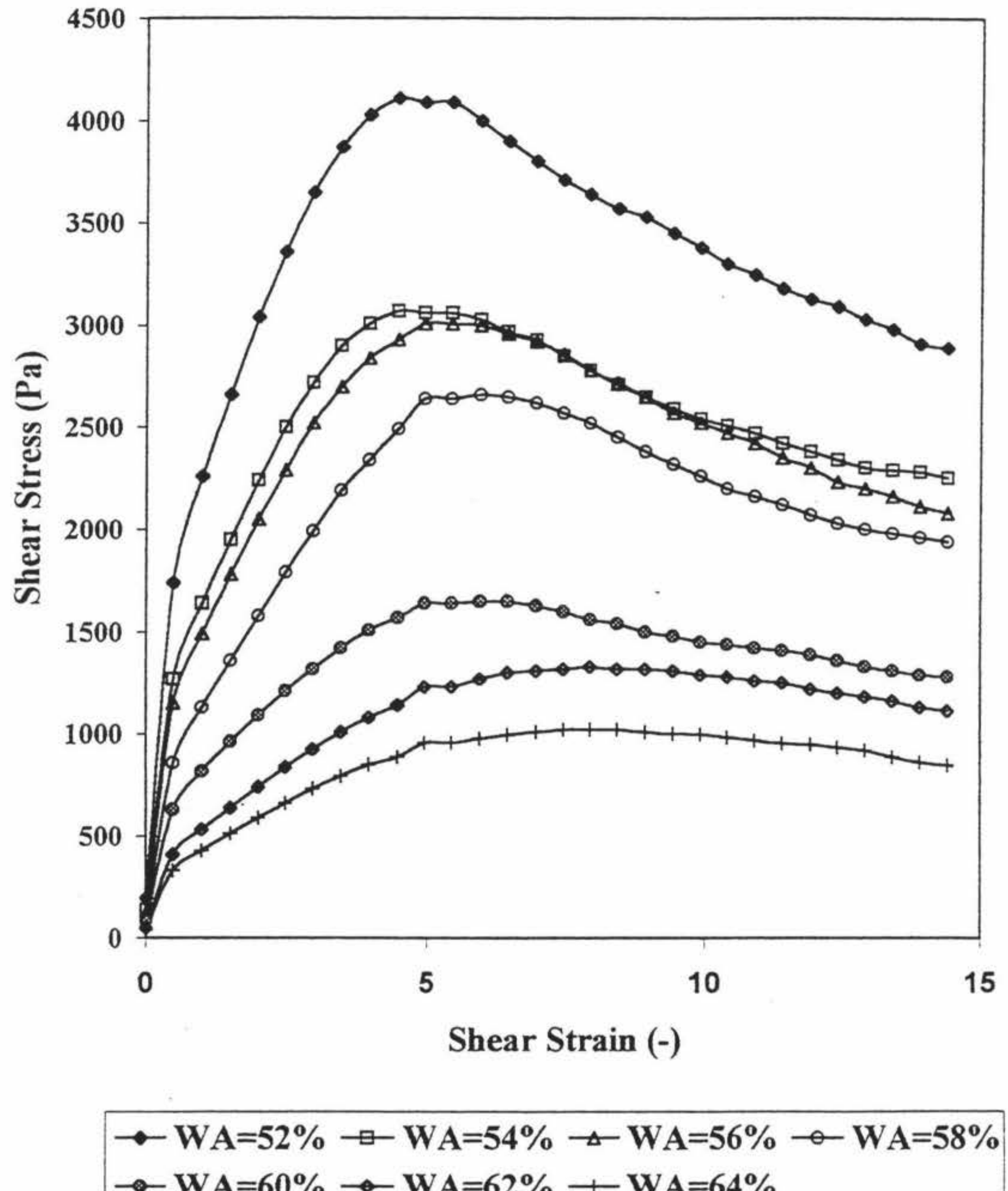


Figure 4.18a Effect of water absorption on shear stress as determined from the large deformation shear stress growth test. Tests were carried in Bohlin rheometer, PP30 parallel plate geometry with a 2 mm gap and sandpaper. Measurement temperature was 32 °C.

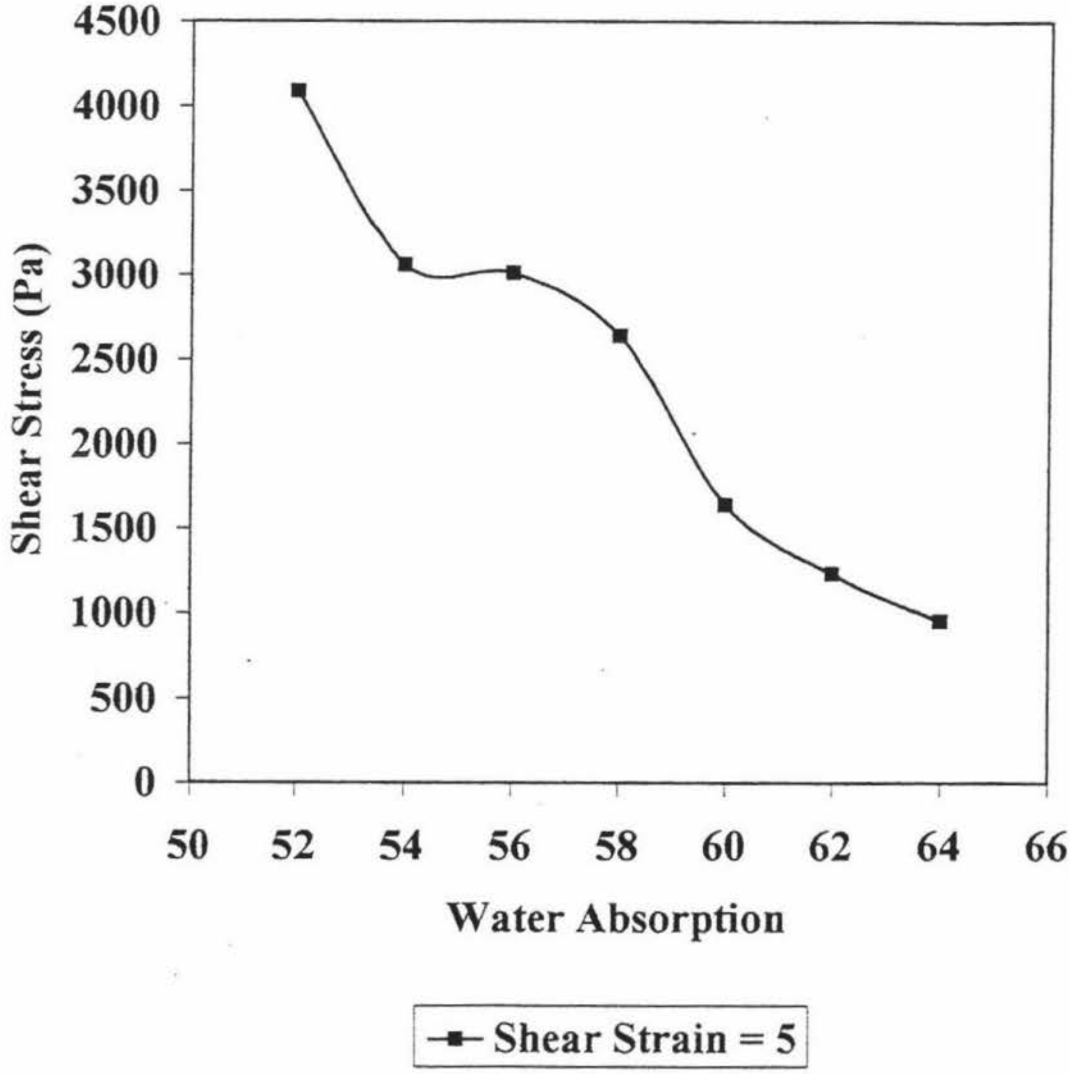


Figure 4.18b Effect of water absorption on the peak shear stress as determined from the large deformation shear stress growth test. Tests were carried in a Bohlin rheometer, PP30 parallel plate geometry with a 2 mm gap and sandpaper. Measurement temperature was 32 °C.

4.4.2 Effect of Resting of Wheat Flour Dough

Dough is dynamically changing once flour is mixed with water. The effect of resting time on dough properties is very important in the day to day operation of a bakery. Thus, it is important to study the effects of this variable on the dough rheological properties using some of the methods developed in this work. For this part of the work the small deformation oscillatory shear test and the large deformation shear stress growth were used to study doughs prepared with Bakers flour. The standard recipe was used and dough was mixed with different levels of work input and tested in the Bohlin rheometer. Results of the small deformation experiment are illustrated in Figure 4.19.

The figure shows that for optimum mixed doughs, even considering the large variation among replicates, the storage modulus appears to increase with resting time. Conversely under and over-mixed dough do not show large variations with resting time. Results of large deformation tests (Figure 4.20), however, show a very different behaviour. Values of the measured peak shear stress decreased with resting time for under and optimally mixed dough whereas increased time for over-mixed time.

Based on these results, it is evident that the small deformation test was not able to detect the effect of resting time on the dough rheological properties whereas the large deformation test did. It is worth nothing that time scales for both experiments were different. For the small deformation test the time was 70 minutes whereas for the large deformation test 180 minutes. Results obtained from the large deformation test for underdeveloped and optimum-mixed dough agreed with those reported by Abdelrahman and Spies (1986). These authors reported that the viscoelastic properties of dough changed with resting time, in particular the phase angle increased and the storage modulus decreased. In both cases the variations were highly dependent on the water absorption used to prepare the dough. Opposite results were reported by Piazza and Schiraldi (1997) and Watanabe et al (1998). The former reported that the glass transition of the dough increased with resting time and attributed this phenomenon to further polymerisation of gluten protein whereas the later, using both fundamental and empirical measurements, found that the dough become more elastic with resting time. These results agree with those obtained in this work for over-mixed dough. However, there is no mention in these works at what levels of work inputs the doughs were mixed.

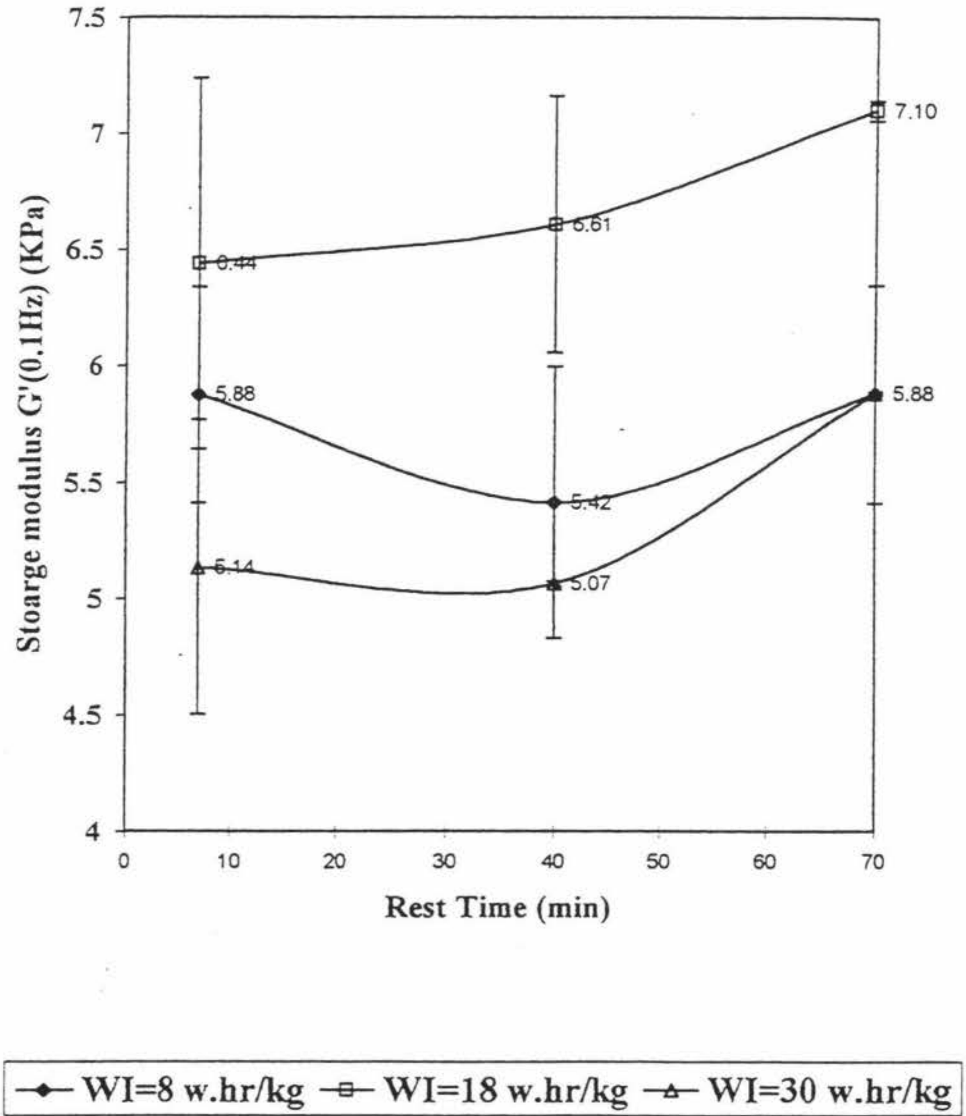


Figure 4.19 Effect of resting time on dough rheological properties. Small deformation test. Bohlin Rheometer parallel plate geometry with a 2 mm gap and sandpaper. Dough was prepared with different levels of work input; Bakers flour dough, the standard recipe and Water Absorption of 59%, Measurement temperature 32 °C.

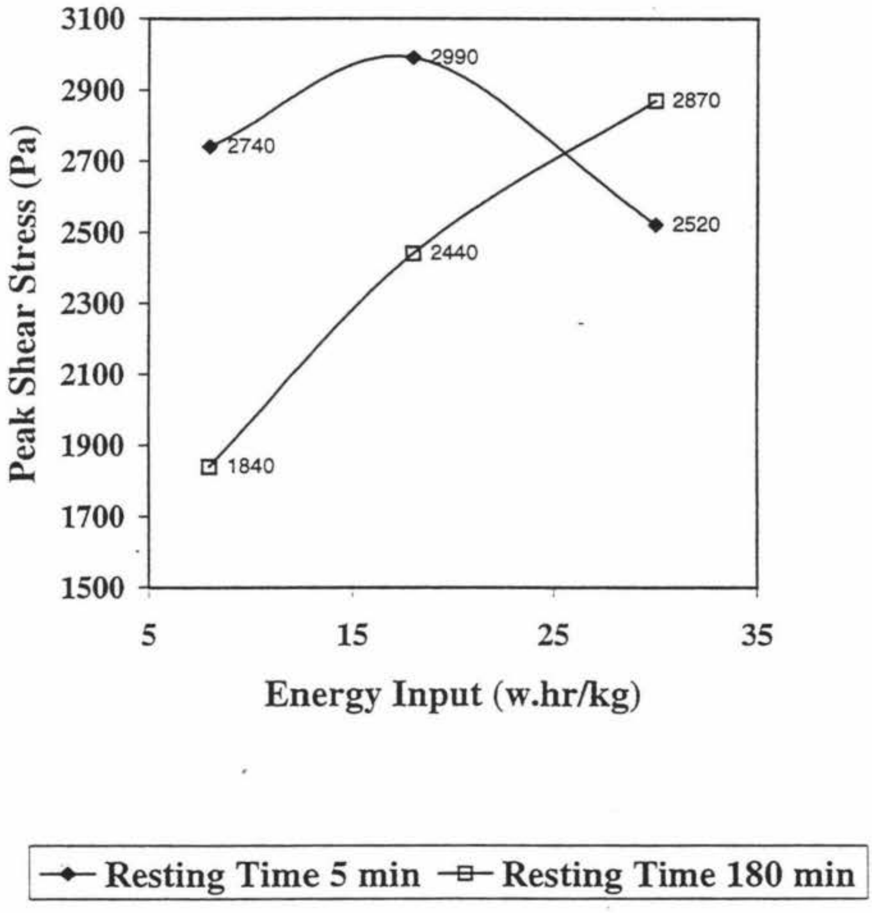


Figure 4.20 Effect of resting time on dough rheological properties. Shear stress growth test. Bohlin Rheometer, Parallel plate geometry with 2-mm gap and sandpaper, Doughs were prepared with different levels of work input. Bakers flour dough, standard recipe and Water Absorption of 59%, Measurement temperature was 32 °C.

4.4.3 Effect of vegetable oil replacing water absorption (Shear Stress Measurements)

Crackers and cookies are characterised by a formula that is high in sugar and oil, but low in water (Menjivar and Faridi, 1990). The rheological properties of dough and how they are affected by oil are then very important from a practical point of view. Thus, in this work the effect of replacing part of the water in the recipe by oil was studied using the large deformation shear stress growth test.

Shear stress versus strain plots of doughs prepared with different levels of oil using Bakers flour and an optimal mixing level of 18 W. hr/kg are shown in Figure 4.21. All the experiments were carried out using parallel plates geometry with a gap of 2 mm and the plates covered with sandpaper. The figure illustrates that a peak force is obtained for shear strains in the range 4-6. Similar result has been obtained with standard dough by Mani et al (1992). In this work, when the peak shear stress is plotted as a function of the percentage of oil added Figure 4.22 is obtained. This figure clearly shows that the consistency of the dough, measured by the peak shear stress, decreases with the oil content up to about 4%-8% and after increases.

The same effect has been observed by Miller (1985), who found that increasing the level of fat in the recipe had a soften effect and lowered the consistency of short doughs.

In this work, however, it was found that after a level of 8% oil the consistency of the dough increase with the oil content. It is thought that the increase in dough consistency at high levels of oil is due to the small availability of water, which is replaced by oil.

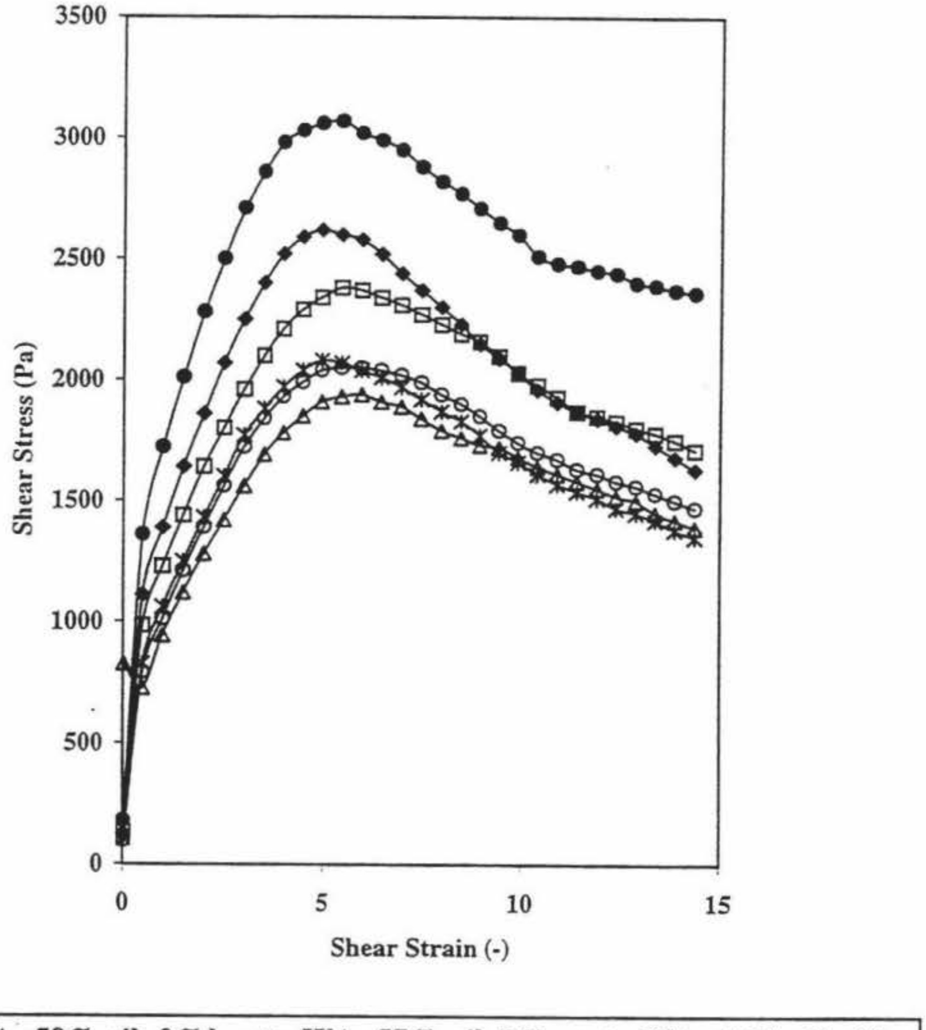


Figure 4.21 Effect of oil on the rheological properties of dough measured using the large deformation shear stress growth test. Bohlin rheometer, parallel plates geometry a 2-mm gap and plates covered with sandpaper. Bakers flour, dough prepared with a work input of 18 W. hr/kg. Measurement temperature was 32 °C.

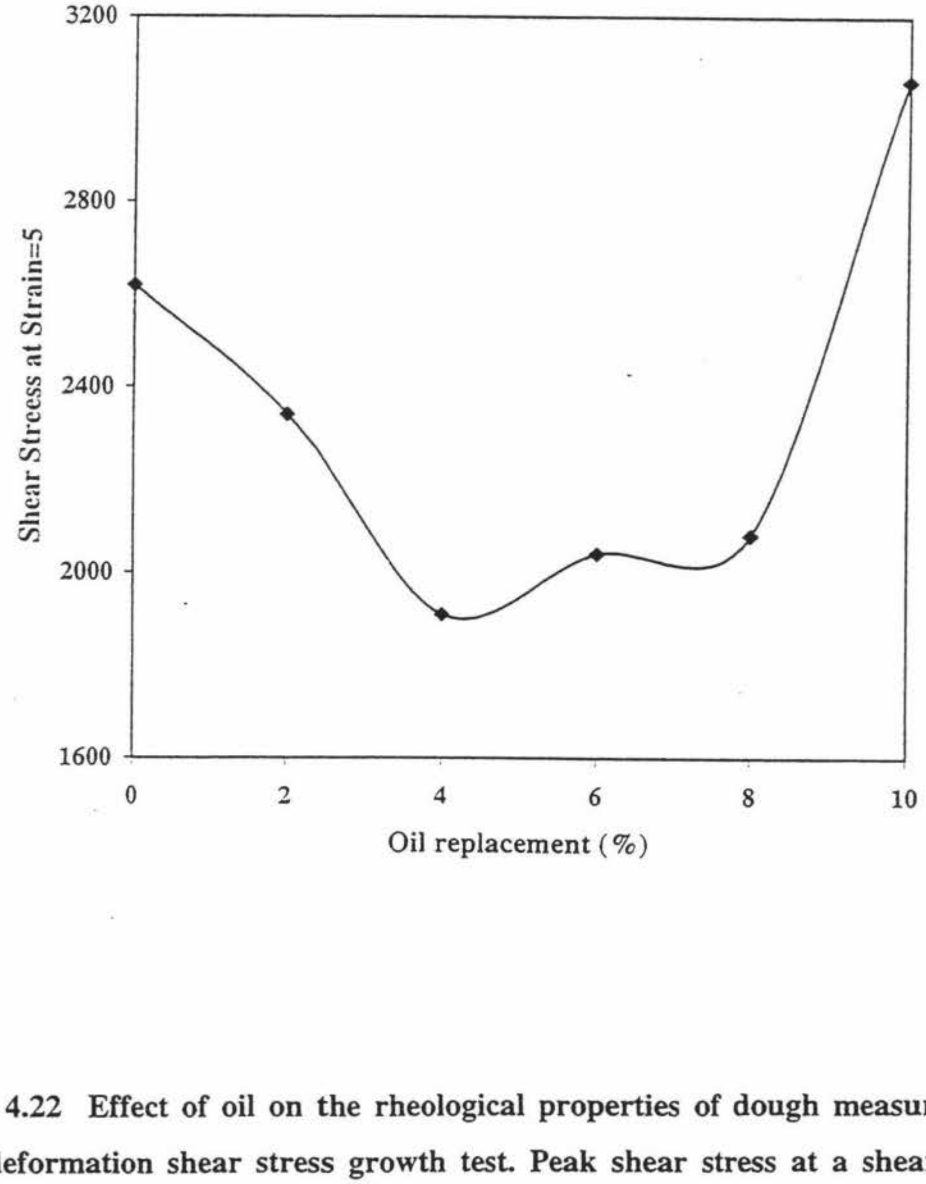


Figure 4.22 Effect of oil on the rheological properties of dough measured using the large deformation shear stress growth test. Peak shear stress at a shear strain of 5. Bohlin rheometer, parallel plate geometry a 2 mm gap and plates covered with sandpaper. Bakers flour, dough prepared with a work input of 18 W. h/kg. Measurement temperature was 32 °C.

4.5 Effect of Sheeting on Wheat Flour Dough

4.5.1 Introduction

Sheeting has a similar function than mixing but is more gently. It has been found that dough can be developed by sheeting it repeatedly between rolls (Moss, 1980). Stenvert et al. (1979) showed that sheeting bread dough resulted in a closely interconnected protein structure that could break down after continued sheeting. This is similar to the breakdown of the protein network in the MDD mixer beyond the optimum mixing level which was described in sections (3.2) During the sheeting process the necessary energy to develop the dough is supplied by the sheeting rolls. Several researchers (Kilborn and Preston, 1982, Levine 1996a, Levine 1996b, Raghavan, et al 1996) tried to link the rheological dough properties to sheeting behaviour. However, a direct comparison between rheological data, energy input and baking quality has not been made. The work presented in this section presents data that relate rheological properties of sheeted dough to bread making potential. For the MDD experiment energy input to the dough is measured from the current drawn by the MDD mixer during mixing. Unfortunately these measurements are not available during sheeting of dough samples. Thus, the number of sheeting passes was used as the variable to indicate the input of energy to the sample. As the number of sheeting passes could not be converted in mixing energy (or work input) the dough was baked to establish, through loaf volume measurement, the optimum number of sheeting passes.

Dough undergoes large deformations during mixing and sheeting. At large deformation the rheological behaviour of dough is highly non-linear and is subjected to extensional and shear flow. Thus, the shear stress growth and the planar extensional flow were selected to carry out the rheological measurements of dough after sheeting.

4.5.2 Baking tests

For these experiments two different flours were used: Beta flour (a strong flour) and Halo flour (a soft flour). Further details of these flours are given in section Chapter 3.

Results of the baking tests, measured as the volume of the loaf resulting from doughs prepared with different sheeting passes, are given in Figure 4.23.

The figure illustrates that the maximum volume varied among flours. It was about 30 passes for Halo flour and about 60 passes for Beta flour. As expected Beta flour (a strong flour) produced loaves with larger volume that Halo flour (a soft flour).

4.5.3 Rheological measurements—Planar Extensional Flow Test

Doughs from the two flours (Halo and Beta) were prepared by mixing flour and additives with water in a Hobart mixer for 1 minute and sheeting the resulting dough for the specified number of sheeting steps. Results of the planar extensional flow test on these doughs are plotted in Figures 4.24 and 4.25, for Halo and Beta flours respectively. Figure 4.24 illustrates that the maximum extensional stress increases with the number of sheeting passes until approximately 20 passes, and then decreased very slightly. The figure would be indicating that Halo flour would have a peak at around 10-20 sheeting passes. These measurements are in general agreement with the baking tests described in the previous section. Similarly the maximum extensional stress for Beta flour is around 20-30 sheeting passes which also agreed with the baking test (Figure 4.25). Baking tests and rheological measurements for Halo and Beta flour provided information that was strongly correlated, That is, the dough that provided the highest loaf volume was the one having the highest extensional stress.

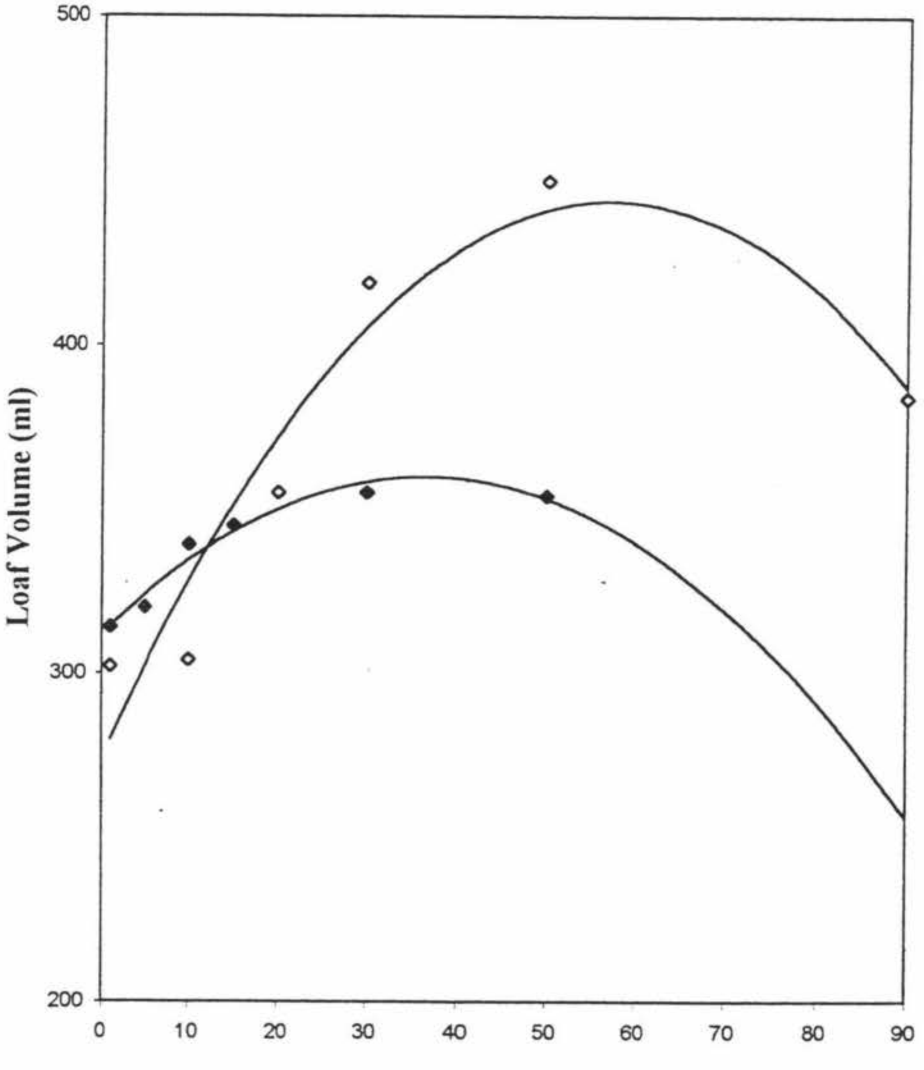


Figure 4.23 Effect of sheeting on the loaf volume of two different flours. Doughs were prepared with a standard recipe and the WA of 59% for Halo, 61% WA for Beta flour, mixed for 1 minute in a Hobart mixer and sheeted for the specified number of passes in a manual sheeter.

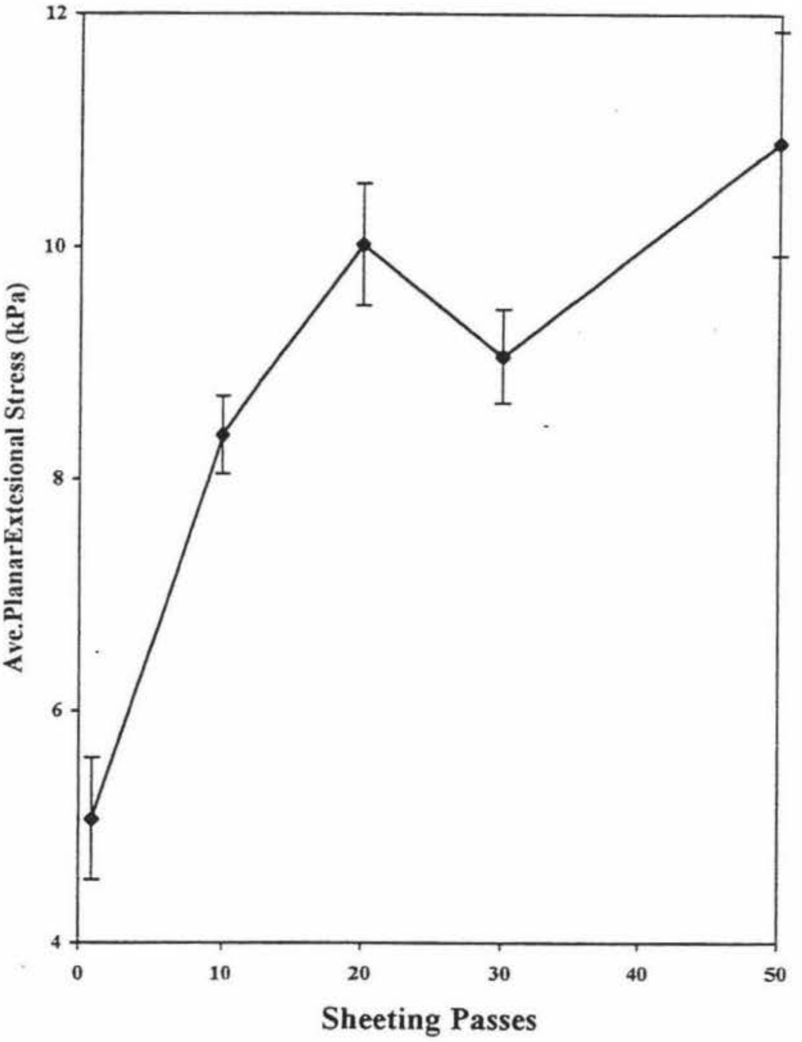


Figure 4.24 Effect of sheeting on the dough extensional properties, Halo flour, standard recipe, Water absorption 59%, sheeter gap 3 mm Deformation rate 60 mm/min, measurement temperature 25 °C.

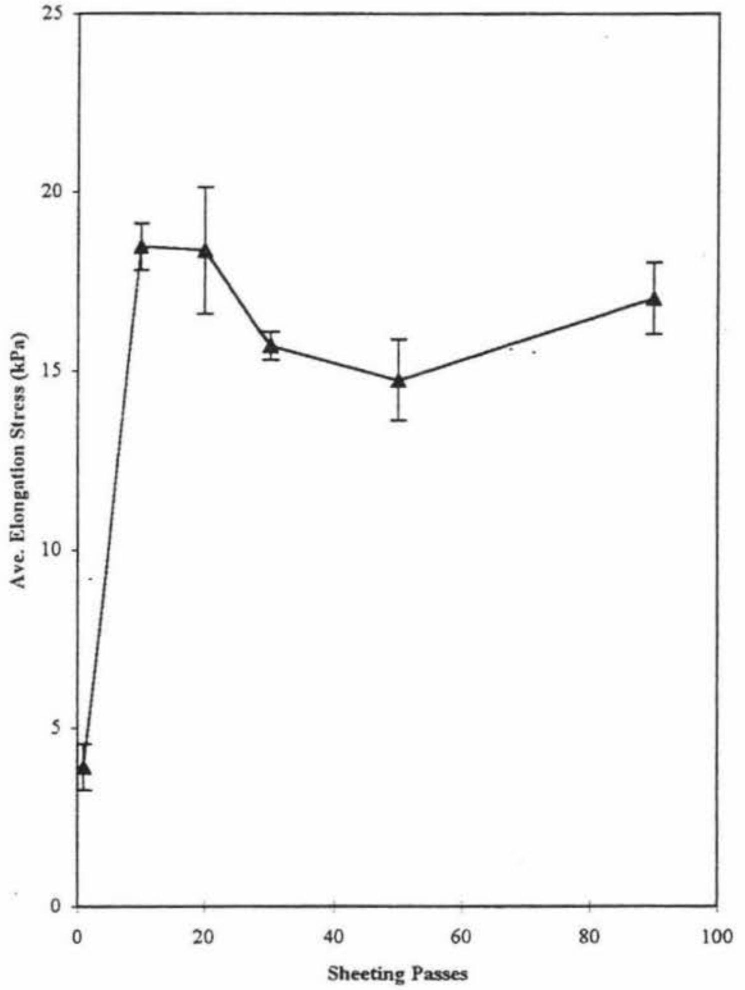


Figure 4.25 Effect of sheeting on the dough extensional properties. Beta flour, standard recipe, water absorption 61%, sheeter gap=3 mm, deformation rate (Instron) 60mm/min, measurement temperature 25 °C.

CHAPTER FIVE

GENERAL CONCLUSIONS AND DISCUSSION

5.1 Conclusions

The correlation between fundamental rheological properties of wheat flour dough and processing conditions applied during breadmaking, notably mixing and sheeting was studied.

It was found that rheological tests using both small and large deformations are appropriated to study fundamental rheological properties of wheat flour dough and how they are affected by processing conditions and dough formulation. The test used were:

- Small Shear Deformation Test
- Large Deformation
    - Shear Stress Growth
    - Shear-Extensional test (Extrusion Test)
    - Planar Extensional Flow

5.1.1 Small Shear Deformation Test

Effect of mixing

Results of small deformation shear tests showed that the rheological properties measured, notably storage modulus G' and the phase angle δ depended on mixing conditions. More reproducible and reliable results were obtained when serrated plates or sandpaper attached to the plates were used. Thus slippage of the samples was considered.

Despite of the large variation obtained among replicates, small deformation tests showed that optimum- mixed doughs exhibited relatively higher values of storage modulus (G') and lower values of phase angle (δ) indicating a more elastic dough.

Results from small deformation shear tests showed that non-mixing dough had similar rheological behaviour than mixed (under-mixed, optimum-mixed and over-mixed) doughs. For all doughs the storage modulus G' increased with the frequency of oscillation indicating their viscoelastic characteristics. The distribution of moisture in non-mixing doughs, however, was far to be uniform. Due to the absence of mixing, moisture distribution in non-mixing dough relies on the size distribution of the ice mixed with the flour. The size of the ice particles, in turn, depends on the way the ice is comminuted and sieved before the mixing so it is very difficult to control. That is the main reason for the high variability observed in non-mixing doughs.

It was also found that non-mixing dough exhibited a higher moisture than mixed dough even though the amount of ice used was corrected by the difference in density between liquid water and ice. When lower amounts of ice were used to prepare non-mixing dough with similar moisture contents than those of mixed dough it was found that the problem of uneven moisture distribution became worse and some lumps of dried flour were noticed on the dough. Thus, mixing is not only important to develop the dough but also to provide a uniform distribution of water.

Effect of water absorption

Water absorption affected the rheological properties of dough measured with the small deformation test. Decreasing water absorption increased the storage modulus G' but the phase angle did not change appreciably. Bread quality is not strongly related with water absorption (Larsen, 1991) but obviously high water absorption results in doughs hard to be handled. However, high water absorption is desired because loaf weight depends on it. Bakers want to sell as much as water as possible.

5.1.2 Large Deformation Tests

5.1.2.1 Shear Stress Growth Test

Results from the large deformation tests indicated that there were significant differences among doughs prepared with different mixing conditions (non-mixing, under mixing, optimal mixing and over mixing). Both Bakers and Soft flour doughs showed that optimal mixed doughs exhibited the highest shear stress peak at the largest shear strain. Similar results were also reported by Lindborg (1995) although the work was concerned with different flours rather than mixing degree.

5.1.2.2 Planar Extensional Flow and Extrusion Tests

Planar extensional test and the extrusion test (a mixture of extensional and shear flow) also showed that significant differences among doughs prepared with different mixing levels. The type of dough also affected the result of the planar extensional test.

5.1.3 Effect of oil

The effect of oil on dough was studied using a large deformation test. Results showed that the consistency of the dough, measured as the peak shear stress, decreased with the oil content up to about 4% - 8% and then increased. Increase in dough consistency at high levels of oil content is probably due to the lower availability of the water being replaced by the oil.

5.1.4 Effect of Resting Time

The effect of resting time on dough properties was studied using the small deformation oscillatory shear test and the large deformation shear stress growth test. Results from the small deformation test showed that for optimum-mixed Bakers flour dough the storage modulus G' increased with resting time. Both under and over mixed dough did not show large variations with resting time. Results from large deformation test showed that peak shear stress of under and optimum-mixed dough decreased with resting time whereas over mixed Bakers flour dough increased.

5.1.5 Effect of Sheeting

It was found that sheeting could develop dough. Different flours produced doughs with rheological properties dependent on the number of sheeting passes. Baking test confirmed that there is an optimal number of sheeting passes which depends on the flour. Rheological measurements using large deformation tests (planar extensional flow tests) showed that extensional stresses were obtained for doughs sheeted to their optimum sheeting level.

5.1.6 Confocal Laser Scanning Microscopy

A Confocal Laser Scanning Microscope was used to observe the difference of Bakers and Soft flour doughs prepared with different mixing conditions. A deep frozen cutting method was introduced to prepare thin slices of dough specimens by using a Cryostat instrument. Results showed that an optimum MDD mixed dough has a well-hydrated and uniform gluten network.

5.2 Discussion

5.2.1 Effect of Energy Input

Dough can be formed by mixing flour and water. Mixing needs energy and without the energy input flour may not be hydrated properly and water may not be distributed quickly and uniformly to form a well developed dough. A gluten network is formed when sufficient water to hydrate the wheat flour protein is added. Water in excess may increase the dough stickiness and decrease its consistency that would cause problems for further handling and processing. At a given water absorption, however, too much energy input may damage dough structure because of depolymerisation of the gluten protein. This could cause a decrease in the ability of gluten to hold water that could be then associated with the starch. Thus, the dough may become stickier. Therefore any flour needs to be mixed up to a point under which the highest loaf volume and finest crumb structure can be obtained and the dough offers the best conditions for processing. This point is called optimum mixing point.

Different flours need different work input and different amounts of water. These two quantities are usually determined by using empirical baking tests. It was one of the objectives of this work to study fundamental rheological properties of dough produced with different amount of mixing and water absorption.

MDD is a fast development-processing tool in modern baking industries. MDD mixing and sheeting operations are also commonly used in fully automated bakeries. Thus the rheological properties of dough and how they are affected by mixing and sheeting have to be known before any process control can be implemented.

In the past, flour specifications always were given by flour millers to help the bakers setting up the processing conditions. These specifications included MDD work input, water absorption, falling number, protein content and moisture content. The parameters were measured using empirical instruments. Unfortunately, empirical methods do not provide data that can be used at conditions that are different than those under which the sample is measured. Thus, empirical tests do not provide data that can be used for scale-up processes. It is thought that the knowledge of fundamental rheological properties could fill this gap.

Results obtained in this study indicated that large deformation tests could be used to measure differences among dough prepared with different work inputs. Although small deformation tests showed a similar trend, the differences were not so large.

Sample preparation was a very important step particularly when a small deformation test was applied. The reproducibility of the shear stress growth test was good and showed that this test could be more suitable than small deformation test to determine the effects of mixing.

The same conclusion can be drawn regarding the extrusion and the planar extensional tests, both large deformation tests.

5.2.2 Effect of Water Absorption

Water content is a very important factor affecting the rheological properties of dough. It has been reported that the amount of water present in dough affects both the rheological properties of the dough and the quality of the finished baked product (Abdelrahman and Spies, 1986). In general, as the water content of dough increase, both G' and G" decrease (Hibberd 1970a, 1970b: Hibberd and Paker, 1975b; Navickis et al., 1982; Dresse et al., 1988). Water content in doughs also affects the dough behaviour during resting time. Optimally mixed doughs, tested immediately and 30 minutes after mixing, showed that increased water absorption caused the elastic response (G') of dough to change at different rates.

Data for non-mixed and under mixed doughs had a large variability because these samples were not mixed uniformly and had a poor moisture distribution. Results seem to indicate that mixing provides a more uniform moisture distribution. Surprisingly, moisture measurements indicated that the dough moisture increased with work input even though the same water absorption was used. Thus, these results would be showing that work input had an important effect on the equilibrium moisture or bond water in the dough sample. This effect was also noted by Frazier (1985).

Because of the important effect of water absorption, loss of moisture in dough samples may cause large errors. Unfortunately evaporation of moisture through the dough surface is inevitable during the measurements. This problem, however, was minimized by applying a thin film of vaseline on the sample edge.

5.2.3 Effect of Resting Time

It is reported in the literature that the viscoelastic properties of dough vary largely with resting time and resting temperature. In this study, it was found that G' values slightly increased with resting time when the dough was under-mixed and optimal-mixed. However, G' values of over mixed dough slightly decreased with resting time. The reasons for this phenomenon could be explained by the breakdown of disulphide bonds when the dough is over-mixed. It appears that the process of disulphide cross-linking is not reversible. They are not reformed again upon rest after the dough is over-mixed.

5.2.4 Effect of Sheeting

Sheeting is a very important processing operation in bakeries. Dough undergoes large deformations during sheeting but more gently. At large deformations the rheological behavior of dough is highly non-linear and is subjected to extensional and shear flow. Results from the planar extensional test showed that there is an optimum number of sheeting passes for different flour. However, the optimum number of sheeting passes was more obvious for Halo (a weak flour) that that of Beta flour (a strong flour).

REFERENCES

Abdelrahman, A. A., and Spies, R. D. (1986). Dynamic rheological studies of dough systems. Fundamentals of Dough Rheology, 87-103, (ed. H. A. Faridi and J. M. Faubion), AACC. St. Paul, MN.

Amemiya, J. I. and Menjivar, J. A. (1992). Comparison of small and large deformation measurements to characterize the rheology of wheat flour doughs. J. of Food Engineering, 16, 91-108.

Baird, D. G. and Athan, E. L. (1982). Invited Review: Food Dough Rheology. Chem. Eng. Commun, 15, 1-25.

Bakes, F. Gras, P. W. and Gupta, R. B. (1994). Mixing properties as measure of reversible reduction and oxidation of doughs. Cereal Chem., 71 (1), 44-50.

Baldwin, P. M., Adler, J., Davies, M. C., and Melia, C. D. (1994). Hole in starch granules: confocal, SEM and light microscopy studies of starch granule structure. Starch, 46, Nr.9.S. 341-346.

Bass. E. J. (1988). Wheat flour milling. Wheat: Chemistry and Technology, Vol. 2. 1-68, (ed. Y. Poneranz). AACC. St. Paul, MN.

Bechtel, D. B. Pomeranz, Y. and Francisco, A. (1978). Breadmaking studied by light and transmission electron microscopy. Cereal Chem., 55, 392-401.

Blonk, J. C. G. and Aalst, H. V. (1993). Confocal scanning light microscopy in food research. Food Research., 26, 297-311.

Bloksma, A. H. and Bushuk, W. (1988). Rheology and chemistry of dough. Wheat: Chemistry and Technology, Vol. 2, (ed. Y. Pomeranz), AACC. St. Paul, MN.

Bloksma, A. H. (1990a). Rheology of breadmaking process. Cereal Foods World, 35, 228-236.

Bloksma, A. H. (1990b). Dough structure, dough rheology, and baking quality. Cereal Foods World, 35, 237-244.

Bohlin, L. and Carlson, L. G. (1980). Dynamic viscoelastic properties of wheat flour dough dependence on mixing time. Cereal Chem., 57(3), 174-177.

Bozzola, J. J. and Russell, L. D. (1991). Electron microscopy. 2-11, 14-37.

Brooker, B. E. (1991). The study of food systems using confocal laser scanning microscopy. Microscopy and analysis, 11, 13-15.

Bushuk, W. (1995) Structure of dough. AACC Short course lecture on frozen dough technology in Christchurch, New Zealand, (Print by Dept. of Food Science, University of Manitoba, Winnipeg, Manitoba, and Canada). 1-66.

Bushuk, W. (1985). Flour proteins: structure and functionality in dough and bread. Cereal Foods World, 30, 447-451.

Campos, D. T., Steffe, J. F., and Ng, P. K. W. (1996). Mixing wheat flour and ice to form undeveloped dough. Cereal Chem., 73. 105-107.

Castell-Perez, M. E. and Steffe, J. F. (1986). Viscoelastic Properties of Dough. Dough rheology and baked product texture, (ed. H. A. Faridi, and J. M. Faubion,). New York: Van Nostrnd Reinhold.

Chatraei, S. H., Macosko, C. W. and Winter, H. H. (1981). Lubricated squeezing flow: a new biaxial extensional rheometer. J. Rheol., 25. 433-443.

Cogswell, F.N. (1972). Converging Flow of Polymer Melts in Extrusion Dies. Polym. Eng. Sci., 12, 64-73.

Cullen-Refai, A., Faubion, J. M. and Hoseney, R. C. (1990). Lubricated uniaxial compression of fermenting doughs. Cereal Chem., 65, 401-403.

Cooke, P. M. (1994). Chemical microscopy. Anal. Chem., 66, 558R-594R

Cumming, D. B. and Tung, M. A. (1977). Modification of the ultrastructure and rheology of dehydrated commercial wheat gluten. Can, Inst. Food. Sci. Technol. J., 10, 109-119.

Dreese, P. C., Faubion, J. M., and Hoseney, R.C. (1988a). The effect of different heating and washing procedures on the dynamic rheological properties of wheat flour gluten. Cereal Foods World, 33 (2), 225-229.

Dreese, P. C., Faubion, J. M., and Hoseney, R.C. (1988b). Dynamic rheological properties of flour, gluten, and gluten-starch doughs. I: Temperature-dependent changes during heating. Cereal Chem., 65, 348-353.

Dreese, P. C., Faubion, J. M., and Hoseney, R.C. (1988c). Dynamic rheological properties of flour, gluten, and gluten-starch doughs. II: Effect of various processing and ingredient changes. Cereal Chem., 65, 355-359.

Eliasson, A. C., (1990). Rheological properties of cereal proteins. Dough rheology and baked product texture. 67-110, (ed. H. Faridi and J.M. Faubion, Van Nostrand. Reinhold), New York.

Evans, L. G., Volpe, T., and Zablk, M. E. (1977). Ultrastructure of bread dough with yeast single cell protein and/or emulsifier. J. of Food Science, 42, 70-74.

Faubion, J. M., Dreese, P. C., and Diehl, K. C. (1985). Dynamic rheological testing of wheat flour doughs. Rheology of wheat flour products, 91-116, (ed. H. Faridi), AACC. St. Paul, MN.

Faubion, J. M. and Hoseney, R. C. (1990). The Viscoelastic Properties of Wheat Flour Doughs. Dough rheology and baked product texture. 29-62, (ed. H. A. Faridi, and J. M. Faubion), New York: Van Nostrnd Reinhold.

Ferry, J.D. (1970). Viscoelastic Properties of Polymer. 2nd ed. New York: John Wiley & Sons.

Finney, K. F., Yamazaki, W. T., and Morris, V. H. (1950b). Effects of varying quantities of sugar, shortening, and ammonium bicarbonate on the spreading and top grain of sugar-snap cookies. Cereal Chem., 27, 30-41.

Flint, O., Moss, R., and Wade, P. A. (1970). A comparative study of microstructure of different types of biscuits and their doughs. Food Trade Rev., 40 (4), 32-39.

Frazier, P. J., Daniels, N. W. R., and Russell Eggett, P. W. (1975). Rheology and the continuos breadmaking process. Cereal Chem., 56, 106r-130r.

Frazier, P. J., Fitchett, C. S., and Russell Eggett, P. W. (1985). Laboratory measurement of dough devilment. Rheology of wheat products, 151-176, (ed. H. Faridi), AACC. St. Paul. MN.

Funt Bar-David, C. B., and Lerchenthal, CH. H. (1975). Rheological and thermodynamic properties of gluten gel. Cereal Chem., 52, 154r-169r.

Hamada, A. S., McDonald, L. M., and Sibbitt, L. D. (1982). Relationship of protein fractions of spring wheat flour to baking quality. Cereal Chem., 59, 296-301.

He, H. and Hoseney, R. C. (1992a). Factors controlling gas retention in nonheated doughs. Cereal Chem., 69(1), 1-6.

He, H. and Hoseney, P. C. (1992b). Effect of the quality of wheat flour protein and bread loaf volume. Cereal Chem., 69 (1), 17-19.

Heertje, I. Van der Vlist, P., Blonk, J.C.G., Hendrick, H. A. C. M. And Brakenhoff, G. J. (1987a). Confocal scanning laser microscopy in food research, Food Microstructure, 6, 115-120.

Heertje, I. (1993). Structure and function of food products. Food Structure, 12, 343-364.

Hibberd, G. H. (1970a). Dynamic viscoelastic behavior of wheat flour doughs. II. Effects of water content in the linear region. Rheol. Acta. 9, 497-500.

Hibberd, G. H. (1970b). Dynamic viscoelastic behavior of wheat flour doughs. III. The influence of the starch granules. Rheo. Acta, 9, 501-505.

Hibberd, G. H. and Paker, N. S. (1975a). Measurement of the fundamental rheological properties of wheat-flour doughs. Cereal Chem., 52, 1r-23r.

Hibberd, G. H. and Paker, N. S. (1975b). Dynamic viscoelastic behavior of wheat flour doughs. Rheol. Acta, 14, 151-157.

Hibbard, G. E. and Wallace, W. J. (1966). Dynamic viscoelastic behavior of wheat flour doughs. I. Linear aspects. Rheol. Acta., 5, 193-196.

Hoseney, R. C., Hsu, K. H., and Junge, R. C. (1979). A simple spread test to measure the rheological properties of fermenting dough. Cereal Chem., 56, 141-143.

Hoseney, R. C. (1985). The mixing phenomenon. Cereal Foods World, 30, 453-457.

Hoseney, R.C. (1986). Component interaction during heating and storage of baked products. Chemistry and Physics of Baking, 216-226, (ed. J.M.V. Blanschard, P.J. Frazier and T. Galliard).

Hoseney, R. C. and Rogers, D. E. (1990). The formation and properties of wheat flour doughs. Food Science and Nutrition, 29, I2, 73-93.

Janssen, A. M. (1995). Obelisk and Katepwa wheat gluten: A study of factors determining bread making performance. Ph.D. Thesis. (Dept. of Biochemistry Groningen University, The Netherlands), 1-147.

Khoo, U., Christianson, D. D., and Inglett, G. E. (1975). Scanning and transmission microscopy of dough and bread. Baker's Dig., 49, 24-26.

Kilborn, R. H. and Tipples, K. H. (1972). Factors affecting mechanical dough development I. Effect of mixing intensity and work input. Cereal Chem., 49, 34-47.

Kilborn, R. H. and Tipples, K. H. (1973a). Factors affecting mechanical dough development.III Mechanical efficiency of laboratory dough mixers. Cereal Chem., 50, 50-69.

Kilborn, R. H. and Tipples, K. H. (1973b). Factors affecting mechanical dough development. IV. Effect of cysteine. Cereal Chem., 50, 70-86.

Kilborn, R. H. and Tipples, K. H. (1974). Implications of the mechanical development of bread dough by means of sheeting rolls. Cereal Chem., 51, 648-657.

Kokelaar, J. J. (1994). Physics of breadmaking. Ph.D. thesis. Wageningen Agricultural University, The Netherlands, 1-129.

Lang, C. E., Neises, E. K., and Walker, C. E. (1992). Effects of additives on flour-water dough mixograms. Cereal Chem., 69, 587-591.

Larsen, N. G. and Greenwood, D. R. (1991). Water addition and the physical properties of mechanical dough development doughs and bread. J. of Cereal Sci., 13, 195-205.

Lastztity, R. (1997). The chemistry of cereal proteins. 2nd ed., Bragger, New York, Tokyo,

Levine, L. and Drew, B. A. (1990). Rheological and engineering aspects of sheeting and laminating of doughs. Dough rheology and baked product texture. 513-555, (ed. H. A. Faridi, and J. M. Faubion), New York: Van Nostrand Reinhold.

Levine, L. (1996a). Research note. Estimating sheeting roll closing forces through measurement of power consumption. J. of Food Proc. Eng., 19, 113-119.

Levine, L. (1996b). Model for the sheeting of dough between rolls operating at different speeds. Cereal Foods World, 41, 692-697.

Lindborg, K. M. (1995). Rheological studies of wheat flour doughs. The development of structure during mixing. Ph.D. thesis, LUND University. Dept. of Food Engineering.

MacRitchie, F. (1984). Baking quality of wheat flours. Advances in Food Research, 29, 201-277.

Mani, K., Tragardh, C., Eliasson, A. C., and Lindahl, L., (1992a). Water content, water-soluble fraction, and mixing affect fundamental rheological properties of water flour doughs. J. of Food Sci., 57, 1198-1210.

Mani, K., Eliasson, A. C., Lindahl, L. and Tragardh, C. (1992b). Rheological properties and breadmaking of quality of wheat flour doughs made with different dough mixers. Cereal Chem., 69 (2), 222-225.

Matsumoto, S. (1979). Rheological properties of synthetic flour doughs. Food Texture and Rheology. 291-301, (ed. P. Sherman). New York: Academic Press.

McKenna, A. B. (1995). Food Microstructure Seeing the unseen at the New Zealand Dairy Research Institute. Food Technologist, 24 (4), 34-38

Menjivar, J. A. and Faridi, H. (1990). Rheological properties of cookie and cracker doughs. in Dough Rheological and Baked Product Texture. 283-322, (ed. H. Faridi and J. M. Faubion Van Nostrand. Reinhold), New York.

Miller, A. R. (1985). The use of a penetrameter to measure the consistency of short doughs. In Rheology of wheat products, (ed. N. Faridi), AACC. St. Paul MN.

Minsky, M. (1957). Microscopy Apparatus. United States Patent 3,013,467, Dec. 1961.

Mitchell, T. A. (1989). Methods used in monitoring and controlling the quality of bread with particular reference to the mechanical dough development process. Modern methods of plant analysis new series, Volume 10 plant fibers, Berlin, Springer-Verlaag.

Morgenstern, M. P., Newberry, M. P., and Holst, S. E. (1996). Extensional properties of dough sheets. Cereal Chem., 73, 478-482.

Moss, H. J. (1980). Strength requirement of dough designed for repeated sheeting compared with those of normal doughs. Cereal Chem., 57: 195-197.

Moss, R. (1974). Dough microstructure as addicted by the addition of cysteine, potassium bromate, and ascorbic acid. Cereal Sci. Today. 19, 557-560.

Muller, H. G. (1973). An introduction to food rheology. (ed. William Heinemann Medical Books Ltd.,)

Navickis, L. L., Anderson, R. A., Bagley, E. B., and Jasburg, B. K. (1982). Viscoelastic properties of wheat flour doughs: Variation of dynamic moduli with water and protein content. J. Text. Stud., 13, 249-259.

Paredes, L. O. and Bushuk, W. (1983a). Development and 'undevelopment' of wheat dough by mixing: microscopic structure and its relations to bread-making quality. Cereal Chem., 60, 19-23.

Paredes, L. O. and Bushuk, W. (1983b). Development and 'undevelopment' of wheat dough by mixing physic-chemical studies. Cereal Chem., 60, 24-27.

Paredes, L. O. and Bushuk, W. (1982). Development and underdevelopment of wheat dough by mixing: Microscopic structure and its relations to bread making quality. Cereal Chem., 60, 24.

Pawley, J. B. (1990). Handbook of biological confocal microscopy. 1-13.

Petrofsky, K. E. and Hoseney, R. C. (1995). Rheological properties of dough made with starch and gluten from several cereal sources. Cereal Chem., 72, (1), 53-58.

Piazza, L. and Schiraldi, A. (1997). Correlation between fracture of semisweet hard biscuits and dough viscoelastic properties. Journal of texture studies. 28, (5), 523-541.

Pomeranz, Y. (1988). Composition and functionality of wheat flour components. Wheat: Chemistry and Technology, AACC. St. Paul. MN.

Pyler, E. J. (1988). Bread making process, Dough rheology. Baking science & technology. (3rd ed.). 589-614, 850-903.

Raghavan, C. V., Srichandom Babv, R., Nagin, Chand and Srinivas Rao, P. N. (1996). Response surface analysis of power consumption of dough sheeting as a function of gap, reduction ratio, water, salt and fat. J. of Food Sci. and Tech., 33, 313-321.

Ramkumar, C. (1998). The effect of pH and time on rheological change during early cheese maturatioin. PhD thesis.

Ramkumar, C., Campanella, O. H., Watkmson, P. J., Bennett, R.J. and Creamer, L. K. (1998). The effect of pH and time on rheological change during early cheese maturation. J. of texture studies. (in Press)

Redlinger, P. A., Setser, C. S., and Dayton, A. D. (1985). Measurements of bread firmness using the Instron universal testing instrument: differences resulting from test conditions. Cereal Chem., 62,(3), 223-226.

Sandstedt, R. M., Schaumburg, L., and Fleming, J. (1954). The microscopic structure of bread and dough. Cereal Chem., 31, (43)

Shotton, D. (1993). Electronic light microscopy techniques. in Modern Biomedical Microscopy. 2-35.

Smith, J. R., Smith, T. L., and Tschoegl, N. W. (1970). Rheological properties of wheat flour doughs. Rheol. Acta., 9, 239-252.

Spies, R. (1989). Application of rheology in the bread industry. Dough rheology and baked product texture (ed. Faridi, H. A., and Faubion, J. M.), New York: Van Nostrnd Reinhold.

Stenvert, N. L., Moss, R., Pointing, G., Worthington, G., and Bond, E. E. (1979). Bakers Dig. 53, 22-27.

Szczesniak, A. S. (1988). Applying rheology to dough and baked goods. Cereal Foods World. 33, 1253-1256.

Szczesniak, A. S., Loh, J., and Mannell, W. R. (1983). Effect of moisture transfer on dynamic viscoelastic parameters of wheat flour / water systems. J. Rheol.. 27, 537-542.

Tipples, K. H. and Kilborn, R. H. (1975)."Unmixing"—The disorientation of developed bread doughs by slow speed mixing. Cereal Chem. 52, 248-256.

Tipples, K. H. and Kilborn, R. H. (1977). Bakery Digest. 48, (5) 34

Tipples, K. H. and Kilborn, R. H. (1979). Dough development studies and the phenomenon of unmixing. Food Technology in Australia. 4, 141-143.

Varriano-Marston, E. (1977). A comparison of dough preparation procedures for scanning electron microscopy. Food Technology, Oct. 33-36

Vaughan, J. G. (1979). Food Microscopy. Academic Press, 75-186.

Watanabe, E., Bell, A. E. and Brockway, B. E. (1998). The effect of protein disulphide isomers on dough rheology assessed by fundamental and empirical testing. Food Chemistry, 61 (4), 481-486.

Wall, J. S. (1979), The role of wheat proteins in determining baking quality. In Recent Advances in the Biochemistry of Cereals, 303, (ed. D. L. Laidman and R. G. Wyn Jones,), Academic Press, London.

Wehrli, H. P. And Pomeranz, Y. (1969). The role of chemical bonds in dough. The Bakers Digest. 12.

Weipert, D. (1990). The benefits of basic rheometry in studying dough rheology. Cereal Chem., 64 (4), 311-317.

Weipert, D. (1992). Descriptive and fundamental rheometry in a new light. Cereal Food World, 37, 15-16, 18-20, 22-24.

Wilson, A. J. (1983). Measurement of work input in industrial mixers. Research Report. New Zealand Institute for Crop and Food Research.

Zheng, H. (1997). Rheological changes of dough during dough development Diploma thesis. Food & Technology Department, Massey University